MAINTRAIN 2020 Paper

Reliability Engineering Analytics by André-Michel Ferrari P.Eng, CRE.

Abstract

Reliability Engineering is an established science with rigorous concepts involving mathematical and statistical methods, and those can often appear daunting for some maintenance or risk practitioners. The role of the reliability engineer is to master, explain, and apply those concepts as well as work with peers to make the correct decision(s) regarding the maintenance of operating assets or future design capabilities. Those decisions are crucial, especially when it comes to the safety of frontline workers, capital investments, or the preservation of the environment. This presentation defines the role of the reliability engineer (mainly in an owner/operator environment) but also helps non-reliability practitioners understand some of the basic tools used in this field. The term reliability is often generalized and not fully understood, so this presentation will help to clarify its definition and intent. Misinterpretation or incorrect calculations involving equipment life characteristics—such as mean time to failure, bathtub curves, or failure probabilities—will be covered. The paper also explains some of the most commonly used concepts in Reliability Engineering calculations, as well as potential pitfalls encountered such as oversimplifying, applying incorrect analytical approaches, or mixing terms such as availability and reliability. The presentation will also define the "true" and "value-added" role of Reliability Engineering in an industrial environment and how it productively interfaces with other teams involving maintenance engineering, risk management, or spare parts management.

1 - Reliability Engineering theoretical concepts overview

The concept of Reliability is often misused, misunderstood and misinterpreted. Reliability in its academic root, is defined ***as the probability that a system will perform its intended function in a specified mission time and within specific process conditions***.

Hence the ***time*** variable is crucial in understanding the reliability of a system. An example is that of the new Space X shuttle as shown in Diagram 1 below. The question asked is:

- What is the probability that the Space X shuttle will complete a lift off/touch down cycle in 10 minutes in "clear" weather conditions? In other words, what is the probability of success of the mission or the reliability of the Space X shuttle within the defined mission time?

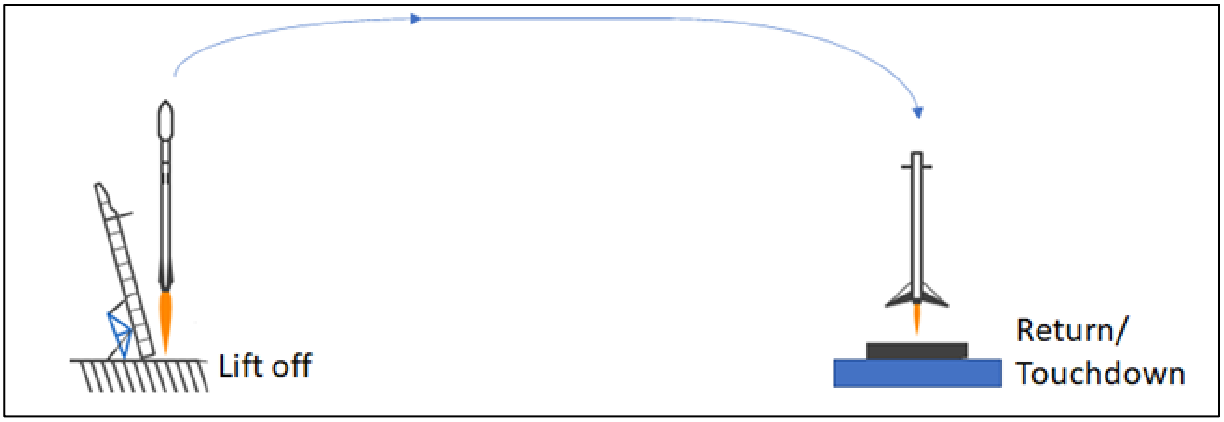


Diagram 1 - Illustration of a Reliability concept (Spare X shuttle mission)

Reliability is the probability of success and 1 minus the probability of failure. Reliability is calculated using historical records of a system or component. An example is shown below in Diagram 2 where a number of “n” components are run on a test bench until they fail. Each failure is recorded and once all the failure records are collected, a normalized frequency graph can be constructed. This frequency graph helps define the **statistical distribution** that best represents the life cycle of each component in the population. Using specific mathematical transformations applied to the distribution, the probability of failure after any mission time can be derived as well as other information such as failure rate or the expected number of failures over time.

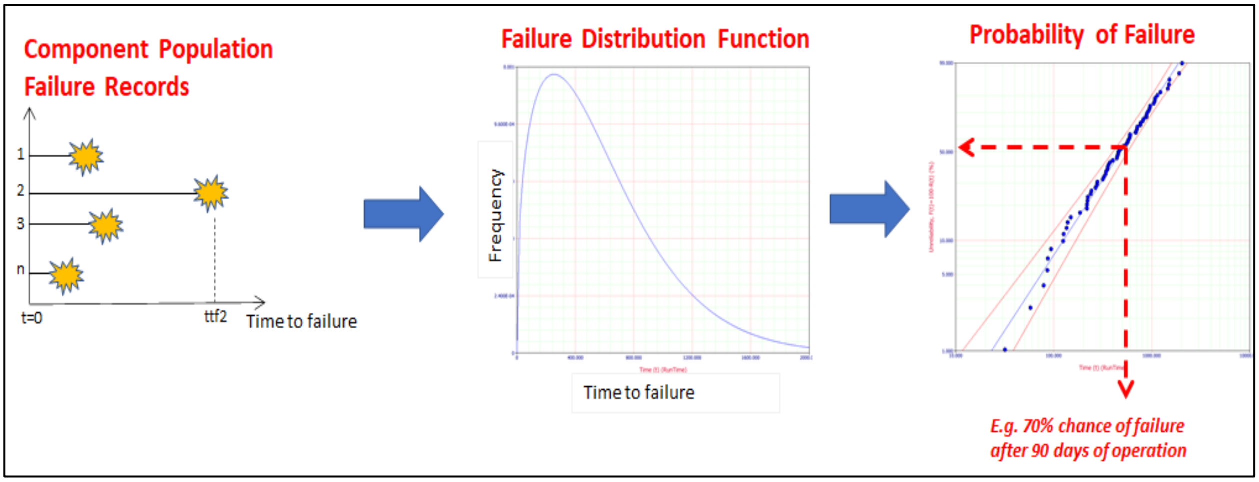


Diagram 2 – Theoretical overview of a Reliability analysis

Hence, the derived statistical information can provide decision makers with key information about the operation of their assets such as:

- Is this probability of failure at a specific time acceptable?
- Given the consequence, is the “risk” acceptable?
- What can we do to make it better? Preventive maintenance, re-design, redundancy?
- Can the analysis give us more information on this component?

One of the common statistical analysis conducted is called the **Weibull** analysis. However, the term Weibull is actually a specific statistical distribution – **the Weibull distribution**. In the same vein as one would define a lognormal, normal or exponential distribution.

Every statically distribution has governing parameters. The “classical” Weibull distribution has 2 main parameters.

- **β (beta) is the shape parameter and indicates failure patterns such as ageing or infant mortality**
- **η (eta) is the scale parameter and indicates the characteristic life or expected time to failure**

The Weibull distribution is a very practical distribution as it can provide decision makers with a variety of information such as life behaviors of mechanical components as well as production systems (e.g. factory output). Additionally, with the appropriate mathematical transformation, it provides a linear graphical representation for the probability of failure as shown in Diagram 2. Other than the fact that engineers like straight lines, the latter is also useful to evaluate life characteristics of the system or component being studied.

$$\boxed{f(T) = \frac{\beta}{\eta}\left(\frac{T}{\eta}\right)^{\beta-1} e^{-\left(\frac{T}{\eta}\right)^{\beta}}}$$

Weibull normalized frequency equation (or probability density function)

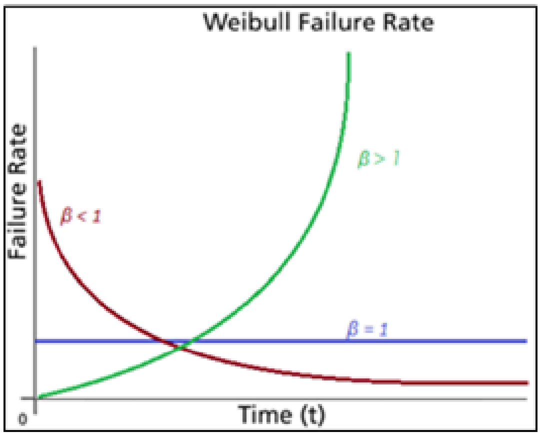


Diagram 3 – Weibull Probability Density function and failure rate curves (β dependant)

As shown in Diagram 3, the Weibull failure rate curve varies with the value of β, hence why β is named the shape parameter. If β is equal to 1, the Weibull distribution is identical to an exponential distribution which is characterised by a constant failure rate. Due to possible variation of the shape parameter β, the Weibull distribution, or specifically 3 Weibull distributions combined (with β<1, β=1, β>1) provide what is known as the **bathtub curve** illustrated in Diagram 4 below.

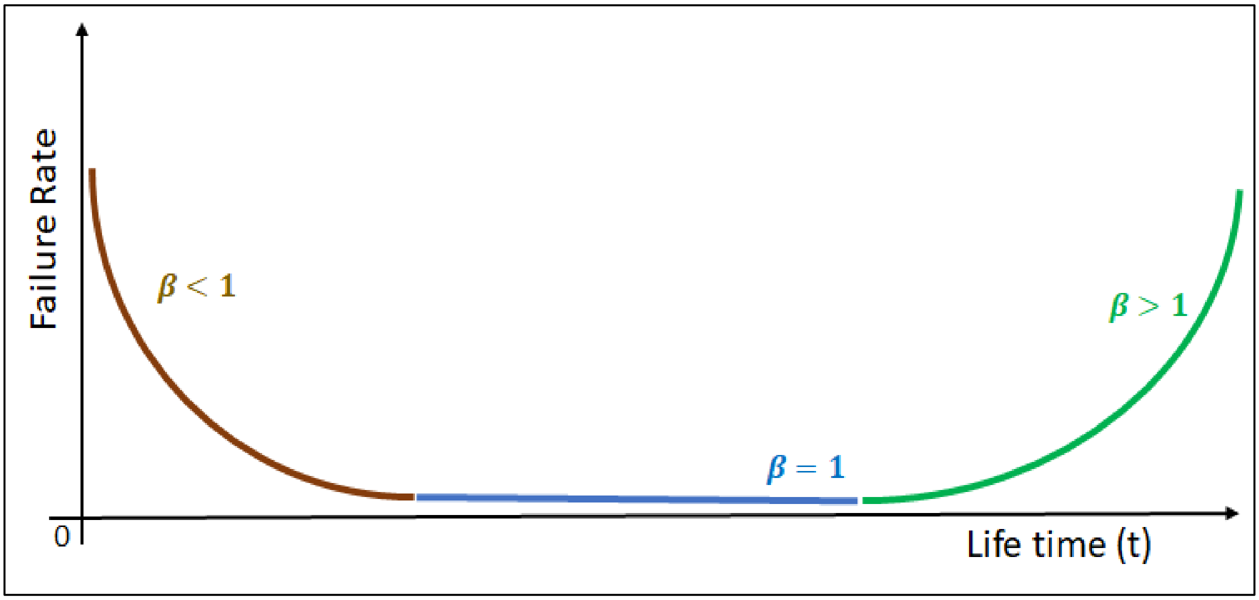


Diagram 4 – Theoretical bath tub curve

As mentioned, and illustrated in Diagram 4, the bathtub curb is a failure rate curve with 3 combined Weibull distributions. Each section or distribution provides the following information to the decision makers:

- Section 1 or β<1 is called the infant mortality section. This corresponds to early failures and a **decreasing** failure rate over time which in essence is undesirable. Infant mortality represents premature failures due to manufacturing defects or poor maintenance practices.
- Section 2 or β=1 is called the random failure section or useful life. This corresponds to the normal life of a component or asset where external factors influence its survival. Normally preventive maintenance or proactive repairs are not effective in this period due to the random nature of failures.
- Section 3 or β>1 is called the ageing section. This corresponds to the time in the life of a component where age related failures appear and increase over time. The use of the component over time has induced enough stresses leading to obsolescence and an increase in repair frequency and subsequently cost.

2 Pitfalls and misconceptions in Reliability Engineering

The following paragraphs highlight common errors and misconceptions that occur in the general workforce when using Reliability Engineering concepts.

As mentioned earlier, the term "Reliability" is defined as a probability of a component not failing in a specified time period. It is very different from the failure rate which is related to the increase or decrease of failures over the lifetime of the asset. So, in essence a probability curve and a failure rate curve provide different types of information to the decision maker:

- the probability curve relates to risk provided we know the related consequence (i.e. Risk = Probability x Consequence)
- the failure rate curve provides information on the behavior of the asset (e.g. ageing or infant mortality). A sharp increase in the failure rate curve at a point in time can also indicate sudden deterioration which needs to be addressed.

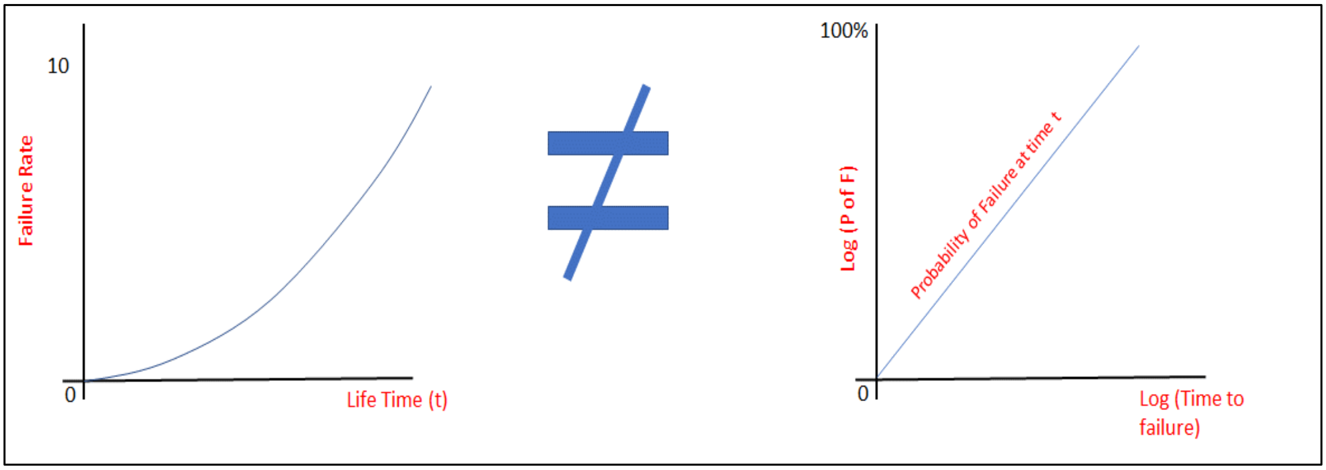
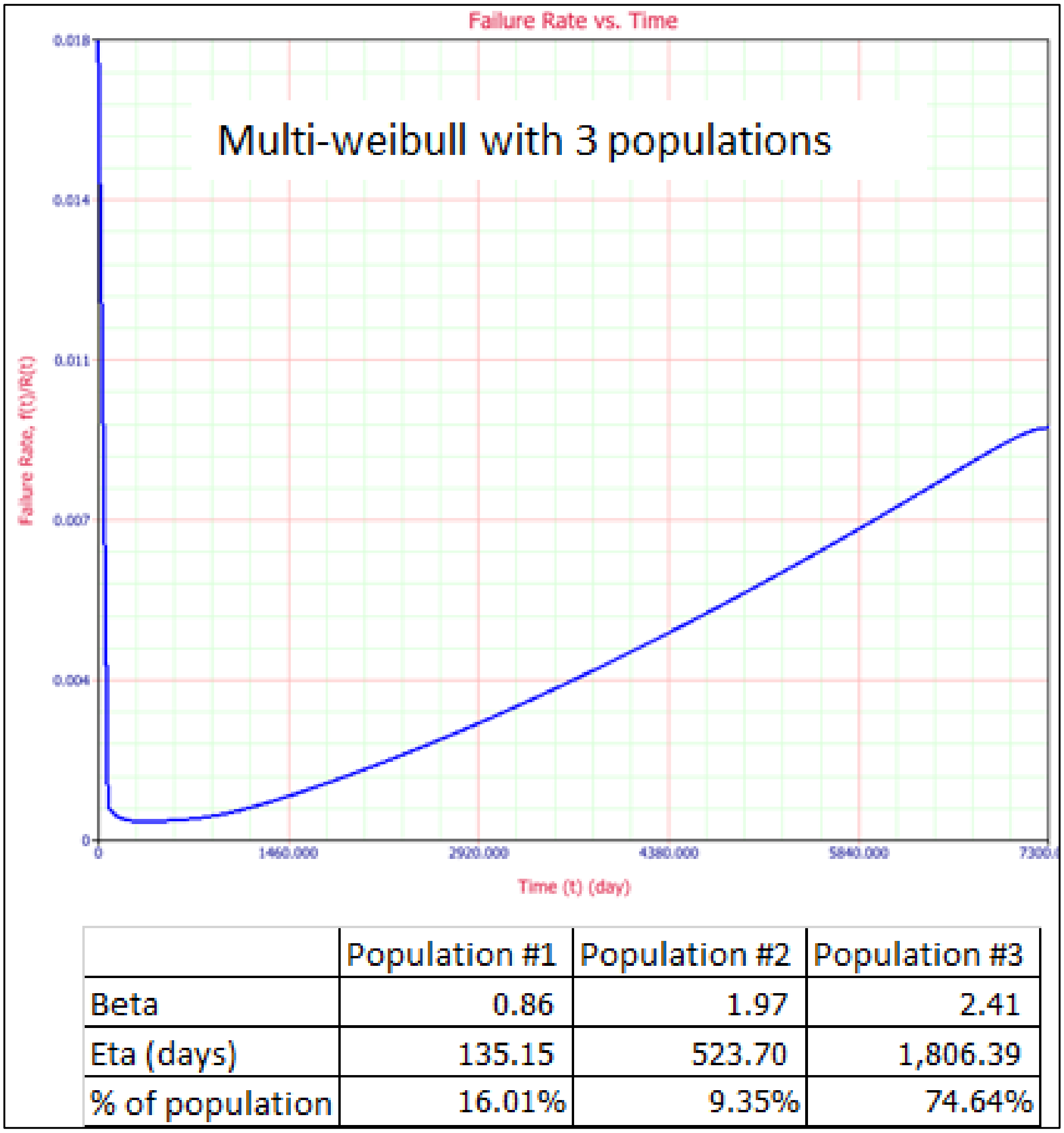


Diagram 5 – Illustration of a failure rate curve versus as probability curve.

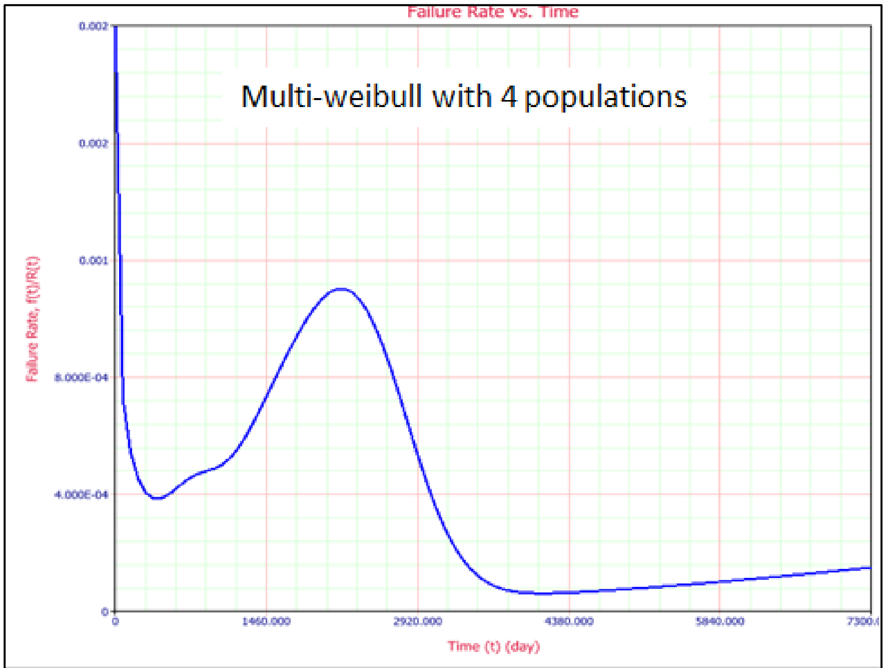
The bathtub curve illustrated in Diagram 4 above is conceptual and symmetric. In reality, bathtub curves are rarely this way. Diagram 6 and 7 show the asymmetrical nature of the bathtub curves for different components. In addition, the diagrams also highlight the weight of the different sections of the curves. So, for example in Diagram 6 below, population #2 and 3 which are the ageing sections of the component's life, bears 84% of the entire population weight. This means that ageing is the dominant failure pattern for this component which in essence is a good thing. Infant mortality counts for only 16% of the failures; the operator should perform an investigation on the latter (e.g. root cause analysis) to identify why these undesirable early events are occurring. The component in Diagram 6 has no visible random failure section so if the component survives infant mortality it directly goes into an ageing process. The different populations highlighted in both diagrams can also be assimilated to different failure modes affecting the life of the asset in question.



	Population #1	Population #2	Population #3
Beta	0.86	1.97	2.41
Eta (days)	135.15	523.70	1,806.39
% of population	16.01%	9.35%	74.64%

Diagram 6 – Illustration of a failure rate and bathtub curve with 3 populations

Diagram 7 illustrates a combination of two bathtub curves with 4 populations or failure modes. It is not unusual to see the increase in failure rates in the middle of the life of a component. In other words, the "hump" seen in Diagram 7 defines an increase in the failure rate of the component relative to a specific failure mode that needs to be investigated if undesirable.



	Population #1	Population #2	Population #3	Population #4
Beta	0.78	3.35	2.94	2.79
Eta (days)	381.77	755.53	1,910.00	10,173.07
% of population	30.14%	5.65%	53.86%	10.36%

Diagram 7 – Illustration of a failure rate and bathtub curve with 4 populations

Another major pitfall in Reliability calculations is MTBF or Mean Time between Failures. We have demonstrated above, that the failure rate of a system or component is usually dynamic and changes over time. MTBF is essentially reducing the variability into one constant failure rate. In other words, MTBF reduces the continuum of time to one single point. This over simplification often leads to erroneous decision making and costly errors when managing assets.

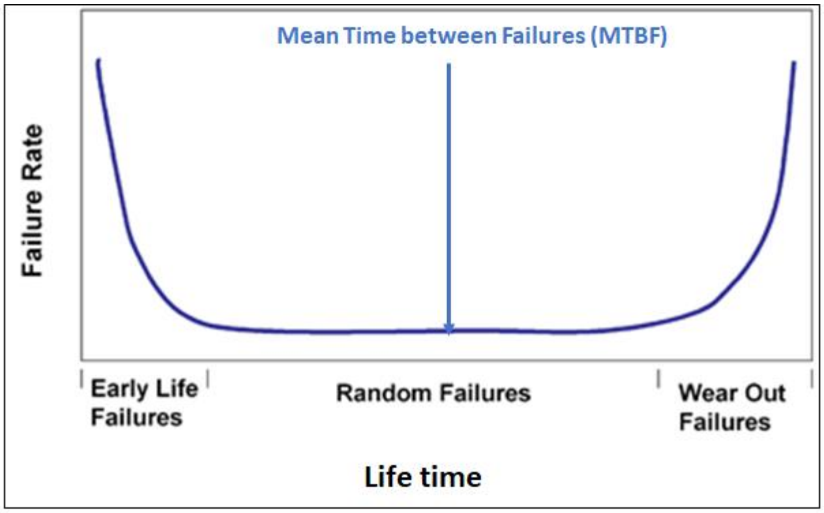


Diagram 8 – Illustrating MTBF when it reduces the entire life to one point in time

In exceptional cases, MTBF can be used to compare the expected life of two components (e.g. comparing the expected life of two bearing types). It provides a rough judgement on performance. However, it should never be used to make critical decisions and if the decision is critical, a thorough life analysis with the tools described above, should be conducted.

Another sets of terms that is often confused is Availability and Reliability. The term reliability has been extensively defined above as a probability. Availability is typically a ratio of uptime versus downtime or the percent of time the equipment is in an operable state as described below.

$$\text{Availability (\%)} = \frac{\text{Uptime}}{\text{Uptime + Downtime (or total time)}}$$

Availability is typically used to understand the windows of downtime that would affect a component or system's performance over time. An example comparing the two metrics is provided in Diagram 9 below and clearly shows that even though availability might be relatively high, Reliability might be low in the mission time considered (i.e. 1 year).

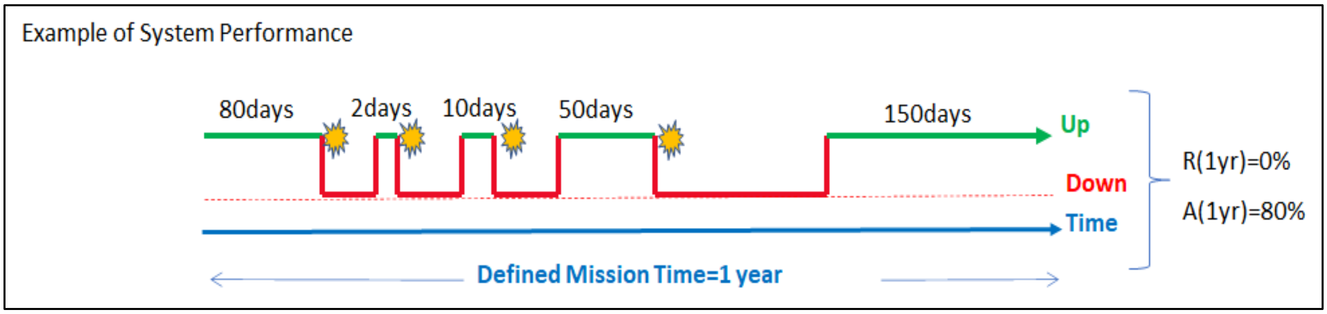


Diagram 9 – Illustrating the difference between reliability and availability through basics calculations

The last example in this section of a typical error found in Reliability Engineering calculations is the confusion between repairable and non repairable systems.

A repairable system is expected to fail one or multiple times over its life. It will be repaired and restored to as close as possible to its original functional state. However, it is very rare that it will be restored to an "as good as new" state because other parts of the system which have not failed yet are in a state of deterioration and will sooner or later fail. Subsequently, failures on this system will occur more and more frequently over time. A good example of a repairable system is an automobile. It is for the same reason that when we talk about repairable systems, any repair conducted on the system brings it to an "**as good as old**" state.

On the flip side. A non repairable system is only used once and typically a consumable such as a light bulb. Replacing the light bulb in its original location makes the lighting system in essence "**as good as new**" and the new light bulb is expected to last as long as the last one.

Hence, mathematically speaking, repairable and non repairable systems have to be treated differently when a study of their life cycle is conducted.

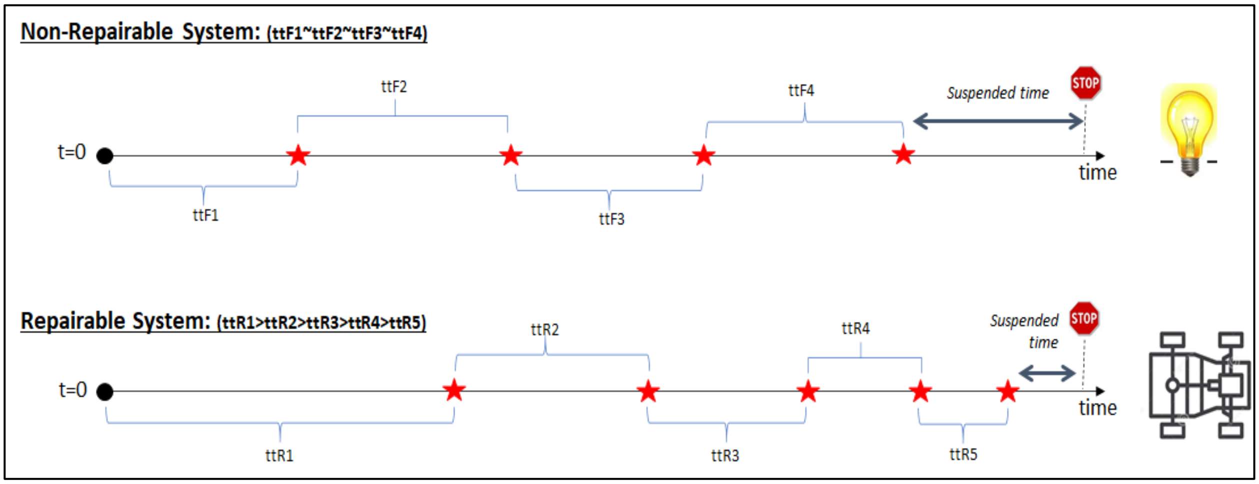


Diagram 10 – Illustrating the difference between repairable and non-repairable systems

In summary, it is important for the Reliability practitioners to understand all the above-mentioned concepts as well as the pitfalls so that they can assist the asset managers in making the optimal and best-informed decisions. The other challenge is to obtain a reasonable amount of records in order to complete a robust reliability analysis of the system being considered.

3 Roles of Reliability Engineers in an operating environment

Reliability Engineering and Maintenance engineering are complementary yet very different functions. The Maintenance Engineer is somewhat close to the field and operating assets and has first hand information about issues affecting availability or reliability. Additionally, the Maintenance Engineer focuses on short to medium term tasks with such as:

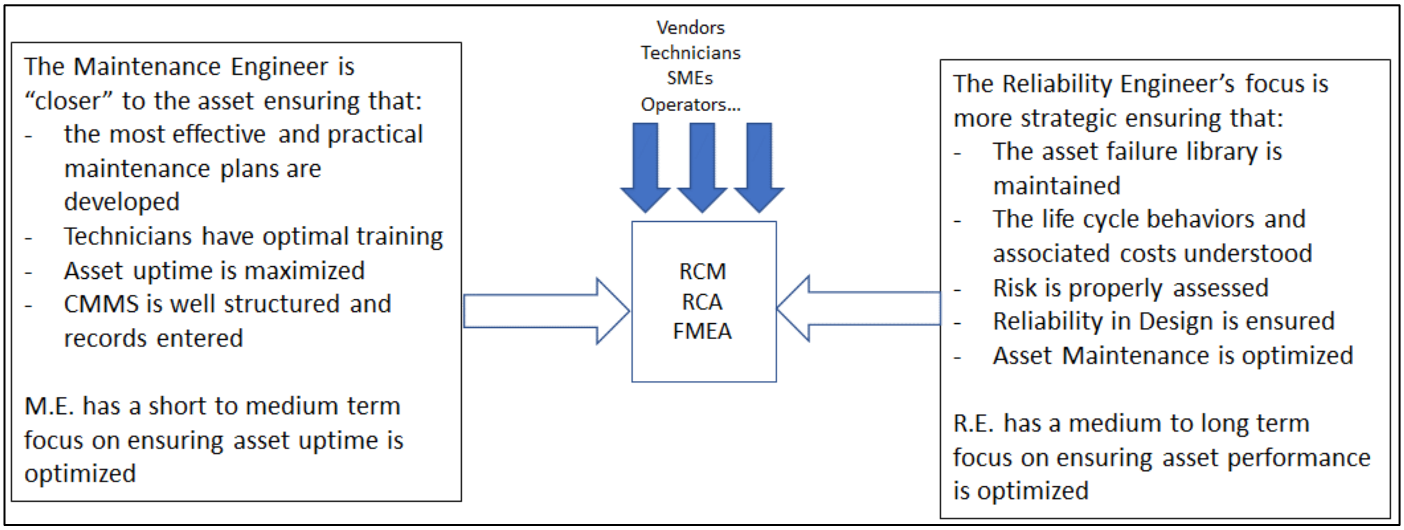
- Ensuring that the most effective and practical maintenance plans are developed
- Technicians have optimal training and expertise
- Asset uptime is maximized
- The Computer Maintenance Management System (CMMS) is well structured and all records entered properly

The Reliability Engineer on the other hand, has a more strategic role looking at the long-term performance of an asset and using analytical techniques as described above to calculate and improve reliability parameters associated with all equipment systems in the organization. The Reliability Engineer’s focus is to ensure that:

- The asset failure library is maintained
- The life cycle behaviors and associated costs understood

- Risk is properly assessed
- Reliability in the design phase is ensured
- Asset maintenance is optimized

In a colloquial description, the maintenance engineer is in essence, the “eyes and ears” of the Reliability Engineer in the field, whilst the Reliability Engineering is the “voice” of the Maintenance Engineer in the boardroom.



The Maintenance Engineer is “closer” to the asset ensuring that:

- the most effective and practical maintenance plans are developed
- Technicians have optimal training
- Asset uptime is maximized
- CMMS is well structured and records entered

M.E. has a short to medium term focus on ensuring asset uptime is optimized

The Reliability Engineer’s focus is more strategic ensuring that:

- The asset failure library is maintained
- The life cycle behaviors and associated costs understood
- Risk is properly assessed
- Reliability in Design is ensured
- Asset Maintenance is optimized

R.E. has a medium to long term focus on ensuring asset performance is optimized

Diagram 11 – Maintenance and Reliability Engineering functions in an operating environment

The partnership between the two functions is often seen in Asset Management processes such as Failure Modes and Effect analysis (FMEA), Root Cause Analysis (RCA) or Reliability Centered Maintenance (RCM) as shown in Diagram 11 above. These processes also involve multiple other subject matter experts such equipment vendors, technicians or operators.

As mentioned above, Reliability Engineering techniques can also be used in RCAs. One of the little-known techniques is using life analysis parameters contour plots (based on Weibull parameters). This technique allows the RCA analyst to understand whether failure modes are independent or not. In other words, if failure modes are dependant then one could cause the another one to occur. This technique can be used to build the appropriate logic tree and enhance the RCA process.

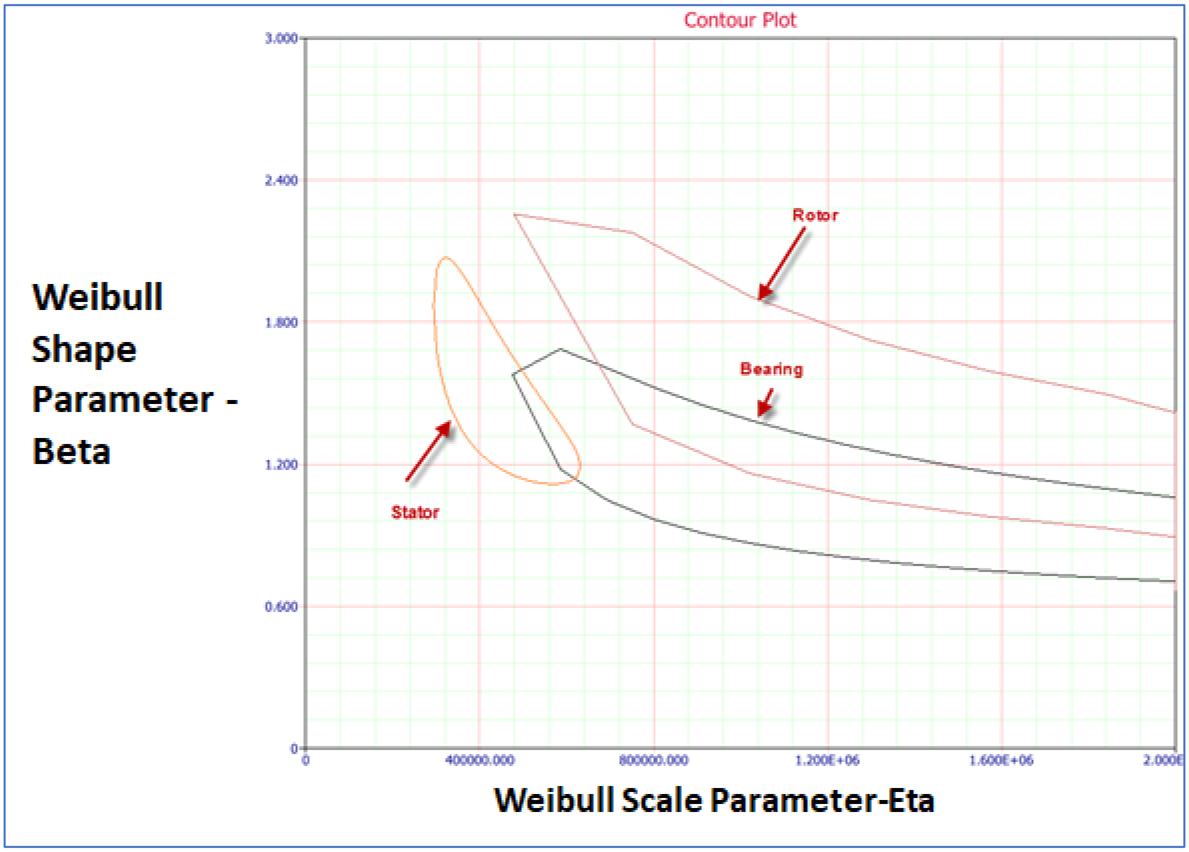


Diagram 12 – Weibull contour plot analysis for an electric motor

Diagram 12 illustrates this concept for an electric motor. The overall interpretation of this analysis is that the stator and rotor failure have independent failure modes whereas as a bearing can cause both a rotor and/or stator to fail.

Another technique often used by Reliability Engineering in Asset Management is the **Optimal Replacement Time** technique. Diagram 13 shows the Cost Per Unit Time vs. Replacement Interval plot and it can be seen that the corrective replacement costs increase as the replacement interval increases. In other words, the less often a PM action is performed, the higher the corrective costs will be (more unplanned events). Obviously, as a component operate for longer times, its failure rate increases to a point that it is more likely to fail, thus requiring more corrective actions. The opposite is true for the preventive replacement costs. The longer the interval between PMs, the lower the costs associated with PMs. But if PMs occur too often, the costs increase. If we combine both costs, we can see that there is an optimum point that minimizes the overall cost. In other words, one must strike a balance between the risk (costs) associated with a failure while maximizing the time between PM actions. The corresponding time is the **optimal time to replace the component being studied**.

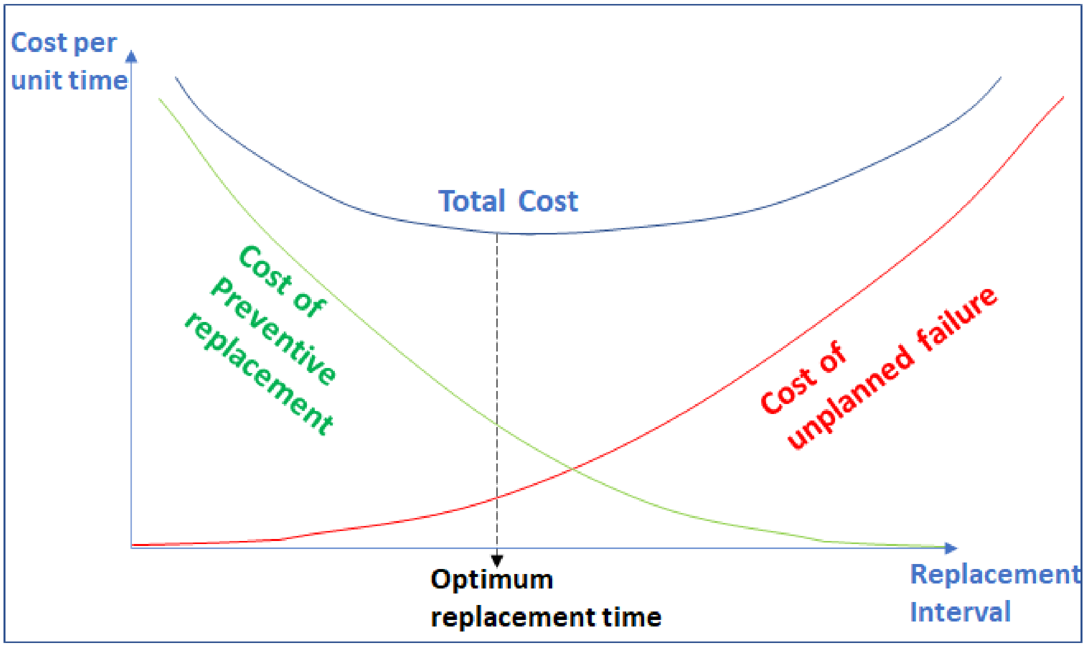


Diagram 13 – Generic optimum age replacement model

Conclusion

This paper highlights the overall functions of Reliability Engineering in an operating environment. It also provides information about the pitfalls and misconceptions that lead to inaccurate decision making when considering the life of an asset. Overall, when doing a reliability analysis, it is important to understand what the decision maker or asset manager really needs. Equally crucial is the availability of good data samples and historical records. When the analysis is completed, the outcome is usually very rich in diverse information that can be used in different ways as shown all throughout this paper.