

# New Metrics to Assess Reliability and Functionality of Repairable Systems

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## ABSTRACT

The classical definition of reliability may not be readily applicable for repairable systems. Commonly used concepts such as the Mean Time Between Failures (MTBF) and availability can be misleading because they only report limited information about the system functionality. In this paper, we discuss a set of metrics that can help with the design of repairable systems. Based on a set of desirable properties for these metrics, we select a minimal set of metrics (MSOM) which provides the most information about a system, with the smallest number of metrics. The metric of Minimum Failure Free Period (MFFP) with a given probability generalizes MTBF because the latter is simply the MFFP with a 0.5 probability. It also generalizes availability because coupled with repair times it provides a clearer picture of the length of the expected uninterrupted service. Two forms of MFFP are used: transient and steady state. Other metrics of cost, planning horizon, number of failures within the planning horizon are also used. We also present in this paper the metric of effective age which has been used in the literature for remanufactured products. It uses a relatable unit of years to report the performance of a repaired system. In doing so, the metric results in the effective age of the system as a linear weighted sum of the ages of the components. The system topology information (e.g. reliability block diagram) is then used to calculate the coefficients of the weighted sum associated with each component, leading to a very simple and useful model to assess system functionality. We demonstrate the value of the MSOM using the design of a four-joint unmanned ground vehicle.

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## 1. INTRODUCTION

Although most systems are repairable, it can be difficult to describe their performance over time. Since such systems require repair, the frequency and amount of repair determines to a large extent, whether a system has good "performance". An appropriate maintenance strategy can make a system available most of the time. At the same time however, it cannot make up for too many service interruptions and high service cost. The tradeoffs between performance, service interruptions and cost are hard to capture. The term *reliability*, which is defined as the probability of meeting the intended requirements for time  $t$ , is hard to apply directly to a repairable system for various reasons (Kapur and Lamberson, 1977). Every repair brings the value of the reliability function to 1. Depending on the type of the performed repairs however, different subsequent reliability curves can be obtained. The resulting non-monotonicity in the reliability function is always hard to reconcile because the probability that a system has not failed before time ' $t$ ' is not monotonically decreasing. A reliability of 1 indicates that the

system never failed before, but in reality it did, which is why the repair was performed in the first place. Clearly either the definition of reliability must be modified or a new measure of performance is needed.

To address these the issues, classical reliability theory uses metrics such as the mean time to failure (MTTF) and availability to assess the expected performance from a system. These metrics are based on the various times a (set of) system(s) fail and how long it takes to repair and put them back into service. It is easy to argue that these metrics only capture one statistic of the time to failure. For example, the MTTF only captures the mean, while availability is simply the ratio of the expected system uptime to the expected total duration of installation (uptime plus downtime). Clearly, a system that has a skewed distribution of time to failure will not have its performance well represented by MTTF. Similarly a system that requires constant repair but can be repaired quickly will have high availability, but it is hard to get any meaningful service out of it. Figures 1 and 2 represent this information pictorially.

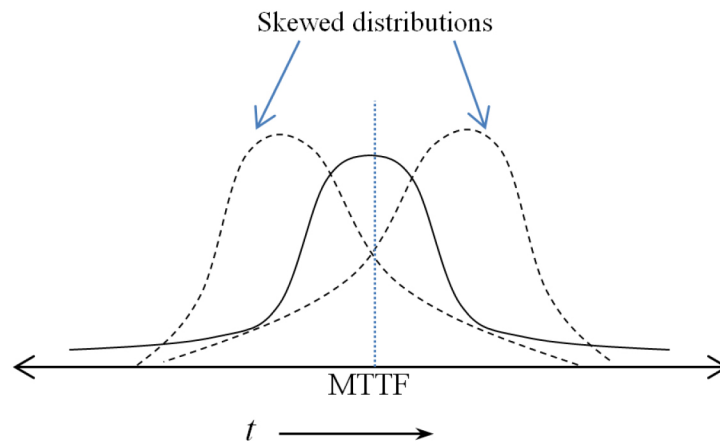


**Figure 1.** *MTTF represents the expected time to failure correctly only for symmetric distributions (center pdf, solid line). Most systems will fail before MTTF for right-skewed distributions and after MTTF for left-skewed distributions.*

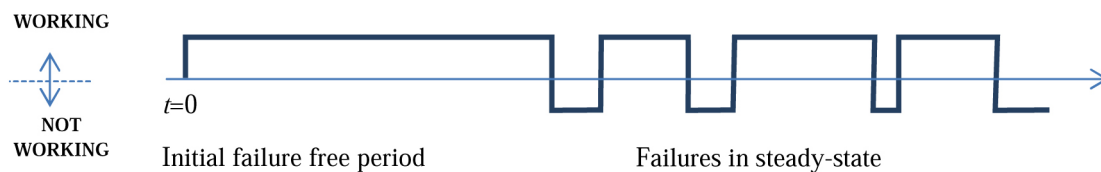


**Figure 2.** *Availability is high if repair time to operation time ratio is small. It greatly depends on whether the system is in steady-state or initial (transient) state of operation.*

## Literature Survey

It is important to consider how these issues are tackled in the literature. While most reliability texts and books assume systems to be non-repairable (Kapur and Lamberson, 1977, Haldar and Mahadevan, 1999), there is significant work in assessing the performance of repairable systems (Rigdon and Basu, 2000) also. Most methods use a statistical *process* instead of a failure time distribution. In the well known power law model, the inter-failure times are represented by a homogenous Poisson process (HPP) characterizing full repair or by a non-homogenous Poisson (NHPP) process for minimal repair (Crow, 1974 and 2012). Usually, because repaired systems are composed of used and new components, inter-failure times decrease with time. Alternatively, repairs can often lead to discovery of design flaws or installation errors that are subsequently fixed. In such cases, it is possible for the inter-failure time to increase (Wang and Coit, 2005). Therefore, characterizing repairable systems using a statistical process can account for decreasing, increasing or static inter-failure time allowing us, at least theoretically, to model their performance under various operating and repair strategies. We believe that practical application of these techniques in the commission and maintenance of systems poses serious challenges which we will discuss in the next section. The research thrust of this work is therefore stated as: “Is there a minimal set of metrics (MSOM) that can capture most, if not all, characteristics of a repairable system thereby

allowing for tradeoff decisions?” A systematic study is clearly required.

## Why Metrics?

We have mentioned that the metrics of MTTF and availability convey limited information. It is tempting to perform the Modeling of failure-times using a statistical process as has been done in the literature, is therefore, an option. We believe that such a method impedes decision making, particularly when tradeoffs of performance, with other attributes such as cost must be made. A carefully chosen small set of metrics on the other hand, can provide a very clear picture of performance. For example, if we want to assess the difference between transient and steady-state performance for a repairable system, it is much easier to compare the mean time to first failure and the mean time to failure during the steady state operation. Another advantage is that a small set of metrics can be used to represent and portray system performance using a Pareto front. Pareto (or non-dominated) fronts have been shown to be effective in making decisions over multiple attributes (Deb et al., 2002) if the number of attributes is small. Parameterized processes can be hard to relate with because their parameters are not necessarily “attributes”.

**Table 1. Candidate metrics and their limitations**

| Metric                                                            | Issues                                                                                                                                                                           |
|-------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Time to first failure ( $T_f$ )                                   | It is useful only when the system is new or when fully repaired after each failure.                                                                                              |
| Mean time between failures ( $T_m$ )                              | It provides only the mean of the time to failure.                                                                                                                                |
|                                                                   | It does not provide any other statistic.                                                                                                                                         |
| Minimum failure free period (MFFP) with probability $p$ ( $T_p$ ) | The MFF is specified with a given probability. Still, it provides only one statistic of time to failure. Two different MFFPs (transient and steady-state) can resolve the issue. |
| Number of failures within the planning horizon ( $N_f$ )          | Over a planning horizon, the number of failures is a good metric of system performance. However, it also represents only one statistic of the time to failure.                   |
| Planning horizon ( $P$ )                                          | It specifies the time over which system repair is performed. It provides a benchmark for other metrics. It cannot be used by itself.                                             |
| Effective age ( $\bar{t}$ )                                       | It represents the age of a system in years, taking into account technical obsolescence and physical reliability. It only provides the performance at a specific time.            |
| Repair time ( $t_r$ )                                             | The amount of time it takes to take the system offline and perform repairs.                                                                                                      |
| Cost ( $c_r$ )                                                    | The amount of needed money to commission and perform maintenance on the system.                                                                                                  |

## 2. DESIRABLE PROPERTIES FOR THE METRICS

In this section, we discuss the desirable properties (desiderata) the minimal set of metrics (MSOM) should have. While the desiderata may not be exhaustive, we believe it can cover most aspects of a repairable system performance. These desiderata can be considered as axioms. They are as follows:

**D1. Should model transient behavior:** The MSOM should be able to model the performance of a repairable system when it is first installed with all new components.

**D2. Should model steady-state behavior:** The MSOM should be able to model the performance of a repairable system when it has undergone a few repair and installation cycles. In this “steady-state” operation, the system can have new and old components.

**D3. Should describe repair frequency:** The MSOM should show how often repairs are required for the system.

**D4. Should describe a measure of performance starting from an arbitrary time:** The MSOM should be usable for a fleet of systems where the end-user selects one system from the fleet at an arbitrary time and expects a certain performance level or a trouble-free mission length.

**D5. Should consider initial and repair costs:** Because performance comes at a cost, MSOM should quantify this tradeoff.

**D6. Should describe technical obsolescence:** Most engineering systems are designed for a specific period of use.

Aside from functional loss, there is always the issue of technical obsolescence. The MSOM should be able to account for this.

**D7. Should help identify the best repair strategy:** The MSOM should identify, to a fair degree of accuracy, the best repair strategy for system maintenance. While a repair strategy may not be explicit in the metrics (e.g. how many components repaired and when), one should be able to perform optimization using the MSOM as attributes.

**D8. Should determine the total period of operation:** The MSOM should indicate how long the system will be in place, even with constant repair, before being replaced by a new technology.

Table 1 lists all metrics we can include in our proposed MSOM. Table 2 shows the desired properties each metric satisfies. Note that some metrics satisfy multiple desired properties.

Table 2 shows that there are many ways to define the MSOM. In this research, we choose a MSOM which consists of the Minimum failure free period  $T_p$ , the number of failures  $N_f$ , the planning horizon  $P$ , the effective age  $\bar{t}$ , and the cost  $c_r$ . Note that  $T_p$  is a generalization of both the MTTF and the time to first failure. To capture both, we separate  $T_p$  into two constituents; the initial MFFP  $T_p^0$ , and the steady-state MFFP  $T_p^S$ . In the next section, we describe the effective age metric.