Intelligent Maintenance

Condition-based maintenance, model-based and data-driven fault detection.

DDV Workshop, 22-Aug-2018

IPU Representatives

- Søren Merit, CEO
- Jorrit Wronski, Senior R&D Engineer, Thermal Systems
- Kevin Rice, Senior R&D Engineer, Mechatronic Systems and Controls

Agenda and Topics

- IPU – A brief introduction (Søren)
- Intelligent Maintenance of Mærsk Line Containers (Jorrit)
- System Monitoring and Fault Detection (Kevin)
- Workshop and Brainstorming – Intelligent Maintenance (Søren).

IPU – A brief introduction

- IPU delivers integrated product and process development for industry

- IPU was established as an independent non-profit institution in 1956 by 4 professors at DTU
- Located at DTU campus in daily contact with researchers and within walking distance to a vast range of labs
- IPU has donated for more than 130 million DKK in gifts to DTU over the years

- 70% of activities are consulting jobs for industry
- 30% of activities are research projects with DTU and other international partners
- Today 21 specialists incl. 7 Ph.Ds. and 8 nationalities

- Advanced materials & surfaces technology
- Thermodynamics & energy technology
- Advanced automation, robotics and autonomous systems technology
- Modelling of physical systems (cyber physics, digital twins, data analytics)

- Product development
- Manufacturing process development
- Development support tools & systems
- Design reviews
- Significant capabilities within several application areas including i.e. Design for Manufacturing (DfM) and Condition-Based Maintenance

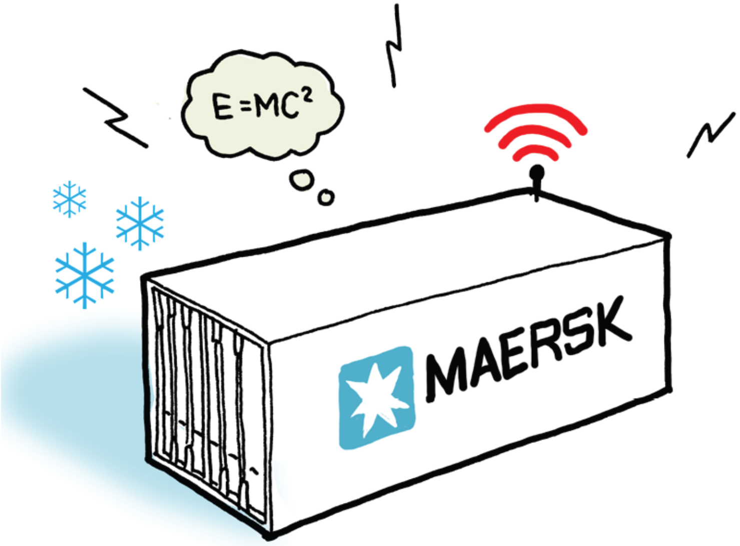
Intelligent Maintenance of Mærsk Line Containers

Jorrit Wronski

22. August, 2018

Motivation & Goals

- Remote Container Management (RCM)
  - Connectivity and transparency – being in control
  - Improved customer experience – documentation
  - Monetary savings – maintenance and operation

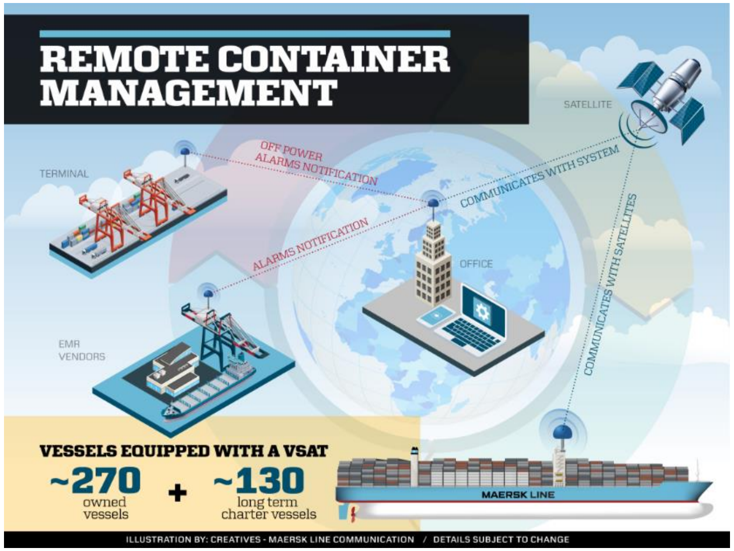


- Company spends more than $ 200.000.000 on pre-trip inspections (PTI)

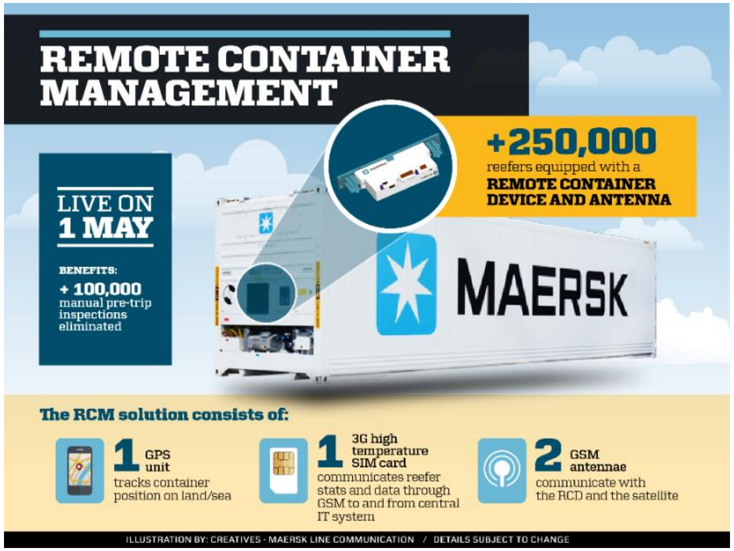
- **How can we avoid manual inspections and improve cargo safety and energy consumption?**

Timeline 2010-2017

- 2010 Maersk and IPU start cooperation on reefer alarm prediction system (RAPS/ePTI) as part of their remote container management programme (RCM)
- 2012 Agreement with Ericsson and AT&T for hardware and data transport



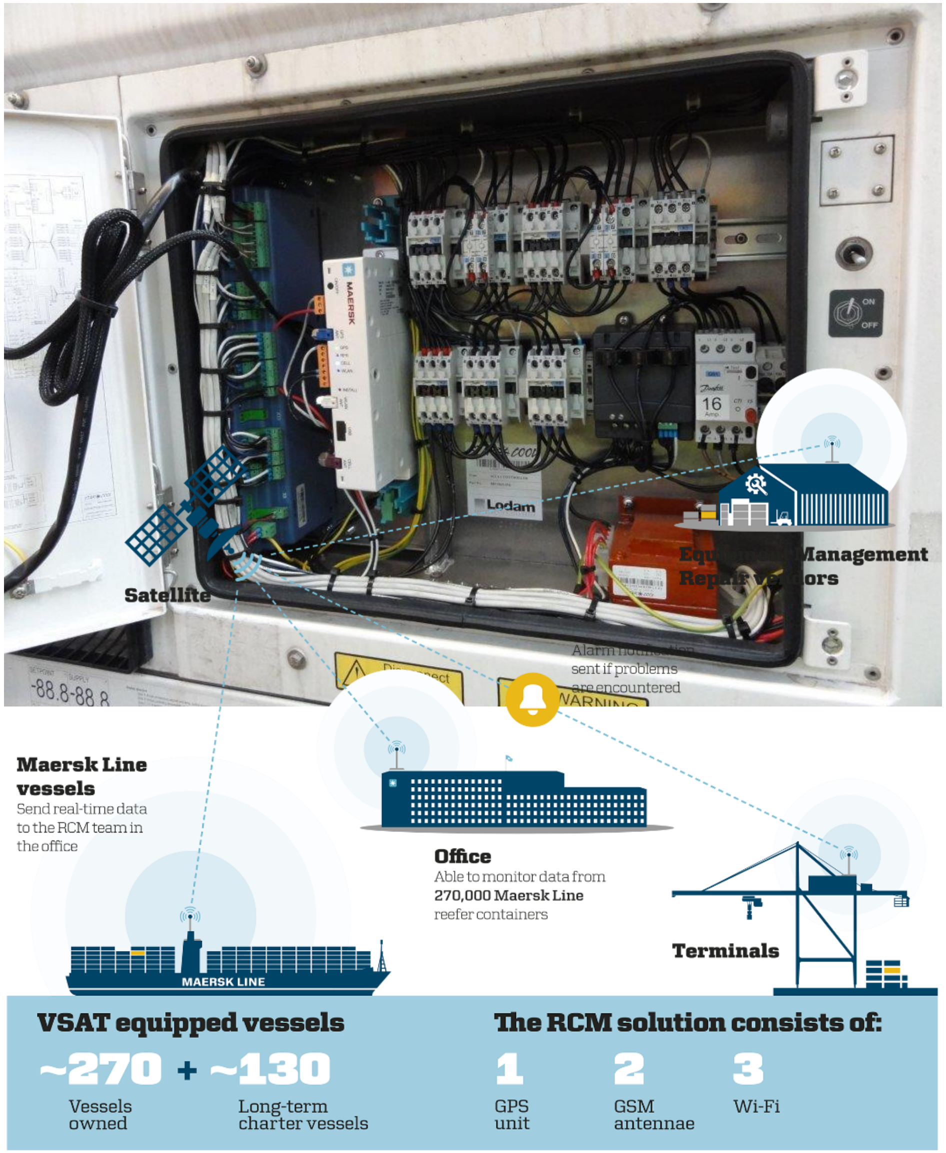
- Satellite communication installed on 400 vessels
- Local GSM communication between container and vessel established
- System launched on 1st of May 2015



- IPU develops models of containers
- … and detection algorithm

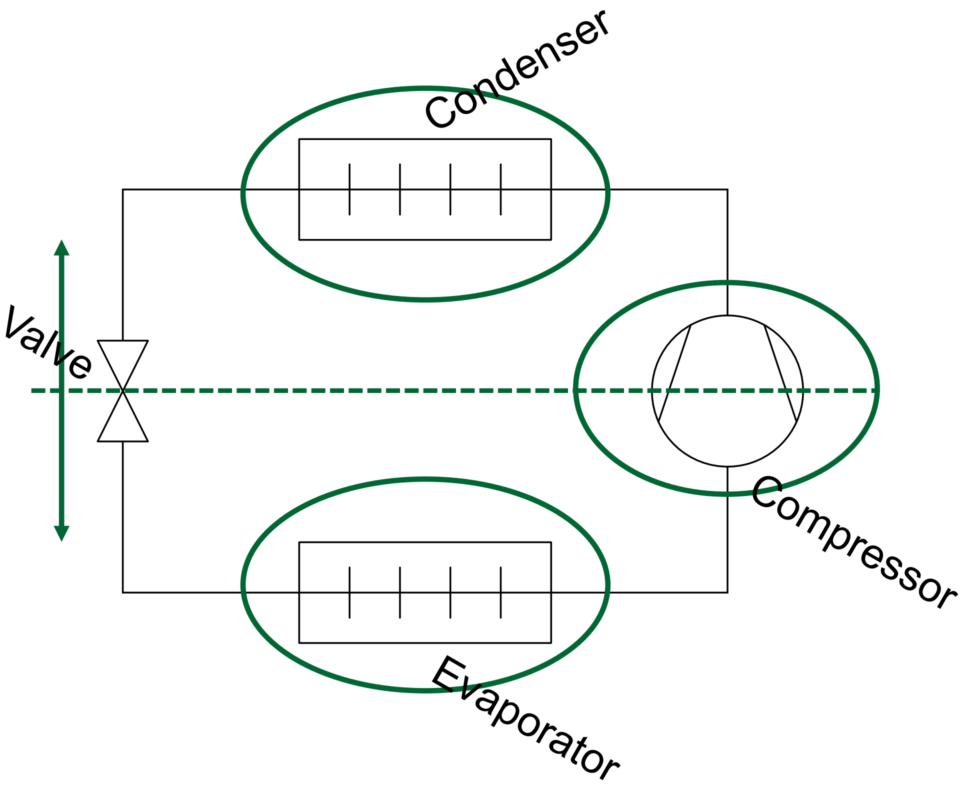
Data Processing Chain

- Sensor readings are collected
- Data is transmitted via GSM on-board the vessel and via commercial GSM net when on land.
- Satellite communication brings data to head quarters
- Pre-processed data set is fed to fault detection algorithm
- Alarms and warnings are reviewed and actions are taken (container service ordered)



Container Models

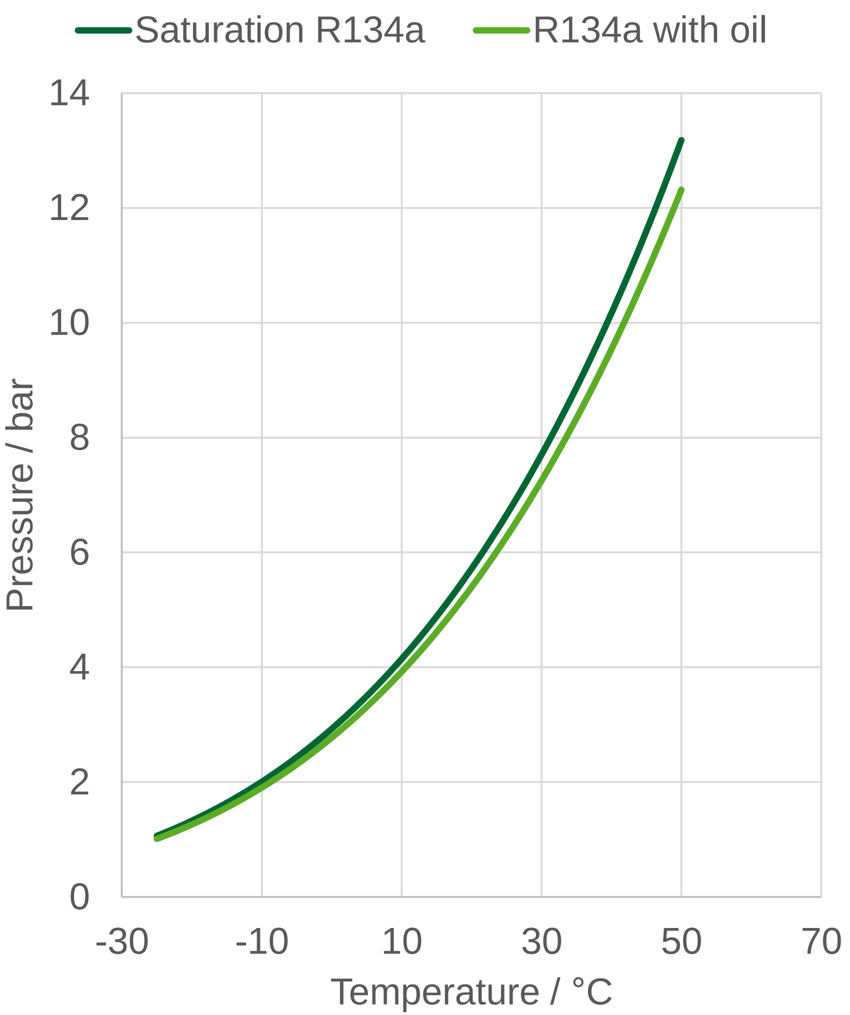
- Requirements:
  - Fast calculation models
  - Include all major properties
- Basic refrigeration system:
  - Heat uptake, heat release, power consumption
  - High and low pressure parts
  - Internal temperatures
  - Other temperatures (ambient, cooling water, reefer, set point)



- Typical relations:
  - High ambient temperature → high condenser pressure → high load
  - Poor heat transfer → increased temperature difference → high load

Redundancy Examples 1

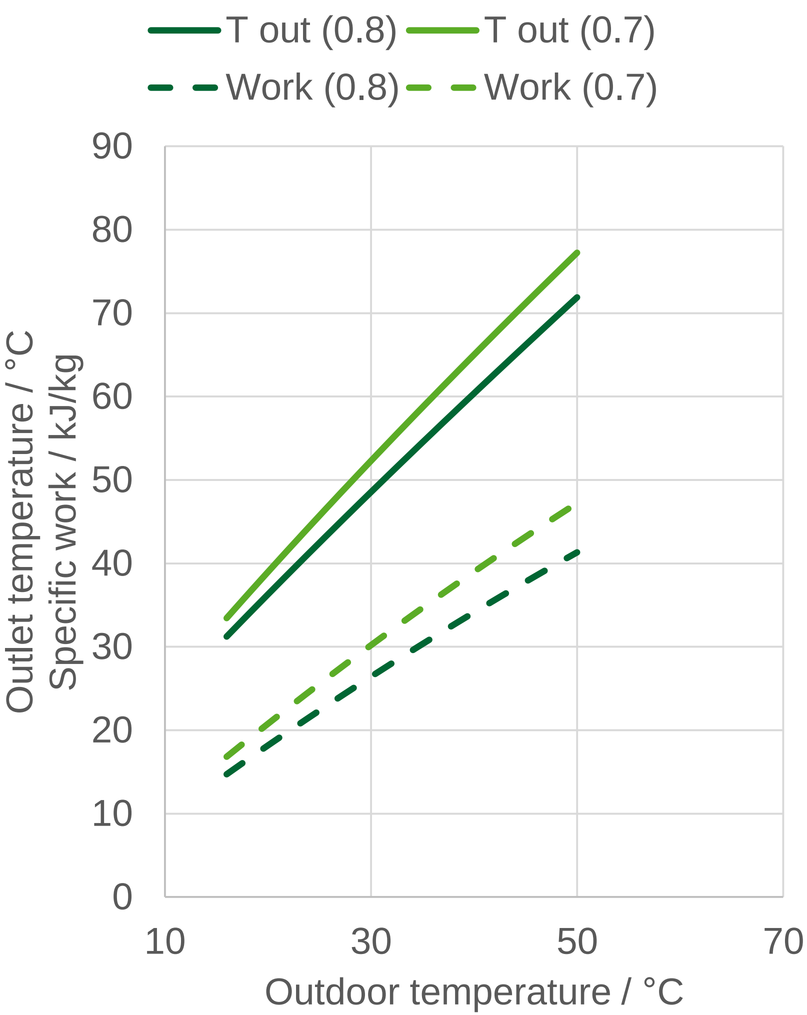
- Saturation pressure and temperature
  - A direct relation between two measured quantities
  - Uncertainties around 0.1 bar and 0.7 K
  - Pressures directly affect the energy consumption, see next slide.



Redundancy Examples 2

- Compressor efficiency and outlet temperature and used work
  - Evaporation at 5 °C
  - Condensation at 30 °C
  - For R134a: 2.9 bar to 7.7 bar

  - Compressor efficiency affects required work input and outlet temperature:
  - 80% efficiency:
    T = 48.5 °C, dh = 26.4 kJ/kg
  - 70% efficiency:
    T = 52.3 °C, dh = 30.2 kJ/kg



Redundancy Examples 3

- Other possible redundancies and interrelations are:
  - Heat exchanger performance as a function of flow rate, temperatures and fluid properties
  - Pressure drop in piping and valves as a function of flow rate
  - …
- Remember the measurement uncertainties!

What did we deliver?

- A computational component processing approximately 200.000 hourly updates providing alarms and warnings to monitoring systems.
- Calibrated high performance models of all reefer refrigeration plants and their variants – validated with on-site full-scale tests at IPU.

- The large majority of technical issues is detected before cargo is affected.($)
- Over 60% of all pre-trip inspections can be skipped ($$$)

Learnings so far

- Technical do's and don'ts
  - Exploit your physical understanding of the problem or data-set – especially when building the model
  - Balance the amount of time used on cleaning up data and improving the detection algorithm.
  - Time is on your side, a longer timeline will limit false predictions.
  - Ensure constant alignment with the process - cannot be done from the desk only.

- Organization and project alignment
  - Secure the easy wins first and build from there.
  - Ensure the efforts brings value to the organization.
  - Align with stakeholders and involve their knowledge, inputs and ideas if sensible.
  - It will most likely never be perfect, set reasonable goals.

> *ePTI which was developed in close coordination with IPU, has not only resulted in significant direct cost reductions. ePTI also gives Maersk Line full cold chain transparency, improves and optimizes operational processes and offers faster turn times benefiting our customers. All this whilst ensuring that the equipment we release for our customer is in fully cargo worthy condition suitable for transport of temperature sensitive cargo. We look forward to further develop the ePTI algorithm together with IPU to get the full benefits from the huge amount of data now made available through RCM.*
>
> — Lars-Henrik Jensen, Operations Manager,
> Remote Container Management, Maersk Line

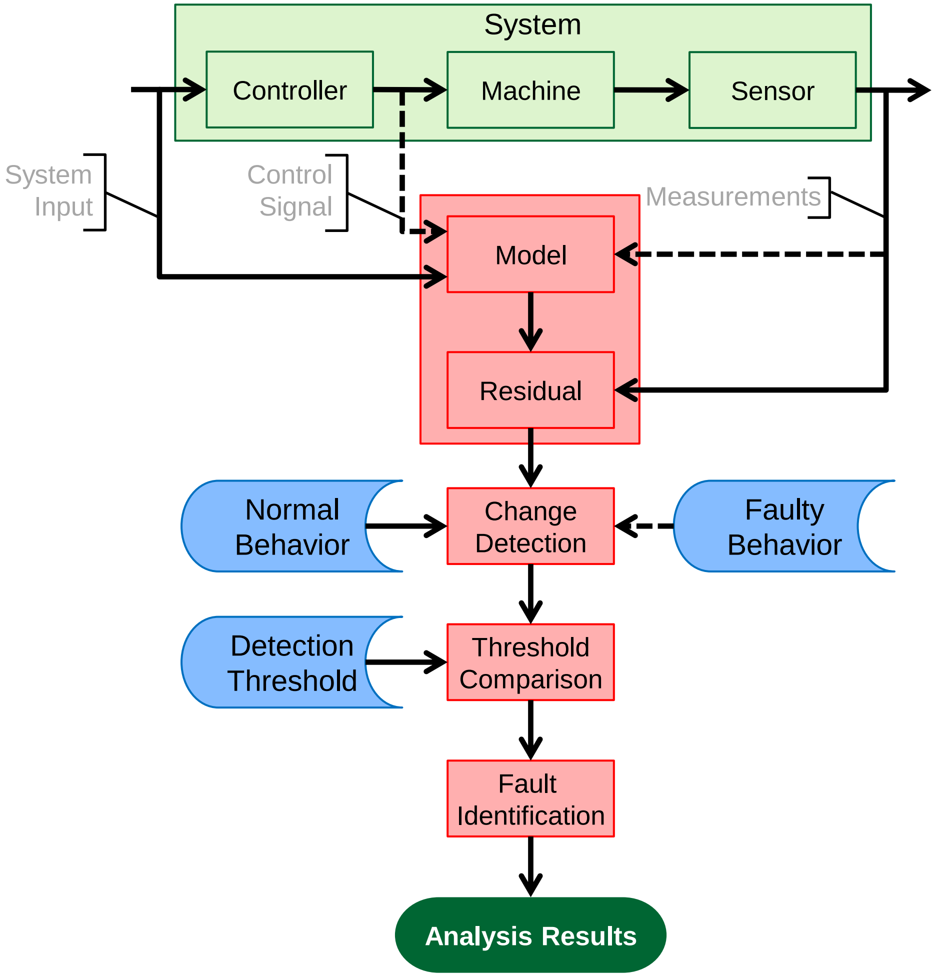
System Monitoring and Fault Detection.

Kevin Rice

22. August, 2018

System with monitoring and fault detection

- A system considered for monitoring typically consist of a controller, machine and sensors.
- System faults are typically categorized as:
  - Controller faults – incorrect control signal resulting in incorrect machine operation.
  - Machine faults – actuator- or component failure.
  - Sensor faults – incorrect sensor values.
- Depending on available system data – system health can be monitored and failures detected.



Models for simulation and analysis

- A physical model is generated and simulated for reference.
  - See 3-phase PM Synchronous Motor.
  - Should be fitted based on measured data.
- Models for simulation/analysis are mathematically complicated.
  - Simplification techniques can be used depending on required accuracy, failure to be monitored, operation mode, etc.
  - Models never match reality 100% - understand what is sufficient case-by-case.
- Models and desired failure to be captured → results in necessary sensor signals.

Permanent Magnet Synchronous Motor [1]

$$\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_m i_q$$

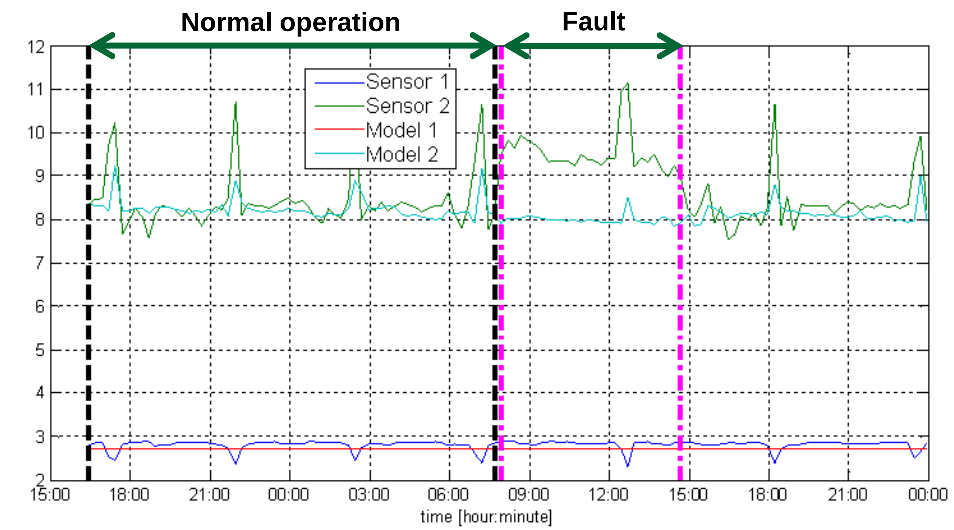
$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p\omega_m i_d - \frac{\lambda p\omega_m}{L_q}$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q) i_d i_q]$$

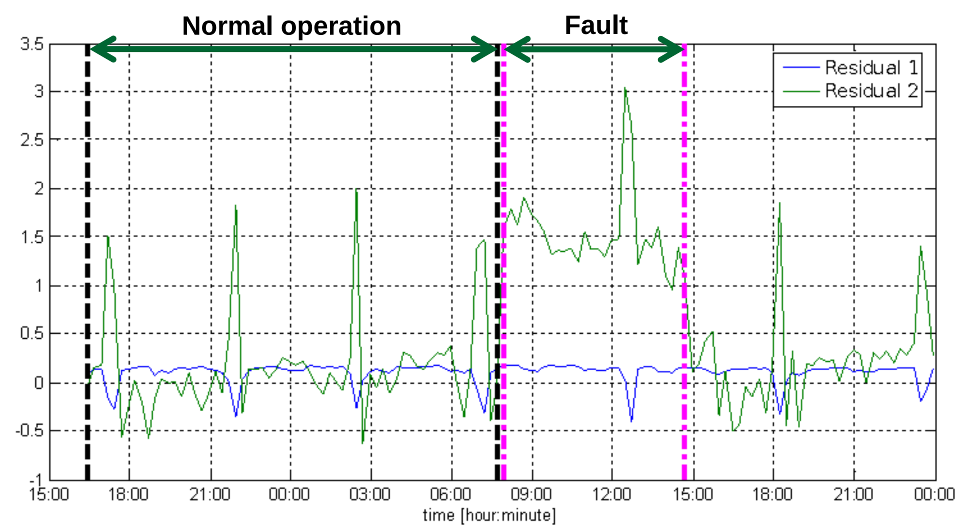
PMSM model [2]

Residuals

- Residual generation can vary in complexity, depending on the system and failure monitored.
  - Can be as simple as comparing simulated value with measured.
  - Complicated residuals are based on model in a filter like structure [3].



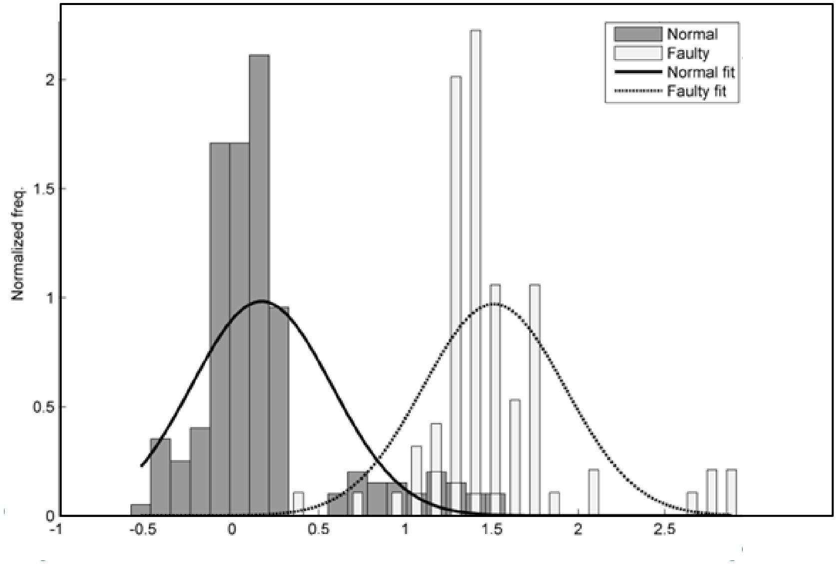
- Change detection is performed using some statistical approach on the residual.
  - High signal-to-noise ratio measurements can still be utilized for analysis.
  - Can help minimize false detection.

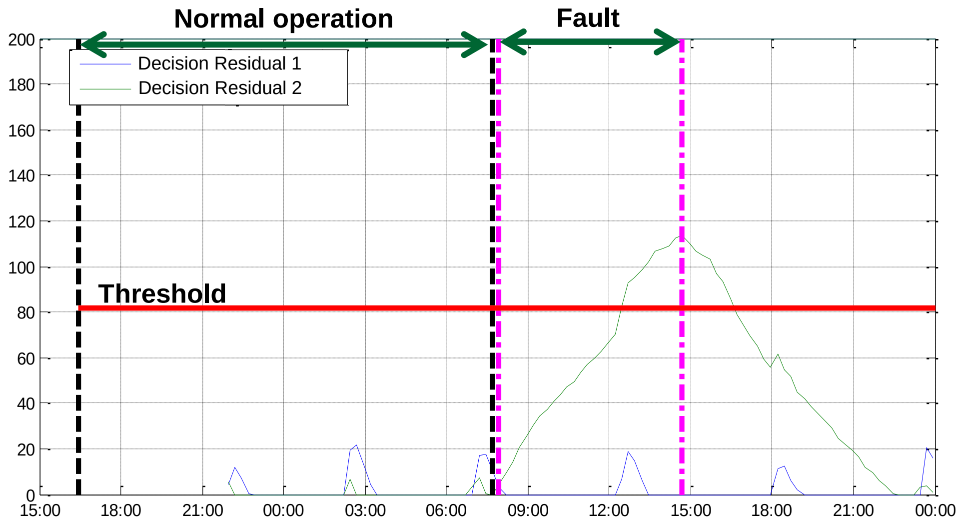


Change Detection

- Statistical model of normal and faulty behavior, and signal-to-noise ratio affects the detection time
  - Cumulative log-likelihood is typically used with some threshold [3].

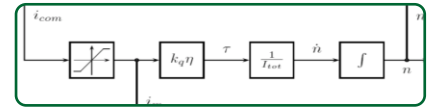
$$S_m(\mu_1, j) = \sum_{m'=j}^{m} \ln\left(\frac{p_{\mu_1}(x_{m'})}{p_{\mu_0}(x_{m'})}\right)$$





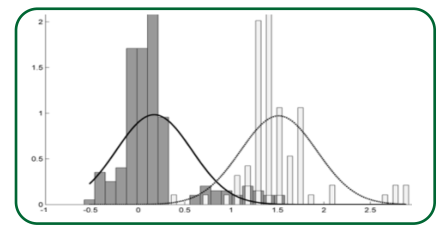
Design Process of Monitoring System

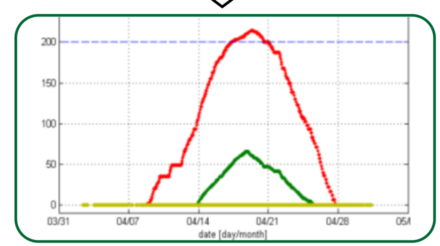
1. Well-defined failure to be detected.
2. Model the system or subsystem.
3. Overview of variables – i.e system inputs, measured values.
4. Generate residual based on model and available variables.
5. Failure detection based on statistics analysis of residual in case of normal and faulty operation.
6. Adjust threshold of detection according to performance criteria.

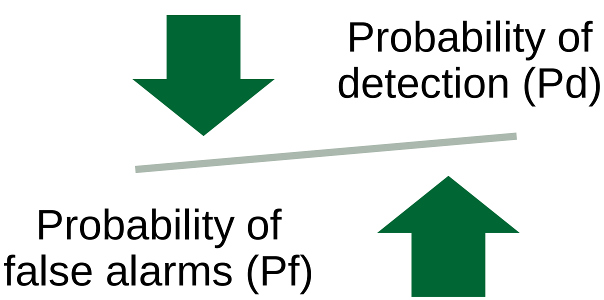


$$K = \{i_{com}, i_m, n_m, \theta_m\}$$

$$c_3 : \; i_{com} k_q \eta \frac{1}{I_{tot}} - \frac{dn_m}{dt} = 0$$







Lesson learned

- If system monitoring and fault detection is desired consider following
  - Risk Assessment, FMEA, Experience → which faults are desired to monitor (system downtime, human injurie, high cost, etc.)
  - Business case → system monitoring and fault detection vs. normal procedure

- Investing in a new system – i.e process line, etc. – with multiple sensors for process monitoring does not necessary support implementing system monitoring
  - Which sensor values are necessary to monitor a fault, is highly dependent on the fault and model.
  - Consider understanding which failure are crucial to monitor – and think this into the system during early development.

References

- [1] https://new.abb.com/motors-generators/nema-low-voltage-ac-motors/definite-purpose-motors/synchronous-permanent-magnet-motors
- [2] https://se.mathworks.com/help/physmod/sps/powersys/ref/permanentmagnetsynchronousmachine.html
- [3] Diagnosis and Fault-Tolerant Control, M. Blanke, M. Kinnart, J. Lunze & M. Staroswiecki, 2003 Springer, ISBN 3-540-01056-4

Workshop and Brainstorming - Intelligent Maintenance

Søren Merit

22. August, 2018

1. Recap(10:30-10:35)
2. Exchange of Experiences (10:35-10:40)
3. Group Work (10:40-11:30)
4. Presentation (11:30-12:00)
5. Conclusion (12:00-12:15)

IPU's view on condition-based maintenance

Must be..
Anchored in overall risk analysis and business case

Must be based on..
Digital model of physical system

Articulate an ambitious long-term aspiration for the Maintenance System

Must be..
Data-based approach

Must..
Include domain experience

Install a systematic maintenance development approach

Business case of condition-based maintenance

Investment in condition-based maintenance

Operating cost of condition-based maintenance process and systems

Improve Customer Satisfaction
Delivery performance

Reduce cost and risk
Minimize superfluous inspections and maintenance procedures

Improve plannability
Planned access to challenging areas and locations

Identifies problem areas
Easier to plan approach, people, tools and spare parts

Improve Availability / Capacity
Non-planned breakdowns,

Improve Plannability
Availability, robustness, early warnings

Reduce Labour Cost
Operators, technicians, non-planned overtime, 3rd party service providers

Reduce Material Cost
Scrap

Reduce Quality cost
QC analyses, NC handling, quarantine

Reduce equipment cost
Early detection, spare parts

Challenges we meet in our projects

How to approach the maintenance opportunity from a top-down perspective?	**How to scale up the activities beyond key processes and machinery?**	**How to work with complicated systems?**
What to do, when data are not available?	**What to do when data volumes are huge?**	**How to ensure sufficient data quality?**

Exchange of Experiences

Formål

- Formålet med gruppearbejdet er at dele erfaringer og ideer på tværs af virksomheder og brancher ift databaseret vedligeholdelse
- Desuden vil det være interessant, om grupperne kan pege på indsatsområder, som alle / mange virksomheder vil have udbytte af få belyst / finde løsninger til

Gruppearbejde

1. Kort intro af gruppens medlemmer
2. Vælg en repræsentant for gruppen, der kan præsentere konklusionerne i plenum senere
3. Hver deltager fortæller kort om, hvad status er i jeres virksomhed med hensyn til datadrevet vedligeholdelse
4. Hvad er efter jeres mening de bedste muligheder med datadrevet vedligeholdelse?
5. Hvad er efter jeres mening de væsentligste udfordringer med datadrevet vedligeholdelse?
6. Hvor kan det give mening at arbejde sammen på tværs af virksomheder ift data drevet vedligeholdelse?

Plenum

1. Hver gruppe præsenterer kort sine konklusioner
2. Kommentarer fra alle
3. Opsummering