# Using Maintenance Strategy to Improve The Availability of Complex Systems

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## Abstract

In today's marketplace for high volume printers, reliability and availability are key performance factors that can affect the financial performance of both vendor and customer. Equipment having fewer failures and requiring less service will have higher availability and productivity and generally be perceived as offering better value. Higher availability translates directly to getting more out of the equipment and a higher return on investment.

The availability of complex equipment is affected by both the intrinsic reliability of the system and maintenance strategy. Generally, the reliability distribution of complex repaired systems follows the exponential distribution function. This distribution of failures, at the system level, is a result of having many elements in the system with a mixture of life distributions and or characteristic parameters. When there are many different and non-synchronized life distributions, the hazard rate (failure rate) is constant when measured over a long period. With a constant hazard rate a preventive maintenance strategy is not effective. However, within a complex system, lower level subsystems and components often have well defined wear-out modes of failure. Even though the total system has a constant hazard rate and exponential failure distribution, it is possible to improve equipment availability by managing the repair or replacement of those components with wear-out modes of failure. This paper compares several alternative maintenance strategies and shows how under certain conditions service hours can be reduced and equipment availability increased.

## The Reliability Challenge

Printer availability is one of the more important product qualities, especially in the high volume end of the market. Typically, capital costs for acquiring the equipment are significant and as a result end users place a premium on high availability. Equipment availability is directly related to cost of ownership. This is especially true for users who are selling the output. Loss of availability in this environment generally means, at the very least, opportunity costs and may at times lead to significant out of pocket costs when work must be subcontracted rather than done in-house. In all cases, loss of equipment availability is an inconvenience that makes planning difficult and leads to disappointed customers all the way along the value chain. The challenge for the printer system designer is to create cost effective products having consistently high availability and excellent image quality that can be sustained over a prolonged period.

## Reliability

Reliability is the probability of survival of a system or component for a given duration. The duration could be defined either in terms of time or number of uninterrupted production cycles, or a combination of factors. For our purpose, we will define reliable operation as operation within specification, so as to include both "hard" failures and gradual reductions in performance characteristic (soft failures), for example image quality. The most serious and immediate is a "hard" failure such as a component which completely stops functioning, preventing continued operation. "Soft" failures are also possible. The system performance gradually degrades until the quality of the output slips below a minimum acceptable level. Complicating the situation is the fact that the minimum acceptable level can be affected by a number of factors including environment, application and customer expectations. For example, printing parts lists or financial statements is less demanding than printing images likely to highlight subtle image artifacts.

Whatever metric drives failures should be used to measure reliability. For our discussion we will use time. The reliability of complex systems typically follows the exponential distribution, paradoxically one of the simplest probability density functions (PDF). This means that the failure rate per unit time is a constant. This rate is often referred to as the hazard rate. If we started with a given number of units operational at the beginning of a test, a fixed percentage of the survivors would fail per unit time. This constant hazard rate determines the nature of the PDF. The exponential distribution is a one parameter probability distribution and is given by

$$f(t) = \lambda e^{-\lambda t} \qquad (1)$$

where $\lambda$ is *1/MTBF*. MTBF is mean time between failures. Reliability and fraction failed are given by:

$$Reliability = e^{-\lambda t} \quad (2)$$

$$FractionFailed = 1 - e^{-\lambda t} \quad (3)$$

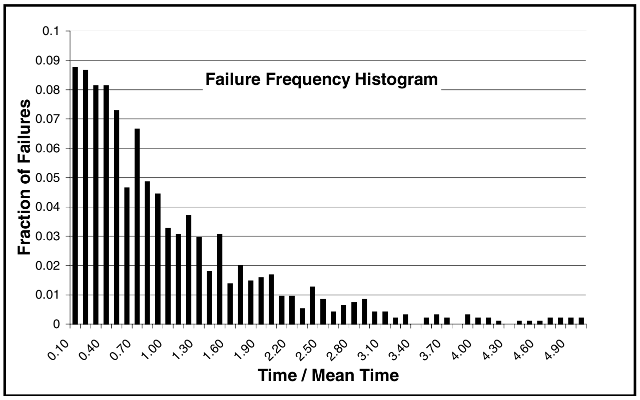


*Figure 1. System Failure Histogram*

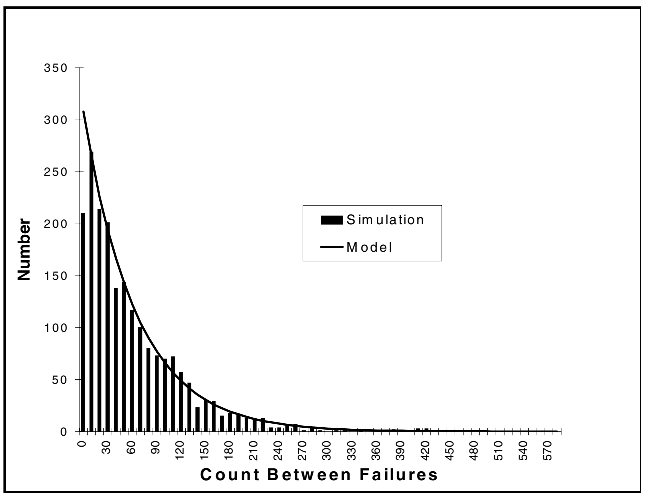


*Figure 2. Failure Histogram for System*

This distribution, in addition to being interesting mathematically, is of great value in characterizing many components and systems. Components whose failure modes are dominated by external events, will commonly fit this distribution. An example of this would be a transformer whose failure mode is the break down of the electrical insulation due to an input voltage spike or transient. Most common electronic components also follow this distribution. This distribution also has a characteristic which is not at all intuitive. It is part of our every day experience to think that "old" things are more likely to break than "new" things. And therefore, if one replaces the old component with a new one, the chances of a failure are reduced. For constant hazard rate components, however, this is **not** the case at all. If you replace such an old part, with a "perfect" new one and do it without making any "mistakes" your chances of a failure will not be decreased at all. Given the vanishingly small chances of a perfect part and error free installation, the best strategy for maintaining such components is "If it's not broken, don't fix it". Complex repaired systems can often be characterized by this same distribution. Figure 1 shows the life distribution for the time between failures for a high volume printer. The time scale for the data has been expressed in arbitrary units, since all manufacturers have an understandable concern about public display of this very important information. One might be tempted to assume that this characteristic distribution is due to the many electronic components in such devices. A simple simulation can easily demonstrate such system level behavior, even when none of the components that make up the system have a constant hazard rate. Figure 2 is the failure interval frequency histogram for a system comprised of 20 parts, each of which has fixed life, with no uncertainty. The parts' lives were from a uniform distribution over the range of 500 to 2000. The resultant system would have a mean time between failures (MTBF) of only 65 units. There are several other important observations we can make, which have significant implications for "real" world systems. Figure 3 is a plot of the Reliability function for the "data" and the function shown above, with the rate set equal to the average of the intervals from the data. First because the distribution is so heavily skewed to the short intervals, the median interval (the 50% level) is only 47. This is to say that half of the customers would experience a failure before even reaching the average value! Maybe to make the point even more striking, if the units are days, this system would be expected to run over two months between failures, on **average.** But the figure points out that there is about a 10% chance that the system would need a new service call only 6 days after being repaired.

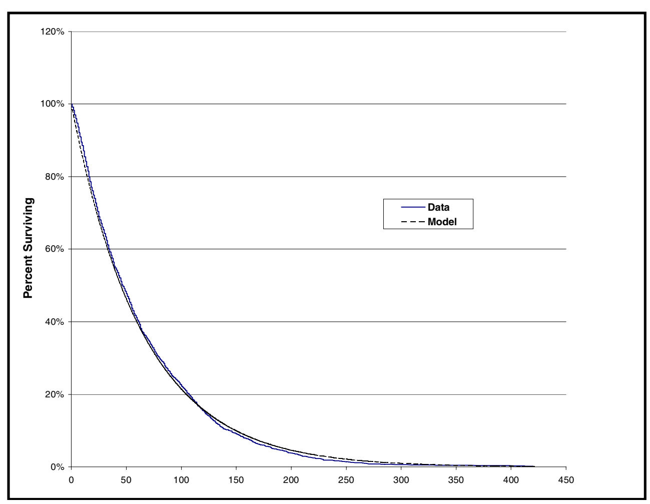


*Figure 3. Reliability for System with Exponential PDF*

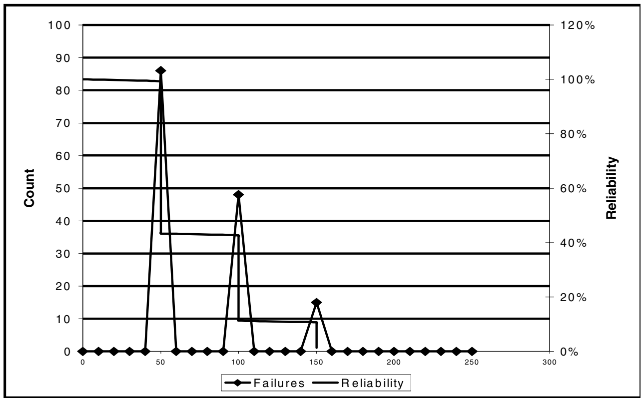


*Figure 4. System Failures and Reliability*

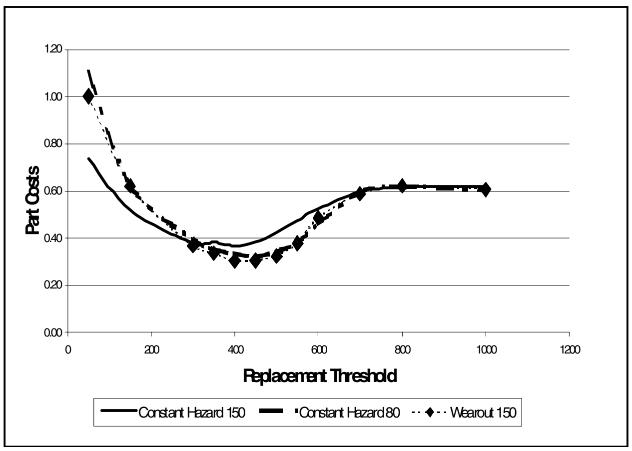


*Figure 5. Total Service Cost vs. Replacement Threshold*

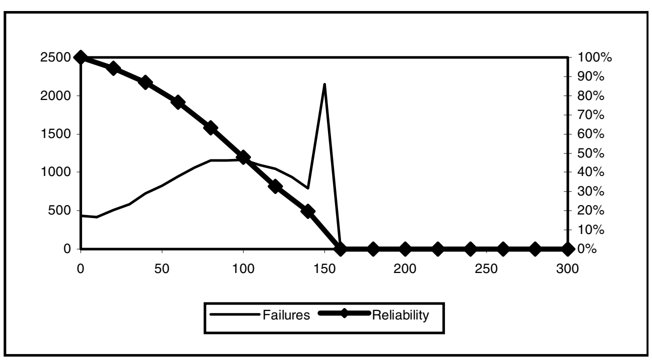


*Figure 6. Effect of linkage of parts replacement*

Well then are we just stuck with this distribution? Fortunately, no, at least in some cases. As was stated above the system "appears" to have a constant hazard rate, but can in fact be made up of many individual components, which are very predictable. In Figure 4 we see the histogram for a similar set of parts, but with the lives adjusted to be multiples of some large common denominator, 50 for this example. Note that customers of this system would enjoy a relatively long interval of failure free operation, which of course makes production planning much easier. Further, with such a system the customer could choose to have "Preventative Maintenance" done before an important job. Unfortunately, in the real world such perfect parts do not exist. As soon as realistic variability in the wear-out life of the parts is included, the system returns to a constant hazard behavior. A strategy that does work in the real world is often called "First Call After." Using this strategy, the preventive maintenance actions are no longer scheduled. Rather, when a service call is made for system failure, all subsystems are checked to see if life is beyond the service threshold. Items beyond the replacement threshold are serviced or replaced. The primary goal of this strategy is reduced costs, however it can have some impact on availability. The typical service call has two major cost components, the parts costs plus installation labor, and the response time costs. These two factors can be traded off against each other. If we let the part run to failure, we will have the lowest part cost, but will also generate a service call. If the part has a hazard rate that increases with usage (wearout failure mode), we can select a threshold age for the part. The part is replaced at the first service call after the threshold, thus saving the cost of one additional service call. Figure 5 shows the predicted results for this strategy. The solid curve shows some cost savings for the case of a system which has constant hazard components and one part having a Weibull distribution with a beta factor of 3. If the system MTBF is significantly lower than the component life, we can reduce costs further since there are more opportunities to replace the part before failure. The dotted curve in Figure 5. shows this. The curve with markers shows that further reductions are possible if the system life distribution had more of a wearout mode than constant hazard rate. This concept can be taken further to also improve the availability as well as the costs. If we add the strategy of linking part replacements the shape of the reliability curve can be improved, with fewer short interval failures. This is shown in figure 6.

All of these strategies are dependent on the subsystem and components of our NIP equipment having a wearout characteristic. Some parts do have this today, however, many do not. The technology challenge we all face is driving more and more of the components to have this characteristic. Many tools exist to do this. The tools associated with Robustness, in particular against external noise factors, have been particularly useful.

## Conclusions

Although complex systems typically exhibit constant hazard rates, maintenance strategies can be formulated that will give results superior to a "run to failure" strategy. The challenge for the system designer is to eliminate the causes of random failure to enable the cost-effective use of preventive maintenance strategies.

## Bibliography


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2. Elsayed A. Elsayed, Reliability Engineering, Addison Wesley Longman, 1996


## Appendix

The following analysis is for a non-deterministic replacement interval for a component. It is assumed that a service call is generated by failure of either the system or the component and that the system PDF is the exponential distribution. When the system generates the failure, the system is repaired and in addition the component is replaced if its life is beyond the replacement threshold. The component PDF is not restricted; the Weibull distribution is often useful for describing the PDF for the life distribution of components since it can model a range of behavior including infant mortality and wear-out. The following cases represent only two of numerous possible maintenance strategies.

### Strategy To Minimize Total Cost

The minimum cost replacement interval $t_r$ is found by minimizing total cost:

$$TotalCost(t_r) = \frac{FractionFailed(t_r) \times CostOfFailure}{TotalTime} + \frac{(1 - FractionFailed(t_r)) \times CostOfReplacement}{TotalTime} \quad (1a)$$

$$TotalTime(t_r) = FractionFailed(t_r) \times MTTF(t_r) + (1 - FractionFailed(t_r)) \times MTTRP(t_r) \quad (2a)$$

$$FractionFailed(t_r) = \int_{-\infty}^{t_r} f_C(t)dt + \int_{t_r}^{\infty} R_S(t - t_r) f_C(t)dt \quad (3a)$$

$$MTTF(t_r) = \frac{\int_{-\infty}^{t_r} t f_C(t)dt + \int_{t_r}^{\infty} t R_S(t - t_r) f_C(t)dt}{\int_{-\infty}^{t_r} f_C(t)dt + \int_{t_r}^{\infty} R_S(t - t_r) f_C(t)dt} \quad (4a)$$

$$MTTRP(t_r) = \frac{\int_{t_r}^{\infty} t R_C(t) f_S(t - t_r)dt}{\int_{t_r}^{\infty} R_C(t) f_S(t - t_r)dt} \quad (5a)$$

where $f_c(t)$ is the component PDF, and $f_s(t)$ is the system PDF. $R_c(t)$ and $R_s(t)$ are the component and system reliability respectively and are derived from the respective PDFs. $MTTF(t_r)$ is mean time to failure associated with the replacement interval $t_r$ and $MTTRP(t_r)$ is the mean time to replacement for components replaced after the replacement threshold but before failure.

$$CostOfReplacement = Parts + Labor \quad (6a)$$

$$CostOfFailure = Parts + Labor + CostOfUnscheduledService \quad (7a)$$

### Strategy To Maximize Availability

The replacement interval that gives maximum availability is found by minimizing down-time as a fraction of total time.

$$DownTimeFraction(t_r) = \frac{DownTime(t_r)}{DownTime(t_r) + TotalTime(t_r)} \quad (8a)$$

$$DownTime(t_r) = FractionFailed(t_r) \times (ResponseTime + MTTR) + (1 - FractionFailed(t_r)) \times MTTR \quad (9a)$$

where $MTTR$ is the mean time to repair.

In addition to these strategies we could conceive of other objectives such as minimizing the total cost to society. In this calculation we would include opportunity costs associated with unavailability of the equipment for both end user and supplier, in addition to the obvious ones of parts and labor.

## Biography


John King is Reliability Manager at Heidelberg Digital, LLC. Mr. King has had experience in the development and commercialization of both ink jet and electrophotographic printing systems. His current interests are in improving the reliability and availability of printer systems. He holds a BME degree from Rensselaer Polytechnic Institute and an MS in Engineering Mechanics from the University of Pennsylvania. He is a member of the American Society of Mechanical Engineers.

John Thompson is Manager of Special Projects at Heidelberg Digital LLC. Mr. Thompson has over 30 years of experience in the development of electrographic equipment. He holds an MS in Electrical Engineering from the University of Rochester.