Towards R&D Breakthroughs in Imperfect Maintenance Modeling

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“In fact, you are "part of an experiment" (I know it sounds bad, but usually in this case the guinea-pig survives.)” (E. Zio)

So I decided to train to have the odds in my favor...
Preamble

- Large events like PSAM/Esrel:
  - Important in exchanging ideas and networking
  - … but time for discussion very short after talks

- Ever dreamt of smaller events with the right experts, less presentations, more animated talks, a fight between ideas…
  … and a smell of burnt neurons at the end of the day?
ESRA-funded seminar on imperfect maintenance modeling
hold on May 11 in the EDF R&D premises near Paris
(coorganized by C. Bérenguer and W. Lair)
 +/- 15 participants, mostly linked to the ESRA TC on
maintenance modeling
Time to jump into action...
Outline

- Preamble
- Classical imperfect preventive maintenance models
- The industrial perspective
- Relevance of alternative approaches
- Conclusions
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Classical imperfect preventive maintenance models

- Different ways of modeling aging and maintenance efficiency
- Workshop focus: lifetime distribution and effective age concept
- Various classical models for imperfect maintenance… that are sometimes paradoxical and opposite to engineering intuition
Models based on shifting time in the lifetime distribution

- Reduction of the equipment’s failure rate: decrease of the failure rate by a factor $0 < \gamma < 1$

- Reduction of the equipment’s effective age: rejuvenation of part of the service duration of the component after restoration of part of its performances
Age

(Calendar) age of an equipment $t$: time interval elapsed from its operation start in an as-good-as-new state

Effective age of an equipment $\tau$: fictitious age, given the undergone repair and maintenance actions, and to be considered for the prediction of the future failure probability of this equipment

→ Linked to a measure of the level of rejuvenation brought to a component after an intervention
Possible equivalence between both approaches?

*(iff monotonously increasing failure rate)*

Reduction of the failure rate due to a PM

Rejuvenation by reduction of the effective age

Equivalence with a translation of the time origin

Effective age
Before maintenance

Proba density function of the next failure time: \( f(t) \)
(associated cdf \( F(t) \))

After maintenance

Proba density function of the next failure time:

\[
\tilde{f}(t) = \begin{cases} 
0 & t \leq t_{PM} \\
\frac{f(t-(t_{PM}-\tau_{PM}))}{1-F(\tau_{PM})} & t > t_{PM}
\end{cases}
\]

\( \rightarrow \) Left-truncation of the distribution

\( \equiv \) Distribution conditional to a (fictitious) failureless operation until \( \tau_{PM} \)

Implicit assumption!

Intrinsic failure time distribution \( f(t) \) unaffected by the maintenance process
No direct equivalence $\Delta \lambda \leftrightarrow \Delta \tau$:

- Preventive Maintenance (PM): not only when $\lambda$ has increased in a perceivable way...

- Successive PM actions: can maintain (for a while) a piece of equipment in an unchanged status wrt failure likelihood, but other performances can degrade, residual wear-out accumulates..., effects of the usage time appear – often before translating into a failure probability increase.
Maintaining before the effects of aging become visible

postponing the onset of aging by PM actions

Modeling standpoint: shift in the onset of aging

\[ \lambda(t) \]

\[ t_{PM} \]

\[ v \]

\[ v_{PM} \]

\[ \nu_{PM} - \nu \]

consistent treatment for \( \lambda \) and for \( \lambda \leftrightarrow \)
Evolution of the effective age?

- Linked to the **maintenance efficiency** $\rho$

\[ \tau_n = \tau_{n-1} + (1-\rho)\Delta t \]

**Kijima 1**
- $\equiv$ Proportional Age Setback
- $\equiv$ Arithmetic Age Reduction $\text{ARA}_1$

**Minor PM**
- Recovery of part of the additional aging since the last intervention

**Major PM**
- Recovery of part of the aging since the start of operation

**Kijima 2**
- $\equiv$ Proportional Age Reduction
- $\equiv$ Arithmetic Age Reduction $\text{ARA}_\infty$

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Intermediate case: Arithmetic Age Reduction $\text{ARA}_m$

\[ \tau_n = \tau_{n-1} + \Delta t - \rho \sum_{j=0}^{m-1} (1-\rho)^j (n-j)\Delta t \]

(difficult to relate to practice however)

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Particular cases

Minimum repair or inspection without rejuvenation

component reset in operation with no modification in its degradation level

→ « as bad as old »
→ Effective age unchanged ($\rho = 0$)

Perfect maintenance

component brought back to its initial performances by totally suppressing the effects of aging

→ « as good as new »
→ Effective age reset to zero ($\rho = 1$)
Let’s hit some points…

1. Usually: $\rho_i = \rho = 1 - \varepsilon \ \forall i$

Moreover if $\Delta t_i = \Delta t \ \forall i$, and if the component is reliable:

After the $n^{th}$ PM action without any failure from the start ($\text{ARA}_\infty$):

$$
\tau_n = \varepsilon.(\tau_{n-1} + \Delta t) \\
= \varepsilon.\left(\varepsilon.(\tau_{n-2} + \Delta t) + \Delta t\right) \\
= \ldots \\
= (\varepsilon^n + \varepsilon^{n-1} + \ldots + \varepsilon).\Delta t
$$

- Effective age $\rightarrow$ limit value independent of the number of PM actions carried out
- No more trend towards degradation
- Not realistic!!

Rem: situation not met with $\text{ARA}_1$
2. Numerical value of $\rho = 1 - \varepsilon$?

Related to the gain in the mean residual lifetime (MRL) of the component

Before maintenance

$$MRL^- = \int_{t_{PM}}^{\infty} (t - t_{PM}) \cdot \frac{f(t)}{1 - F(t_{PM})} dt$$

After maintenance

$$MRL^+ = \int_{t_{PM}}^{\infty} (t - \tau_{PM}) \cdot \frac{f(t - (t_{PM} - \tau_{PM}))}{1 - F(\tau_{PM})} dt$$

$$= fct(\varepsilon)$$

$\rightarrow$ gain in the mean residual lifetime:

$$MRL^+ - MRL^- = fct(\varepsilon)$$

$\rightarrow$ via expert elicitation
3. Implicit hypotheses

- pdf after maintenance $\equiv$ pdf before maintenance, only a shift in time
  Verifiable??

- Equipment with a unique failure mode. What if multiple failure modes or multi-component systems?
  ➔ dependences between maintenance impacts
4. Maintenance impact proportional to a PM period?
   - Any variability in the maintenance epoch affects the resulting state of the component
     Consistent with practice??

5. Relevance for maintenance optimization?
   - Estimation of $\rho$ made from field data
     i.e. based on a previously applied PM policy (hence $\Delta t$)
   - $\rho$ then used to optimize $\Delta t$ for future operation
     $\Rightarrow$ Implicit assumption that $\rho$ and $\Delta t$ are independent. True??
     Resulting state after PM possibly not strongly dependent on $\Delta t$, but not $\rho$!
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The industrial perspective

While struggling theoreticians can still iron out problems...

... industrials must stay in troubled waters!
Some difficulties and challenges

- Parameter estimation when only small / highly censored historical data samples are available?
- Parameter estimation when different values of (Weibull parameters, efficiency) provide highly similar behaviors?
  - Expert judgement, Bayesian approach…?
- Heterogeneity in systems and in operational conditions
  - Covariates, frailty models…?
- Selection of a model (Kijima 1 or 2, …)?
  - Goodness-of-fit tests and model selection criteria?
- Optimization of the periodicity of a systematic planned maintenance strategy consisting in carrying out several tasks?
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Main idea: Escaping the linearity of Kijima-1 and -2 models to account for intuition…

- Actual execution time of a PM a bit later than/half of the scheduled time « in a reasonable way »
  - No impact on the resulting degradation state of the item
- Too long delay: Irreversible degradation and/or more intensive/costly maintenance to be carried out
  - Maintenance “elasticity”

- PM action: list of well-scheduled tasks to be carried out
  - Component returned to a target degradation (i.e. age)
  - As-Good-As-Expected (AGAE) Maintenance
How long can you stay in “elasticity” conditions? How long can you rejuvenate the component back to its AGAE state?

No matter how regularly and neatly the car is preventively maintained, its performances will unavoidably tend to decrease as a result of aging

→ Inescapability of aging

→ Replacement compulsory at some point
Initial failure rate

\( \rho \) variable, \( \tau_{el} = 6 \)

\( \rho \) variable, \( \tau_{el} = 12 \)

\( \text{ARA}_1, \rho = 0.7, \tau_{el} = 6 \)

\( \text{ARA}_1, \rho = 0.7, \tau_{el} = 6 \)

Intrinsic failure rate

\( \text{ARA}_1 / \text{Kijima-1} \)

Elasticity + inescapability of aging

\( \text{ARA}_\infty / \text{Kijima-2} \)
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Conclusions (1/2)

- Review of imperfect maintenance impact models based on the effective age concept
- Usually easy to implement… … yet some drawbacks and counter-intuitive characteristics

**Challenges:**

1. Guidelines for industrials to select a model and estimate parameters
2. Relevance of alternative approaches dropping the implicit linearity of the classical models?
Conclusions (2/2)

- Relevance of discussions in workshops associated to technical committees?
  - The experts are there
  - Crosspoints between methods and actual problems
  - Open discussion not always instantaneous however...

- Still a useful step towards more efficient problem solving and fruitful collaborations