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By Menachem P. Berg

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ABSTRACT

Most maintenance studies deal with the problem of long-term maintenance-costs optimization, given the cost of the available maintenance actions: repair or replacement. The focus in this paper is on the improvement in performance, with respect to certain performance criteria of interest, that results from a maintenance action. The comparison of the random quantities involved is done by means of suitable probabilistic ordering notions. Different modelling situations are considered, and for each of them conditions are obtained on the life distributions of the present item and the new (or repaired) one that ensure performance improvement with regard to the different performance criteria. Apart from providing a decision tool for maintenance application, the work also contributes to clarifying relationships between (probabilistic) ordering notions and aging properties within the maintenance context.

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INTRODUCTION

Maintenance studies in the literature (Barlow and Proschan (1965)) usually derive optimal maintenance policies, based on the costs of the available maintenance actions, with regard to a long-term cost objective function. In this paper, maintenance actions are investigated with respect to the performance improvement they bring about in the future evolution of the failure process. More specifically, we consider several performance criteria of interest, and examine their improvement by maintenance actions like replacement, failure or preventive, and repair or overhaul (to different extents). Generally, the focus is on performance improvement in the foreseeable future rather than the long-term one; the latter may be of less relevance in our era, of high quality items on one hand and rapid technological changes on the other hand.

The underlying failure modelling stipulated here is age- (or usage-) based, as is the case with most maintenance and reliability studies (avoiding a causal failure model because of the extent of (often unrealistic) assumptions involved, data needed and associated expenses). Correspondingly, the focal probability tool is that of the life-distribution (a term we keep because of its wide use, even though it is a clear misnomer when repairs are involved, as is the case with most heavy and expensive machinery, in which case it is indeed the time-to-first (or next) failure that we deal with) or, even preferably the hazard (or failure-rate) function (see Berg (1995) for an elaborate examination of these issues).

Since the future evolution of the failure process is random under any maintenance action, or without it, the comparison must be by probabilistic tools, i.e., by means of (probabilistic) ordering notions. There is a host of such ordering notions, and the choice of an appropriate one, for a given situation, is yet another issue to be addressed.

THE MATHEMATICAL SETTING

Performance improvement must be, by definition, with respect to a given performance criterion. The most natural and common one is the time to next failure, and accordingly we denote by V and W , the time-to-failure without and with a certain maintenance action, respectively. To demonstrate this performance improvement we need to verify that

$$W \underset{ON}{>} V \quad (1)$$

where ON is the (probabilistic) ordering-notion used for comparison.

In the reliability context, on intuitive grounds, suitable ordering-notions are the following:

(i) MO = means ordering, defined as

$$W \underset{MO}{>} V \quad \text{if} \quad E(W) \geq E(V),$$

where $E(\cdot)$ is the expectation operator. This is the most common and basic comparison tool. It has an obvious drawback because of its limited focus, but it also has a clear advantage: it is a complete ordering in the space of distributions, and hence all random variables can be unequivocally compared.

(ii) SO = stochastic ordering, defined as

$$W \underset{MO}{>} V \quad \text{if} \quad \bar{G}(x) \geq \bar{F}(x), \quad \forall x$$

where $\bar{G}(\cdot)$ is the survival function (i.e., 1 minus the c.d.f. of W) and $\bar{F}(\cdot)$ – the same for V . The relevance of SO to reliability is clear: it compares the no-failure (or, survival) probability for any given time period. It is stronger than MO , i.e.,

it implies it, but it is not a complete ordering (i.e., not all pairs of random variables possess a SO relationship).

(iii) HRO = hazard-rate ordering, defined as

$$W \underset{HRO}{>} V \text{ if } r_G(x) \leq r_H(x), \quad \forall x$$

where $r_G(\cdot)$ and $r_H(\cdot)$ are the hazard (failure-rate) functions of W and V , respectively, i.e. $r_G(\cdot) = -\frac{d\bar{G}(x)}{dx}/\bar{G}(x)$.

The HRO intrinsic relevance to reliability contexts stems from the focal role in reliability theory of the hazard function it is based upon (see again Berg (1995)). The HRO is stronger than SO, and like SO it is also not a complete ordering.

The validity of relationship (1), given a specific ON, depends on the state of the present item and the maintenance action planned. As far as the former is concerned, the only possible information we can have about the present item, within an age-based modelling context, is its age (say) d . We shall thus assume throughout that

$$V = X(d), \quad d > 0$$

where $X(d)$ is the life of the item when it is of age d (or, indeed, its "remaining" life at age d) and thus $X \equiv X(0)$ is the life of a new item.

We categorize maintenance actions through the following three situations.

Situation 1: The maintenance action is a *replacement* by a *new* item of the same type. In this case

$$W = X$$

and we thus need to verify the validity of the relationship

$$X \underset{ON}{>} X(d), \quad d > 0$$

given the survival function $\bar{F}(\cdot)$ of X . The survival function of $X(d)$ is determined by $\bar{F}(\cdot)$ and is given by

$$P(X(d) > x) \equiv \bar{F}_d(x) = \frac{\bar{F}(x+d)}{\bar{F}(d)}, \quad x \geq 0$$

Situation 2: The maintenance action is a *repair* (or overhaul if it is planned), whose effect is rejuvenation of the item; that is, making it equivalent, in terms of its "remaining" life, to an item of age $\tilde{d} < d$. Note that a replacement by a used item of the same type gives a mathematically equivalent situation – so both types of maintenance actions are covered here. In this case

$$W = X(\tilde{d}) \quad \text{where } 0 \leq \tilde{d} \leq d ,$$

and we need to verify the validity of the relationship

$$X(\tilde{d}) \underset{ON}{>} X(d) \quad 0 \leq \tilde{d} \leq d .$$

Situation 3: *Replacement* by a *different* type of item (whether new or used). In this case we need to verify the validity of the relationship

$$W \underset{ON}{>} X(d) , \quad d > 0$$

given the survival functions $\bar{G}(\cdot)$ and $\bar{F}(\cdot)$ of W and X , respectively.

In all situations we shall be looking for conditions that validate the respective relationships for all possible relevant age, which means that these conditions are sufficient no matter what the ages are. Furthermore we shall want the conditions, whenever possible, to be also necessary, implying that they cannot be relaxed without violating the relationship for at least some ages.

THE MATHEMATICAL ANALYSIS

We are looking for conditions for the validity of the relationship in each situation and for each ordering notion. This boils down here to nine exercises which we now consider successively.

(1) Situation 1, $ON = MO$

We want

$$X \underset{MO}{>} X(d) \quad \forall d > 0$$

The required condition here, which is sufficient and necessary, is that $F(\cdot)$ possesses the NBUE (new better than used in expectation) aging property (see

Barlow and Proschan (1975) for this and later aging properties). That simply follows from the definition of NBUE.

(2) Situation 1, ON = SO

$F(\cdot)$ needs to possess only the NBU (new better than used) aging property.

Once more this follows from the definition of NBU.

(3) Situation 1, ON = HRO

$F(\cdot)$ needs to possess only the IFR (increasing failure rate) aging property.

Proof.

We first observe that if $r(\cdot)$ is the hazard function of $F(\cdot)$ then the hazard function of $X(d)$ is given by

$$r_d(x) = r(d+x) \quad \forall d > 0, \forall x > 0 \quad (2)$$

Next, it is easy to see that

$$r(x) \leq r(d+x), \quad \forall d > 0, \forall x > 0 \quad \text{iff} \quad r(x) \uparrow x,$$

where $\uparrow$ stands for increasing, but not necessarily strict increasing.

(4) Situation 2, ON = MO

We want

$$X(\tilde{d}) \underset{MO}{>} X(d) \quad \forall (\tilde{d}, d): 0 \leq \tilde{d} \leq d. \quad (3)$$

Here the required condition, which is sufficient and necessary, is that $F(\cdot)$ possesses the DMRL (decreasing mean remaining life) aging property. This follows from the definition of DMRL, since (3) is equivalent to $E(X(d)) \downarrow d$.

(5) Situation 2, ON = SO

Only the IFR aging-property is required.

Proof.

The proof follows from the well-known equivalence relationship (Barlow and Proschan (1975)):

$$r(x) \uparrow x \quad \text{iff} \quad X(d) \underset{SO}{\downarrow} d, \quad (4)$$

where $\underset{ON}{\downarrow}$ stands for random variables decreasing, with respect to ON, e.g., here

$X(d)$ is decreasing SO with respect to d .

$$X(\bar{d}) \underset{SO}{>} X(d) \text{ for any } \bar{d} \leq d.$$

(6) Situation 2, ON = HRO

The required condition is that $F(\cdot)$ possesses the IFR aging property.

Proof.

The proof follows from (2) and

$$r(d+x) \uparrow d, \forall x > 0 \quad \text{iff} \quad r(x) \uparrow x. \quad (5)$$

The above conditions are conveniently summarized in Table 1.

Table 1: Summary of conditions for situations – categories 1 and 2:
replacing item is of the same type as the replaced one

Replacing item \ ON Type	MO	SO	HRO
New	NBUE	NBU	IFR
Younger	DMRL	IFR	IFR

Remark: all conditions are sufficient and necessary.

(7) Situation 3, ON = MO

We want

$$W \underset{MO}{>} X(d), \quad \forall d > 0. \quad (6)$$

Two sufficient conditions for (6) to hold are:

$$(i) \quad W \underset{MO}{>} X \quad \text{and} \quad X \underset{MO}{>} X(d), \quad \forall d > 0$$

or

$$(ii) \quad W \underset{MO}{>} W(d) \quad \text{and} \quad W(d) \underset{MO}{>} X(d), \quad \forall d > 0$$

or, equivalently

- (i) $W \underset{MO}{>} X$ and X possesses the NBUE aging property

or

- (ii) $W \underset{ACMO}{>} X$ and W possesses the NBUE aging property,

where ACMO (age-consistent means-ordering) is defined as

$$E(W(d)) > E(X(d)), \forall d > 0,$$

(that is, in general, **ACON** extends an ordering relationship **ON** to the remaining life from any given age). A characterization of ACMO is $\int_x^\infty \bar{G}(u)du \Big/ \int_x^\infty \bar{F}(u)du \uparrow x$,

which, however, is not a convenient one. As a matter of fact $W \underset{SO}{>} X$ is not sufficient for ACMO, but HRO (being ACSO) is.

(8) Situation 8 $ON = SO$

Repeating the steps above, we obtain the *sufficient* conditions

- (i) $W \underset{SO}{>} X$ and X possesses the NBU aging property

or

- (ii) $W \underset{HRO}{>} X$ and W possesses the NBU aging property .

To verify the first part of the latter condition use the characterization of HRO (Ross (1983)), which states that

$$W \underset{HRO}{>} X \text{ iff } W(d) \underset{SO}{>} X(d) \quad \forall d$$

(or, using the general notation above, $ACSO = HRO$).

(9) Situation 3, $ON = HRO$

Repeating the above steps we finally obtain here (using again some arguments used earlier) the *sufficient* condition

$$W \underset{HRO}{>} X \text{ and } \{X \text{ or } W \text{ possesses the IFR aging property}\}.$$

To verify the above we use the following two observations:

- (i) HRO itself is age-consistent, i.e., using the general notation above,

ACHRO = HRO. That property follows immediately from (2) and the equivalence relationship:

$$h(x+d) \leq r(x+d) \forall x, d \quad \text{iff} \quad h(x) \leq r(x) \forall x$$

(ii) Relationship (4) is also valid when SO is replaced by HRO, i.e., HRO is equivalent, *in this context*, to (the usually weaker) SO. This result follows from (2) and (5).

These conditions are summarized in Table 2.

Table 2: Summary of conditions for situations – category 3: replacing item is of different type than the replaced one

MO	SO	HRO
$\{W \succ X\}$ and $\{X \text{ NBUE}\}$ _{MO} or $\{W \succ X\}$ and $\{W \text{ NBUE}\}$ _{ACMO}	$\{W \succ X\}$ and $\{X \text{ NBU}\}$ _{SO} or $\{W \succ X\}$ and $\{W \text{ NBU}\}$ _{HRO}	$\{W \succ X\}$ _{HRO} and $\{X \text{ or } W \text{ IFR}\}$

Remark: All conditions are sufficient.

INTERMEZZO

Besides the main purpose of the paper, namely the verification of performance improvement following a maintenance action, the above results also serve another end. We see how aging properties, introduced separately over time, interrelate in a clear manner within our general framework of different situations (or models) and ordering notions. This byproduct of our study contributes to the broader goal of scientific endeavor, namely, the creation of order in ideas and results.

OTHER PERFORMANCE CRITERIA

The performance improvements considered above, relate to the time-to-(next) failure criterion. Another possible performance criterion is a monetary one, and deals with the utility improvement due to the maintenance action considered. This is important since often the monetary element is ignored in maintenance studies with only direct maintenance costs being considered.

The utility dimension can be introduced in different ways. Here we opt to relate it to the "life" (i.e. time-to-failure) of the item, which will enable us to utilize results derived earlier. Define

$U(x)$ - the utility gained from a life of length x .

We adopt a maximum-expected-utility approach (still the dominant one, despite the controversy, in modern economics theory, and the only permissible one when utility is constructed in Bayesian axiomatic contexts). We want to verify the validity of the relationship: $E(U(W)) \geq E(U(W(d)))$, or using the notation here:

$$U(W) \underset{MO}{>} U(X(d)) . \quad (7)$$

Sticking to our approach of looking for universal conditions, we search for conditions that will validate (7) for all functions $U(\cdot)$ of interest (which is also useful in view of the enormous difficulties in actually constructing a utility function in any given particular circumstance). In reliability contexts, it seems that the only restriction we can impose on $U(\cdot)$ is that it is increasing (concavity, for instance, with its risk-aversion interpretation in finance, is not really relevant here) and thus we would like (7) to hold for all increasing $U(\cdot)$. However, that is equivalent (e.g., Ross (1983)) to:

$$W \underset{SO}{>} X(d),$$

so that all the results obtained earlier for SO, with regard to each of the situations considered, are automatically valid here.

Yet another performance criterion of interest, which still focuses on the

immediate future, is the anticipated *quality* of operations; one possible measure is the number of minor operation interruptions in a coming time period (assuming no replacement or major repair in that period). Such minor failures are fixed by what is technically called minimal repairs (e.g., Barlow and Proschan (1965)); following such a repair the item resumes operation, but is not improved (in the above terminology this corresponds to the borderline special case of $\tilde{d} = d$).

This (minor) failure process is an NHPP (nonhomogeneous Poisson process), whose intensity function equals the hazard function of the underlying "life" distribution. This is well known, and easily verifiable due to the independent-increment-property in the failure process of an item, induced by minimal repairs. Consequently, the comparison needed in this case, for a future time-interval of length t , is

$$N_W(t) \underset{ON}{<} N_{X(d)}^{(t)} \quad (8)$$

where $N_Y(t)$ denotes the number of minimal repairs in $[0, t]$, when Y is the life random variable. By the above statement (in the preceding paragraph) we have

$$N_W(t) \sim \text{Poisson} (H(t) = \int_0^t h(u) du),$$

and

$$N_{X(d)}(t) \sim \text{Poisson} (R_d(t) = \int_0^t r_d(u) du = \int_d^{d+t} r(u) du = R(d+t) - R(d)).$$

We now use the fact (Ross (1983)) that the Poisson family is increasing hazard-rate ordered with respect to its parameter, i.e., if $X(\lambda) \sim \text{Poisson}(\lambda)$ then $X_\lambda \overset{\uparrow}{HRO} \lambda$, and therefore also $X_\lambda \overset{\uparrow}{SO} \lambda$ and $X_\lambda \overset{\uparrow}{MO} \lambda$ (that is, in this context, HRO, SO and MO are equivalent). Hence (8) holds for either MO, SO or HRO if and only if

$$H(t) \leq R(t+d) - R(d), \quad t > 0, \quad d > 0$$

or, equivalently, using the relationships: $\bar{F}(x) = e^{-R(x)}$ and $\bar{G}(x) = e^{-H(x)}$,

$$\bar{G}(t) \geq \bar{F}_d(t), \quad t > 0, \quad d > 0, \quad (9)$$

Once more, if we want the comparison (8) to be universal and hold for all $t > 0$, (9) is equivalent to

$$W \underset{SO}{>} X(d).$$

Thus, again, for any situation considered, the required performance improvement for either one of the three ordering notions (MO, SO, and HRO) coincides with the SO-based comparisons, done earlier for the time-to-failure performance criterion.

CONCLUSIONS AND FUTURE RESEARCH

We have considered in this work comparison of maintenance actions for age-based failure-modelling situations. We have obtained conditions which justify replacement of an item by a new one for different performance criteria that are applied to the current situation, i.e. the improvement induced by the replacing item in comparison to the replaced one. Moreover, for each performance criterion separate analysis is done with regard to various random comparison tools of interest, namely different ordering-notions of particular relevance relevant to the maintenance context.

The pattern of analysis in this paper can be extended in a natural way to further comparison problems of interest, e.g., for yet other performance criteria and ordering notions. Moreover, the same ideas can be applied to other failure-modelling approaches, e.g., those based on stage-wise degradation of the item. In this sense this work sets the ground for a broad study of performance comparisons for maintained items, with respect to different performance criteria of interest, a range of possible situations, and various ordering notions of relevance.

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