A sequential hybrid method for full remaining useful life prediction of bearings

in rotating machinery under varying speed conditions

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Flanders Make

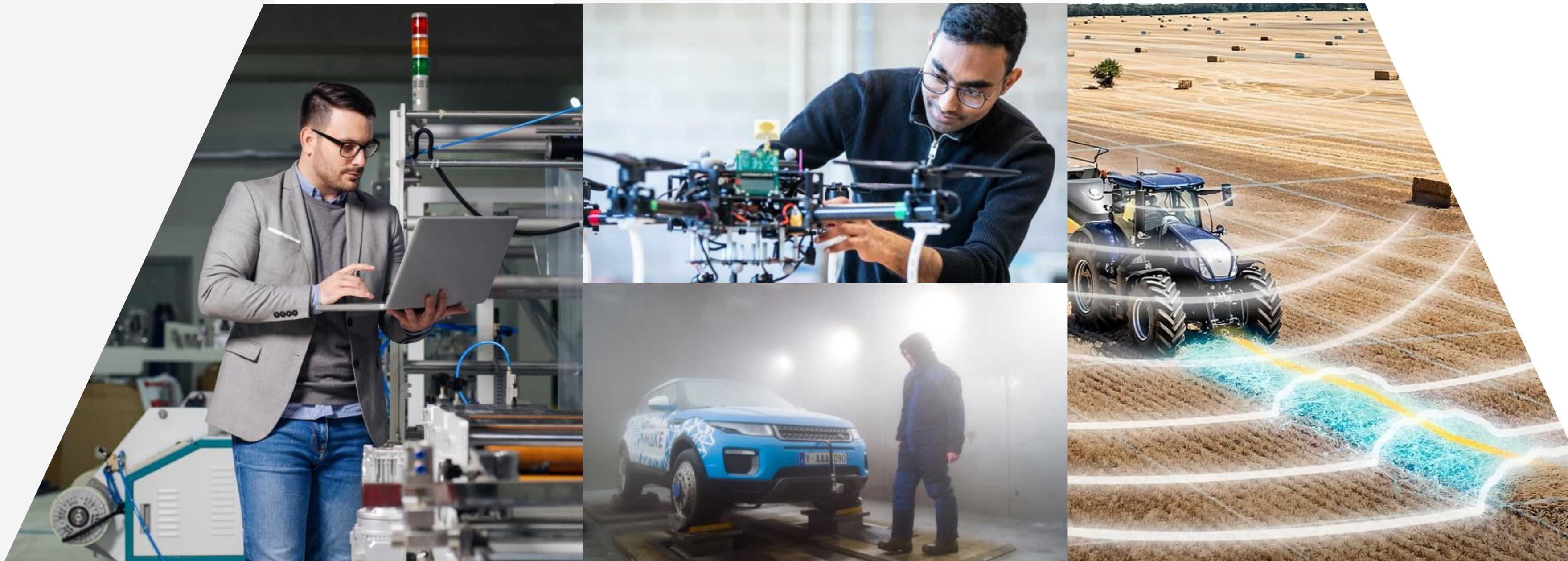
Research institute to supports the Flemish industry

to increase its international competitive strength

Manufacturing industry

Industry with manufacturing challenges

Bridging the gap between academic research and industrial implementation



Sequential hybrid method for RUL prediction

Content

- **Challenges**
- **Background**
- **Model-based RUL prediction**
- **Data-driven RUL prediction**
- **Sequential hybrid method**
- **Conclusions**

Sequential hybrid method for RUL prediction

Challenges

RUL prediction for bearings

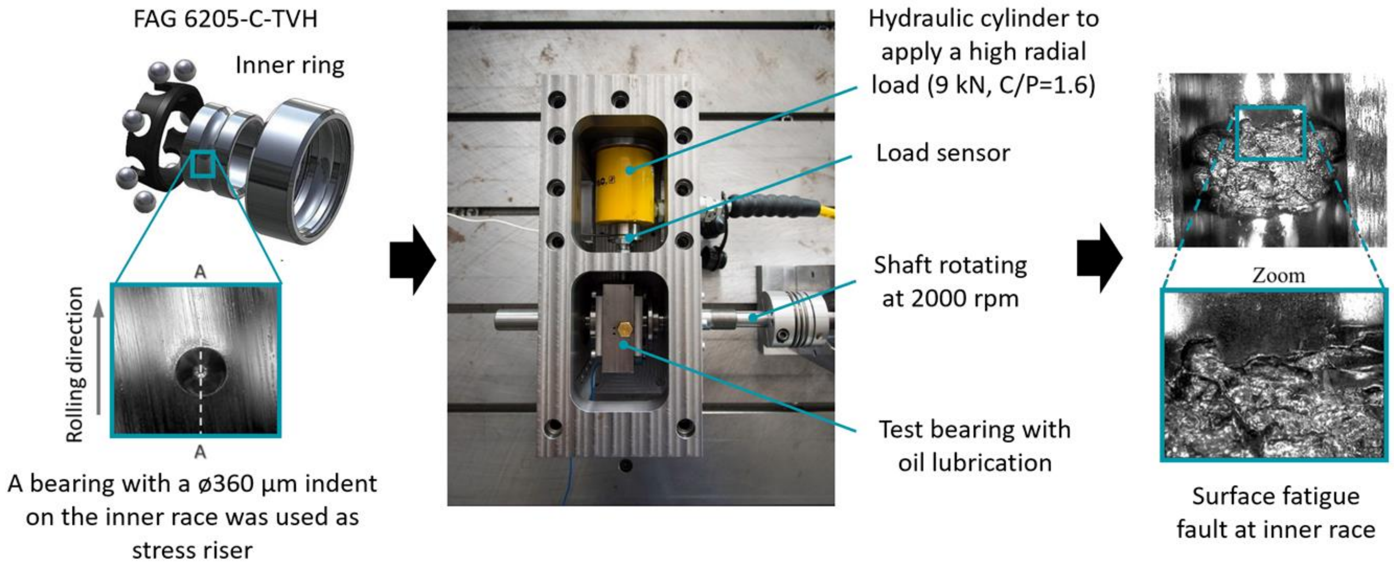
- **Availability of data – faulty and run-to-failure data**
- **Smart maintenance strategies need RUL prediction during entire lifetime**
  - **RUL prediction after anomaly/fault detection not sufficient**
  - **Short degradation time wrt full lifetime**
- **Varying operating conditions**

Sequential hybrid method for RUL prediction

Challenges

Data - Flanders Make data-set

- +200 bearings run-to-failure (20g)
- Accelerated lifetime tests (ALT)
  - High load + damage initiation
- Vibration and/or acoustic measurements
- Different speed and loads + varying speed



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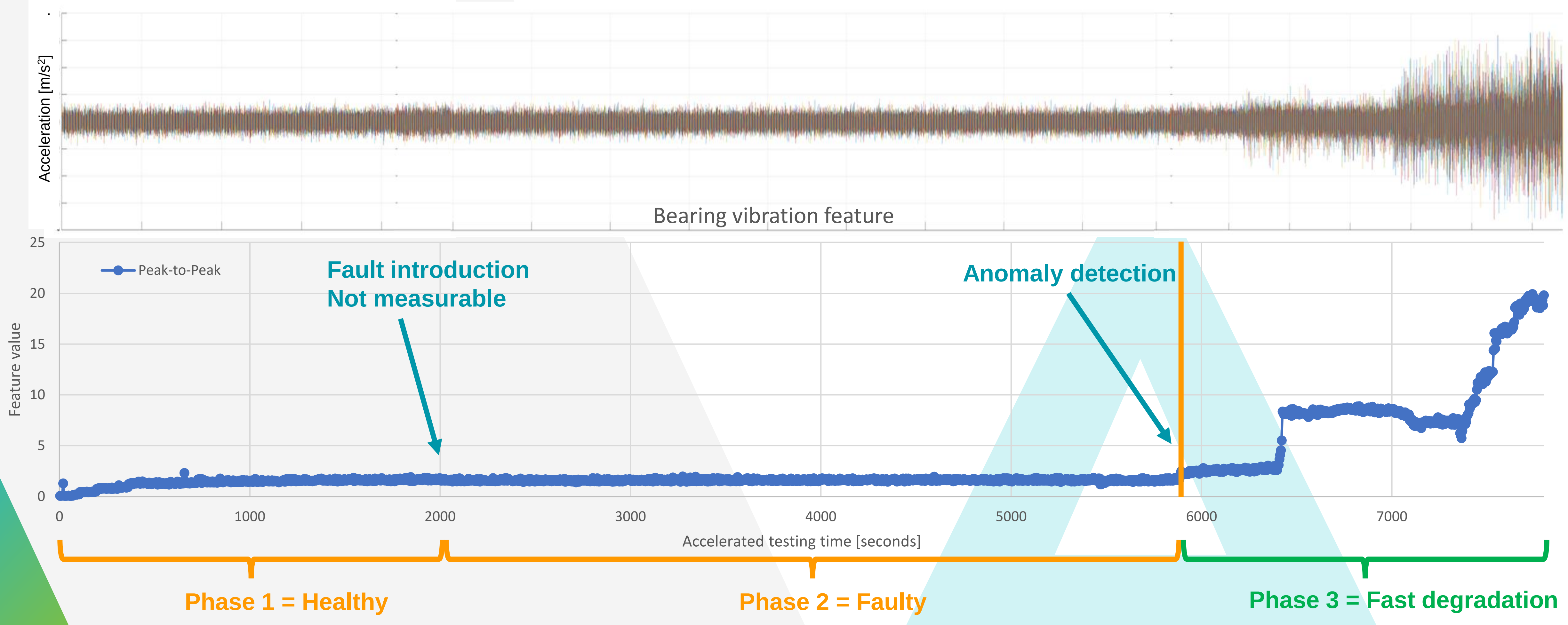
Challenges

RUL prediction during entire lifetime



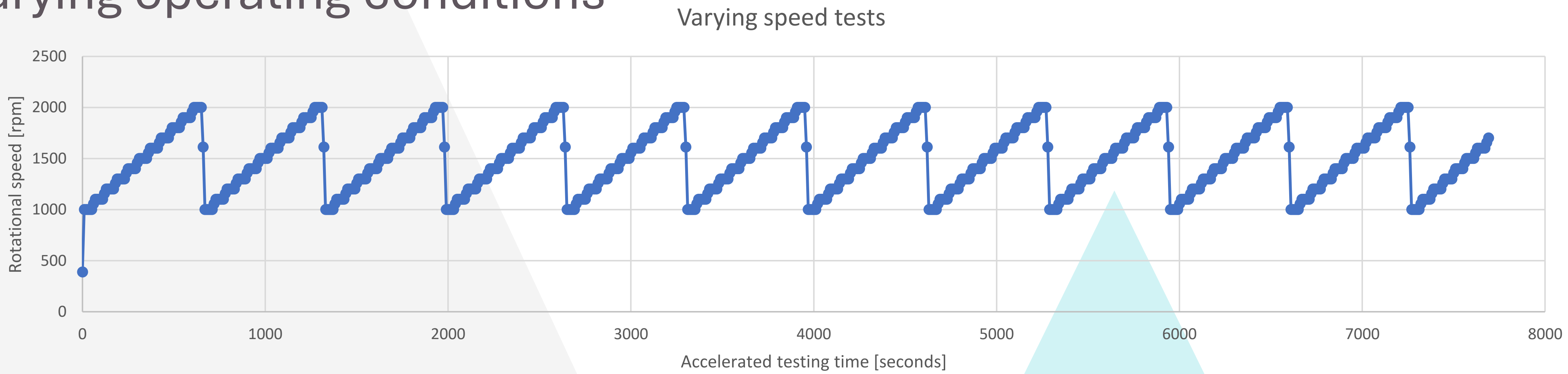
Model-based RUL prediction

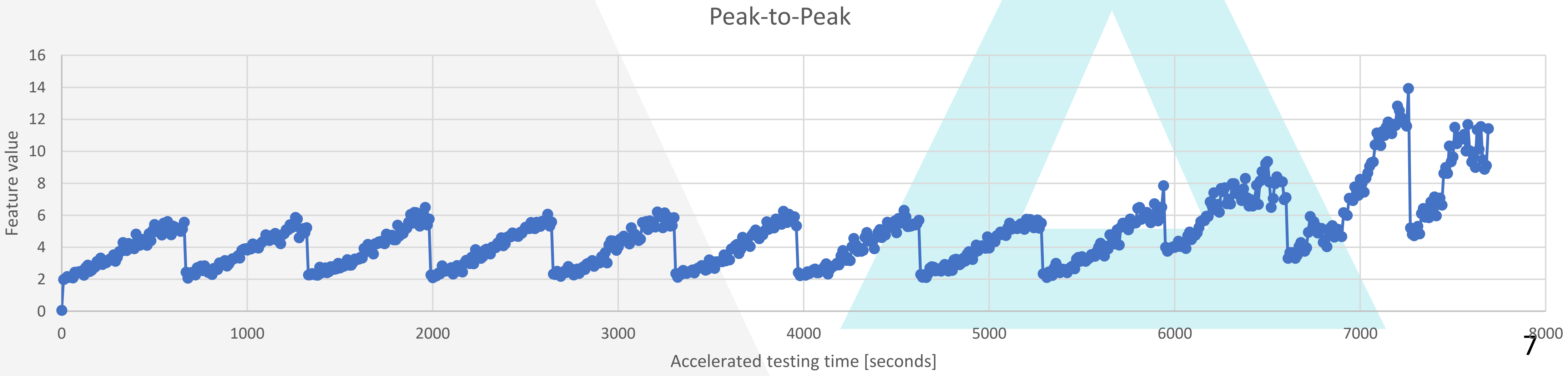
Data-driven RUL prediction

Sequential hybrid method for RUL prediction

Challenges

Varying operating conditions





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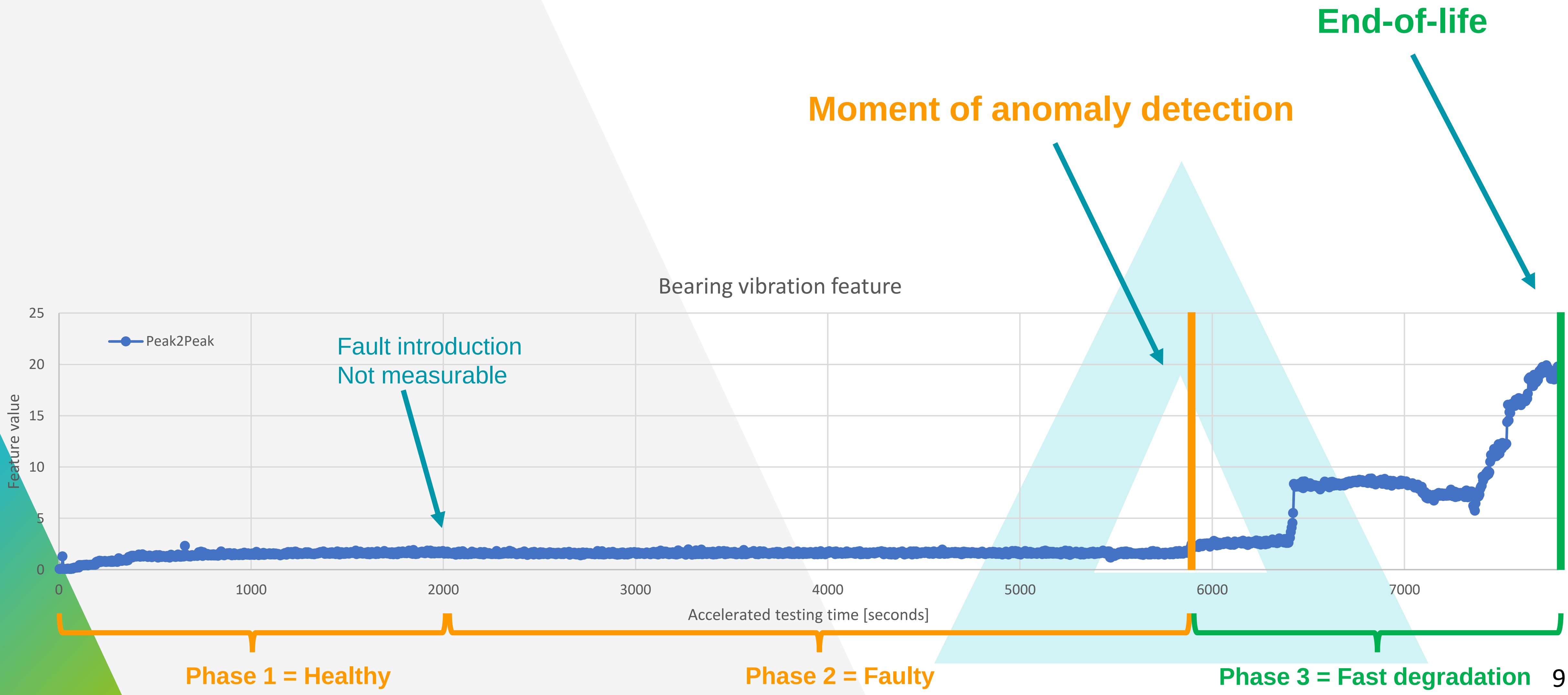
Model-based RUL prediction



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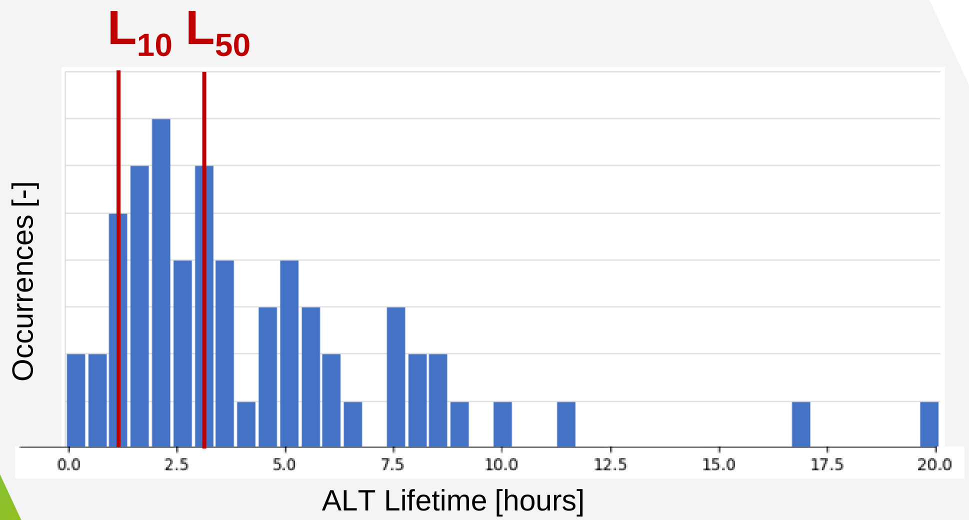
Model-based RUL prediction

Historical data

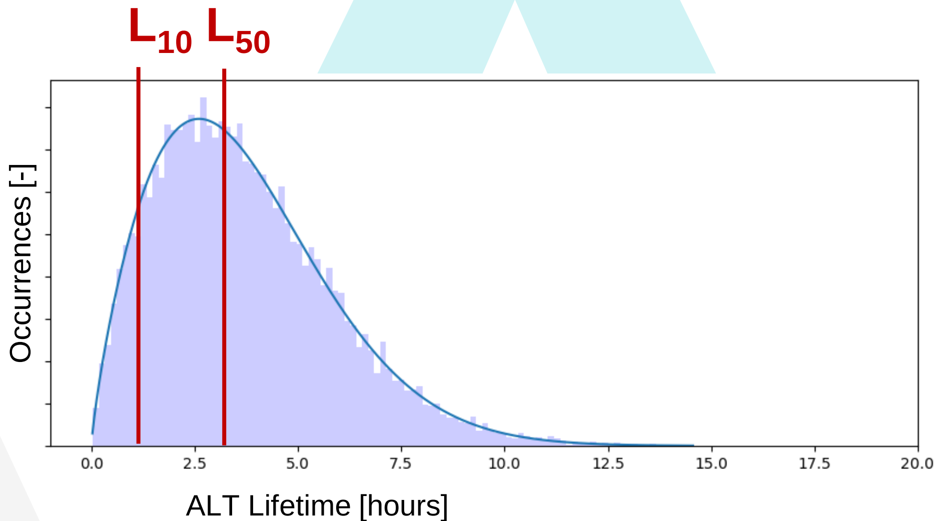
- Histogram of lifetime & anomaly detection
- Average time of degradation (phase 3)

- L10 bearing rating life (1h:15)
- L50 average bearing life (3h:15)



Prior knowledge/estimates

- L10 bearing rating life
- L50 average bearing life
- Weibull or log-normal distribution
  - Weibull:
    - Shape = 2.5 (literature: 0.7 – 3.5)
    - Scale = L50 average bearing life



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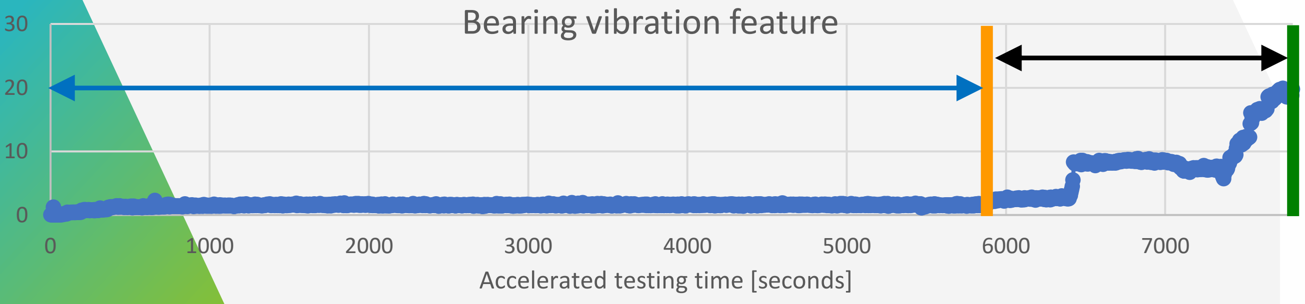
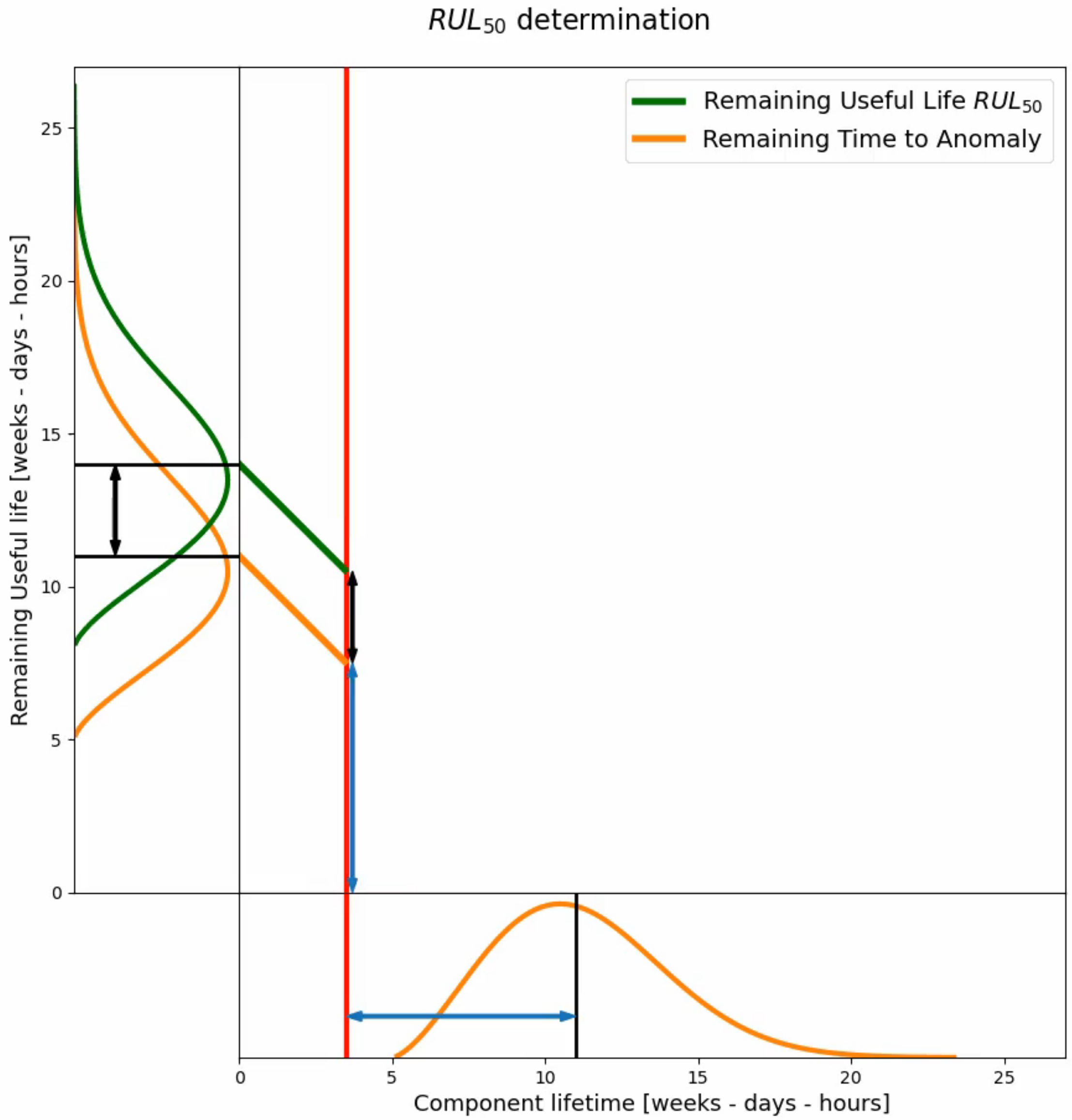
Model-based RUL prediction

- **Distribution of End-of-Life**
- **Distribution of "Moment of anomaly detection"**





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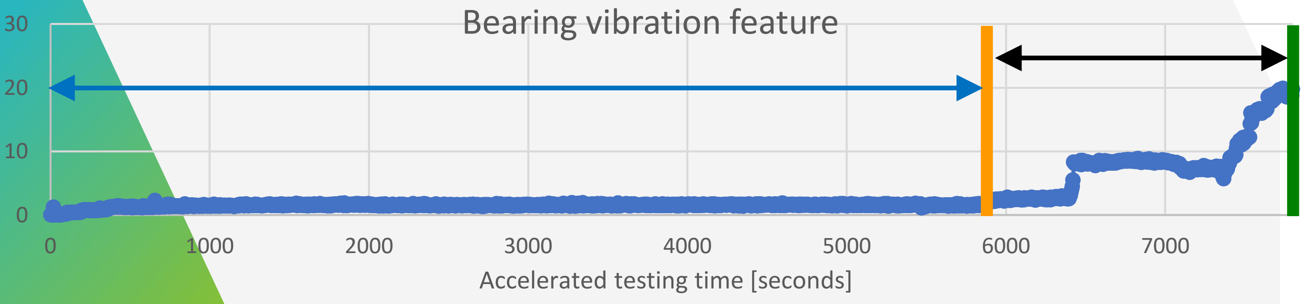
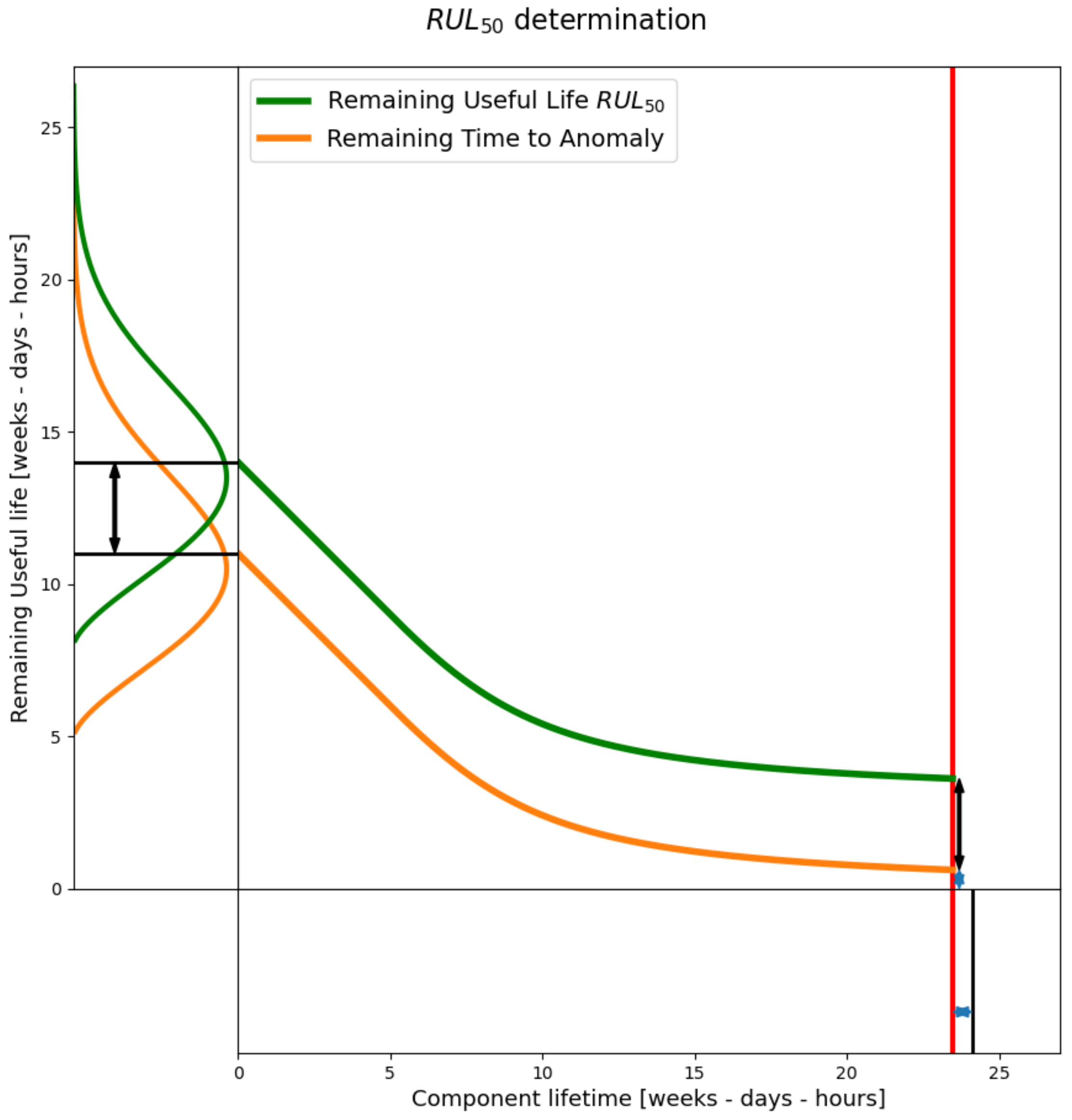
Model-based RUL prediction

- **Distribution of End-of-Life**
- **Distribution of "Moment of anomaly detection"**
- **Model-based RUL prediction RUL_{50}**





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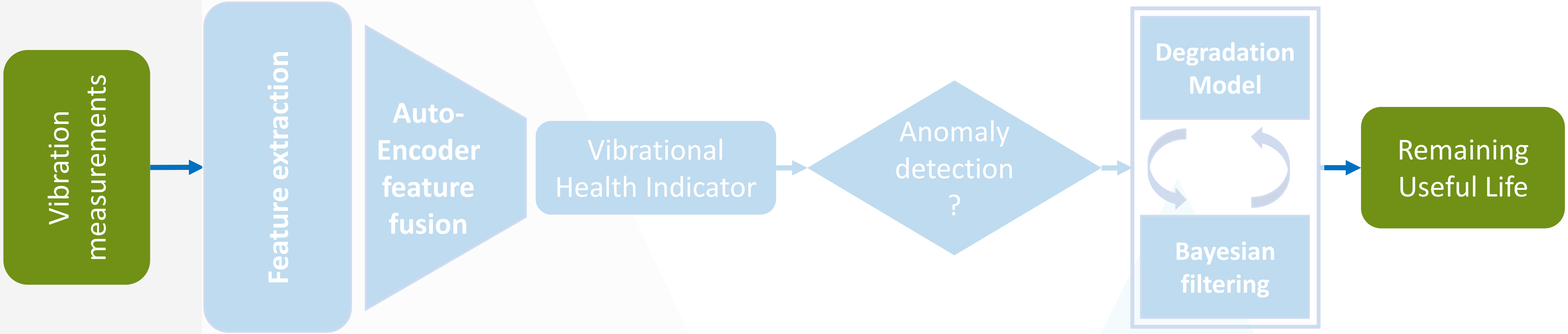
Data-driven RUL prediction



Measurements

- Vibrations
- RPM

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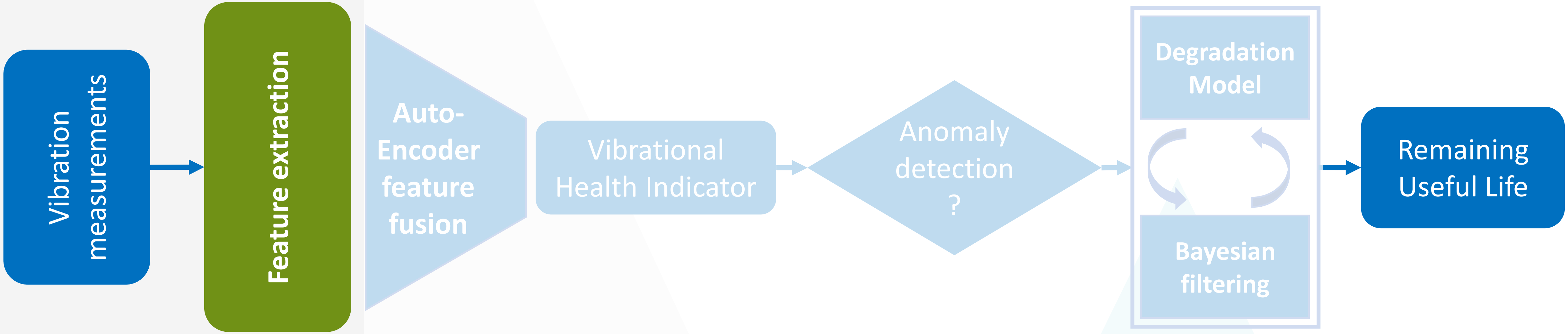
Data-driven RUL prediction



Feature extraction

- Statistical time-domain features (e.g. RMS, peak-to-peak, impulse factor …)
- Statistical frequency-domain features (e.g. max amplitude, frequency of max amplitude …)
- Fault frequency features (e.g. BPFO, BPFI, BDF …)
- (can be extended with ML features or any other relevant features)

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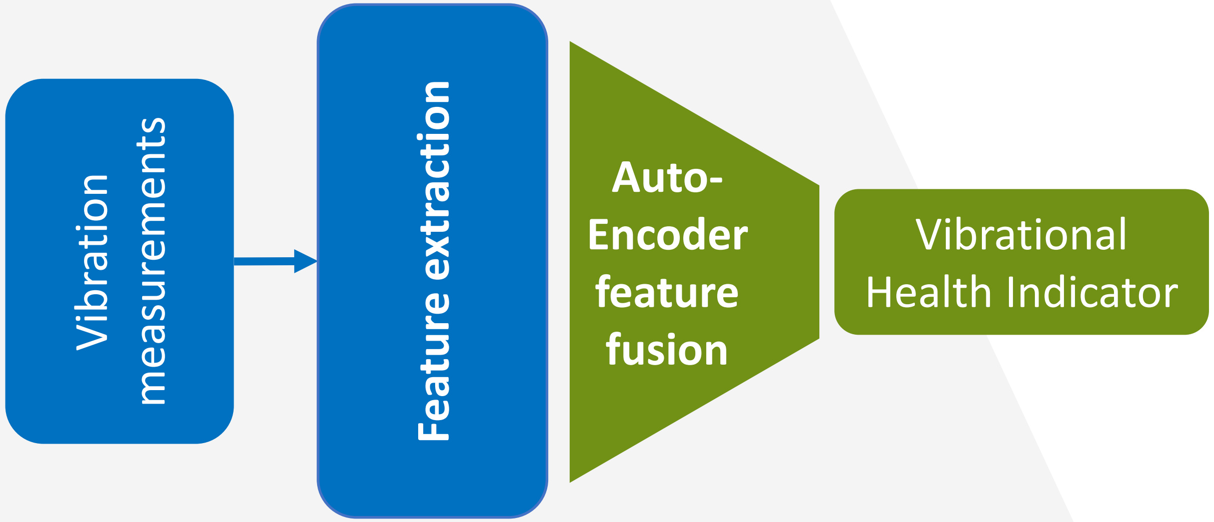
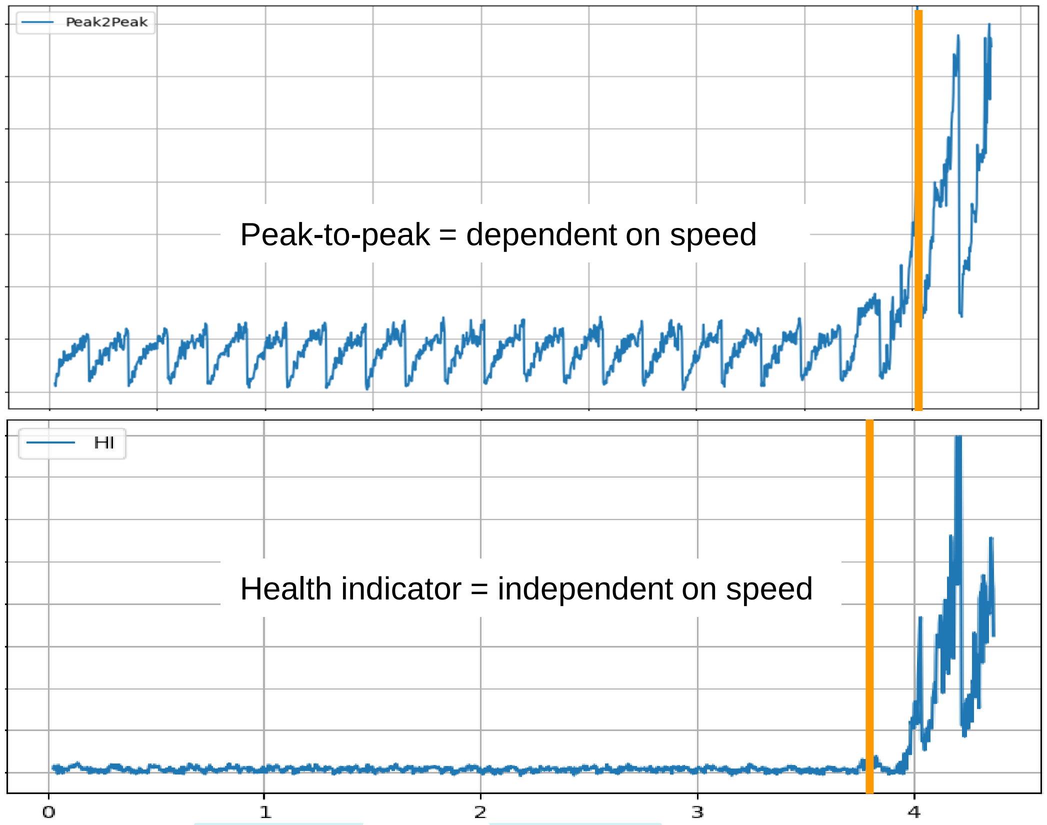
Data-driven RUL prediction





Auto-encoder to generate health indicator

- Smart feature selection – limited AE size
- Only limited healthy training data required
- Reconstruction error = health indicator
- Individual reconstructed features can be used for diagnostics
- Capable of coping with varying operating conditions

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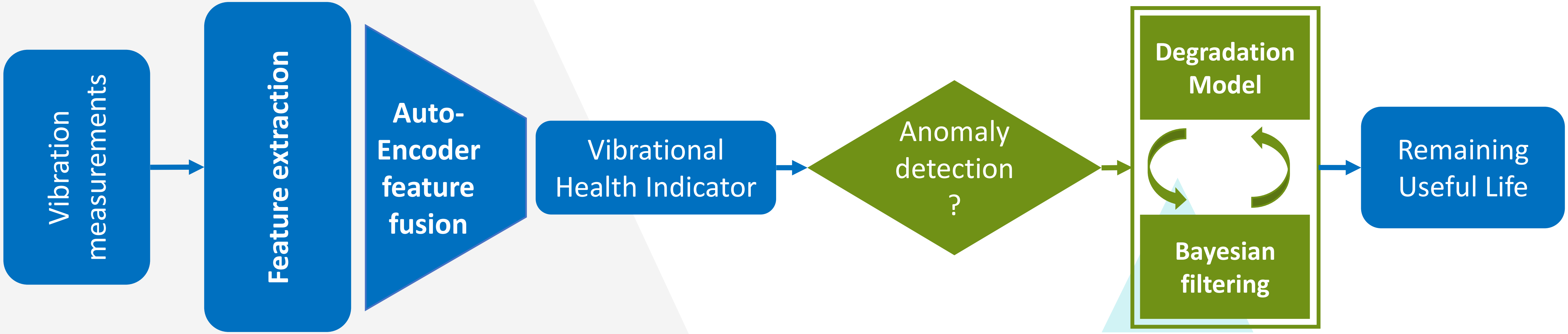
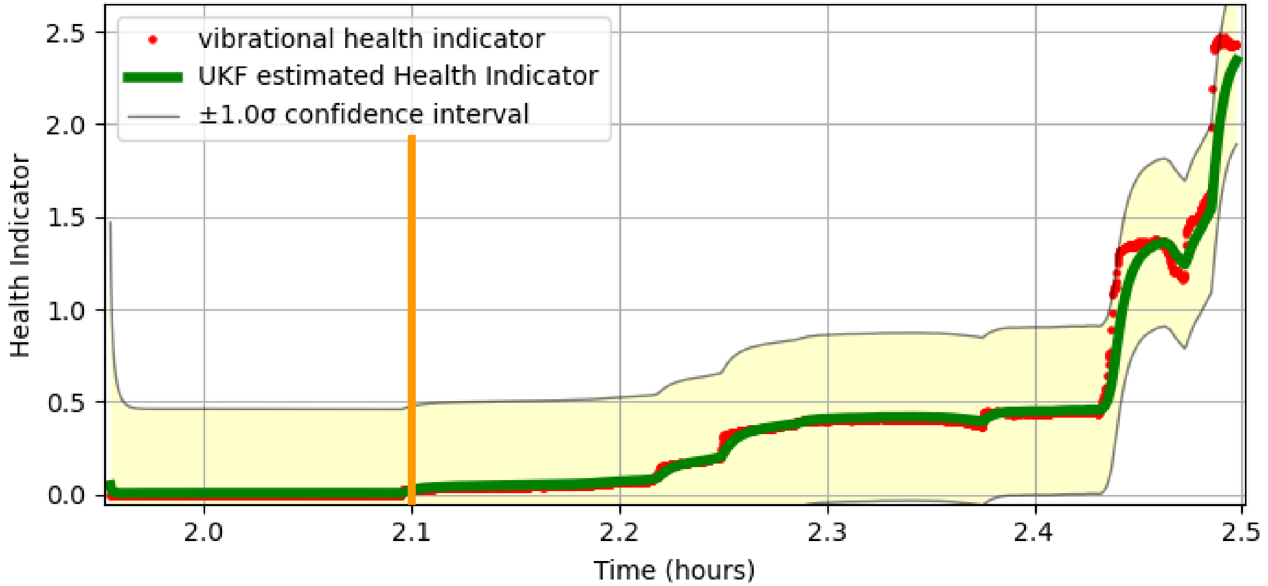
Data-driven RUL prediction



Remaining Useful Life prediction

- Kalman filter with exponential degradation model fitted to the health indicator
- Extrapolation towards threshold results in RUL
- Threshold based on historical end-of-life data (if available) or engineering knowledge



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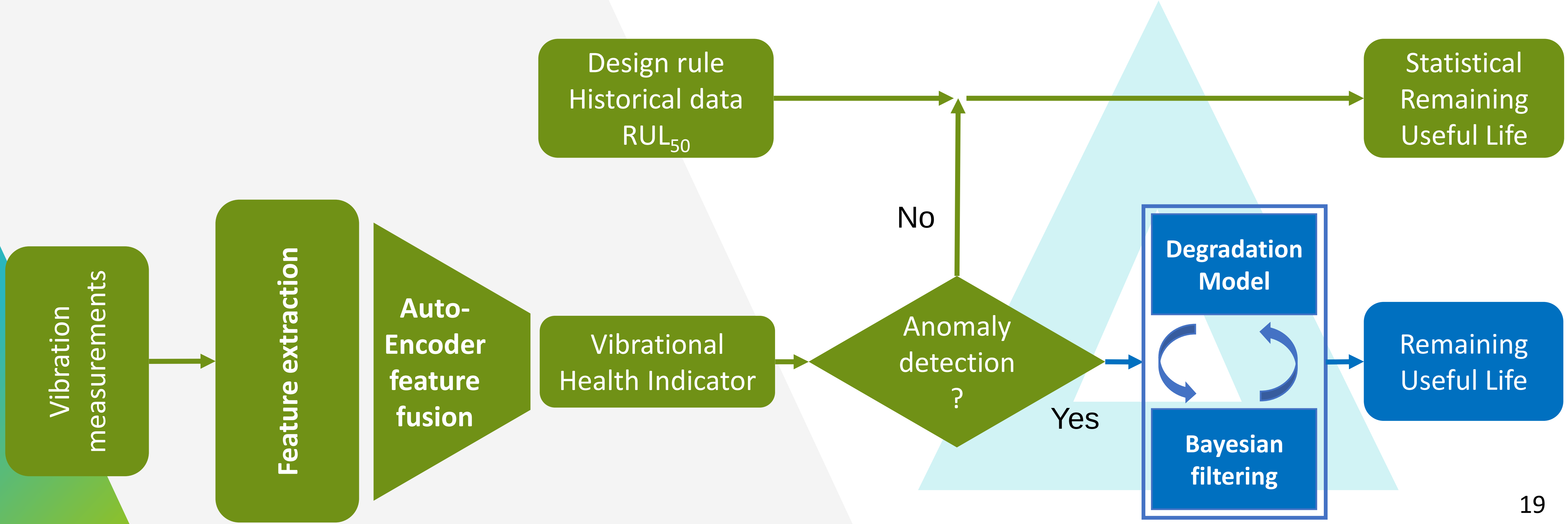
Sequential hybrid method

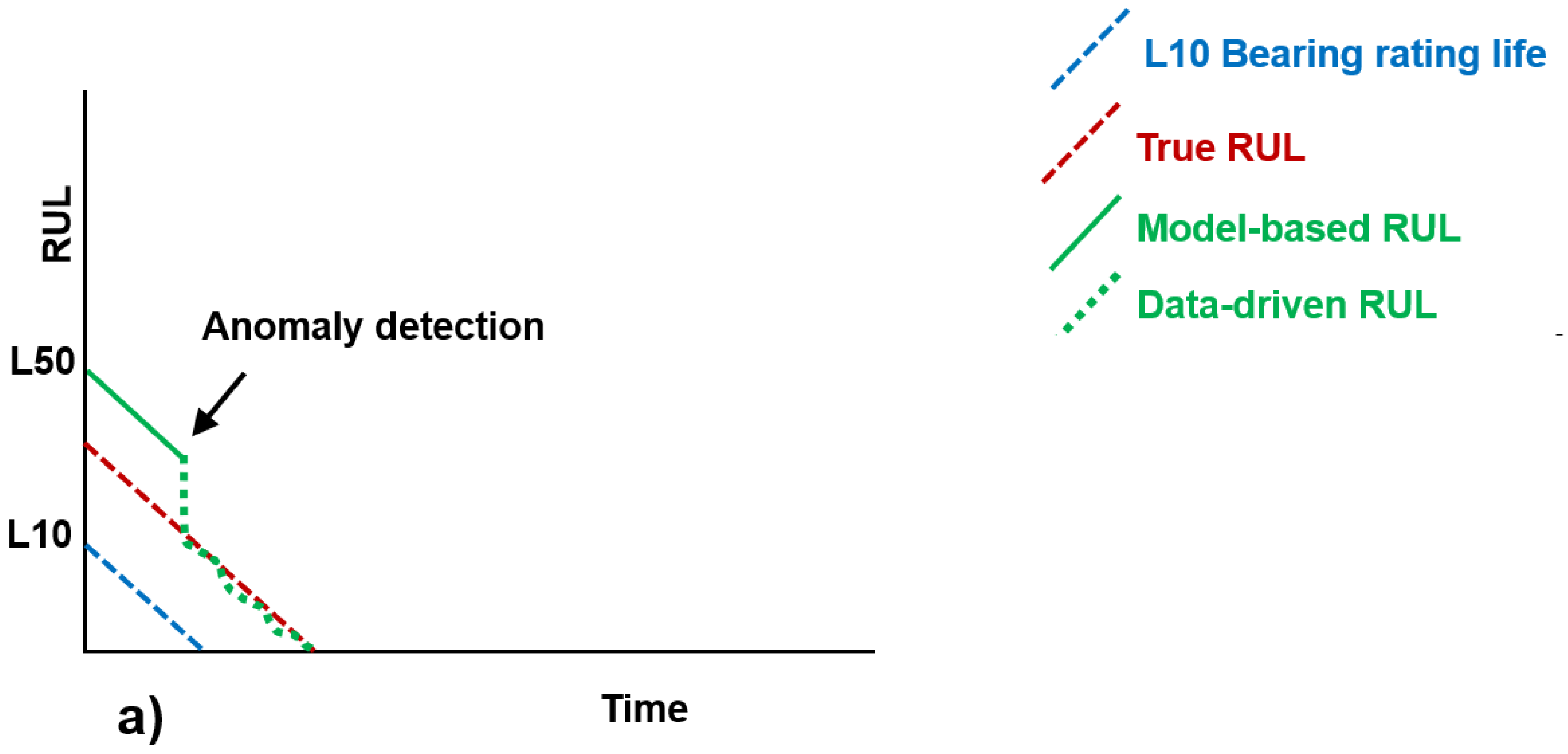
- **Vibration health indicator & RUL_{50} computed in parallel**
- **Data-driven model after anomaly is detected**



Sequential hybrid method for RUL prediction

Sequential hybrid method

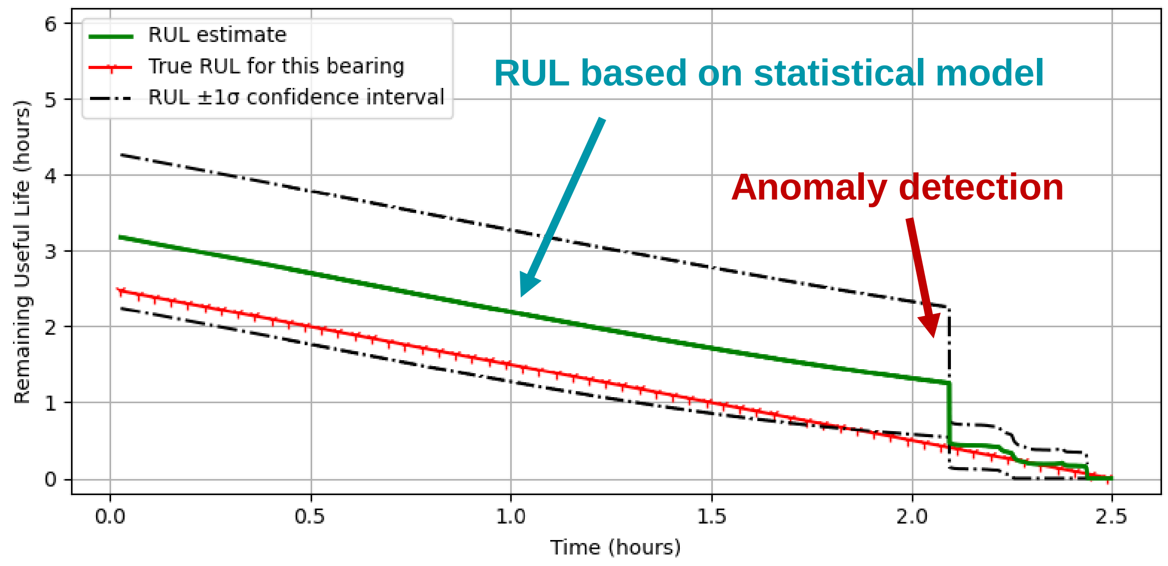
- **Hard switch between methods once an anomaly is detected**
- Short living bearing
  (less than average lifetime)



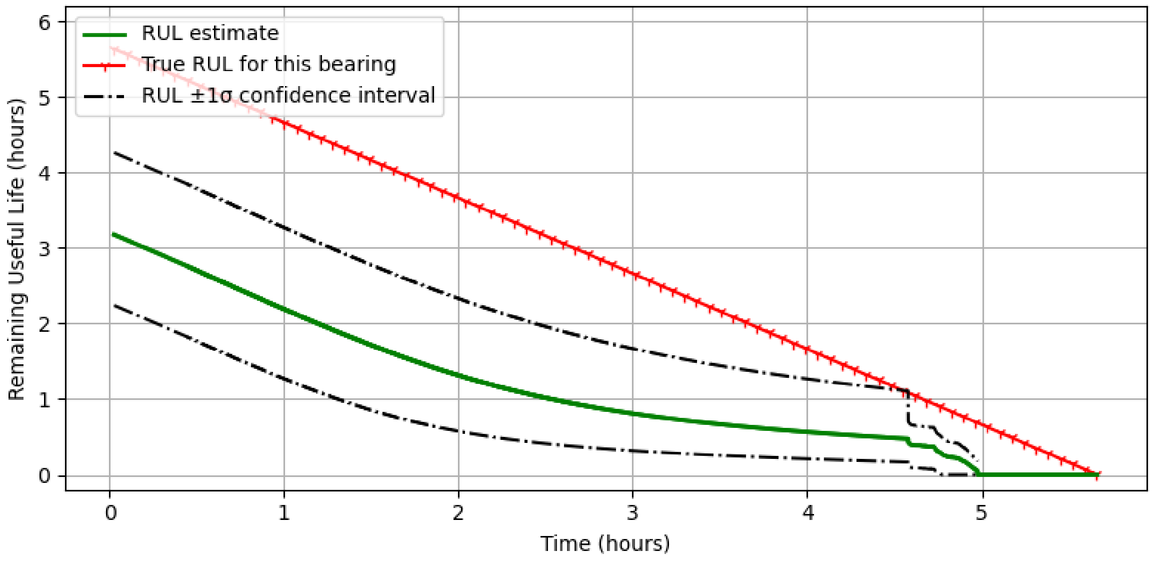
Sequential hybrid method for RUL prediction

Sequential hybrid method

- **Constant operating conditions**
- Short living bearing
  (less than average lifetime)



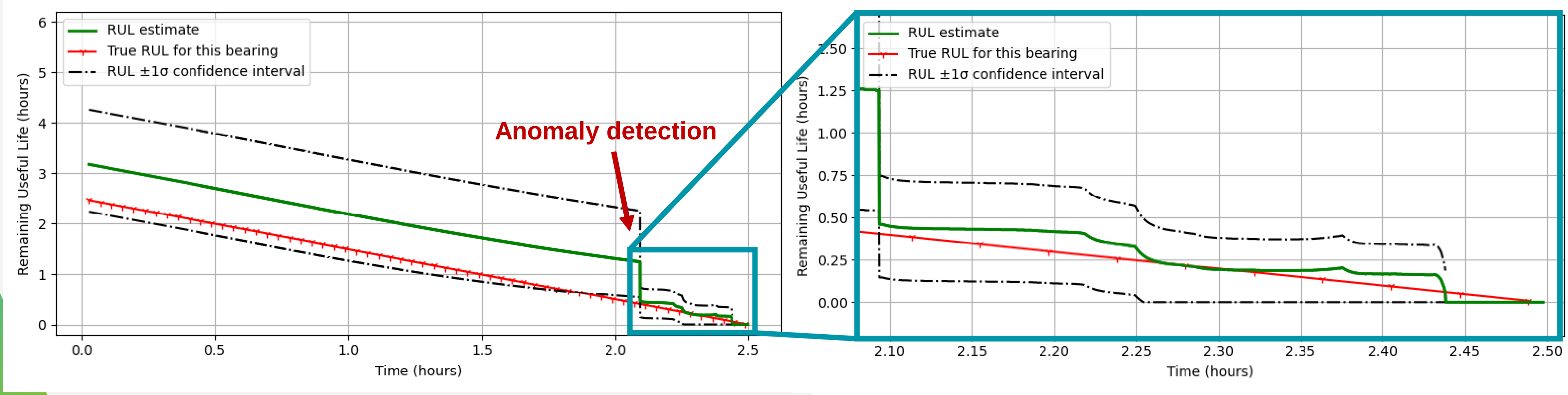
- Long living bearing
  (double of average lifetime)



Sequential hybrid method for RUL prediction

Sequential hybrid method

- **Constant operating conditions**
- Short living bearing
  (less than average lifetime)
- Data-driven RUL prediction
  - **oscillations due to stepwise nature of spalling**



Sequential hybrid method for RUL prediction

Sequential hybrid method

- **Varying operating conditions**
- Short living bearing
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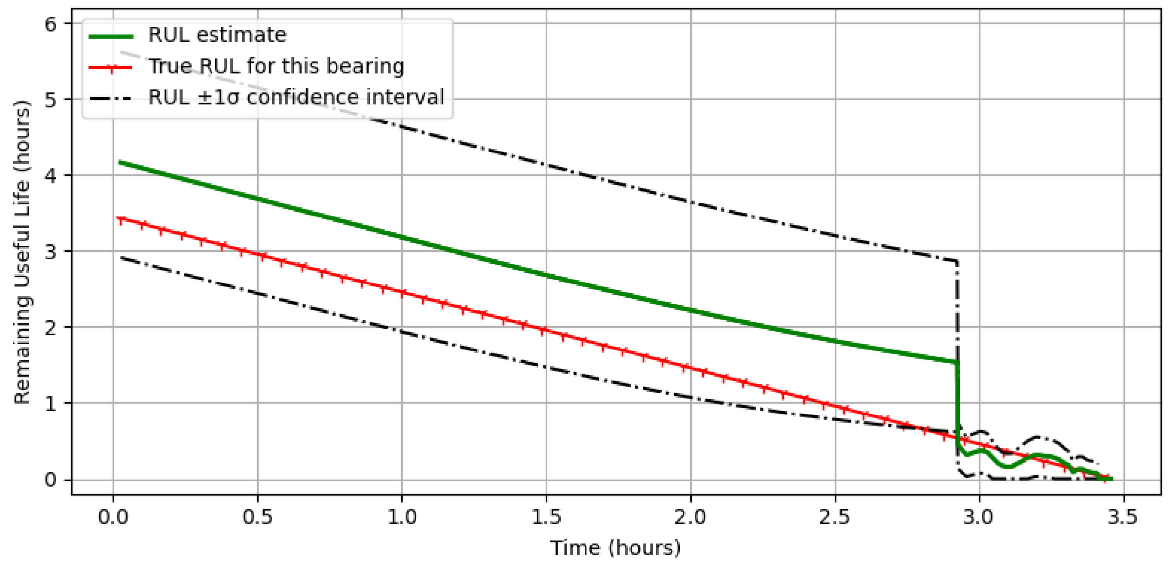

- Long living bearing
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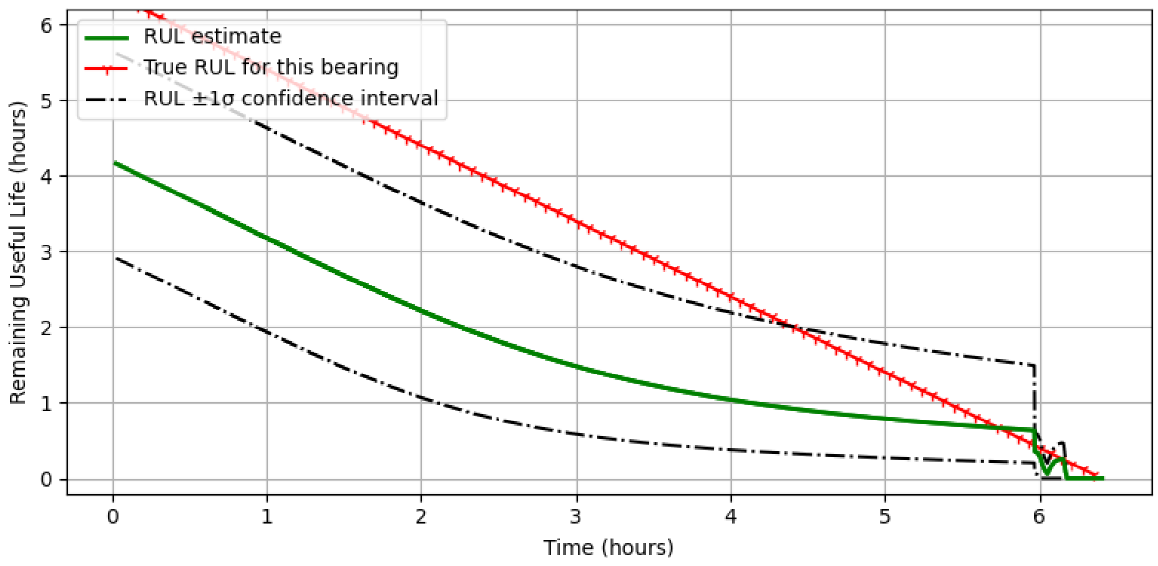
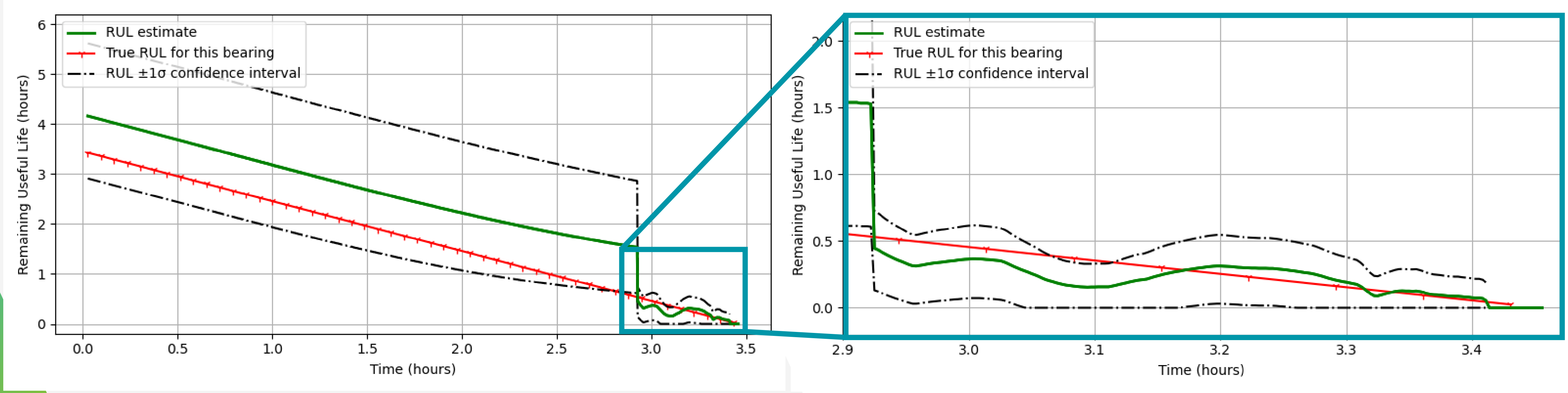


Sequential hybrid method for RUL prediction

Sequential hybrid method

- **Varying operating conditions**
- Short living bearing
  (less than average lifetime)

- Data-driven RUL prediction
  - **oscillations due to varying RPM and spalling**



Sequential hybrid method for RUL prediction

Conclusions

- **RUL prediction for entire lifetime of bearing**
- **Limited healthy and faulty data required**
- **Method handles varying operating conditions**
- **Applicable for different models and components**

Ongoing development

- **Apply expert/engineering knowledge to set up Bayesian network**
- **Fiber optic strain measurements**

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