ESREL 2018

European Safety
and Reliability Conference
Trondheim, Norway, 17-21 June 2018

Industry 4.0 and real-time synchronization of operation and maintenance

Jørn Vatn
Department of Mechanical and Industrial Engineering
NTNU - Norwegian University of Science and Technology, Norway

NTNU Norwegian University of Science and Technology

Background

- Maintenance decisions need to take into account
  - ***Current*** state of the component, system etc ("real-time")
  - Cost of maintenance and failures taking ***current*** operational context into account ("real time")
  - ***Future*** loads affecting the probability of failure
    - These loads may be *influenced* by changing operational profiles

Can we use Industry 4.0 concepts to approach the challenges?

Objectives

- Elaborate on basic elements of Industry 4.0
  - Digital twin, stochastic digital twin
  - Real-time
  - Digital twins interacting
- Present elements of a case study: *towards a set of **interacting** digital twins*

Industry 4.0 (Forth industrial revolution)

- Industry 4.0 is a collective term particularly used in manufacturing to emphasize technologies and concepts of value chain organizations
- Related terms
  - Cyber-Physical Systems
  - the Internet of Things
  - Cloud computing
  - Digital Twin
- Although the term originates from the manufacturing industry, the elements of Industry 4.0 are relevant for most businesses (Maintenance 4.0, Safety 4.0, Ship 4.0,…)
- The current usage of the term Industry 4.0 has been criticized as essentially meaningless

*Focus on the **elements** rather than the term Industry 4.0 as such !*
(avoid buzzwords)

IoT - Internet of Things

- The Internet of Things (IoT) is the network of items embedded with ***electronics***, ***software***, ***sensors***, ***actuators***, and ***network connectivity***
- which enable these objects to ***connect and exchange data***

*IoT is what we need to **connect***

Cloud computing

- Cloud computing is an information technology paradigm that enables ***access*** to shared pools of configurable system ***resources***
- In some presentations the term Internet of Services (IoS) rather than cloud computing

With cloud computing we do not need to think about platforms, how to connect etc (hopefully)

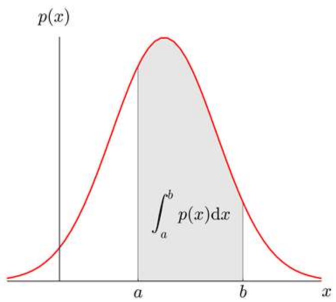
Digital twin

- The digital twin refers to a digital ***replica*** of physical assets, processes and systems that can be used in real-time for control and decision purposes
  - Computerized mathematical model (what we have done over years)
  - Real-time, thanks to IoT
- In contrast to a physical asset, the digital twin can immediately respond to ***what-if*** inquiries

Digital Twin *vs* Stochastic Digital Twin

Stochastic digital twin

- A stochastic digital twin is a computerized model of the ***stochastic behavior*** of a system where
  - the model is updated in real-time
    - based on sensor information and other information
    - accessed via the internet and the use of cloud computing resources
- What-if inquiries result in ***pdf***'s rather than single values



Real time model *vs* test model

“Google maps – Traffic” *vs* “Google maps Bicycle-friendly routes»

Real-time model

- A real-time model is a model where it is possible to obtain values of system performance and system states in ***real-time***
- With real-time we mean that data referring to a system is analysed and ***updated at the rate at which it is received***

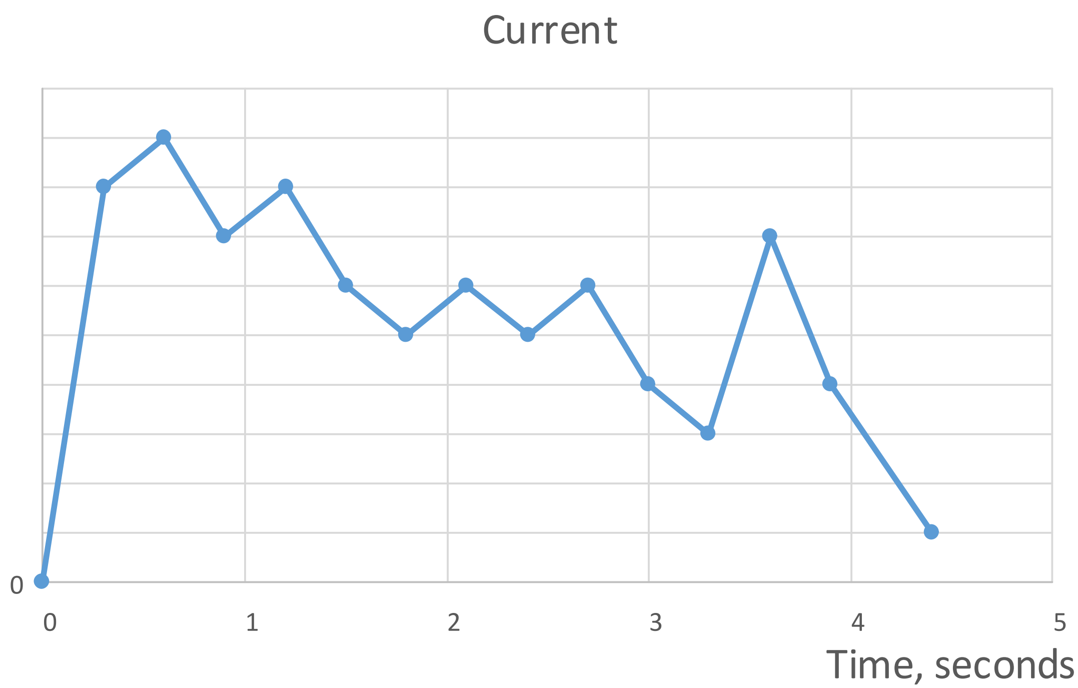
Test model

- A test model is a mathematical model describing relations between future and current values of the variables of interest, but where we are not able to monitor system performance and system states in real-time
- Such a model is often referred to as an ***off-line model*** or a ***sandbox model***
- A test model is still valid in order to establish decision rules to be used in real-time

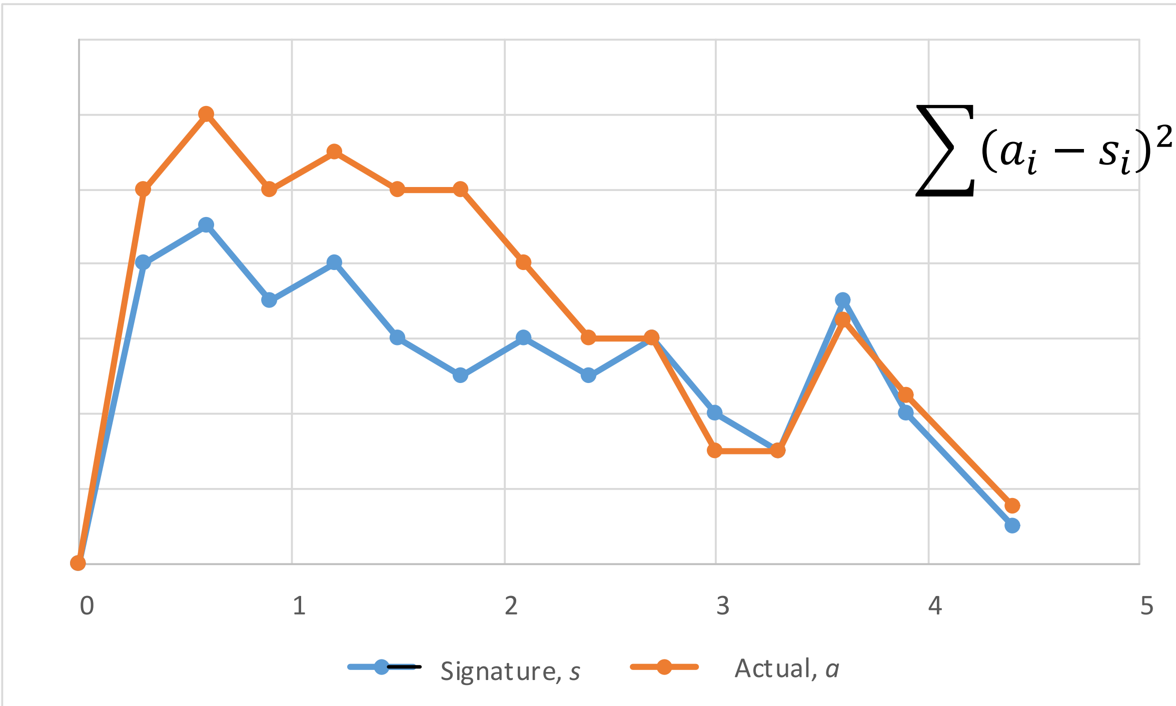
Case study – Turnout monitoring

- Turnouts (switches) are important components in the railway infrastructure, and failure of a turnout will usually give large problems with the circulation, and delays are expected
- A range of condition monitoring techniques exist
- BaneNOR is running at test project in Norway where the *electric current* of the motor is monitored, and represents a *signature* that can alert a coming failure

Signature (Normal operation)



Indication of a potential failure



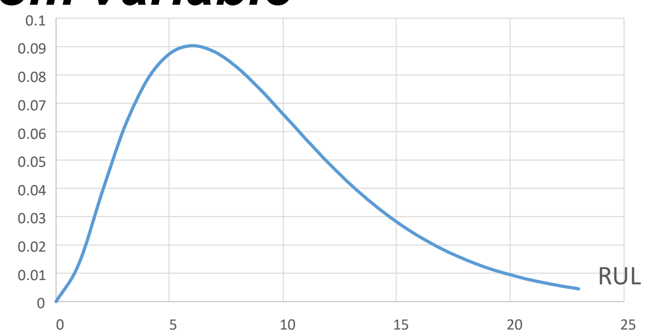
$$\sum (a_i - s_i)^2 > \text{Threshold?}$$

Background theory

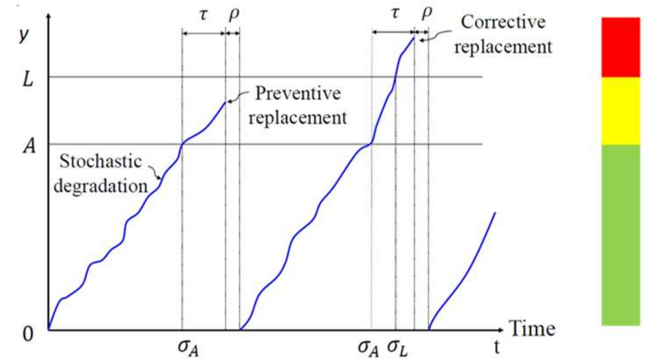
RUL = Residual useful life

RUL = Residual useful life

- Do we need it?
  - Yes
- What is it?
  - ***Useful*** life, not necessarily time to failure
- Is it a single number?
  - No, for decision purposes it is a ***random variable***
- How to assess it?



RUL - assessment



1. Stochastic processes
   – Gamma process, Markov chains etc
2. Life time models
   – $z(t|y, x(t)) = z_0(t)e^{\beta_y y + \beta_x x t}$
3. Physical degradation models with stochastic loads
   – $\frac{da}{dt} = \frac{A(\Delta K)^m}{(1-R)^{m(1-\lambda w)}}$
4. Signal processing approaches
5. Machine learning
6. …..

RUL assessment challenges

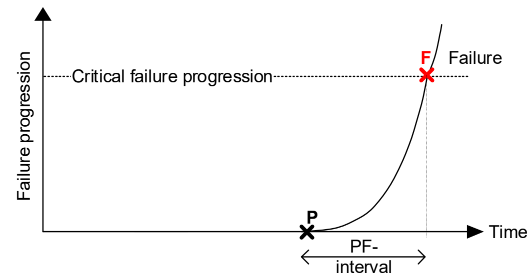
- We have some models and techniques…
- We have some ideas regarding the data we need to feed into models
- We have not convinced the industry to structure and collect data that ***fulfils our needs and wishes***
- Systematic mapping of applicable methods for different failure mechanisms missing
- When to combine?
  - For example machine learning for diagnosis, stochastic process for prognosis
- Can we update our RUL assessment in real-time?

Digital twins

- A maintenance twin
- A production twin (including punctuality)

Digital twin for maintenance (degradation)

- The focus is on "*when to act*" upon a potential failure rather than the classical inspection interval approach
- A PF-model is used for RUL:

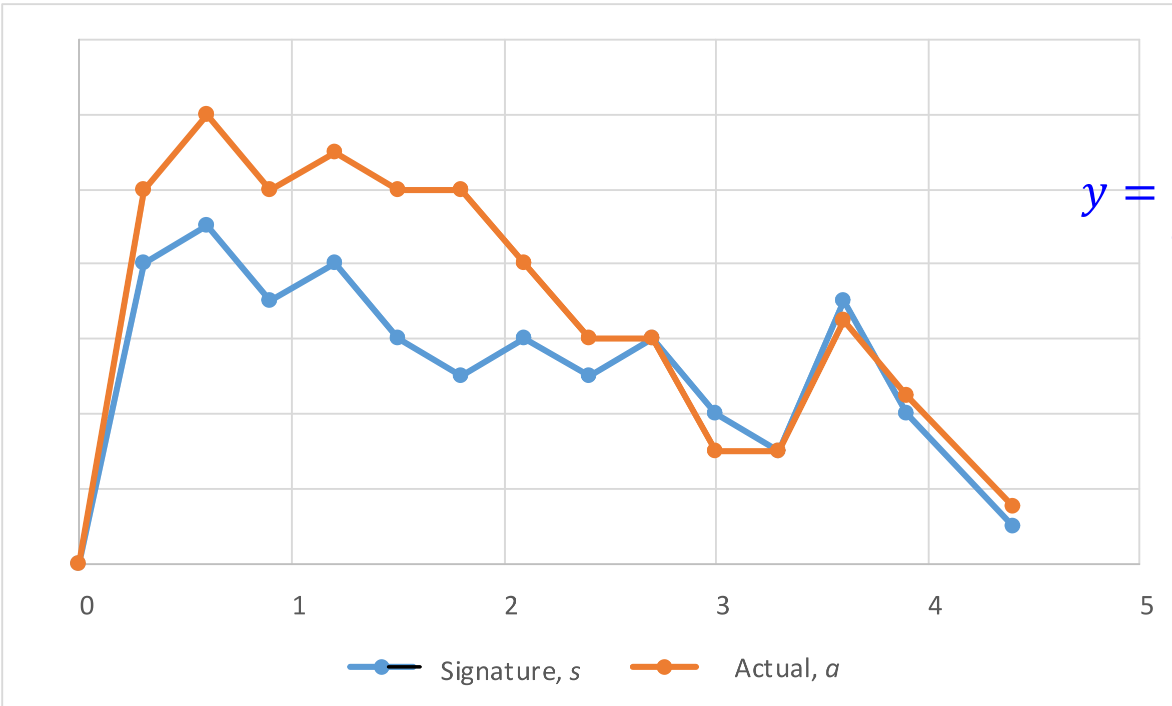


- $z(t|y, x(t)) = z_0(t)e^{\beta_y y + \beta_x x t}$
- Where
  - $z_0(t)$ = baseline failure rate function, T_{PF}
  - y = degradation level at the point of warning
  - $x(t)$ = future load in the near future (t is typically minutes and hours)
  - β_y and β_x regression coefficient in the Cox-proportional hazard model

Real-time ?

- Not actually in Bane NOR, the case study is only illustrative
- But
  - y = current degradation level in real-time is ***in principle accessible***
  - $x(t)$ = future loads
    - This is something the digital twin for the production ***in principle can respond on***, i.e., how many trains are scheduled to pass the coming hours and how many shifting operations are required?
    - In a “what-if” analysis, we may also investigate what is happening if we relax on operation, i.e., if we move crossing to another station to avoid operating the switch (and reduce the likelihood of a failure)

For example *y* is obtained in real-time by



$$y = \sum (a_i - s_i)^2$$

Real-time ?

- Not actually in Bane NOR, the case study is only illustrative
- But
  - y = current degradation level in real-time is ***in principle accessible***
  - $x(t)$ = future loads
    - This is something the digital twin for the production ***in principle can respond on***, i.e., how many trains are scheduled to pass the coming hours and how many shifting operations are required?
    - In a what-if analysis, we may also investigate what is happening if we relax on operation, i.e., if we move crossing to another station to avoid operating the switch (and reduce the likelihood of a failure)

Stochastic digital twin?

- Yes:
  - $F(t|y,x(t)) = 1 - e^{\int_0^t z(u|y,x(t)d}$
  - The cumulative distribution function, *F()*, is essentially what we need for the optimization:

The objective function to minimize:

- $C(t,x) = c_{\mathrm{PM}}(t) + c_{\mathrm{U}}F(t|y,x) + c_{\mathrm{R}}(x)$
  - t = time for *when to act* upon the potential failure = decision variable
  - x = *how many times* we operate the degraded switch = decision variable
  - $c_{\mathrm{PM}}(t)$ = Cost of preventive action, decreases as function of *t*, to be obtained from the production digital twin
  - c_{U} = Punctuality (unavailability) cost upon a failure (production digital twin, or punctuality model)
  - $F(t|y,x)$ = Failure probability, maintenance digital twin
  - $c_{\mathrm{R}}(x)$ = Relaxing cost, i.e., a function of how many times the switch is operated (production digital twin)

Results

- It is assumed that maintenance opportunities exist at time 3, 5, 7 and 9 hours at various "costs"
- Calculation examples are shown in the paper
- Result (optimal intervention time, *t*):

t (hours)	Delay (min)	c_{PM}	c_F	c_{Tot}
3	30	18 500	822	19 322
5	15	11 750	3 422	15 172
7	10	9 500	9 812	19 312
9	0	5 000	22 562	27 562

Konklusjoner

- Moderne (prediktivt) vedlikehold vil i større grad legge tilstands- og belastningsprofil til grunn for beslutninger
- Vi trenger matematiske modeller som jobber i sann tid
  - Dvs digitale tvillinger både for vedlikehold og produksjon/drift
- NTNU er involvert i mange forskningsprosjekter hvor vi ser på hvordan vi kan utnytte resultatene av digitaliseringen
  - Styring (adm støttesystemer)
  - Optimalisering (bruk av informasjon til å fatte riktig beslutning)