ROMEO

An innovative approach for failure diagnosis and prognosis for offshore wind turbines

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ROMEO WP3 - Objectives

Wikinger Wind Farm – Adwen AD5-135

- Full set of diagnosis & prognosis failure mode oriented solutions
- Adwen/SGRE to build **Physical Modules**
- Ensure portability to contribute to enhance the understanding of failure occurrence in offshore wind farms

Module	Description
1	**Gearbox:** Sliding Bearings Wear/Blockage
2	**Converter:** DC link capacitor degradation
3	**Converter:** IGCT failure
4	**Generator:** Rotor Demagnetization
5	**Generator:** Loss of insulation in the stator winding
6	**Blade Bearing:** Fatigue and wear of raceways detection module
7	**Blade Bearing:** Loss of structural integrity detection module
8	**Gearbox:** Cracks in gears detection module
9	**Gearbox bearings:** Wear of raceways/rollers detection module
10	**Main Shaft Bearing:** Fatigue/wear of raceways detection module
11	**Main Shaft Bearing:** Wear/fatigue of rollers detection module
12	**Main transformer:** Loss of insulation in the winding detection module
13	**Main transformer:** Compromised structural integrity detection module

Physical models to be combined with Machine & Deep Learning models

IBM Research | Zurich

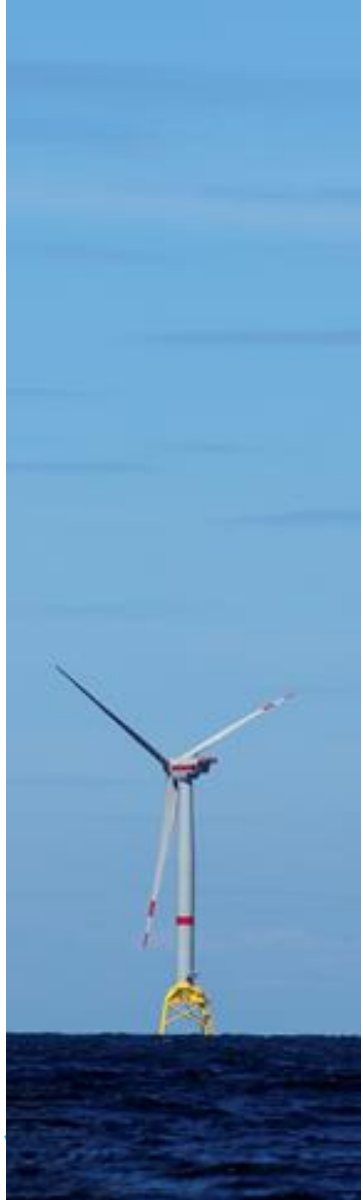
What shall be the drivers?

Design-for-Reliability framework:
Diagnosis shall be a balanced contributor to “the reliable wind turbine”

Component and specific failure mode focus.

Diagnosis awareness for decision taking.
Incorporation of confidence levels.

Enabling prognosis and time limited dispatches



General Approach for Diagnosis & Prognosis

Main definitions

Detection / Diagnosis / Prognosis

Our approach

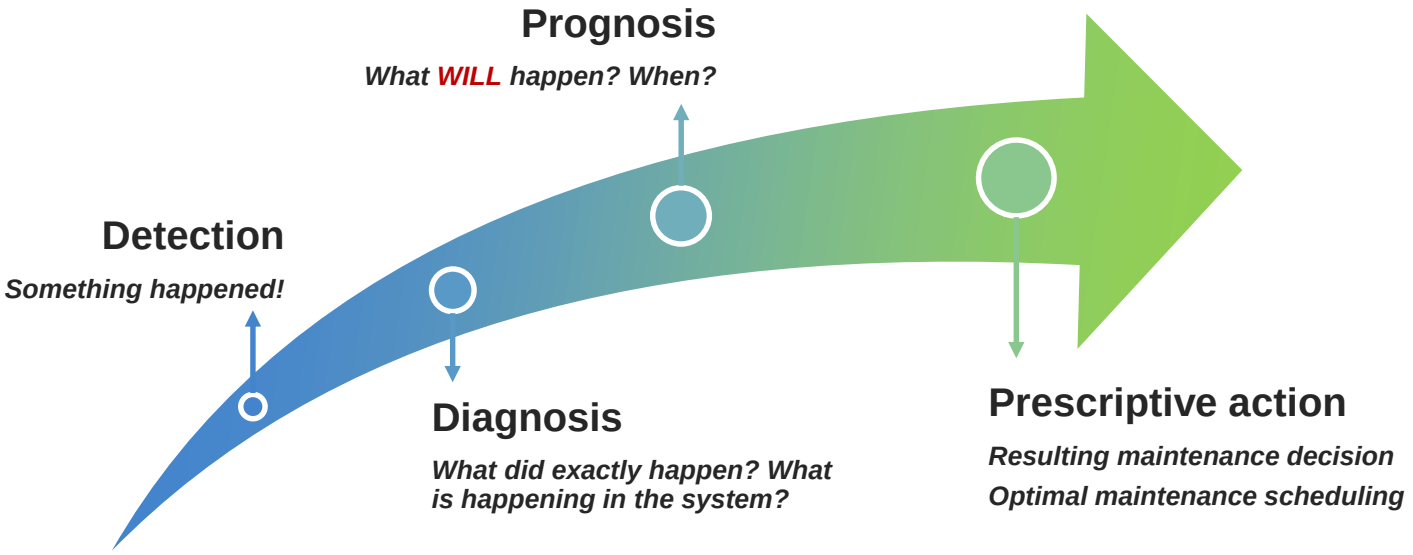
Main definitions & Concepts

- **Fault detection:** The fact of noticing the condition or performance degradation of the system.
  This may occur at any point of the fault state, preferably early enough to provide actionable intelligence.

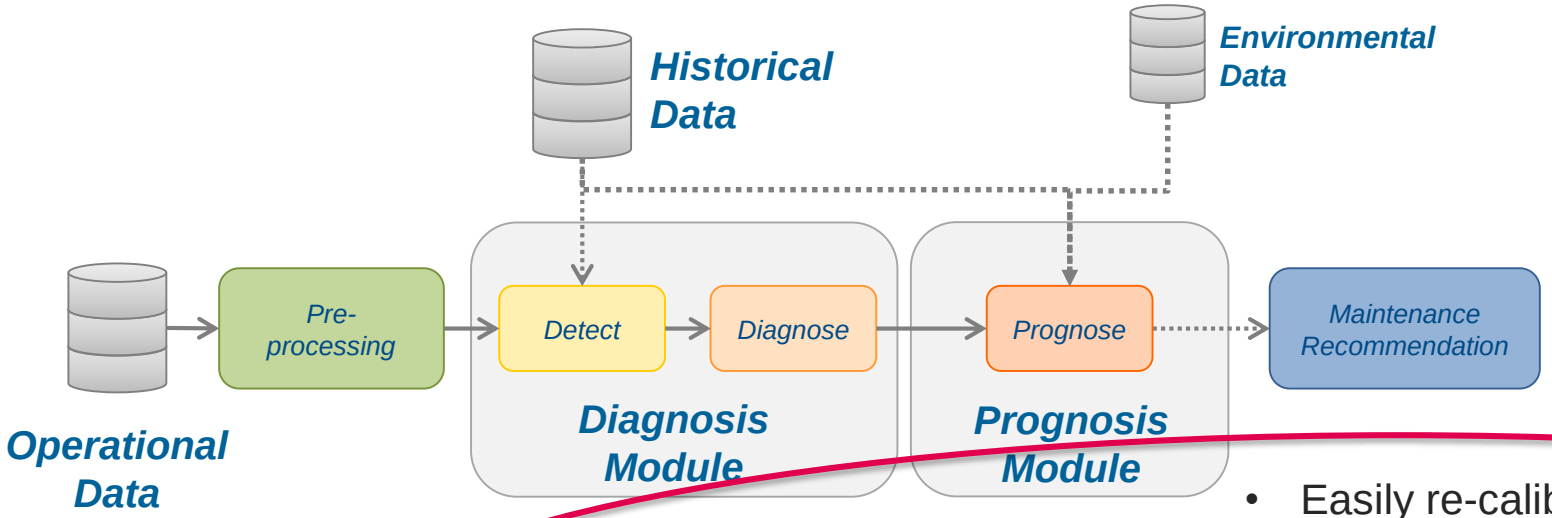
- **Failure diagnosis:** The identification of the most likely failure mode, based on the given conditions of the system.
  This can happen prior or after the functional failure.

- **Failure prognosis:** A forecast (or prediction) of the degradation of the system – in terms of remaining useful life, survival probability or predicted future condition – based on the given conditions of the system.

Detection & Diagnosis & Prognosis



Our approach…



Independent modules for each specific failure mode

- Easily re-calibrated and validated from daily operational data
- Easily calibrated and portable to other wind turbine types
- Easily accommodated in cloud computing eco-systems

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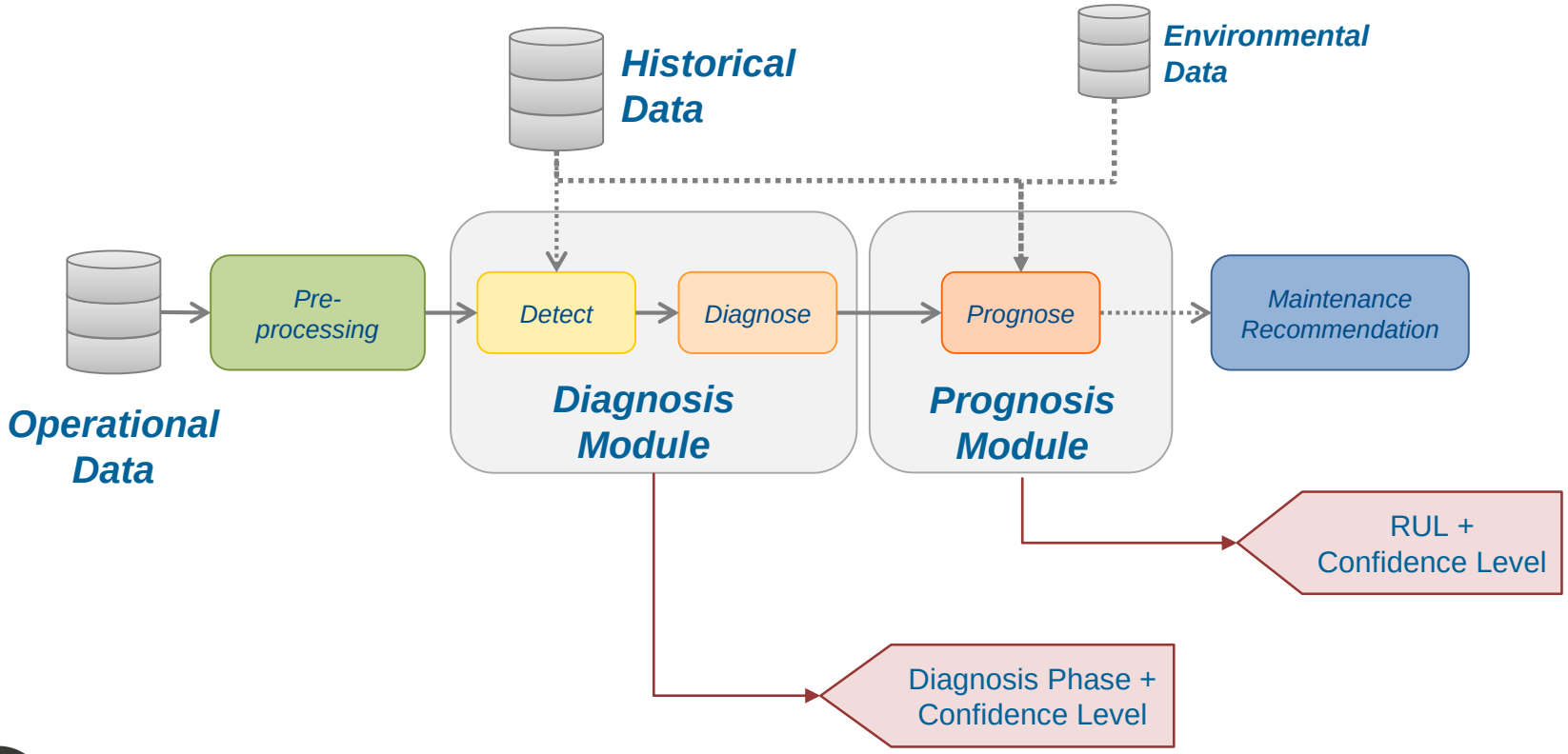
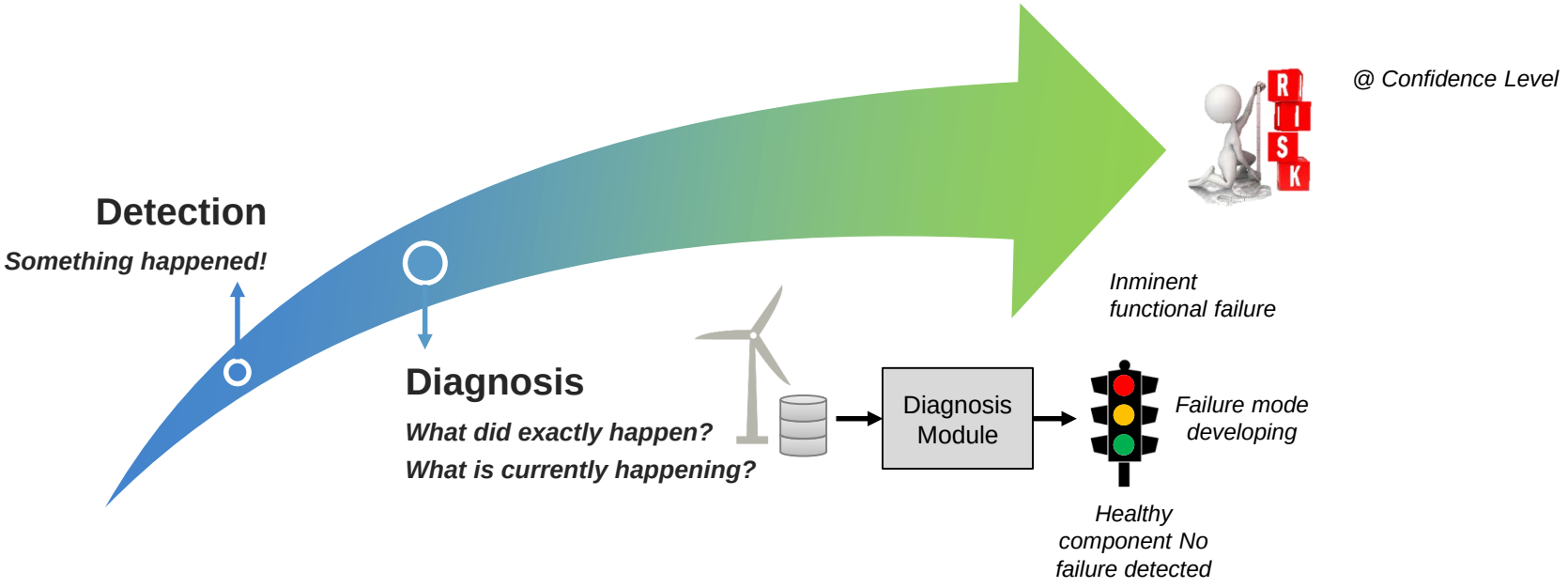
Our approach…



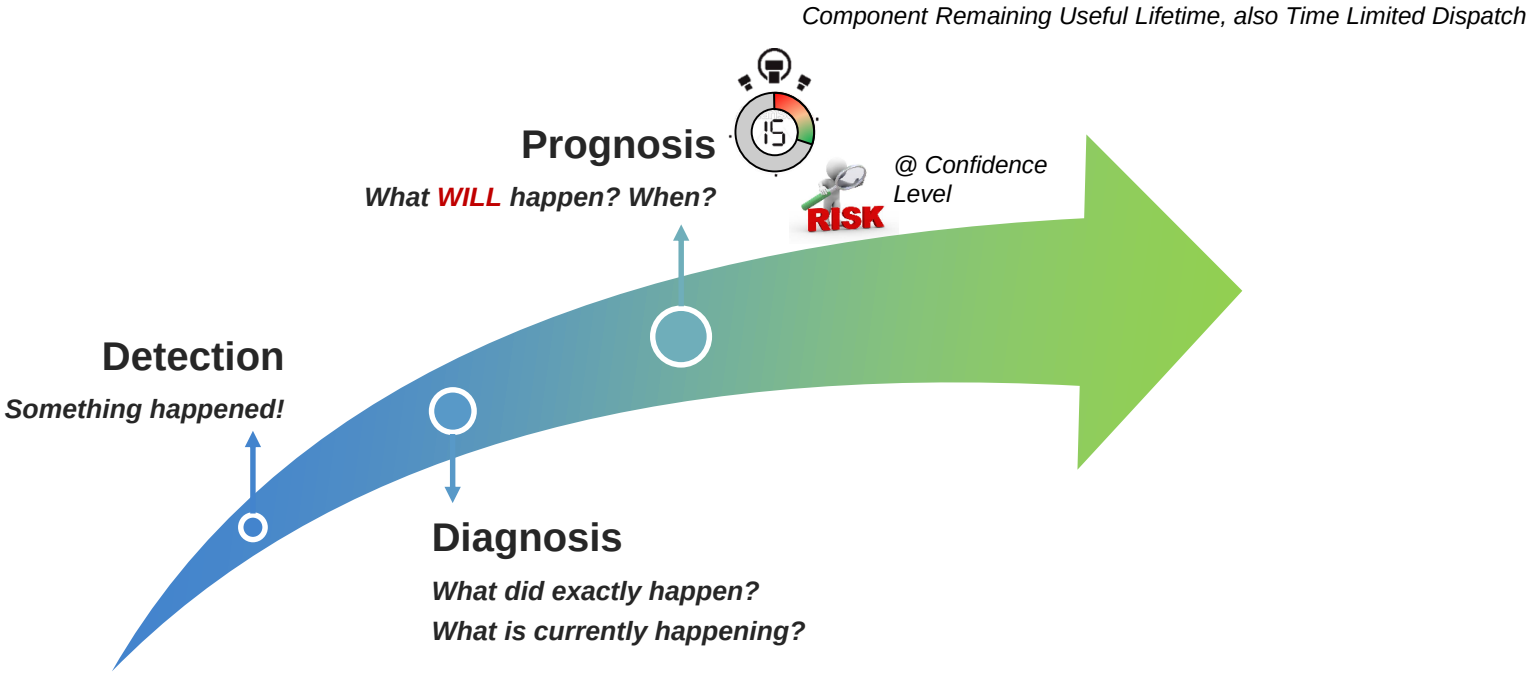
Our approach…

- Typical physical pattern of symptoms related to each failure mode
- **Diagnosis phase**s to assess the level of degradation
- Uncertainty & variability are considered by means of a **Probabilistic Approach**.
- Based on the conditions at a given point ($C(t)$), once a fault has been detected a resulting diagnosis phase ($DPh(t)$) is assessed together with a confidence level.
  - $\boldsymbol{C(t)} \Rightarrow \boldsymbol{DPh(t)=PH}$ and $\boldsymbol{CL(t)=Pr[DPh(t)=PH \mid C(t)]}$
  - $\boldsymbol{C(t)} \Rightarrow \boldsymbol{DPh(t)=PH}$ and $\boldsymbol{CL(t)}$ ⇨ RUL @ desired probability

Our approach…



Our approach…



How do we build tailored Diagnosis solutions?

General Approach - Recommendations

Main objective:

Detect & Diagnose degradation of [component C], ultimately leading to [functional failure F]

What are the key steps I should follow for developing a solution?

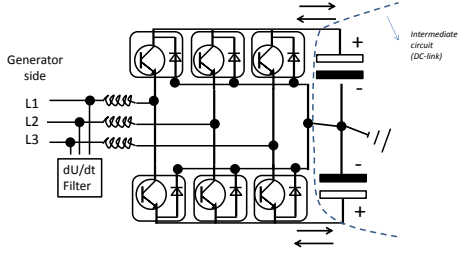
1. In-depth study of the system in terms of configuration & normal operation, from a physical point of view
2. In-depth study of the most common failures, failure mechanisms and how normal operation will be affected (symptoms)
3. Review of the State-of-the-Art for diagnosing the system
   - ✓ Commercial solutions
   - ✓ Most widely applied techniques
   - ✓ Scientific publications
4. Selection of the best solution based on…
   - ✓ Failure mode sought
   - ✓ Data available (Variables & Resolution)

   → **Condition our diagnosis capabilities**
5. Proper development based on historical data from healthy & faulty turbines

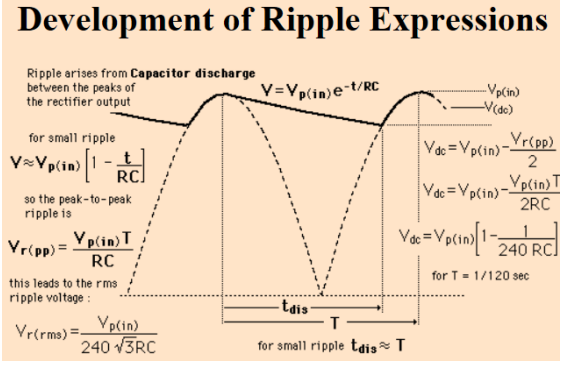
Case Study: Converter DC Link degradation

1 In-depth study of the system in terms of configuration & normal operation, from a physical point of view

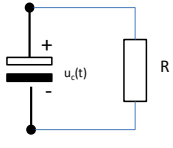
- **<u>Converter</u> function & configuration**:
  - Adjustment of generator frequency & voltage to the grid.
  - Conversion in three steps, three sub-components: rectifier, DC link & inverter.
- **<u>DC link</u> key function & configuration :**
  - Ensures a solid state power conversion process.
  - Acts as a storage of DC power and filters out the variations of the DC voltage prior to further processing of the inverter section.
  - 2 DC capacitors, one per each demi-cycle



- **<u>Ripple effect</u>**
  - A smooth ripple in the DC link guarantees the voltage stability.



- Operation governed by capacity:



↓ *Capacity* ⇔ ↓ *Voltage* ⇔ ↑ *Ripple*

$u_c(t) = u_c(0) \cdot e^{-t/\tau}$; $\tau = RC$

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Case Study: Converter DC Link degradation

2 In-depth study of the most common failures, failure mechanisms and how normal operation will be affected (symptoms)

- **Most common failures:**
  - High energy surges, high temperature, wear out, etc.
- Low failure rate but these components are very heavy, difficult to refurbish and hence very critical.

3 Review of the State-of-the-Art for diagnosing the system

- **State-of-the art:**
  - Electricity sink behaviour
  - Online electrical behaviour
  - Temperature monitoring
  - Unbalance effects
  - Vibration analysis ?

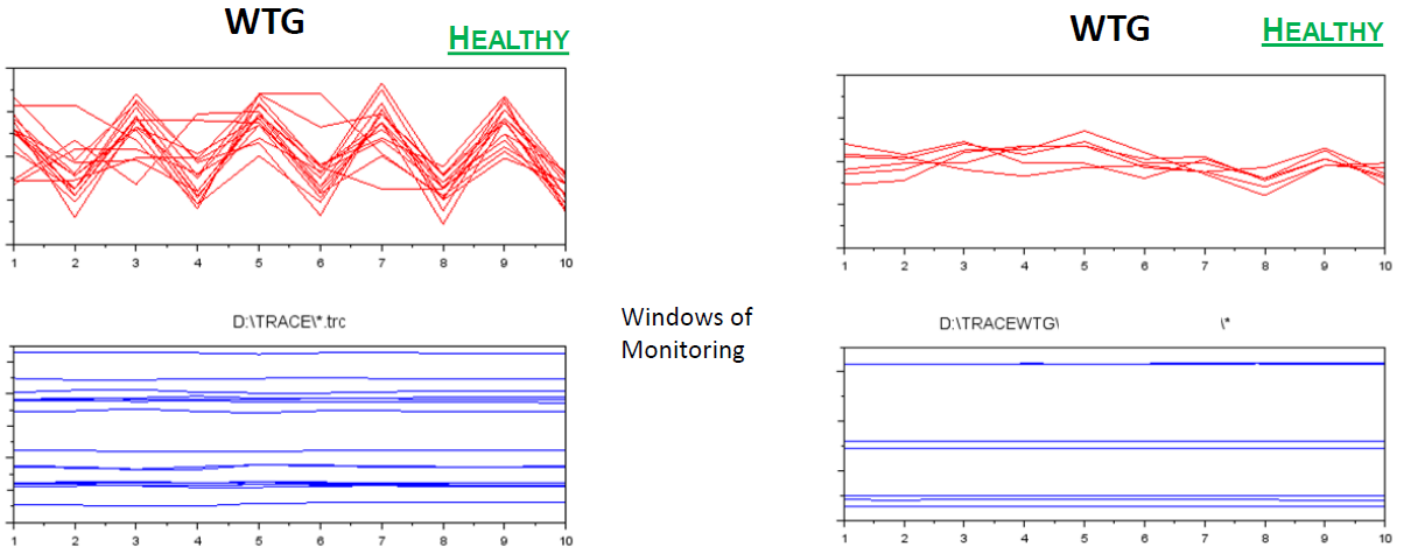
Case Study: Converter DC Link degradation

4 Selection of the best solution

NORMAL BEHAVIOUR MODELS

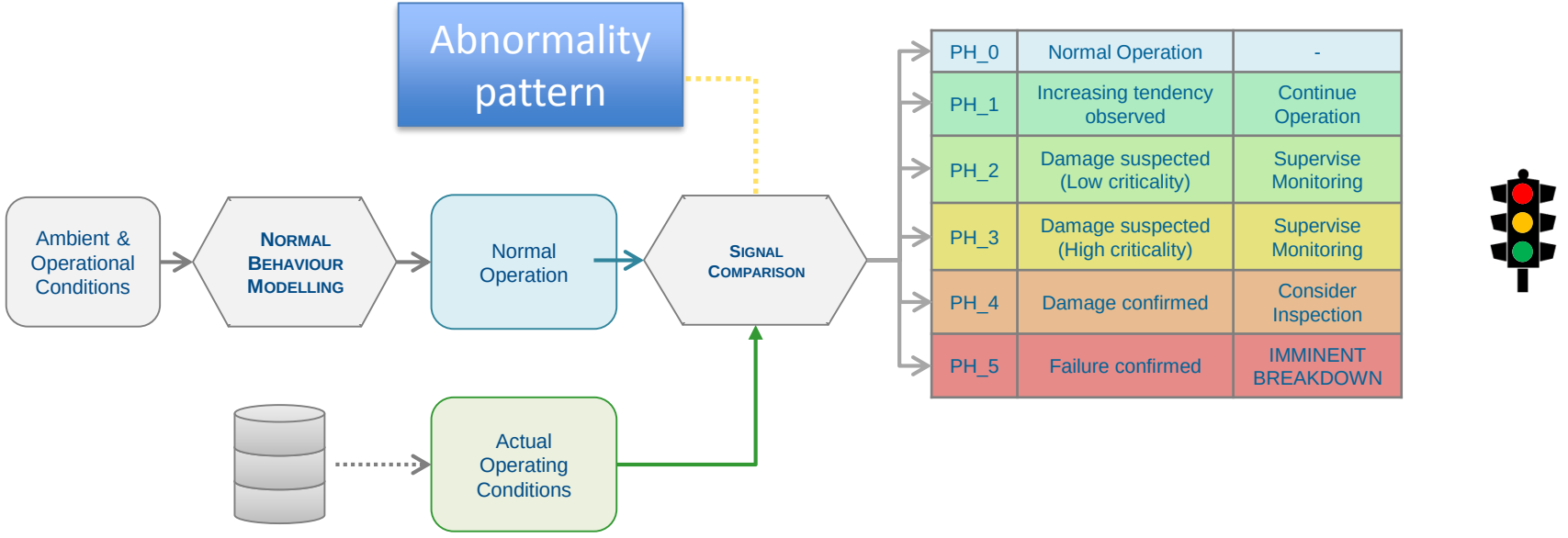
- ⇨ *Actual operating electrical cycles are giving healthy behaviours*
- ⇨ *Significant changes in the signal behaviour are thus indicators for incipient faults.*

- Examples:



General Approach - Recommendations

5 Proper development based on historical data from healthy & faulty turbines



PH_0	Normal Operation	-
PH_1	Increasing tendency observed	Continue Operation
PH_2	Damage suspected (Low criticality)	Supervise Monitoring
PH_3	Damage suspected (High criticality)	Supervise Monitoring
PH_4	Damage confirmed	Consider Inspection
PH_5	Failure confirmed	IMMINENT BREAKDOWN

General Approach - Recommendations

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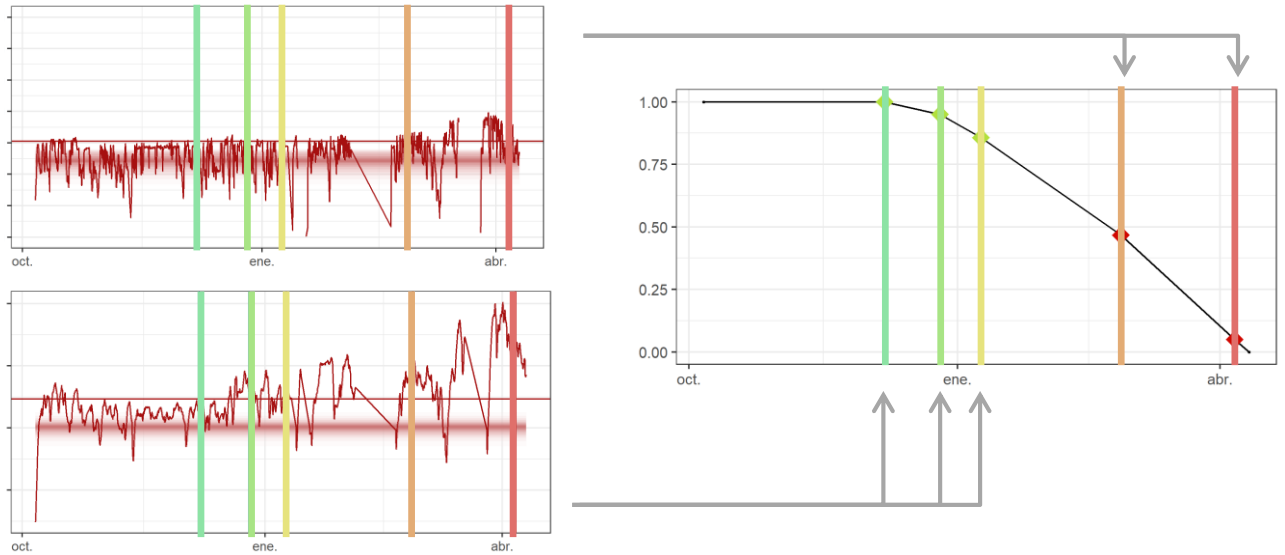
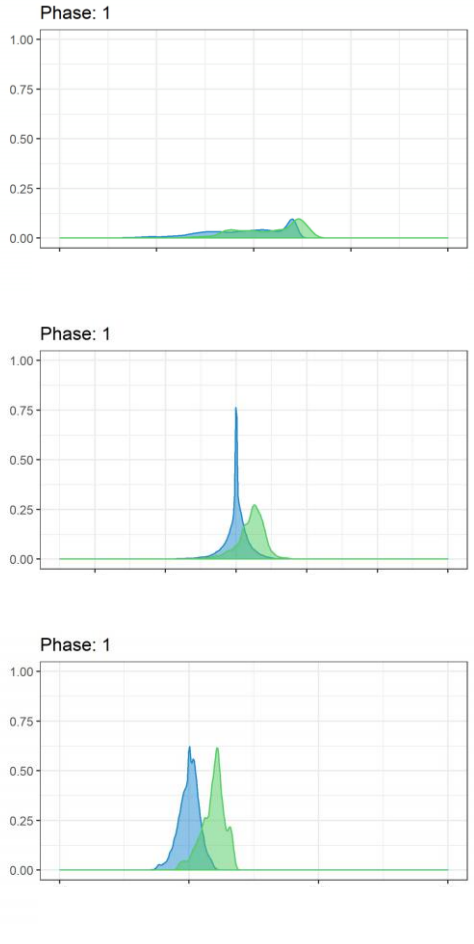
FAULTY DATA – Degradation assessment & phases definition




Phase: 1
1.00
0.75
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0.00
Phase: 1
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Phase: 1
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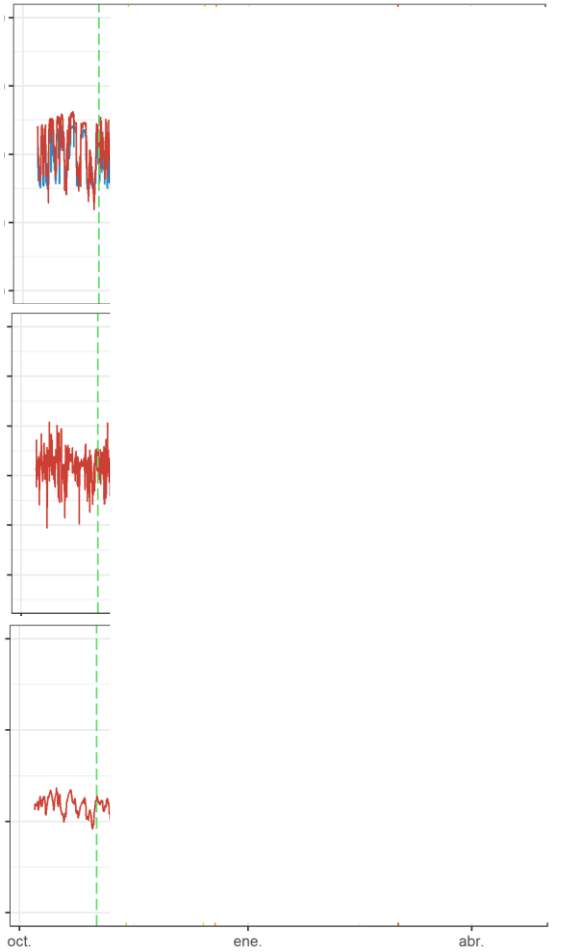
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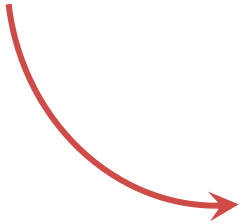
How do we build tailored Prognosis solutions?

General Approach - Recommendations

Main objective:

Predict Remaining Useful Lifetime of [component C], affected by [failure mode F] with a current damaged condition [DPh]



Prognosis is NOT possible if a previous proper diagnosis is not provided

General Approach - Recommendations

Main objective:

Predict Remaining Useful Lifetime of [component C], affected by [failure mode F] with a current damaged condition [DPh]

A

Time To Failure data ↑↑

Survival Analysis

(TTF & reliability modelling)

B

Time To Failure data ↑

Degradation model

(Failure symptoms & Cumulated damage)

C

Time To Failure data ✘

Digital twin @ Subsystem Level

(Generation of failure synthetic data)

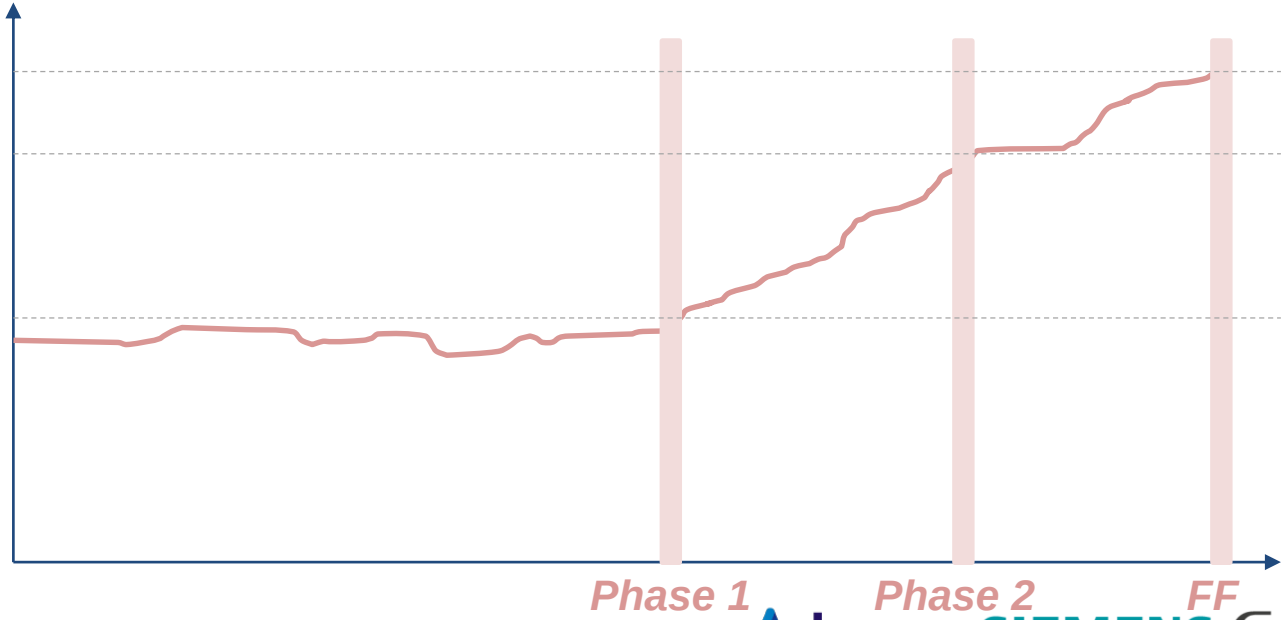
General Approach - Recommendations

B

Time To Failure data ↑

Degradation model

(Failure symptoms & Cumulated damage)



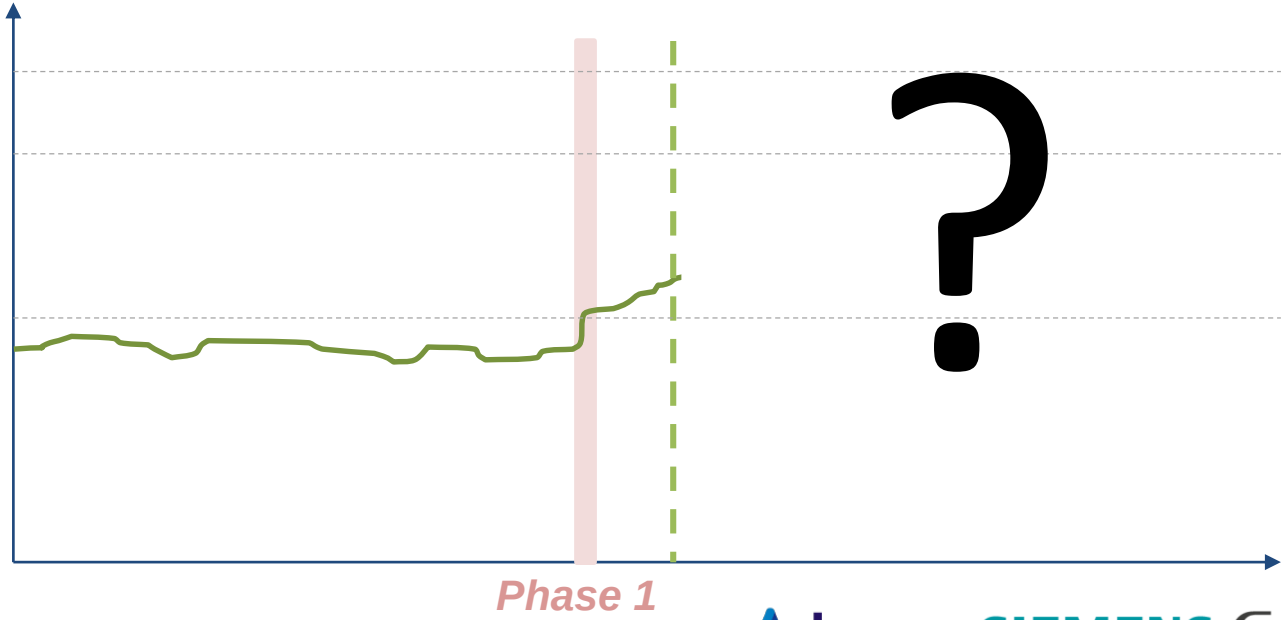
General Approach - Recommendations

B

Time To Failure data ↑

Degradation model

(Failure symptoms & Cumulated damage)



General Approach - Recommendations

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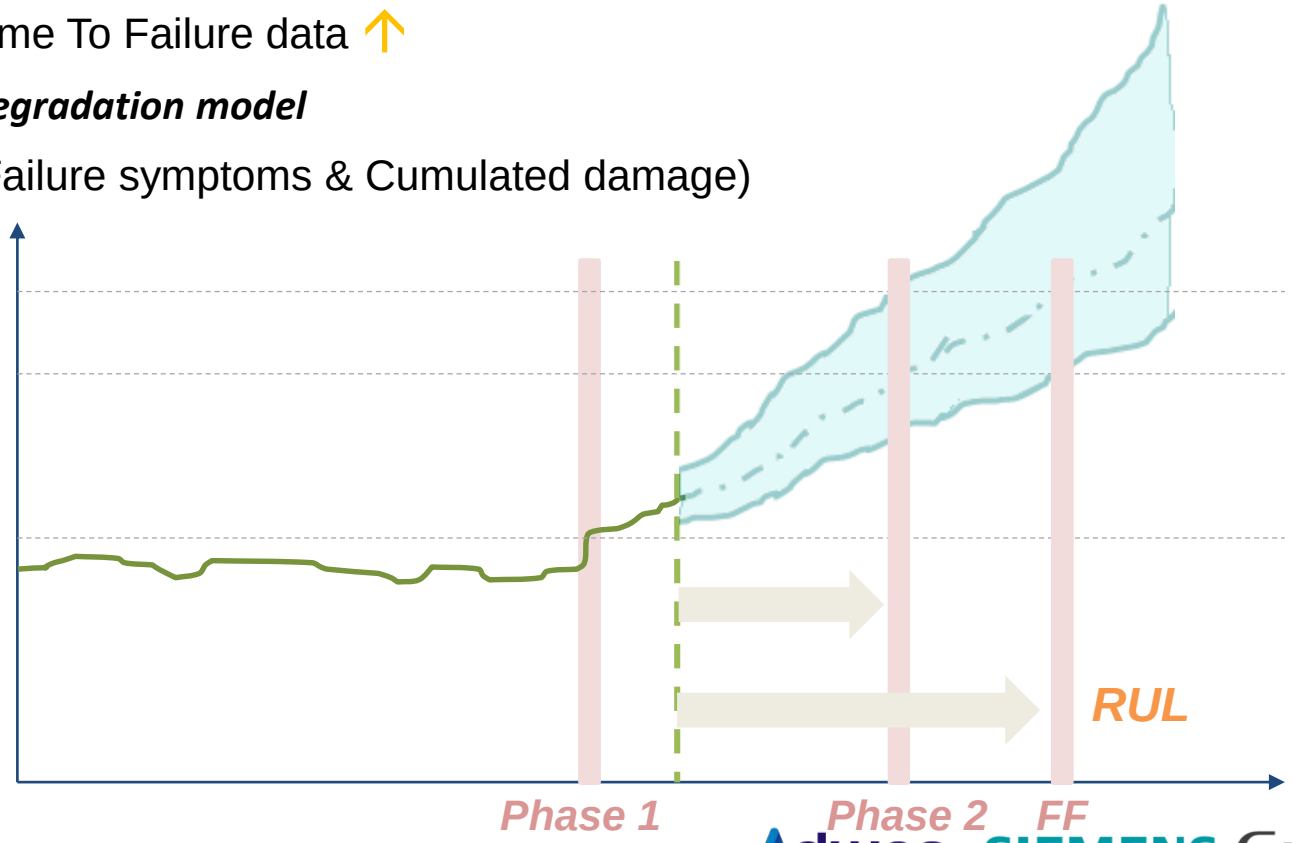

General Approach - Recommendations

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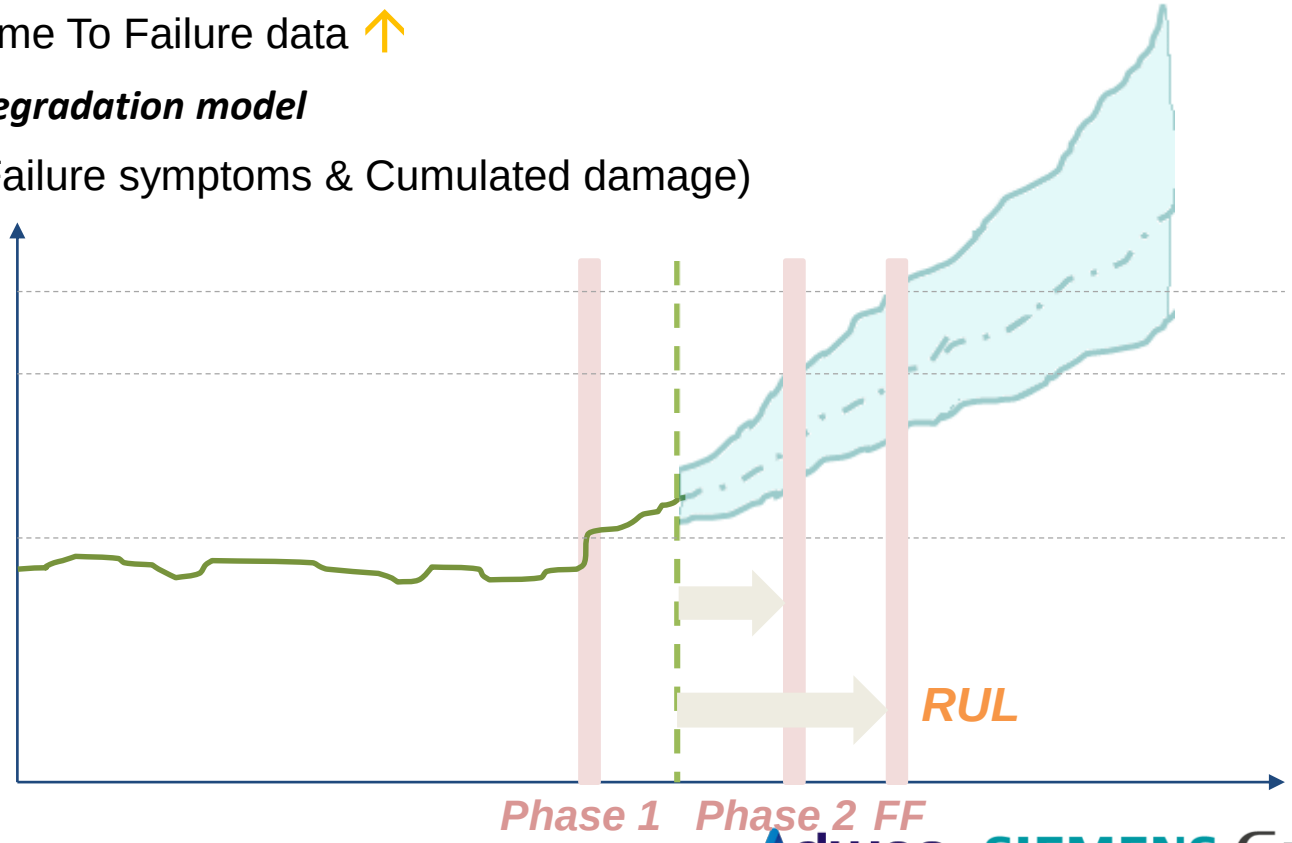

Summary

Summary – what makes our approach unique?

- Development of a **full set of cost-effective diagnosis & prognosis failure mode oriented solutions**
  - In-Depth investigation of component real behaviour & failure symptoms as observed in SCADA data
  - The approach by failure mode makes detection & diagnosis & prognosis more effective
  - Contribution to enhance the understanding of failure occurrence in offshore wind farms
  - Filling an existing gap in both the industry and the academia
- The **probabilistic approach** sets the basis for risk-based Diagnosis & Prognosis, implying important advances beyond the State-of-the-Art
- **Highly effective approach** as the developed solutions can be…
  - Easily understood by service technicians & integrated into maintenance-related decision processes
  - Easily re-calibrated and validated from daily operational data
  - Easily calibrated and portable to other wind turbine types
  - Easily accommodated into cloud computing eco-systems

thank you

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