Data Lakes

Their role in predictive maintenance strategy

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Background

TenneT: AM Strategy Research

TU Delft: Professor of Performance of High Voltage Energy Systems

HAN Univ. of Applied Science: Professor of Reliable Power Supply

Educational background:

Physics & Mathematics, Weibull statistics, PhD Technical Physics + Analytical Chemistry

Fields of expertise:

Electrical grids, Material science, Forensics & Reliability analysis, Diagnostics, Electronics, Superconductivity

Other affiliations:

Utrecht Univ. (83-86), KEMA (86-07), NIMC (Jp, 92-93), NL Def. Acad. (07-12), IWO (≥84)

Overview

- Some basics about data, purposes and hazard rate
- Maintenance styles
    - Corrective Maintenance
    - Planned / Period Based Maintenance
    - Condition Based Maintenance, Health Index and FMECA
    - Health Index view from 3 groups (ENTSOe, Cigré, FIND-GO)
    - Risk Based Maintenance
    - Risk Index & Risk Matrix
- Data considerations for maintenance styles
- Lessons from the learning cycle
- Developments and Conclusions

Up and down the chain

Sources
- Archives
- Specs
- Environment
- Inspections
- Monitoring
- Testing
- Diagnostics
- …

Seeking
Collecting

Data Lakes
- Numbers
- Signals
- Statements
- Recordings
- …

Analysis
Harvesting

Information
- Queries
- Assessments
- Correlations
- Indices
- …

Interpretation
Evaluation

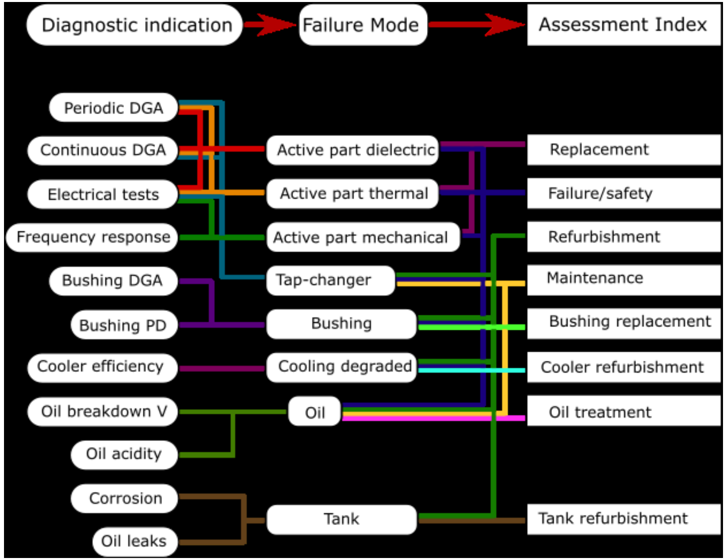
Solving questions & making decisions
- plan
- inspect / monitor
- repair / replace
- mitigate
- …

Performance

Maintenance
Styles

Efforts
Costs

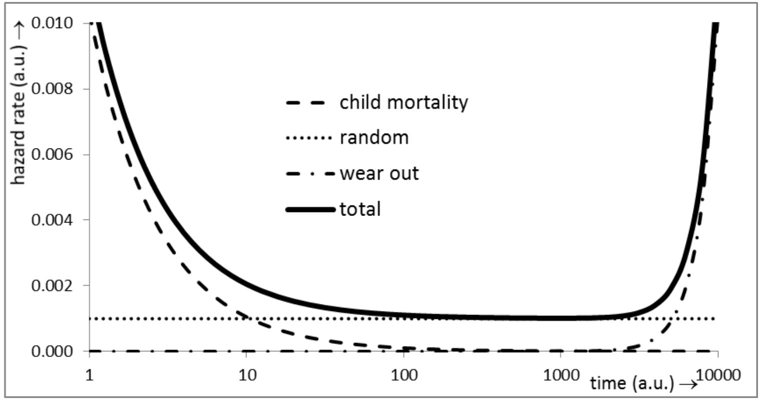
Risk



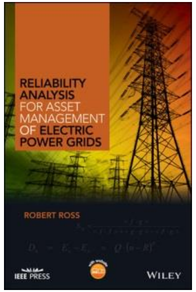
Ref.: Cigré WG 2.49 Tutorial, 2019 Delhi

Some very basic statistics, just a little

The well-known **Bath-tub curve**
is a hazard rate plot



a.u. is 'any unit'



For further reading: ISBN 9781119125174

<u>Failure distribution</u> **F**: failed percentage

$$F$$

<u>Reliability</u> **R**: surviving percentage

$$R = 1 - F$$

<u>Distribution density</u> **f**:
failing percentage per time

$$f = {}^{dF}/_{dt}$$

<u>Hazard rate</u> **h** (also 'failure rate'):
probability per time that a working asset fails

$$h = {}^{f}/_{R}$$

In short for an asset: <u>hazard rate **h = danger to fail** in the next time interval</u> (hr^{-1}, d^{-1}, yr^{-1}, ..)

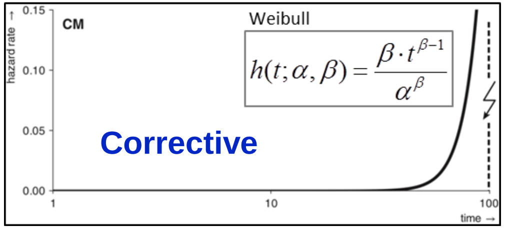
<u>Lifetime</u> **τ**: more or less inverse h

$$\tau \approx {}^{1}/_{h}$$

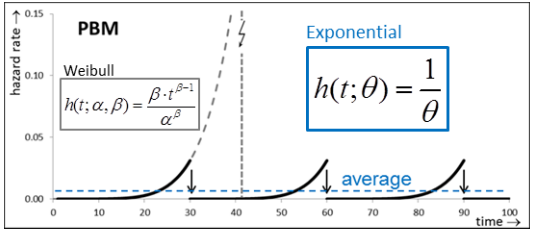
Maintenance actions and styles

Maintenance **Actions**

- Inspections
- Servicing
- Replacement



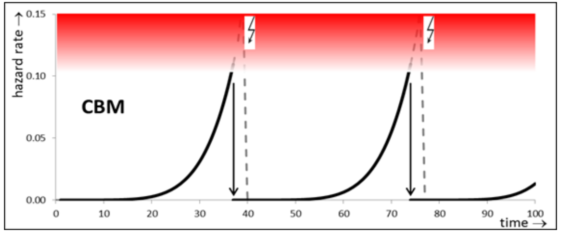
Period Based



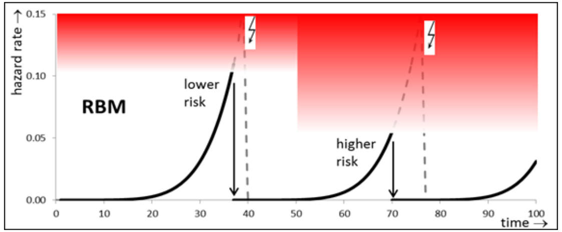
Maintenance **Styles**

- Corrective
- Planning or Period Based
- Condition Based
- Risk Based

Condition Based



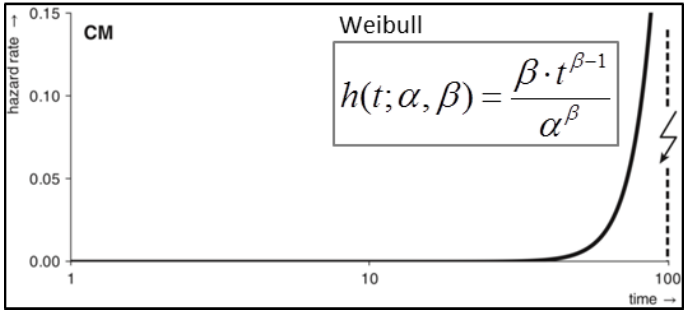
Risk Based



Actions and styles require specific data

NB: Balance effort & effectiveness!

Corrective Maintenance



Main characteristic:

- **Correct malfunction**; use of **full lifetime**
- **Flexibility** in emergency planning required
- **Redundancy** reduces emergency

Typically applied when:

- Effort OPEX >> CAPEX
- Asset inspection or rejuvenation impossible
- Examples: various types of cables; light bulbs

Examples of relevant data:

- Numbers & lifetimes (estimate staff, parts)
- Variation and correlations with circumstances

CM – Corrective Maintenance
Inspections
• Not, apart from checking functionality
Servicing
• Not • Action after failure
Replacement
• After failure • Asset to be specified for CM

Planning or Period Based Maintenance

Main characteristic:

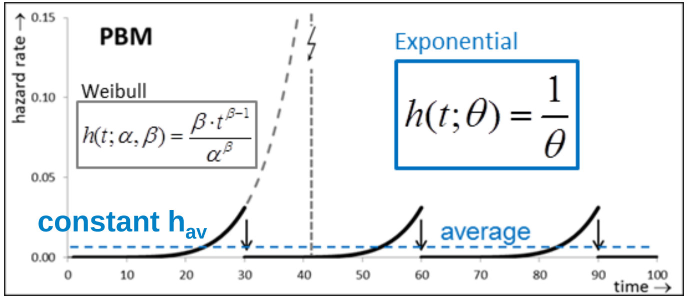
- **Planned preventive** actions; sacrifice lifetime
- **Planning** makes operations **predictable**
- **Redundancy** important, but less than with CM

Typically applied when feasible and:

- Value >> OPEX and CAPEX (⇒ extent life)
- CAPEX >> OPEX or failure costs
- Examples: switchgear, tap changer

Examples of relevant data like CM plus:

- Costs and impact of maintenance
- Planning-related data, keep track of periods



PBM - Period Based Maintenance
Inspections
• Planning based on periods • Period: time, cycles/switching action • Same assets, same planning
Servicing
• Planning • Based on periods • Concept: as good as new • Same assets, same planning
Replacement
• Planned by schedule (often time) • Same assets, same planning

Condition Based Maintenance

<u>Main characteristic</u>:

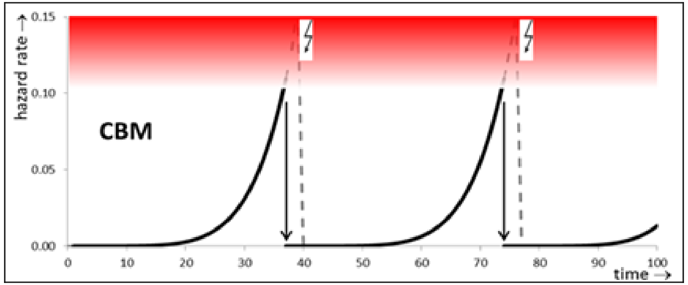
- **Preventive** activities by **individual condition**
- **Flexibility** in timely planning is required
- **Redundancy** important, but less than with CM
- **Diagnostics + interpretation** prerequisite

<u>Typically applied when feasible and</u>:

- Like PBM + individual assessment lucrative
- Examples: trafo on-line DGA

<u>Examples of relevant data like PBM plus</u>:

- Condition and operational data
- Correlations for interpretation (incl. AI, ML)



CBM - Condition Based Maintenance

Inspections

- Present condition sets planning
- Interval based on knowledge rules
- Evaluation per individual asset

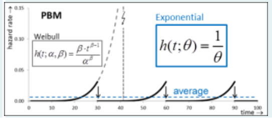
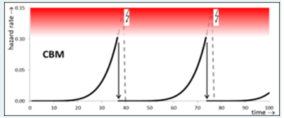
Servicing

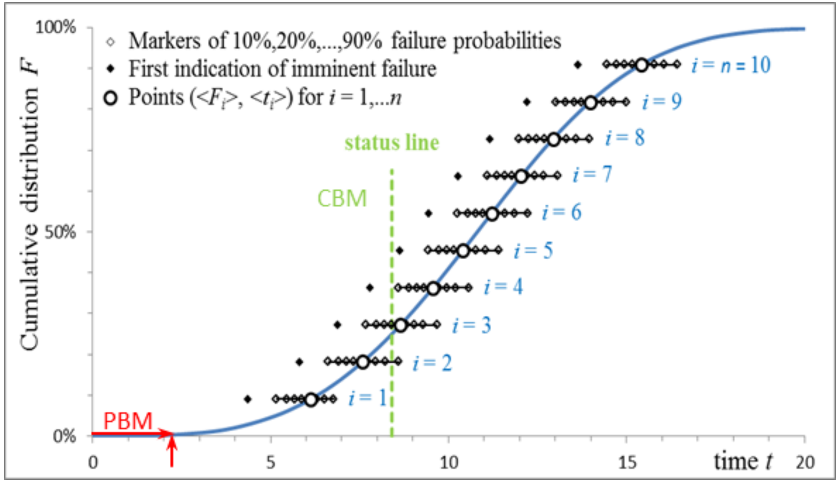
- Based on condition monitoring
- Need: diagnostics & knowledge rules
- Evaluation per individual asset

Replacement

- Just in time according to condition
- Decommissioning by condition
- Need: diagnostics & knowledge rules
- Evaluation per individual asset

Comparison of PBM and CBM

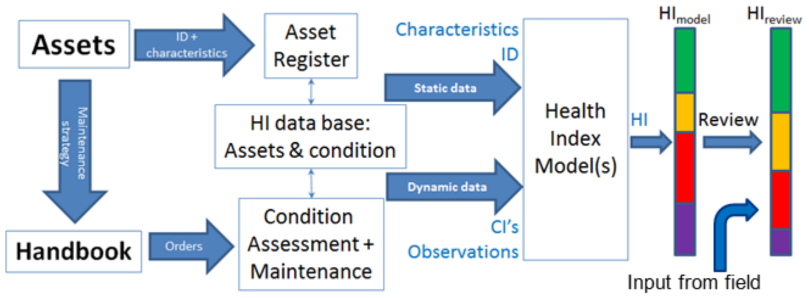
Aspect	PBM	CBM
Maintenance	Preventive	Preventive
		
Criterion	Periods (e.g. time)	Hazard rate (estimated)
Behaviour	Group	Individual
Actions	Predictable	Unpredictable
Requirement	Discipline	Flexibility
Distribution	Cumulative F	Cumulative F + Bayesian *h*
Required Data	Group	Individual Monitoring



- Solid blue line: failure percentage of group
- Diamond series: probabilities after signal of imminent failure
- PBM requires planning
- PBM in red: low failure probability → sacrifice life
- CBM requires reliable condition assessment and interpretation
- CBM in green: status line indicates which assets signal failure
- Average individual life under CBM > life under PBM

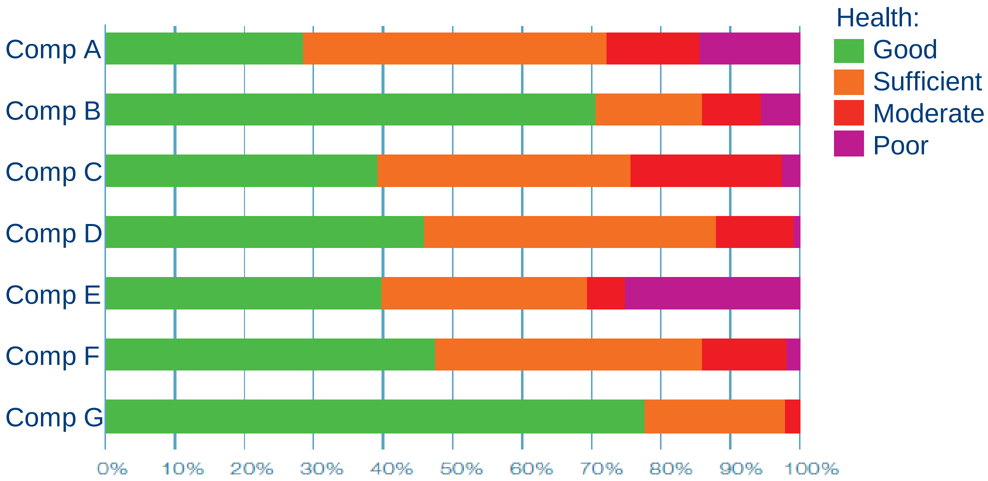
Health Index as a tool for CBM

- **Condition grade**
- **Measure** for hazard rate, remaining life, robustness as for failure, reliability
- Enables quick overview of conditions
- Suitable **aid** for CBM
- Requires ways to assess condition:
    - Diagnostics, inspections, data
    - Interpretation of findings



What it is not:

- It is not a asset management method
- It is not a planning tool
- It is not an investment selection



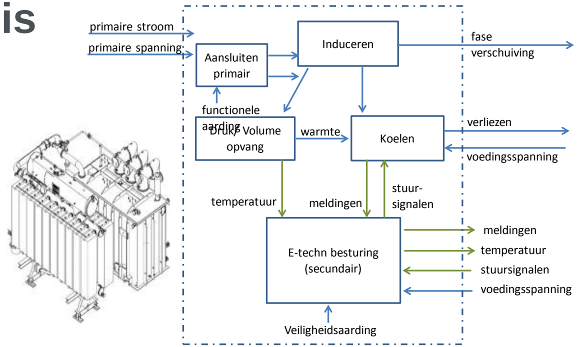
CBM and HI in relation to FMECA

Failure Mode Effect and Criticality Analysis

Elaborate:

- Asset
- Subsystems
- Functionalities
- Why fail?
- How likely?
- How serious?
- Easy to detect?
- Maintenance type
- Condition indicator

FMECA ⇒ condition indicators for HI



Systeemgrens => de omschrijving van de syteem grens heeft betrekking op compensatiespoel maar meer op VS

Aansluitklem/aansluitvlag inclusief bouten en moeren hoort nog bij de compensatiespoel ~~VS~~, veldgeleider niet

Aansluitklemmen in secundaire kast vormt de systeemgrens aan secundaire zijde. Klemmen in kast vermogensschakelaar horen nog bij de **compensatiespoel** ~~VS~~, de bedrading naar de veldkast/huisje niet.

Subsysteem Pool

Alles in en aan de polen, ook de aandrijfisolator die de contacten beweegt

Subsysteem Mechaniek

Mechaniek inclusief overbrengen en constructieve delen tot onderkant isolator polen

Mechaniek inclusief oliepomp en veeropspanmotor

Subsysteem Secundair

Alle besturingssignalen, sensoren, relais, etc. M.a.w. alle "dunne draadje" in de VS.

Het maakt niet uit waar de sensoren en relais zich fysiek bevinden (e.g. in de pool, mechaniek, aandrijfkast).

functies	subsystemen
1 **Induceren**	Wikkeling
	Kern
- isoleren	Wikkeling isolatie (papier)
	lamel - islolatie (laklaag)
	Olie
	Afstandhouders
- koelen	Olie
	behuizing
- bevatten olie en druk	behuizing
- sensoring	Olie als datadrager
	Buchholz (gasrelais)
	Thermometer
2 **Aansluiten Primair**	Doorvoerisolatoren
- geleiding	klem/ geleider
- isoleren	Papier / olie
- beschermen	Veldsturing
- (functionele) aarding	Aansluitingen
3 **Koelen - warmtewissellen**	Radiator
- aan/ afvoeren	Oliepompen + append.
- geforceerd koelen	Ventilatoren
- bevatten	Radiator + append.
Stiphout, Frans van: **e opvangen**	Expansievat/ conservator
	Expansievat/ conservator
Stiphout, Frans van:	Olie level indicator
- scheiden olie/ lucht	Bladder/ long/ balg/ membraam
- lucht drogen	Luchtdroger
5 **E-techn. Besturing (sec.)**	Aansluitkast
- aansluiten besturen/ signaleren/ beveiligen/ voeding	
- besturen/ bedienen	Div schakelingen
	Ringkerntrafo
- verwarmen	Kastverwarming
- behuizen/ beschermen	Aansluitkast
6 **Aarden**	Veiligheidsaarding
	Flensoverbrugging
x Olie	
- Electrisch isoleren	
- Warmte afvoeren	
- Druk beheersen	
- Info drager (levert data)	
Papier	
- isolatiemedium tussen voor de wikkelingen	

Example of FMECA in the making

- Expert rules and diagnostics follow
- Can feed decision support systems

Example of Health Index in Excel – part 1

Static data | **Calculated HI result**

circuitbreaker ID | station ID | station bay ID | provider | brand | type | HI | colour | HI_life | HI_condition | Data_quality

Asset ID	Station	Veld	Netbeheerder	Merk	Type	HIS	HIS	HI_Leeftijd	HI_Conditie	HI_Data
VERMSCH.T011039	Station Doetinchem 380	DTC-HGL380 Z	TenneT GS	ALSTHOM	FX 22	8	ORANJE	9	7	37
VERMSCH.T011056	Station Doetinchem 380	DTC380-LGK150 TR402	TenneT GS	ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T011102	Station Doetinchem 380	DTC-HGL380 W	TenneT GS	ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T011112	Station Doetinchem 380	DTC380 KV	TenneT GS	ALSTHOM	FX 22	8	ORANJE	9	6	47
VERMSCH.T011126	Station Doetinchem 380	DOD-DTC380 W	TenneT GS	ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T011185	Station Doetinchem 380	DOD-DTC380 Z	TenneT GS	ALSTHOM	FX 22	9	GROEN	9	7	10
VERMSCH.T019099	Station Ens 380	ENS380-ENS220 TR404	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T019138	Station Ens 380	LLS-ENS380 W	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T020089	Station Geertruidenberg 380	GT-EHV380 W	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T020214	Station Geertruidenberg 380	GT380-GT150 TR402	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T025203	Station Krimpen a/d IJssel 380	KIJ380-KIJ150 TR403	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	8	47
VERMSCH.T029113	Station Maasbracht 380	MBT380 CC-A	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T029127	Station Maasbracht 380	MBT380-MBT150 TR402	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T029161	Station Maasbracht 380	MBT380 KV1	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T029171	Station Maasbracht 380	MBT-EHV380 W	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0
VERMSCH.T029273	Station Maasbracht 380	VYK-MBT380 W	TenneT GS	GEC ALSTHOM	FX 22	9	GROEN	9	0	0

....

Example of Health Index in Excel – part 2

bouwjaar	conditie accumulator	conditie bluscondensatoren	conditie dempweerstanden	conditie HD circuits	conditie isolator	conditie mech aandrijving	conditie secundaire circuits	conditie tripspoelen	configuratie station	contactdender	dempweerstanden	een na laatste vulling SF6 datum	gasvolume	gelijktijdigheid	gesloten tijd
1989		VOLDOENDE			VOLDOENDE	VOLDOENDE	VOLDOENDE	VOLDOENDE	Dubbelrail	1,0	nee		43,0	105	105
1989									Dubbelrail		nee		43,0		
1989									Dubbelrail		nee		43,0		
1989		VOLDOENDE			VOLDOENDE	VOLDOENDE	VOLDOENDE	VOLDOENDE	Dubbelrail	2,0	nee		43,0	105	100
1989									Dubbelrail		nee		43,0		
1989		VOLDOENDE			VOLDOENDE				Dubbelrail		nee		43,0		
1992									Dubbelrail		nee		43,0		
1992									Dubbelrail		nee		43,0		
1992									Dubbelrail		nee		43,0		
1990									Dubbelrail		nee		43,0		
1990	MATIG	VOLDOENDE		VOLDOENDE	VOLDOENDE	VOLDOENDE	VOLDOENDE	VOLDOENDE	Dubbelrail	2,6	nee		43,0	100	100
1990									Triplerail		nee		43,0		
1990									Triplerail		nee		43,0		
1992									Triplerail		nee		43,0		
1992									Triplerail		nee		43,0		
1990									Triplerail		nee		43,0		

Empty inspection fields occur a lot during early years

Initially
- HI models were deterministic
- Decision tree

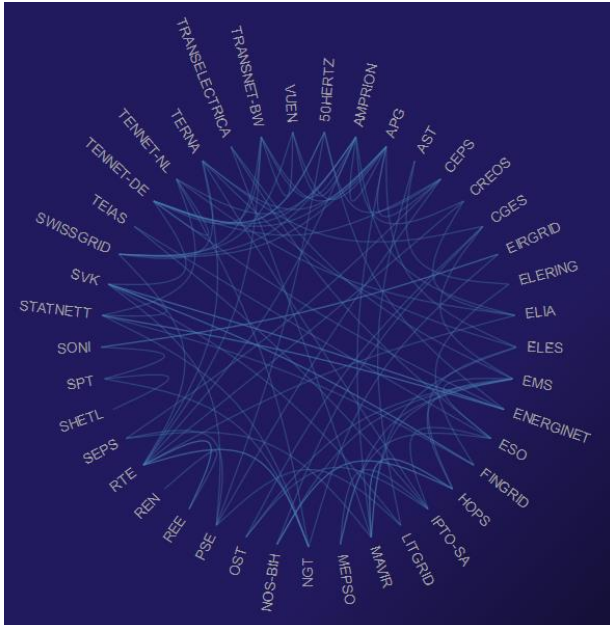
Last years
- FMECA studies for assets with experts

Alternative / additional
- Machine learning with transparency
- Working with a range of dedicated indices (cf. TAI)

ENTSOe WG AIM WS3 – Health Index

ENTSOe =
European Network of Transmission System Operators

- **WG AIM** = Working Group Asset and Implementation Management
- **Workstream 3**: ‘Maintenance and Renovation Strategy’



WS3 (preliminary findings) what is the **Health Index:**

- not standardized as yet
- vision: a score to represent condition, closely related to failure i.e. hazard rate; measure for being fit to function
- overall preference is to strictly stick to technical condition (if needed age as well if relevant data lack)
- obsoleteness, risk, reparability, etc. important too, but should be reflected by other indices

Cigré Working Group A2.49 – TAI and HI

A2: Power transformers and reactors

- **WG A2.49 Subject**:

“Condition Assessment of Power Transformers and Assessment Indices”

- **Cigré Technical Brochure 761**

Developing a TAI

In 5 Steps

01 **Step #01**
Determine the purpose of the Transformer Assessment Score and Index

02 **Step #02**
Identify the failure modes to be included in the TAI

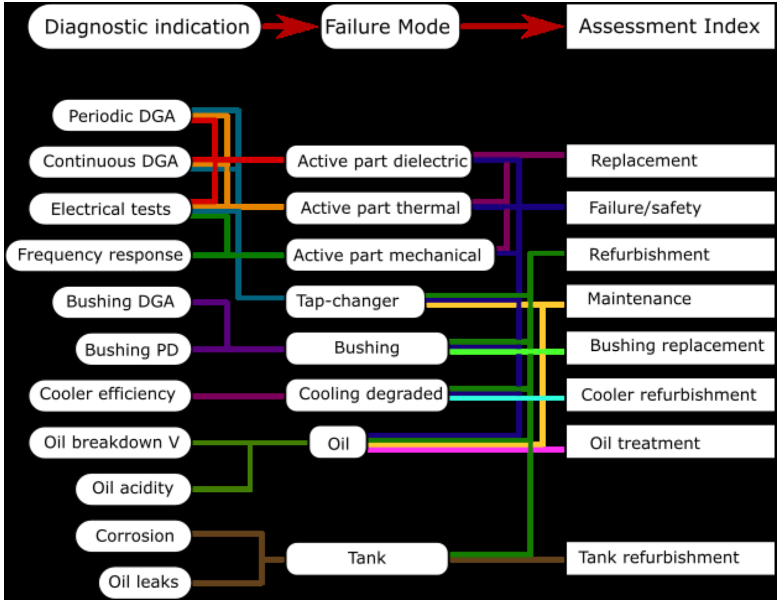
03 **Step #03**
Determine how each failure mode will be assessed

04 **Step #04**
Design a calibrated system for categorising failure modes (scoring matrix)

05 **Step #05**
Calculate a TAI Score for each transformer

Term: **Transformer Assessment Index**

- Name an index according to its purpose
- TAI: generic term for such indices

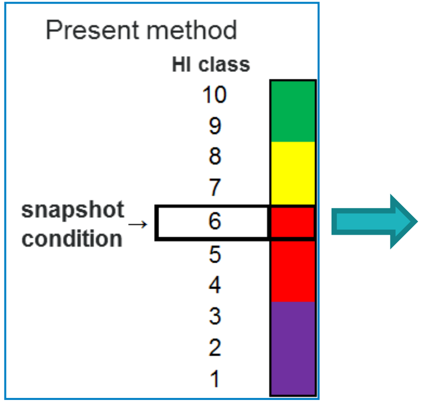


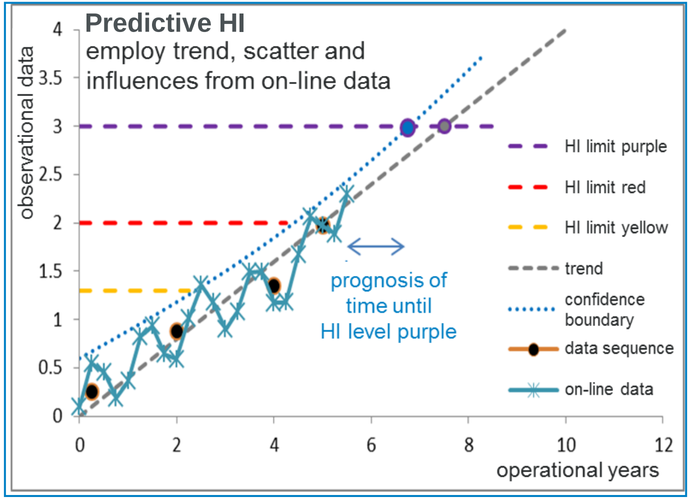
- HI: Fit for purpose - Network operation, dependability

Outlook of indices

HI beyond asset condition – FIND-GO-project objectives:

- **The predictive HI**
  - Extrapolate trends
  - Optimize outage planning
- **Confidence boundaries**
  - Acknowledge scatter
  - Incorporate uncertainties
- **Combined HI**
  - System condition of systems (station, connection)
  - Redundancy and/or series dependency
- **Interaction** System Operation and Asset Management
  - Challenges: **security, managing data lakes**





The FIND-GO project is sponsored by the Dutch Ministry of Economic Affairs and Climate (nr. TEUE418008)
Partners: HAN University of Applied Science, TenneT, IWO, Stedin, Delft University of Technology, GE

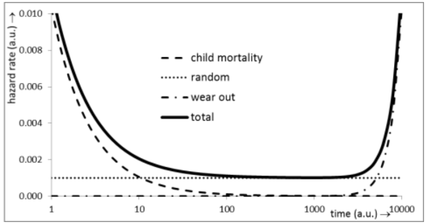
Redundancy – as an alternative / addition

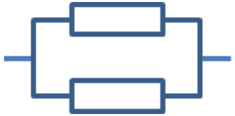
System versus unit (=asset)

- Units **each other's reserve** for complete load
- One unit can go down, but **system remains operational**; maintenance style less important?
- **System failure** after **all units fail**
- **Buys time for repair** without outage
- CAPEX increases, OPEX may decrease

Works well in low region of bath tub

- Effective for non-suspect units
- Falls short with wear-out and common cause



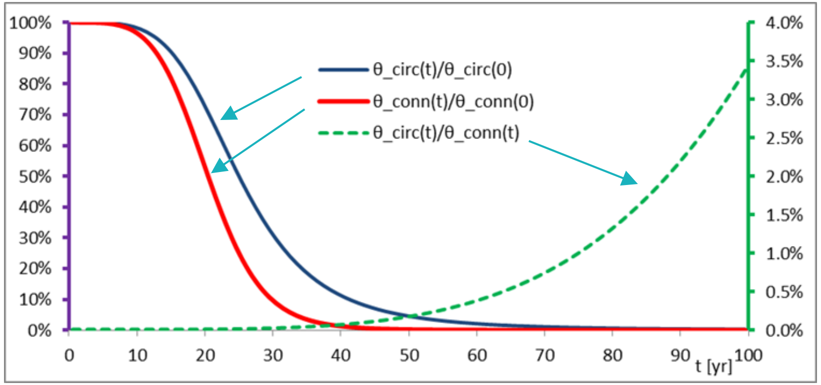


$$MTBF_1 = \frac{1}{\lambda}$$

$$MTBF_2 \approx \frac{\mu}{2\lambda^2}$$

λ = hazard rate
μ = repair rate

Example:
λ = 0.5/yr;
μ = 26/yr
$MTBF_1$ = 20yr
$MTBF_2$ = 7320yr



Blue: relative reduction of MTBF for circuit (=circ)
Red: relative reduction of MTBF for double circuit (=conn)
Green: ratio of MTBF single circuit and double circuit

Risk Based Maintenance – beyond failure rate

Main characteristic:

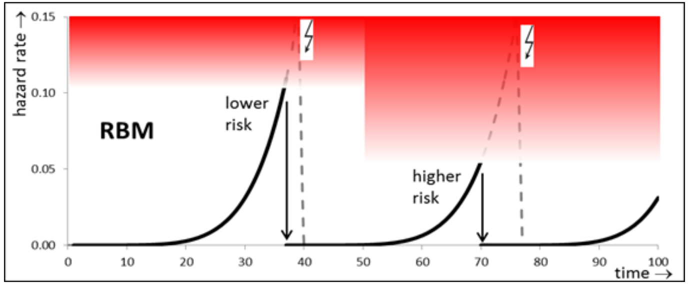
- **Risk = probability** (h) **x impact**
- **Prioritize preventive** actions by individual risk
- **Impact** in terms of business values violation (like security of supply, safety, compliance, ..)

Typically applied when feasible and:

- Performance measured as total of values
- Examples: prioritizing investments by balancing damage from various values

Examples of relevant data like CBM plus:

- Likelihood of various business value violations
- Attributing weights to different outcomes



RBM – Risk Based Maintenance
Inspections
• Planning by condition plus impact
Servicing
• Planning by condition plus impact • Concept: priority for situations where business values are most violated
Replacement
• Planning by condition plus impact • Concept: priority for situations where business values are most violated • RBM may replace earlier than CBM

Risk Index as a tool for RBM

Risk: impact x failure frequency (=*h*)

- Risk level: ⇒ necessity of maintenance (inspection, servicing, replacement)
- Assess Risk per CBV with a Risk Matrix
- Risk assessment for decisions prioritizing

Corporate Business Values (CBV)

- Utility performance on various values
- Monetizing versus gravity scale
- Risk threshold for mitigation per CBV
- Compulsory mitigation from 'medium'
- Risk Index (**RI**): Each CBV weighed in RI for summed violation of CBVs

frequency ≡ hazard rate

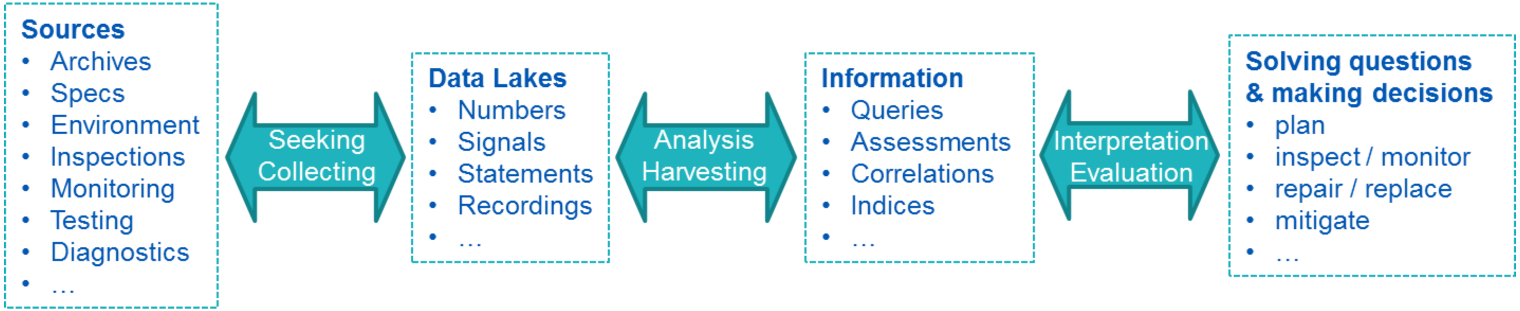
RISK	impact						
	minor	very small	small	moderate	significant	serious	extreme
very often	low	medium	high	very high	unacceptable	unacceptable	unacceptable
often	negligible	low	medium	high	very high	unacceptable	unacceptable
frequent	negligible	negligible	low	medium	high	very high	unacceptable
probable	negligible	negligible	negligible	low	medium	high	very high
possible	negligible	negligible	negligible	negligible	low	medium	high
improbable	negligible	negligible	negligible	negligible	negligible	low	medium
nearly impossible	negligible	negligible	negligible	negligible	negligible	negligible	low

example CBV list:

CBV	%
Safety	S%
Quality of Supply	Q%
Financial	F%
Reputation	R%
Customers	Ct%
Environment	E%
Compliance	Cp%

Whatever maintenance style is optimized ...

- Maintenance styles require case by case decisions
- Decisions lean on information (complete or not)
- Information is based on data (complete, adequate or not); preferably incl. exhaustive historic records
- Data must be collected from sources; often this collection is newly initiated by questions to be solved
- Rather have too much new data, than too little; but how much is feasible/useful?
- As for old data: quite often insufficient, incomplete, suspect or inadequate for present questions;
- ‘TAG’: Consistent Asset Data structure (categories of assets, (sub)components, findings) ↔ FMECA
- The game can also be: ‘What data is available?’ and ‘Can this be an alternative to gather information?’
- ‘What techniques bridge recognized gaps?’: AI, ML, censored statistics, need to provide transparency...



On maintenance style related data

\ Maintenance: Aspects: \	Corrective (CM)	Period Based (PBM)	Condition Based (CBM)	Risk Based (RBM)
Statistics	Group	Group	Individual	Individual
Criterion	Up or down; working or not	Elapsed period (e.g. time, #surges)	Condition (Hazard rate)	Risk (Hazard rate + impact)
Used asset lifetime	Full lifetime	Part of (extended) lifetime	Part of (extended) lifetime	Part of (extended) lifetime
Reactive/proactive	Reactive	Proactive	Proactive	Proactive
Challenge	Unplanned outage → Flexible response → Possible emergency	Sensible general policy Sacrifice less significant lifetime	Adequate (comprehensive) Diagnostics & expert rules	Adequacy in assessing Risk Deal with low h, high impact
Advantage	Exploiting full lifetime	Life extension by renewal, Predictable service and replacement	Life extension by renewal, Exploiting most of lifetime	Overall optimized CBV performance
Information	Group failure Group efforts (In)efficiency of maintenance	Group time to hazard rate Group efforts How to optimize period	Individual hazard rate Individual efforts How to assess hazard rates	Individual hazard rate Individual impact(s) How to assess risk
Data	Up or down state Historic failure times + causes Support for CM choice	Experienced renewal efficiency Service results + experience Support for PBM choice	Support relation condition-failure FMECA results + experience Support for CBM choice	As with CBM + failure impact Impact experience Support for RBM choice
'HI' if all in CBM approach	Up or down state indicator	Elapsed period	Quantified condition (HI)	Quantified risk (RI)

Lessons from the learning cycle

Asset management is a transition

- Some quick wins, but tedious job after that
- Cycles: lifetimes >40y; inspection >years → it is a learning process for the long run
- In place, the effect is lasting and significant

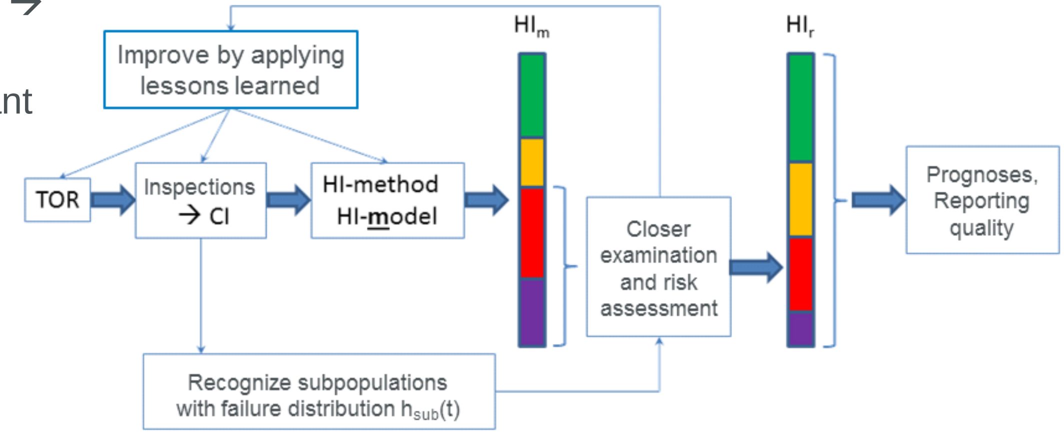
Maintenance actions and styles

- Be aware of plannability ↔ flexibility
- Redundancy is overrated (take care)

Past data scarcely available

- Failures: low probability, high impact
- Data: partly excessive; but which is / is not?
- Check what existing data are useful

Much concern about security: SO versus AM



Developments

Broad trends:

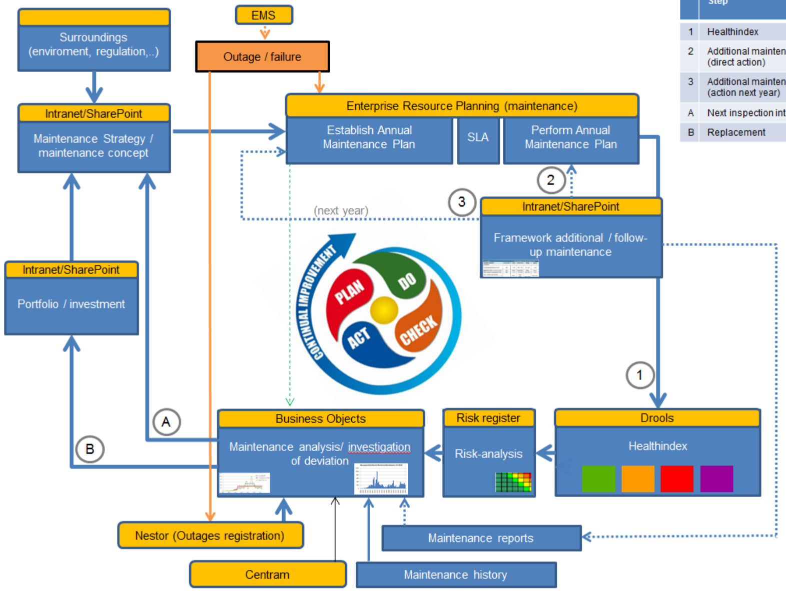
- International cooperation
- Need for efficient use of workforce
- Digitalization + monitoring
- Ambiguous: FMECA studies (expert opinions) and machine learning (seeking hidden patterns)

Comprehensive, accepted AM system:

- Calls for various types of expertise
    - (asset aging, statistics, ict, inspections, monitoring, strategy, maintenance ..)
- Cooperative perseverance of many
- Touches various departments and disciplines
- Requires alignment of interests and skills

Conclusions

- Data lakes are very useful and often missing
- To be managed and to yield information
- Important maintenance styles discussed
- Different information and datatypes per style
- On-line monitoring and diagnostics hand in hand with digitalization and smart grids



	Step
1	Healthindex
2	Additional maintenance (direct action)
3	Additional maintenance (action next year)
A	Next inspection interval
B	Replacement

Development of AM systems (CBM/RBM):

- Take years to gain experience and fine tune (lessons learned)
- Health index, Risk index and other asset related indices not yet harmonized
- Big challenge: algorithms useful for planning
- Consensus on definitions and methods is emerging

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