Chapter 1   Introduction

1.1 Introduction

In the present era of technology, reliability is one of the foremost concerns of each and every industry. Reliability is the trademark of a product/system. It is considered to be one of the most important factors of each and every product/system. As in the aviation industry, if a plane is not reliable then the life of thousands of people, who travel by plane are at a high risk, same thing applies for nuclear reactor, thermal power plant and many of the other systems. In our routine life, we experience and use many things; they may or may not work in a proper way which is expected from them i.e. not performing their function in the required manner. From this, we often make remarks that a particular brand of washing machine, motor, automobile etc. is reliable or not reliable. When we say a system is reliable, we mean that it performs its function without interruption, for a specified time and in a specified condition [1]. A thing or system which performs its operation in a specified manner is known as reliable or consistent.

The complication of industrial systems along with their products is increasing day-by-day. The enhancement in the effectiveness of such complex systems has therefore developed special rank. The effectiveness of the system is understood to mean the suitability of the system for the fulfillment of the intended tasks and the efficiency of utilizing the means put into it. The affordability of execution of the definite tasks is primarily determined by reliability and quality of the system and the reliability characteristics of a system depend much more on the system configuration and working environment. For example, the paper industry comprises large, complex industrial systems arranged in series, parallel or a combination of both of these. Some of the examples of these systems are chipping, cooking, washing, bleaching, screening, stock preparation and paper production. These systems are generally arranged in a hybrid/mixed configuration. Some more examples are sugar mill, thermal power plant, nuclear reactor etc.

Last few decades can be earmarked for the all-around industrial development. Continuous improvement in the area of technology, productivity, maintenance standards and quality has resulted in a cut throat competition in the industries. Today, industries are striving to achieve improvement in efficiency in all the fronts (including production and maintenance) to have a more competitive edge over other similar industries. Therefore, each equipment/operation in
the organization is critically examined to enhance the productivity/profitability. Improvement in product quality and productivity can be achieved by switching over to advanced technology and by increasing the equipment availability and reliability factors [2]. However, if a machine’s reliability and availability increases, then the production can be increased and the nice prospects of finding new customers for more products can be made. Moreover the price of manufacturing will be reduced and ultimately profitability will be increased.

1.2 Need and Scope of Reliability

The reliability forecast of engineering/industrial structures is becoming ever more important because of some important factors such as cost, risk of hazard, competition, public demand and usage of new technology. The high reliability level is desirable to reduce overall cost of production and risk of hazards for larger, more complex and sophisticated systems. A manufacturing industry is basically a profit making organization and it is well known fact that without an optimal level of results, it is not achieved. So, in order to make more and more profit from an organization, it is necessary that machines/systems should be reliable as much as possible. In order to ensure higher productivity and to improve quality of a product, the efficiency of the machines/industry/equipment must be retained at the optimal level. One of the major challenges for the industries, in this highly competitive global market, is to produce high quality products with the usage of less energy and less resources. Due to economic globalization, industries are facing severe competition from local competitors as well as foreign competitors. For success in this environment, the industries must significantly improve the productivity, quality, maintenance standards and minimize the scrap during production [3].

A system is a collection of subsystems, components and units whose proper coordination leads to proper functioning of the system [1]. The term reliable is usually used in the same sense as dependable/trustworthy. When a statement is made to the effect that a particular component is reliable, we mean that the component will behave in the manner which is expected from it. Further, if that particular component happens to fail unexpectedly, we consider it as a chance of failure.
1.3 Reliability Theory

(a) Reliability Definitions

It is generally defined as the probability, that a particular item performs accordingly, which is expected from it, during a given interval of time. In daily life the word reliable is commonly used as a performance measure of a system/machine/component/item without its degradation. A lot of researchers have studied extensively in the field of reliability to evaluate the various reliability measures of a system/machine/component/item. A lot of definitions are given to define the term reliability; out of them some standard definitions of reliability are mentioned below.

- “Reliability is a function of environment as well as the components itself and in particular depends upon environmental variability.” [4]

- “Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered.” [4]

- “Reliability can be defined in terms of dependability where dependability is defined as the probability that a system will be available to operate when needed.” [4]

- “Reliability is the probability of performing a specified function under the given operating condition for a specified period of time.” [4]

- “Reliability is the ability of equipment to preserve its output characteristic within established limits under given operating conditions.” [4]

- “Reliability is the quality over time.” [4]

- “Reliability is the probability of a device performing its purpose adequately for the period intended under the giving operating conditions.” [1]

- “The probability that an item will perform its required function without failure under stated conditions for a stated period of time is known as reliability of that item.” [5]
In all the definitions mentioned above, it is observed that reliability is defined in terms of probability. Reliability is the ratio of number of terms, we expect the output, to the total number of trials. Its maximum value is one and minimum value is zero. A value one shows that the item is 100% reliable and a value zero shows that the item never performs its purpose [1].

The second element in the reliability theory is adequate performance. Basically adequate performance is the thing that is exactly required from an item.

The third and most important thing in the field of reliability theory is the duration of its performance, i.e. the time interval in which performance occurred.

The fourth and last important thing in the field of reliability theory is the operating conditions. The environment or operating conditions in which, we expect a device to function adequately could be with regard to temperature, humidity, shock, vibration and so on e.g. an air conditioner which performs satisfactorily in the specified temperature zone may not have the same performance characteristic for hot and acid climate conditions. Similarly, an automobile shock absorber may be satisfactory if the vehicle is used mainly on highways. However, if the vehicle is generally used on uneven or rough roads, its life span may be short. Hence, it is essential to stipulate the conditions under which the performance characteristics of equipment or a device will have to be evaluated [1].

(b) Measures of System Performance

In this section, we have discussed the factors whose evaluation reflects the system performance. These are discussed below one-by-one:

(i) Reliability

Reliability has been praised for a long time and it came in lime light somewhere from last five to six decades. Its application started in World War I and then it was used in many other areas. As the development of any item depends on its reliability, it is one of the most important departments in every organization/industry.

The term reliability reflects that it is the performance measure of a system or device, how it performs its work or function in a specific time and in specific condition. If a device or system performs its function without failure for the time specified then we can say that particular device is reliable [5]. The various definitions of the term reliability are given in section 1.3(A).
(ii) Availability

The probability that an equipment is operating in a particular condition for a given period of time is known as availability [1]. It is another measure of performance of maintaining equipment/system/component. The probability that a system is available in a specified condition for a specific period is known as availability of the system or it can be stated that availability is a period in which a system is available for functioning. Mathematically, it is the ratio of system uptime and total time (i.e. uptime + down time).

\[
\text{Availability} = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}
\]

(1.1)

Where

- MTBF = Mean time between failures
- MTTR = Mean time to repair

Availability can be classified as:

- Steady state availability
- Achieved availability
- Operational availability
- Inherent availability

Instead of other parameters, systems availability depends much more on the system configuration, i.e. how the subcomponents are interconnected to each other in the system?

- **Availability in Series**

Let we have \( n \) components namely \( x_1, x_2, x_3 \ldots \ldots \ldots \ldots x_n \) connected in series in a system, then the availability of the system is the product of availability of these \( n \) components i.e. if \( A_{x_1}, A_{x_2}, A_{x_3}, \ldots \ldots A_{x_n} \) is the availability of these components individually than the availability of the system is given as:

\[
\text{Availability} = A_{x_1} A_{x_2} A_{x_3} \ldots \ldots A_{x_n}
\]

(1.2)

The above result implies that the availability of a system in which components are connected in series configuration is lower than the individual availability of the components of the system.
**Availability in Parallel**

Let us have two components connected in parallel configuration in a system. The system works only if any one of these two components works. If $A_x$ is the availability of each of these two components than the availability of the system is given by:

$$\text{Availability} = 1 - (1 - A_x)^2 \quad (1.3)$$

Thus, we can observe that the availability of a system in which components are connected in parallel configuration is much higher than the availability of individual components of the system.

In the same way, using equation (1.2) and (1.3), the availability of the system in which the components are connected in mixed (combination of series and parallel) configuration can be calculated.

(iii) **MTTF**

MTTF is a basic measure of reliability of reparable systems. It is extremely similar to mean time between failures (MTBF). The difference between these terms is that while MTBF is expected time to failure after a failure and repair of the components or system, MTTF is the expected time to failure of a component or system i.e. mean time to failure of the components or systems [1]. As a metric, MTTF represents how long a product can reasonably be expected to perform in the field based on specific testing. It’s important to note, however, that the mean time to failure metrics provided by companies regarding specific products or components may not have been collected by running one unit continuously until failure. Instead, MTTF data is often collected by running many units, even many thousands of units, for a specific number of hours. It is defined as:

$$\text{MTTF} = \lim_{s \to 0} \overline{R}(s) \quad \text{or} \quad \text{MTTF} = \int_0^\infty R(t) \, dt \quad (1.4)$$

Where $R(t)$ is the system’s reliability and it is defined as $R(t) = P(T > t) = \int_t^\infty f(x) \, dx$, and $\overline{R}(s)$ is Laplace transform of $R(t)$. 

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(iv) **MTTR**

Mean time to repair of a system is the mean time required to repair the system [6]. It is a much needed parameter for the management of the system. The goal of a system designer is to maintain MTTR as low as possible.

It can be defined as: 

$$MTTR = \frac{\sum \text{Time taken in repair}}{\text{Total number of repairs}}$$

(1.5)

It also can be defined as:

$$MTTR = \lim_{t \to \infty} \left[ P_{\text{down}}(t) \right]_{\text{with all repairs equal to zero}}$$

(1.6)

Where $P_{\text{down}}(t)$ is the probability that the system is in the failed state.

(v) **MTBF**

As the term indicates that MTBF is the mean time among failures of a structure. Mean time between failures is a reliability characteristic used to find out the number of failures occurred per unit time. It is the predicted elapsed time between inherent failures of a system during its operation [5]. It can be calculated as the arithmetic mean time between failures of a system. It is calculated only for repairable system. In the case of non-reparable system MTBF is meaningless. It is one of the most common queries about a system’s life cycle and it is very helpful to the management for decision making regarding system.

It can be defined as:

$$MTBF = \frac{\sum \text{Time between failures}}{\text{Total number of failures}}$$

(1.7)

It also can be defined in terms of density function $f(t)$ as:

$$MTBF = \int_{0}^{\infty} t f(t)\, dt$$

(1.8)
(vi) **Sensitivity Analysis**

Sensitivity analysis helps us to identify critical components of a system or portions of the system that are particularly sensitive to error. By this analysis one can identify that on which failure the management of the system focused most, this helps to improve the performance of a system. The sensitivity of a factor is most regularly defined as the partial derivative of that factor. This measure is then used to estimate the outcome of factor changes on the system’s result without requiring a full system solution for each factor change. These input factors are mostly failure rates.

(c) **Reliability Measure’s in Various Configurations**

System configuration means how the components of a system are connected to each other in the system. It may be connected in series, parallel or mixed configuration, i.e. the combination of series and parallel.

The reliability of a system depends upon the individual reliability of the components of the system, but it also depends upon the configuration in which these components are connected with each other to form the system. There are three types of configuration in which the components are connected to each other in a system. These are:

(i) **Series Configuration**

The simplest way of assembling the components of a system is series configuration. A series configuration is the configuration in which failure of any single component results in system failure. It is the most commonly used structure. In this configuration, all the components are required to perform their work for successful operation of the system. If anyone out of them fails, then the complete system goes into the failed state [1]. A series configuration of \( n \) components is shown in the Fig. 1.1.

![Series Configuration Diagram](image)

Fig. 1.1. Series Configuration
Let \( X_1, X_2, \ldots, X_n \) represents the successful operation of unit \( A_1, A_2, \ldots, A_n \) respectively and their respective probability are denoted by \( P(X_1), P(X_2), \ldots, P(X_n) \). For the successful functioning of the structure, it is required that all \( n \)-unit functions properly simultaneously. If anyone of the unit fails during the operation then complete system is failed. Let the successful operation of the system is denoted by \( P(S) \).

If the performance of the components is independent from each other than the system reliability is given as:

\[
P(S) = P(X_1)P(X_2)P(X_3)\ldots P(X_n)
\]

If the performance of the components is not independent from each other than the system reliability is given as:

\[
P(S) = P(X_1)P(X_2 \mid X_1)P(X_3 \mid X_1 \text{ and } X_2)\ldots P(X_n \mid X_1 \text{ and } X_2 \text{ and } \ldots \text{ and } X_{n-1})
\]

(ii) Parallel Configuration

The system in which successful operation of the system is not dependent upon the successful operation of an individual unit is known as parallel configuration. A parallel configuration system can work until all the components of the system failed. In parallel configuration, system is operational if any one out of \( n \) component works properly. A system which consists of \( n \) component in parallel configuration is shown in the Fig. 1.2.

![Fig. 1.2. Parallel Configuration](image-url)
Let \( X_1, X_2, \ldots, X_n \) represents the successful operation of unit \( A_1, A_2, \ldots, A_n \) respectively and let their respective probability be \( P(X_1), P(X_2), \ldots, P(X_n) \). For the successful operation of the system, it is required that at least one component works properly out of \( n \) components. The system cannot fail completely until and unless all the components of the system fail. Let the successful operation of the system is denoted by \( P(S) \). Then

\[
P(S) = P(X_1 \text{ or } X_2 \text{ or } X_3 \text{ or} \ldots \text{ or } X_n) \\
= P(X_1) + P(X_2) + P(X_3) + \ldots + P(X_n) - P(X_1X_2) - P(X_1X_3) - P(X_1X_4) - \ldots \ldots \ldots - P(X_{n-1}X_n) - P(X_{n-2}X_n) - \ldots \ldots - P(X_2X_n) - P(X_1X_n) \\
+ P(X_1X_2X_3) + P(X_1X_2X_4) + \ldots + \ldots + (-1)^n P(X_1X_2X_3\ldots\ldots\ldots\ldots X_n)
\]

(1.11)

(iii) Mixed Configuration

A system which consists of its components, both in series and parallel configuration is known as a system with mixed configuration. In such systems we use both the rules of series and parallel configuration. A system which consists of three components in mixed configuration is shown in Fig. 1.3.

![Fig. 1.3. Mixed Configuration](image)

In the above system, two units \( X_1 \) and \( X_2 \) are connected in series configuration and these two units are connected with unit \( X_3 \) in parallel configuration. For successful functioning of the above system, it is required that both \( X_1 \) and \( X_2 \) units work properly or unit \( X_3 \) works properly, i.e., the probability of successful operation of the system \( P(S) \) is given by:

\[
P(S) = P[(X_1 \text{ and } X_2) \text{ or } X_3]
\]

(1.12)

Another example of mixed configuration is shown in Fig. 1.4.
The probability of successful operation $P(S)$ of the above system is given by

$$P(S) = P[(X_1 \text{ or } X_2 \text{ or } X_3) \text{ and } (X_4 \text{ or } X_5 \text{ or } X_6 \text{ or } X_7 \text{ or } X_8) \text{ and } (X_9 \text{ or } X_{10})]$$  \hspace{1cm} (1.13)

(d) Redundancies

The existence of more than one means of performing a given function of a system is known as redundancy. It is noticeable earlier that such means will increase system reliability and decrease mean time to failure [6, 7]. Our first approach to improve system reliability is to use superior components with a low failure rate. It is a common approach to improve reliability and availability of a system. In order to design and develop superior and low failure rate components, we require high investment in the research and development activities. In order to maintain system performance, most of the time, we use the redundancy technique except in the case when it is too costly. It can also be defined as:

"Redundancy is the technique which is used to increase the reliability of a system".

Redundancies can be characterized in the following types:
(i) \( k\)-out-of-\( n \): G/F Redundancy

The most common mode of redundancy is \( k\)-out-of-\( n \) redundancy. This type of redundancy is further characterized into two categories, these are \( k\)-out-of-\( n \): G and \( k\)-out-of-\( n \): F.

A \( k\)-out-of-\( n \): G redundancy implies that for successful operation of the system at least \( k \) components out of \( n \) components are required to be good (i.e. required to work properly). If less than \( k \) components are good then the system fails. A \( k\)-out-of-\( n \): F redundancy implies that if \( k \) components out of \( n \) components have failed then the system has failed.

So, we can conclude that a \( k\)-out-of-\( n \): G system can be written as \((n-k+1)\)-out-of-\( n \): F system.

These types of systems have a wide range of application in both industry and defense. Some examples of \( k\)-out-of-\( n \) structure are given below.

- An eight cylinder automobile engine, for successful operation requires at least six cylinders is an example of 6-out-of-8: G systems or we can say 3-out-of-8: F systems [1].
- A shaft lift operated by four cables in which at least two are necessary for safe operation is an example of 2-out-of-4: G systems [1].
- In data processing with five video displays at least three displays are sufficient for full data display. In this case the systems behave like 3-out-of-5: G system [1].

Reliability of \( k\)-out-of-\( n \): G system (with i. i. d. components) is given as:

\[
R(k, n) = \sum_{i=k}^{n} \binom{n}{i} p^i (1 - p)^{n-i}
\]  \hspace{1cm} (1.14)

(ii) Standby Redundancy

Standby redundancy is a technique which plays a crucial role for non-interruption in the functioning of a system. When a system fails, a standby unit is called for uninterrupted operation of the system [7]. It is also defined as a failover technique to make the system more reliable. It is frequently referred as an immediate backup for an essential component without which the complete system fails. Standby redundancy is characterized into three different sections according to their change over time from main unit to standby unit. These are:
• **Cold Standby Redundancy**

A cold standby unit is a unit which takes load when main unit of the system has failed. It is completely inactive until main unit fails, due to this it is known as a cold standby unit. It cannot be failed when it is inactive and its reliability is unchanged until it is active. The cold standby unit takes some change over time when main unit fails [7].

• **Warm Standby Redundancy**

A warm standby unit is a unit which takes load when main unit of the system has failed in the same manner as cold standby units. It is completely inactive though out the task of the system. The warm standby unit is activated when main unit of the system has failed. The change over time of the warm standby unit is much lesser than a cold standby unit [7].

• **Hot Standby Redundancy**

A hot standby unit is a unit which takes load when main unit of the system has failed in the same manner as warm and cold standby units. It is completely active throughout the task of the system and takes immediate charge when main unit of the system has failed without any change over time, i.e. in hot standby redundancy the changeover time from main unit to standby unit is negligible [1, 7].

(e) **Failures**

A phenomenon which leads a system into a non-functional stage or the termination of ability of functioning of an item is known as the failure of the system. It is the first thing to know, failure/cause of failure to make a system work continuously without any interruption (failure) and make it more reliable/available [1]. There are a lot of reasons due to which a system goes into a failed stage. So, in order to make a system more and more reliable, we have to examine exactly and accurately the various types of defects due to which a failure occurs. A system or item is more reliable if it has less failure, i.e. in order to make a system more and more reliable we have to control its various failure rates. It reflects that failure rate plays a very crucial role in system reliability. There are a lot of reasons due to which a particular system or item fails. Knowing, as far as feasible, the potential cause of failure is the essential to prevent them. It is not possible to identify all the causes of failure, but almost all is sufficient for avoiding them.
Some of the causes due to which a system goes into a non-functional state are discussed below as:

(i) **Design Defect**

By the design, we mean how the components of a system are made of. Basically the design defect is, improper shape, using unsuitable material, wrong casting of the parts and many other at the time of manufacturing of the components of the system [5]. It is one of the most dedicated processes to develop a reliable system/component. Due to bad design a system/component might be too unreliable, require too much electricity/power, suffer resonance at the wrong frequency etc.

(ii) **Assembling of the Components**

Basically assembling means how the parts of the system are combined to make it functioning. If the parts in a system are not properly assembled than it may fail at any stage of functioning. Such a failure is known as failure due to bad assembling of the components.

(iii) **Operating Condition**

The circumstances which are required for a system to perform its purpose are known as its operating conditions or normal conditions like an electric fridge, television or electric bulb gets fused if it is supplied with more voltage than it required.

(iv) **Untrained Operator**

An operator of a machine or a system plays a very important role in the system performance. So, the foremost need is that operator must be well trained because if the operator is not trained properly and perfectly, it reduces the reliability as well as availability of the machine/system and directly affects the economy of the system/machine. A system/machine can be failed, although it’s all components work properly due to an untrained operator.

(v) **Major Failure**

A failure by which a system has beyond the accepted limits of degradation is known as a major failure. It can occur at any stage of functioning and results in a huge loss of production to the system or human life and it is a herculean task for the maintenance team to keep the system in working condition after the major failure.
(vi) Minor Failure

A failure due to which a system has failed to the expected limit of degradation is known as minor failure. It can occur at any stage of functioning. After a minor failure, the system can restore to its functioning stage easily by the maintenance team mostly in a short period of time.

(vii) Catastrophic Failure

A failure which occurs due to a natural disaster like earth quake, hurricane, floods etc. and result in death and several injuries to the human life and also to the system are known as catastrophic failure. Due to this type of failure a system may go to the failed state for a long period of time or we can say catastrophic failure is the failure due to which systems can stop working at any stage of functioning for a long time.

(viii) Common Cause Failure

Common cause failure is the failure by which a system stops working at any stage of functioning due to a common fault [9]. We can say that common cause failure is one of the most unavoidable obstacles in the field of reliability. Common cause failure occurs due to bad assembling of components of a system, poor design, poor maintenance of machines, poor working, etc. Operating experience reflect that CCF is the major contributor in system failure.

(ix) Human Error

Human error plays a crucial role in the life cycle of a system/component. It is a universal phenomenon which exists in each and every industry and approximately on every day in different forms. A human error exists when the human associated with the work does not perform his/her work properly which is assigned to him/her. There are a lot of things due to which human error exists some of them are poor equipment designs, ill-trained operators and maintenance personals, work complication, inadequate lighting in the workplace, improper tools used by maintenance personnel, and poorly described operating actions [9,10]. It is observed that most of them are trivial but some of them cause serious damage to the concern industry. As in nuclear power plant, medical services etc. Some of the effects experienced due to human error listed below:
An American study reveals that in a year around 100,000 Americans die due to human errors [11].

It is also noted that 50% of equipment failure occur due to operator error [12].

It is observed by the experts that 90% road accident occur due to human error [13, 14].

(x) Electrical/Power Failure

Power generation is the essential part of an industry/organization for its continued functioning. If the power supply is not in proper form, then it leads to failure of the system, due to power/electrical failure. Electrical failure occurs due to the unusual wiring problem, fault in the power system or many other things.

(f) Maintenance

Maintenance is the process by which, we return back a system into working state from failed state. It plays a very crucial role in the field of reliability for repairable system and it affects the economy of the system directly or indirectly. According to maintenance operations, it is characterized into five categories. These are discussed one by one as:

(i) Preventive Maintenance

It is a maintenance, which is performed when system is in working condition to prevent it from further failure [8]. Such maintenance strategies are adopted in the systems in which failure means a lot of production loss or profit loss or loss of human life like nuclear power plant, thermal power plant, aviation department etc.

(ii) Corrective Maintenance

It is a maintenance which is performed when the system is in a failed condition, to bring it back in working state [8].

(iii) Predictive Maintenance

Predictive maintenance is the series of steps which are performed to a system prior to its performance to predicting the failures; the system can face in future [8]. By this type of maintenance, most of the failure which may exist in future escaped.
(iv) Fault-finding Maintenance

Fault-finding maintenance involves inspection of the components of the system to see whether they are still working or not [8]. This type of maintenance is often performed in the system dedicated to the safety.

(v) Adaptive Maintenance

A maintenance, which is essential over the life of a system to modify the system/software and keep it usable in changed or changing operating condition is known as adaptive maintenance.

(g) Repairable and Non-Repairable System

For reliability evaluation of a system, it is important to know that which type of system we are dealing with. There are two types of systems: repairable system and non-repairable system.

A non-repairable system is one which cannot be restored to operation by any repair action or parts replacement. For a non-repairable system, such as a tube light, electric bill, transistor, reliability is the survival probability over the equipment’s/systems predictable life, when only one failure occurs. During the equipment life the instantaneous probability of the first and only failure is called the hazard rate [15].

A repairable system/equipment is a system/equipment which can be resumed to operate by a repair action or parts replacement. For such items, reliability is the probability that failure will not occur in the time interval of interest. It can also be expressed as the failure rate or the rate of occurrence of failures. However, the failure rate expresses the instantaneous probability of failure per unit time, when several failures can occur in a time continuum.

Sometimes, a system may be considered as both repairable and non-repairable e.g. a missile is an example of a repairable system when it is in store and ready to schedule tests and it becomes an example of non-repairable system when it is launched [5].

(h) Complex Industrial Systems

A system is a collection of subsystem and a subsystem is formed by the combination of its components. In a system its subsystem/parts are interconnected to each other in many distinct configurations. According to its configuration a system can be classified in several categories. e.g. a series system, parallel system, mixed system. A system which consists of many diverse
and independent but interrelated components through many interconnections [16] is known as a complex system and if such system exist in industry than such a system is known as complex industrial system. e.g. nuclear power plant, thermal power plant, paper plant industry, servers of big companies etc.

Complex system cannot be said complex due to a single characteristic (rule). It is said to be complex due to:

(a) Its configuration
(b) Its operation (function)
(c) Its structure, etc.

(i) Method and Techniques for Reliability Evaluation

In this section, we shall discuss about the techniques which are used for reliability evaluation.

(i) Markov Process

Markov process is very useful tool for analyzing random events which are dependent on each other. It is the most powerful technique in the field of reliability, which helps us to evaluate the system’s various performance measures. It is named after the Russian mathematician “Andrei Andreyevich Markov” (1856-1922) [5].

*It is a process in which transition from one state to another state (future state) depends only on the present state of the system and does not depend on the past state or one can say that the transition does not depend on what happened in the past with the system (Fig. 1.5) or we can say that the future stage is dependent only on the present state* [1]. That’s why Markov process is sometimes known as memory less process.

![Markov Process Diagram](image)

Fig. 1.5. Markov Process

As the part of the process, initially on the basis of system configuration a state transition diagram is created, then by the Markov process a number of differential equations are generated (on the basis of input and output or repair and failure) and then by solving these
equation with the help of Laplace transformation, we get the required system’s transition state probabilities. Now with the help of these transition state probabilities, the various reliability measures are calculated. It is applicable to both types of system i.e. repairable and non-repairable.

(ii) **Stochastic Process**

This process is introduced in some way of 19th century by the mathematician “Thorvald N. Thiele”. “A stochastic process is a sequence of events in which the outcome at any stage depends on some probability” or we can say that it is the collection of random variables which are function of real variable \( t \). That’s why sometimes this process is known as a random process. The set of possible values of an individual member of the random process is called state space.

According to the time variable and state space, stochastic process can be classified into four sections. These sections are:

- **Discrete Time and Discrete State Space**

  In this type of stochastic process, time and system state space are discrete variables e.g. in tossing a fair dice, time and state space both are discrete variable i.e. the set of time variable is \( \{1, 2, 3, 4, 5, \ldots\} \) and the set of state space is \( \{1, 2, 3, 4, 5\} \).

- **Continuous Time and Continuous State Space**

  In this type of stochastic process, the time and system state space are continuous variable e.g. measuring the maximum temperature of a city, a time sharing computer system with waiting time.

- **Discrete Time and Continuous State Space**

  In this type of stochastic process, time is the discrete variable and systems state space is continuous variable For example in measuring the temperature of a day after every hour gives discrete time and continuous state space. Stock market, a time sharing computer system are the other examples.

- **Continuous Time and Discrete State Space**
In this type of stochastic process, time is continuous variable and systems state is discrete variable. For example the number of calls received in a call center, population growth.

Under some elite conditions, a stochastic process becomes Markov process. These are listed below:

- The numbers of possible outcomes or states is finite.
- The outcome at any stage depends only on the outcome of the previous stage.
- The probabilities are constant over the time.

(iii) **Laplace Transform**

Laplace transformation is a mathematical tool which solves ordinary differential/partial differential equation under given boundary and initial condition. When, it is applied to an initial or boundary value problem, the problem is converted into an algebraic equation in terms of Laplace variable, then by taking the inverse Laplace transform, one gets the solution of given initial/boundary value problem. Through this process one can directly find the solution of the given initial/boundary value problem instead of finding the general solution.

If \( f(t) \) be a given function and defined for every \( t \geq 0 \) than the Laplace transform of \( f(t) \) is defined as:

\[
L\{f(t)\} = \int_0^\infty f(t)e^{-st}dt
\]

We can write it as \( L\{f(t)\} \) or \( F(s) \) and its inverse Laplace transform as \( L^{-1}\{F(s)\} \) or \( f(t) \).

(iv) **Supplementary Variable Technique**

In the history of reliability theory, a lot of complex industrial systems are solved to find their various reliability measures by using different techniques. Among them, the supplementary variable technique plays a very important role. It was firstly used by Cox [17] in 1955 to solve the M/G/1 queening model. It was firstly used in the field of reliability in 1963 by Gaver.

In order to discuss about reliability measures of a system with the help of Markov process, our first and foremost concern is the system failure and repair rates, but when these rates are time dependent, the system losses its Markovian properties i.e. in this condition the transition from
one state to other state is not only depend on the present state but also depends on past state. For such condition, one cannot allow to use Markov process because system loses its Markov character. In order to overcome such condition, we introduce one or more new variables to convert the non Markovian nature of the system to Markovian. Such a variable which changes non-Markovian nature of the system to Markovian nature is known as supplementary variable and this technique is known as “supplementary variable technique” [17].

(j) Bathtub Graph

The bathtub curve/graph is the graphical representation of an item’s life cycle. In this curve the various types of failure stages of an item are shown with respect to time. It divides the total life cycle of an item into three phases; these are Initial (infant) failure, service failure and wear out failure. Infant failures show a high hazard rate which starts to decrease with respect to time. It occurs due to manufacturing defect, bad assembling of components or due to weak components which cannot be removed completely. After infant failure phase when weak components have been replaced and errors are corrected, items life cycle goes to the next phase which is a service failure. In this phase hazard rates are almost constant. In this phase the failure rate is constant that’s why it is the only part of an item’s life cycle where exponential distribution is valid. This phase of the item is also known as useful phase as one can see it in Fig. 1.6. The next phase of the item life cycle is known as wear-out failure. It is the time of an item life cycle when hazard rates are going to increase with respect to time. The chance of failure in this zone is much higher as compared to the last two sections because most of the components will surpass their service lives [1].
The bathtub graph is a graphical representation of not only an individual component life cycle, but of almost every component life cycle.

1.4 Problem Statement

The industrial mathematical models developed so far considered availability, reliability, MTTF, and cost analysis of complex industrial system as well as general systems, with several types of failures and repairs.

Keeping this in mind the following problem statement is formulated:

- Mathematical models for complex industrial systems with $k$-out-of-$n$ and standby redundancy.
- Performance measures using Markov process/stochastic process/supplementary variable technique.
- Investigate multistate failures in complex industrial systems.
- The sensitivity analysis (with respect to different aspect), cost/profit analysis of various complex industrial systems.
- The reliability indices with human error and catastrophic failure simultaneously.
- Identifying power supplies degradation effects.
1.5 Thesis Organization

Chapter one consists of introduction of reliability theory. In this chapter, the basic and some standard entity about the field reliability and the techniques used are discussed. It gives the description of the terms which are fluently discussed and used in reliability field and also the definition of reliability given by various researchers. The need and scope of reliability in various fields are also discussed.

Chapter two contains the development of reliability theory and the research work done in the past by various researchers. The research done in the various fields with different failures like common cause failure, catastrophic failure, human error, unit failure, electrical failure, power supply failure etc. with different redundancy like $k$-out-of-$n$, standby, hot standby, warm standby, cold standby are examined. Some research gaps identified after the critical literature review, have also been given in this chapter. Finally, problem statement has been discussed.

In chapter three, three different complex models are discussed with standby units, $k$-out-of-$n$ redundancy, common cause failure, electrical failure, human error. In model-I, the considered system consists three units which are connected in a mixed configuration, also one out of these three units is of the types 1-out-of-2: $G$ with the perfect reworking state. In model-II, a complex structure which consists of two substructures with human error is discussed; both of these substructures are connected in series configuration. Out of these two substructures, one is of the type 2-out-of-3: $F$ (with unequal components). A mathematical based diagram is developed to evaluate the various reliability characteristic for the same. In model-III, the system reliability measures with common cause failure is discussed. The considered system consists of two subsystems, one of the subsystems has two units in parallel configuration and other is of the type 2-out-of-3: $F$, these two subsystems are connected in series configuration. Three types of failure, which are common cause failure, electrical failure and unit failure are considered throughout the task. Various reliability measures like reliability, availability, MTTF, sensitivity analysis, and expected profit are evaluated and demonstrated with the help of graph.

Chapter four consists of two models of paper mill plant. In model-IV of this chapter a paper plant is discussed with power supply in standby mode. The considered model contains four subsystems which are connected in series configuration. To avoid the interruption due to power failure, power supply is taken in standby mode. The various reliability measures are evaluated
by substituting the failure and repair rates which are taken from the past of the plant. In model-V, the performance analysis of two important sections of a paper production plant is discussed. These two sections are pulping system and screening system. Further, the pulping section consists four subsections and each of these four subsections is connected to each other in a series configuration. The pulping system and screening system are connected to each other in series configuration. On the basis of in-out parameters, a transition based mathematical model is developed for finding the various reliability characteristics for the same. The results are demonstrated with the help of graphs also.

In chapter five, coal handling unit of a thermal power plant (model-VI) has been discussed to evaluate the various reliability measures with sensitivity analysis. The considered system can have degraded state also. Sufficient repair facility is provided to the system. The system can completely fail by complete failure of any subunits. The results are explained with the help of graphs.

The sensitivity analysis for casting process with stochastic modeling (model-VII) is discussed in chapter six. A mathematical model is developed with the help of Markov process to draw some of the useful results regarding casting process.

In chapter seven, a complex industrial system with a standby unit (model-VIII) is presented. The system consists of $n$ unit in parallel configuration. The considered system can fail due to catastrophic failure, failure of standby unit and human error. The considered systems can also work in degraded state.

Chapter eight demonstrates about the two complex industrial systems. These are marine power plant and a sugar mill. In model-IX, performance evaluation of a marine power plant under the reliability characteristics approach is discussed. A marine power plant consists of three subsystems which are generator, distributive switch board and main switch board. All of these are connected to each other in a mixed configuration. Working based state transition diagram is developed for calculating various performance measures for the same. In model-X, a sugar mill is analyzed. A sugar mill consists of three subsystems namely feeding section, evaporation section and crystallization section. All these are connected in series configuration with each other. On the basis of in-out parameters a state transition diagram is developed to evaluate
various performance measures like reliability, availability, MTTF, sensitivity analysis, expected profit for the same.

Chapter nine presents the “Conclusion and Future Work”. Some suggestions for the future work are also given.