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

Agenda and goals

Overview of effective age models for imperfect maintenance

Some industrial problems

Session 1: how to tackle these industrial problems?

Session 2: relevance of current approaches and of new developments

Session 3: accounting for expertise in imperfect maintenance modeling

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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

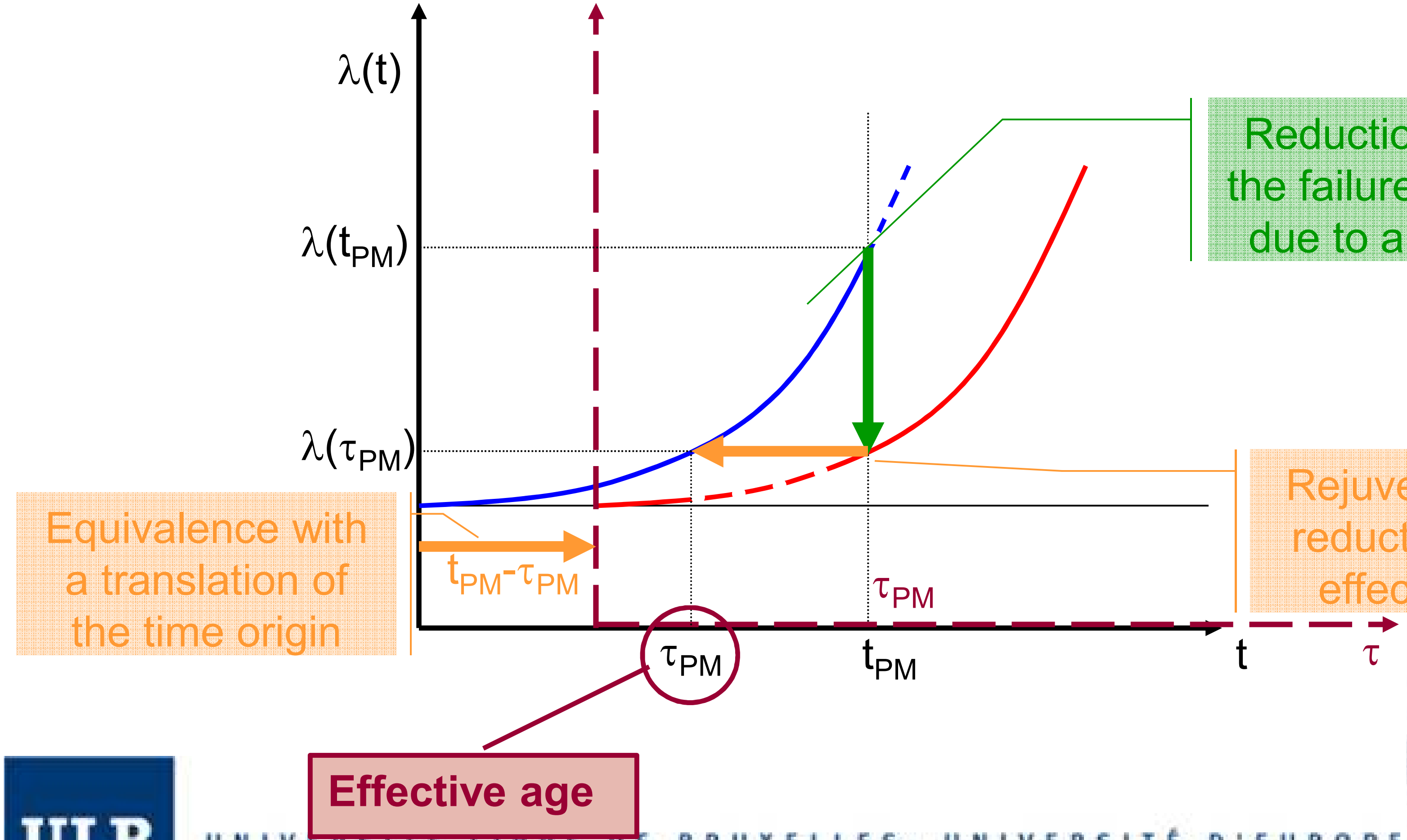
(Calendar) age of an equipment t: time interval elapsed from its operation start in an as-good-as-new state

Effective age of an equipment τ: 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)



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:

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

→ Left-truncation of the distribution

≡ Distribution conditional to a (fictitious) failureless operation until τ_{PM}

Implicit assumption!

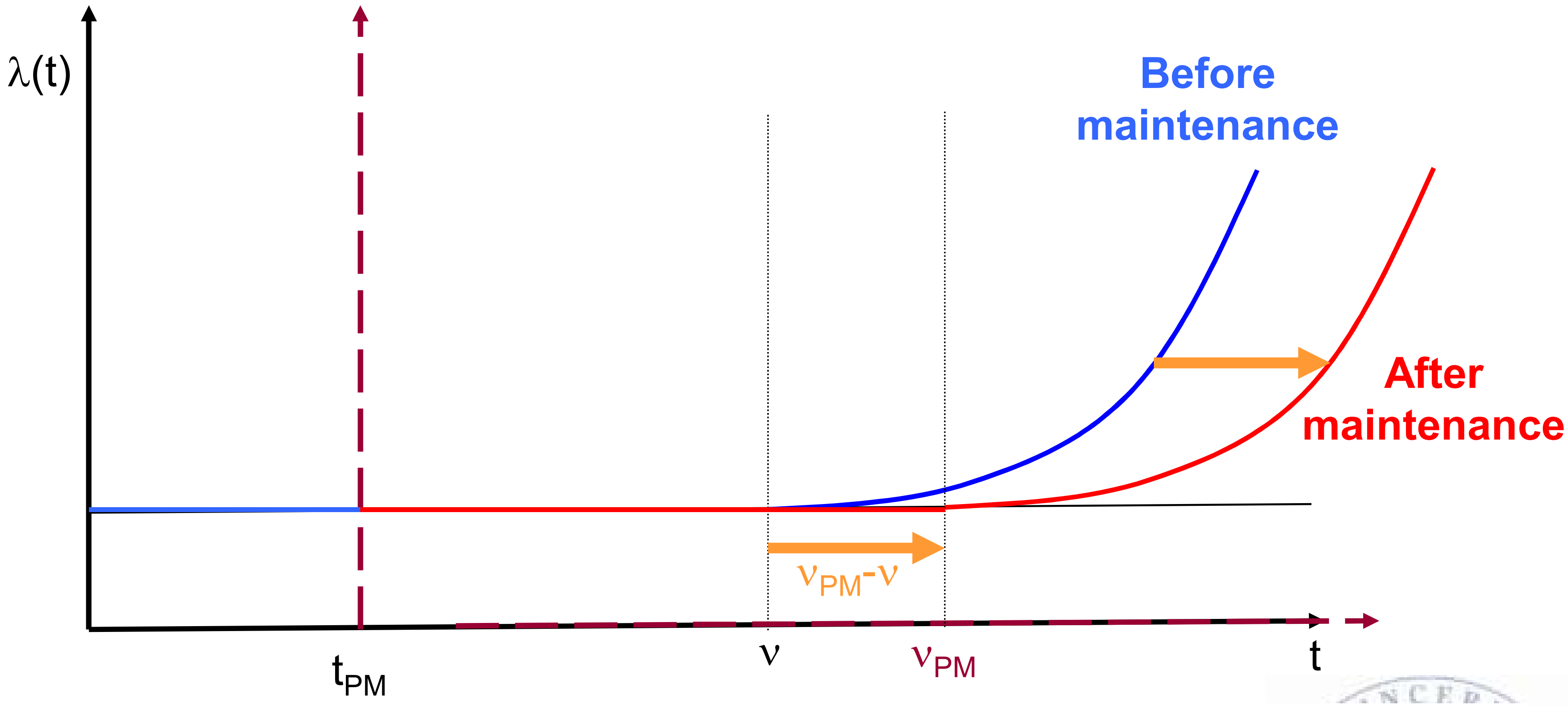
Intrinsic failure time distribution *f*(t) unaffected by the maintenance process

- **No direct equivalence $\Delta\lambda \leftrightarrow \Delta\tau$:**
  - Preventive Maintenance (PM): not only when λ 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

Could a PM be AGAN wrt λ and imperfect wrt (future?) ‘performances’?

→ Maintaining before the effects of aging become visible

→ postponing the onset of aging by PM actions



Modeling standpoint: shift in the onset of aging

≡ reduction in the equipment's effective age

→consistent treatment for λ and for λ↗

Evolution of the effective age?

→ Linked to the **maintenance efficiency** ρ

Kijima 1	Kijima 2
$\tau_n = \tau_{n-1} + (1-\rho).\Delta t$	$\tau_n = (1-\rho).(\tau_{n-1} + \Delta t)$
Kijima 1	Kijima 2
≡ Proportional Age Setback	≡ Proportional Age Reduction
≡ Arithmetic Age Reduction ARA_1	≡ Arithmetic Age Reduction ARA_∞
« 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 M., Morimura H., Suzuki Y., 1988, "Periodical replacement problem without assuming minimal repair", *Eur. J. Oper. Res*; **37**:194–203.

Martorell S., Sanchez A., Serradell V., 1999, "Age dependent reliability model considering effects of maintenance and working conditions", *Rel. Engng. Syst. Safety*; **64**:19–31.

Doyen L., Gaudoin O., 2004, "Classes of imperfect repair models based on reduction of failure intensity or effective age", *Rel. Engng. Syst. Safety*; **84**:45–56.

Intermediate case: Arithmetic Age Reduction ARA_m

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

(difficult to relate to practice however)

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 (ARA_∞):

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

$\Rightarrow$

$$\tau_n = \varepsilon.\Delta t.\frac{1-\varepsilon^{n-1}}{1-\varepsilon} \rightarrow \frac{\varepsilon}{1-\varepsilon}\Delta t$$

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

Rem: situation not met with ARA_1

2. Numerical value of $\rho = 1 - \varepsilon$?

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

Before maintenance

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

After maintenance

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

$$= fct(\varepsilon)$$

→ gain in the mean residual lifetime:

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

→via expert elicitation

3. Implicit hypotheses

- pdf after maintenance ≡ 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 ρ made from field data

  i.e. based on a previously applied PM policy (hence Δt)

- ρ then used to optimize Δt for future operation

  → Implicit assumption that ρ and Δt are independent. True??

  Resulting state after PM possibly not strongly dependent on Δt, but not ρ!

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The industrial perspective

While struggling theoreticians can still iron out problems…

… industrials must stay in troubled waters!

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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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Relevance of alternative approaches

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/ahead 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

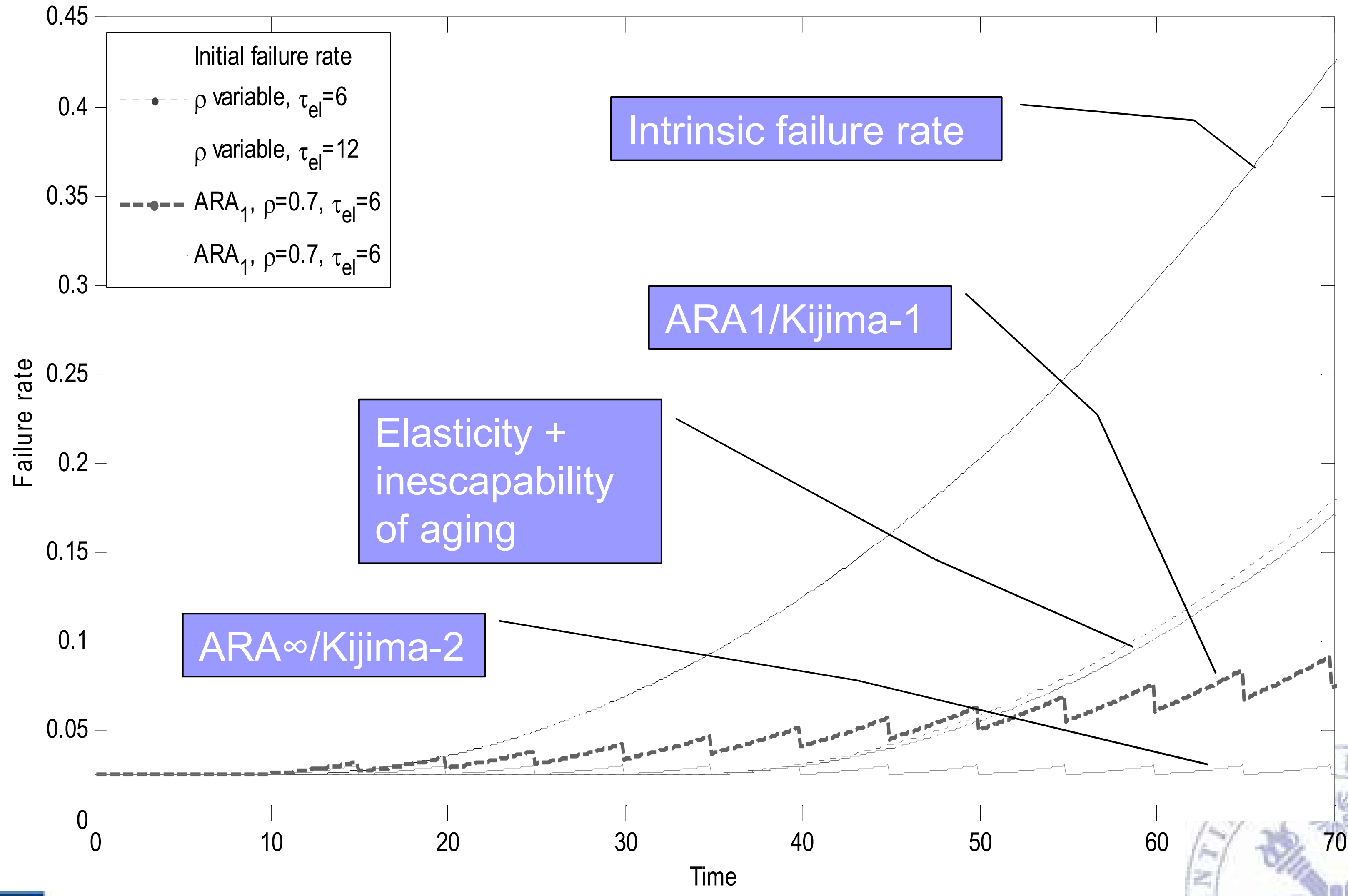
→ Component returned to a target degradation (i.e. age)

→ ***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
ρ variable, τel=6
ρ variable, τel=12
ARA1, ρ=0.7, τel=6
ARA1, ρ=0.7, τel=6
Intrinsic failure rate
ARA1/Kijima-1
Elasticity + inescapability of aging
ARA∞/Kijima-2
Failure rate
Time
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70

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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