Health management and failure prediction to monitor component lifetime

Where today meets tomorrow.

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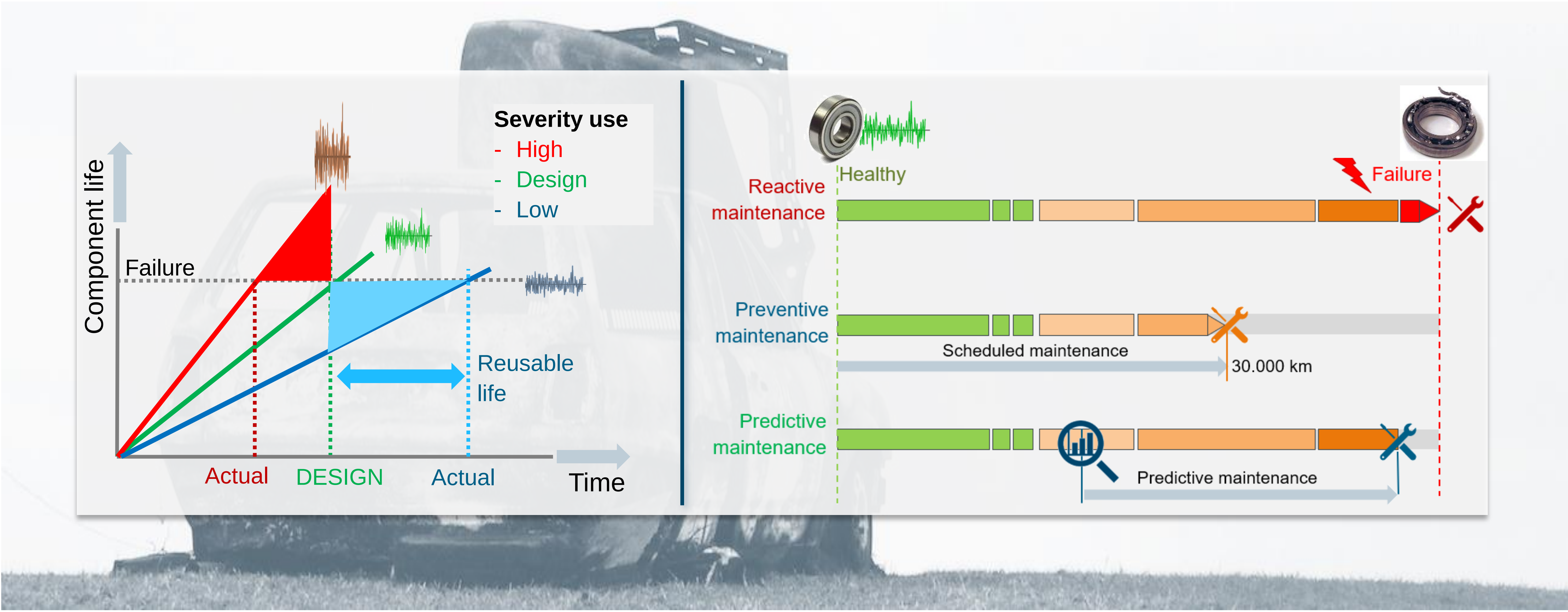
Automotive & Heavy equipment

- Motivation for PHM and failure prediction
- What is PHM and RUL?
- The challenge
- Solutions
- Main ingredients of the process
- Examples

Maintenance concepts and Component lifetime

Fundamentals



World is evolving ….
…new way of mobility, machinery and operation

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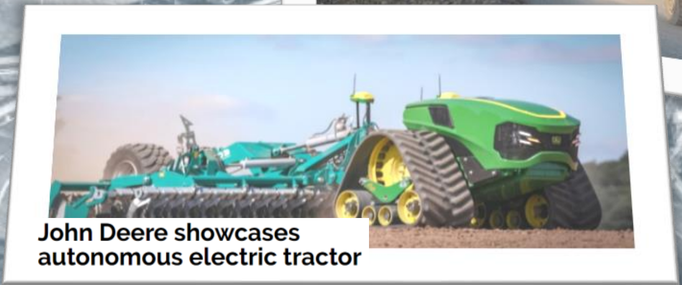
https://www.raconteur.net/business-innovation/mining-automation-mali

https://www.porschepassport.com/



https://roboticsandautomationnews.com/2019/11/19/john-deere-showcases-autonomous-electric-tractor-and-other-new-tech/26774/

World is evolving ….
… the implications

Prognostic and health management (PHM)

Protects the integrity of products

- What happened? (Descriptive)
- Why did it happen? (Diagnostics)
- What will happen? (Predictive)
- How can we make it happen? (Prescriptive)

"It is better to try to keep a bad thing from happening than it is to fix the bad thing once it has happened."

The challenge of RUL
Operational condition and expected loading

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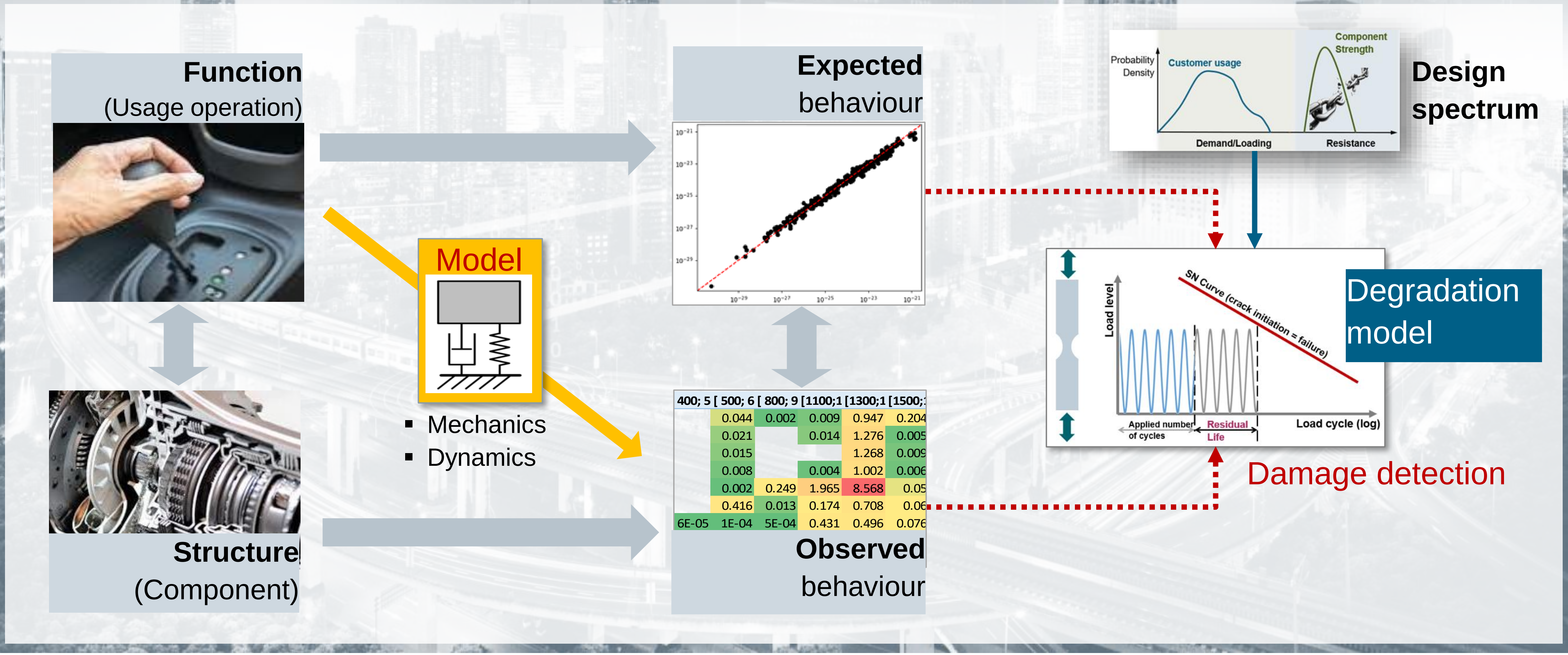

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	0.015			1.268	0.009
	0.008		0.004	1.002	0.006
	0.002	0.249	1.965	8.568	0.05
	0.416	0.013	0.174	0.708	0.06
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The challenge of RUL
Operational condition and expected loading

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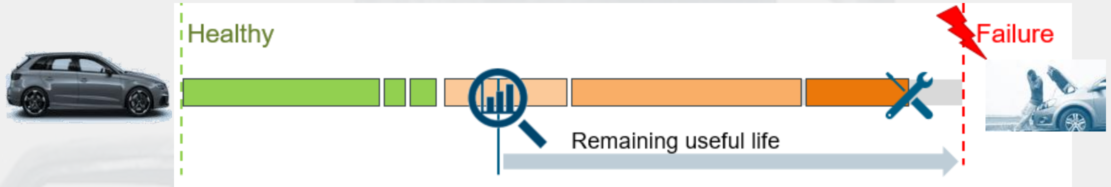


Input

Operational Monitoring
- Loading
- Threshold
- Environment

Structure

Damage Monitoring
- Fatigue damage
- Incident damage

Output

Usage information

Damage indication

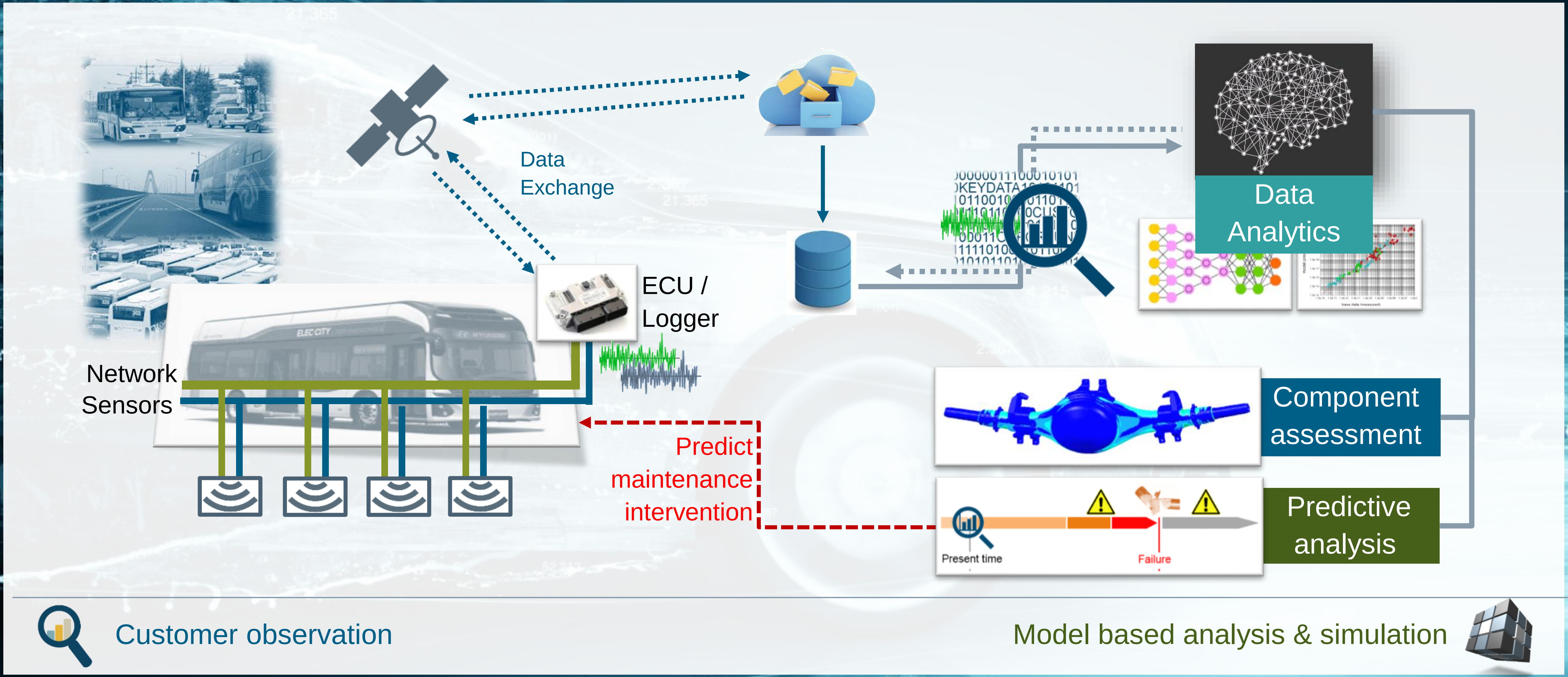
Evaluation results

Health history

State assessment

State prediction

PHM Vision
Health management - From Customer to Simulation



Prognostic and health management
Solutions

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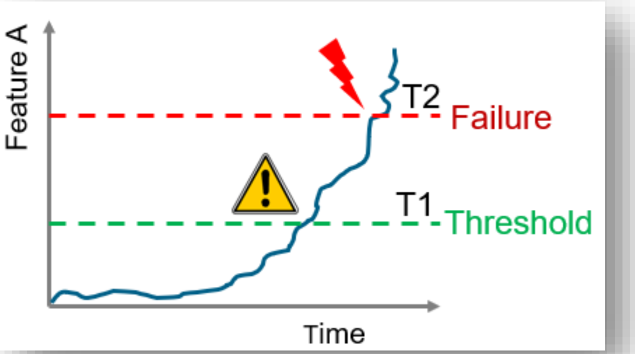
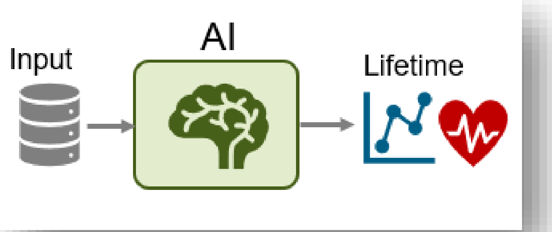
- **Physics-of-Failures (PoF)** – CAE Simulation
  Understand the process and mechanism that induces failures
- **Data driven (DD) methods** – Statistical approaches
  Use given information about failure and root causes for prognostic models
- **Fusion prognostics method** – combine PoF and DD methods
  E.g., Use simulation considering system state from condition monitoring to predict inner component load

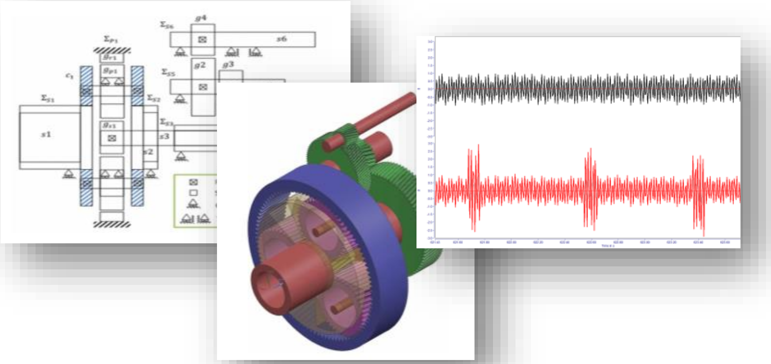
Monitor health indicator
– “exceed threshold” -



AI for lifetime estimation
- Input-Output-relationship -



Simulation (Digital twin)
e.g., for fault diagnostic



Predictive maintenance – Technical concept

From customer data to remaining useful life

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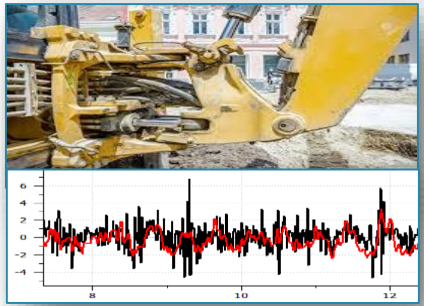
Data collection → **Data processing** → **Diagnostics** → **Prediction**

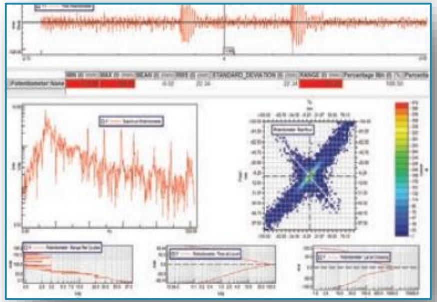
Data collection
- Acquire data
- Log usage information
- Data consolidation
- Virtual sensing

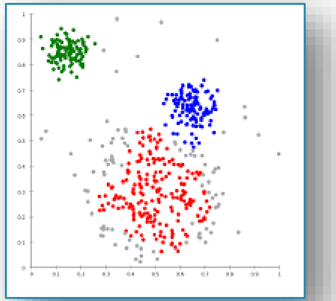
Data processing
- Data reduction
- Data visualization
- Data characterization
- Sensor fusion

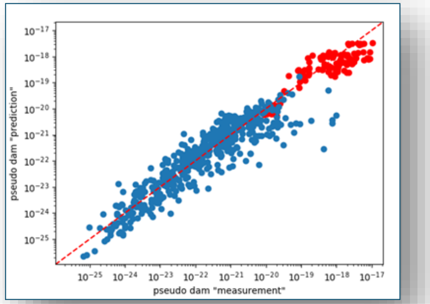
Diagnostics
- Feature selection
- State/Health condition
- Statistical modelling

Prediction
- Degradations model
- Estimation of remaining lifetime – future loads









- PHM Solutions
- Condition Monitoring
- Data science
- Digital twin
- RUL estimation
- Edge device

Condition based monitoring (CBM)

Gathering insight – Get data for health and state assessment

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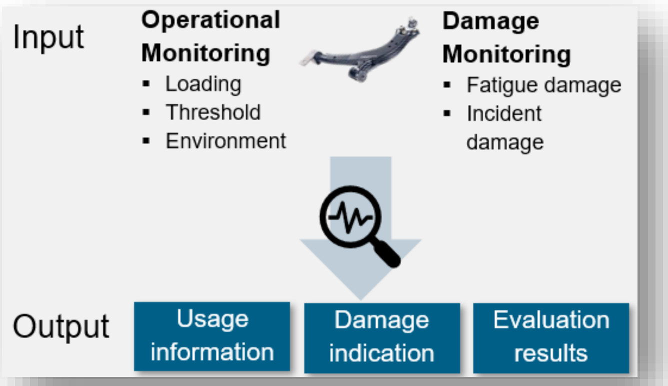

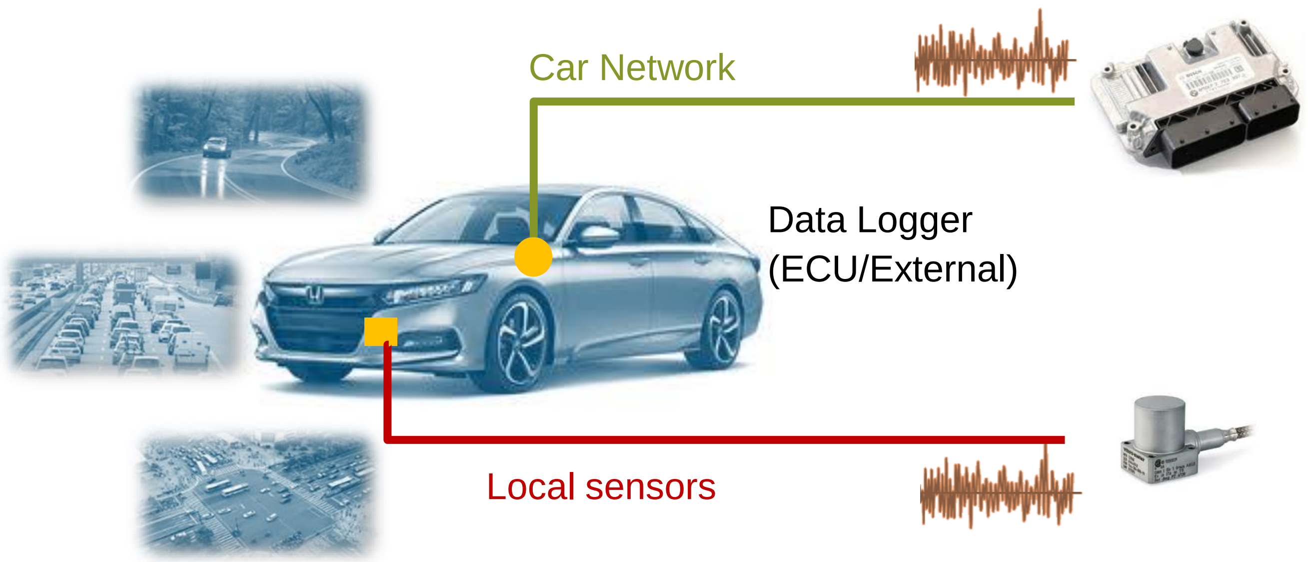

PHM Solutions

Condition Monitoring

Data science

Digital twin

RUL estimation

Edge device

1 Direct measurement

Direct measurement of health indicators

e.g., Capture local fatigue damage by local strain gages

2 In-Direct measurement

Monitor data allowing to estimate health indicator state

e.g., component load, local vibration by accelerometer

3 System operation monitoring

Log usage information to drive a system model to predict local component state and health indicator

Condition monitoring

Gathering insight – Get data for health and state assessment

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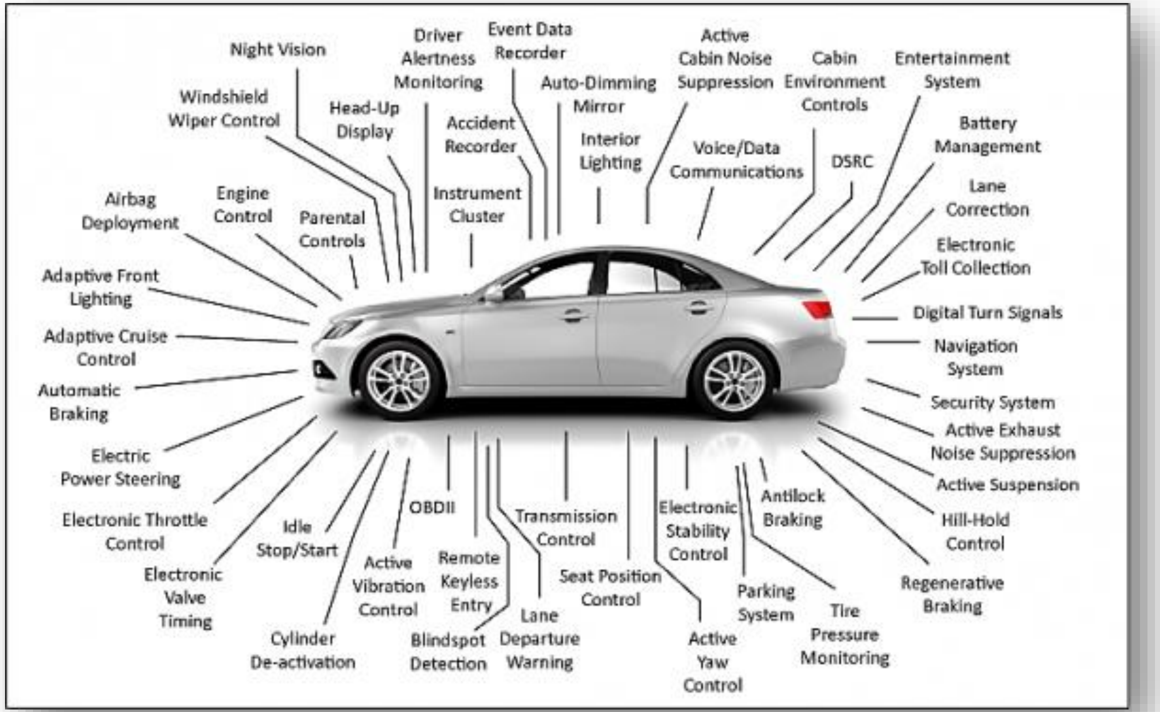
Examples for sensors, information and data available

Overview of vehicle sensor in automotive



https://www.eenewspower.com/design-center/automotive-service-era-electronic-car-1

System monitoring @ mine truck

- PHM Solutions
- Condition Monitoring
- Data science
- Digital twin
- RUL estimation
- Edge device

Data Science
Data Analytics, Data Mining & Machine Learning

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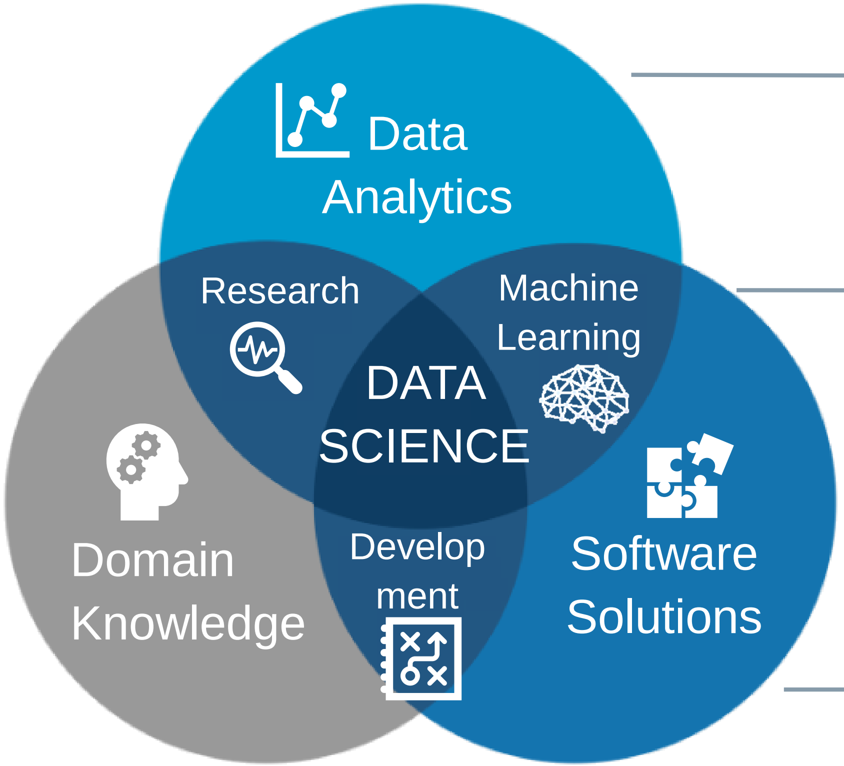


STATE CONDITION

What is current system state?
Load condition and history?

PREDICTIVE ANALYTICS

What happen next, and when?

VIRTUAL SENSING

Smart testing to maximize output

$Out = f(In)$

EMBEDDED SOLUTIONS

Capitalize your data – Integrate ECU solutions

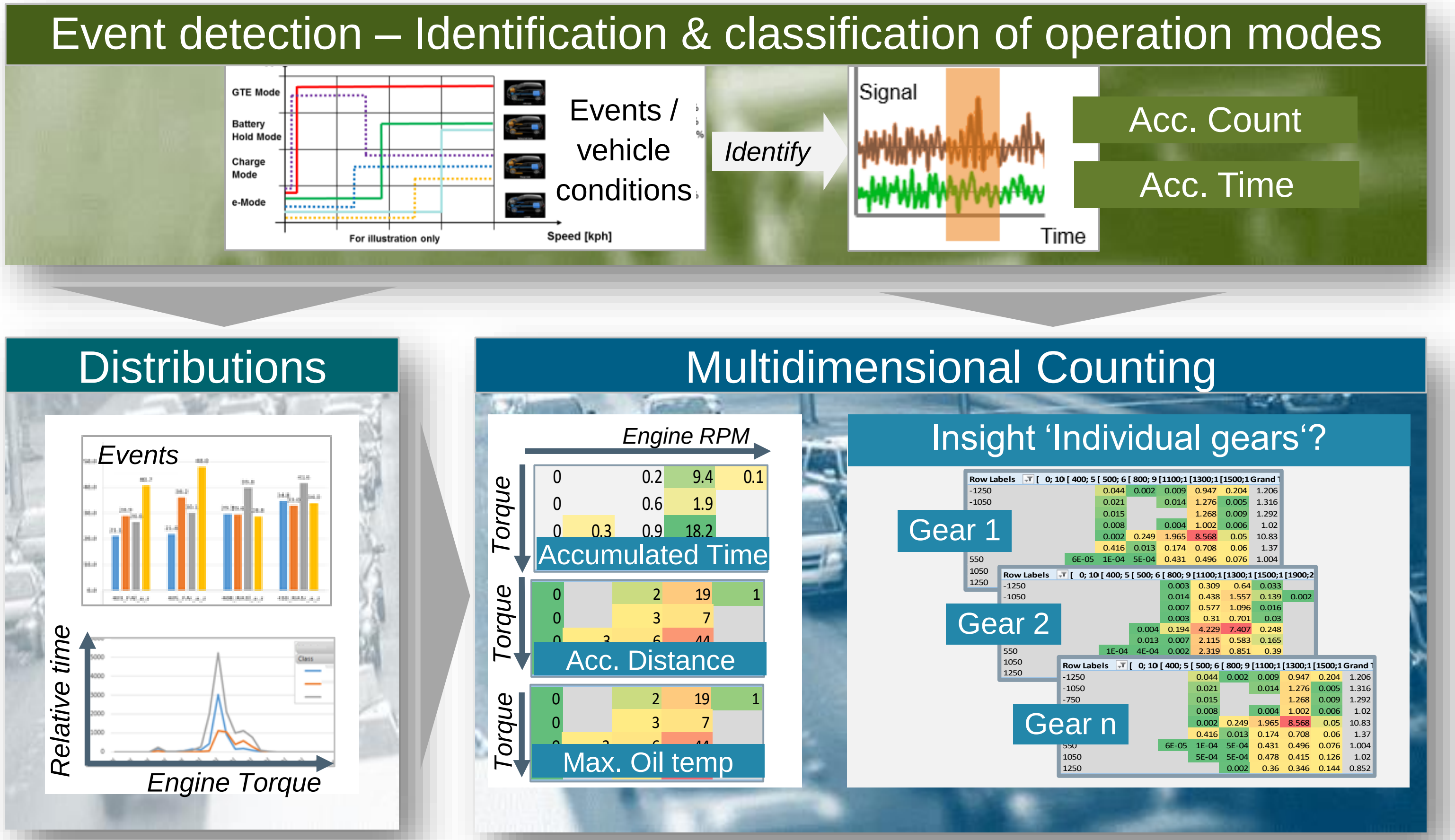
Data processing – Condition monitoring

Application example: Hybrid vehicle & transmission – Get insight

Health & State assessment
→ Get insight on usage condition by **in-depth data analysis**

- **Event detection**
- **Usage distributions**
- **Multidimensional counting**

Quantify & extract relevant incidents/loads/conditions



PHM Solutions
Condition Monitoring
Data science
Digital twin
RUL estimation
Edge device

Data Analytics & Fault Diagnostics

Application example - Bearing fault detection

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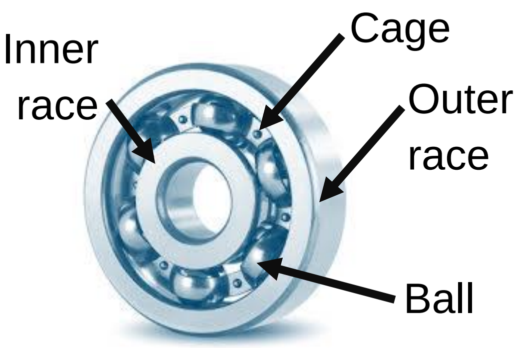
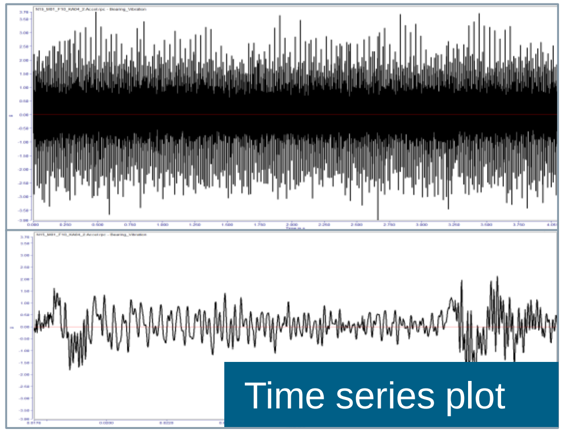


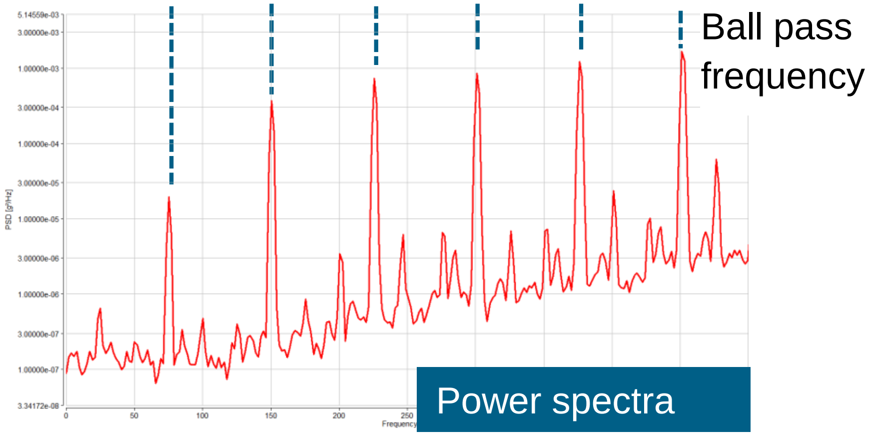
Health indicators for bearing by frequency analysis

e.g.,

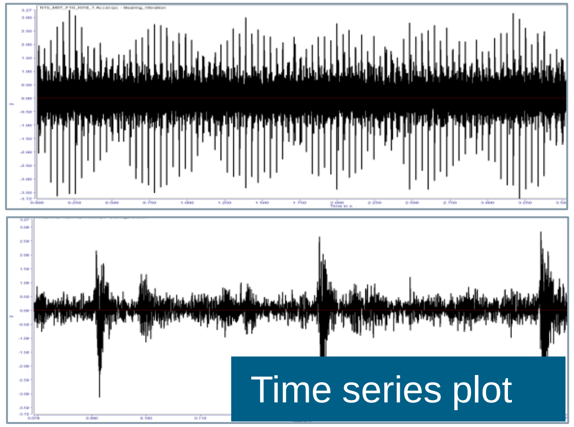
- Power spectra density
- Digital envelope analysis
  - Wavelet transformation
  - Hilbert transformation
  - …..

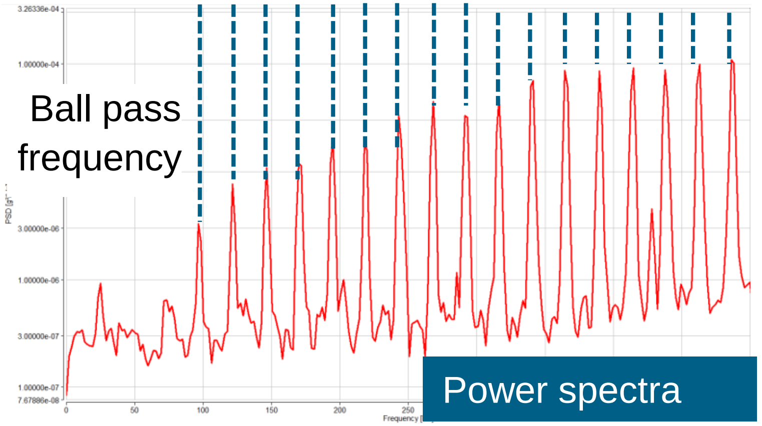
Example A: Bearing failure – Outer race damage





Example B: Bearing failure – Inner and Outer race damage





PHM Solutions

Condition Monitoring

Data science

Digital twin

RUL estimation

Edge device

Artificial intelligence (AI) & Machine Learning (ML)

What is it?

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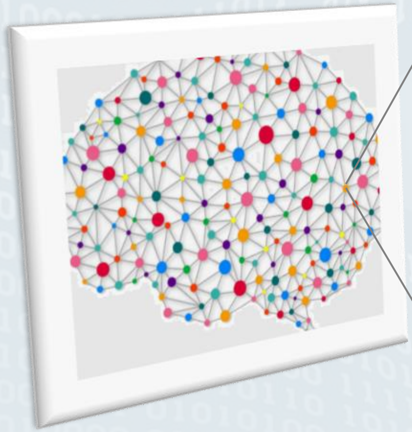
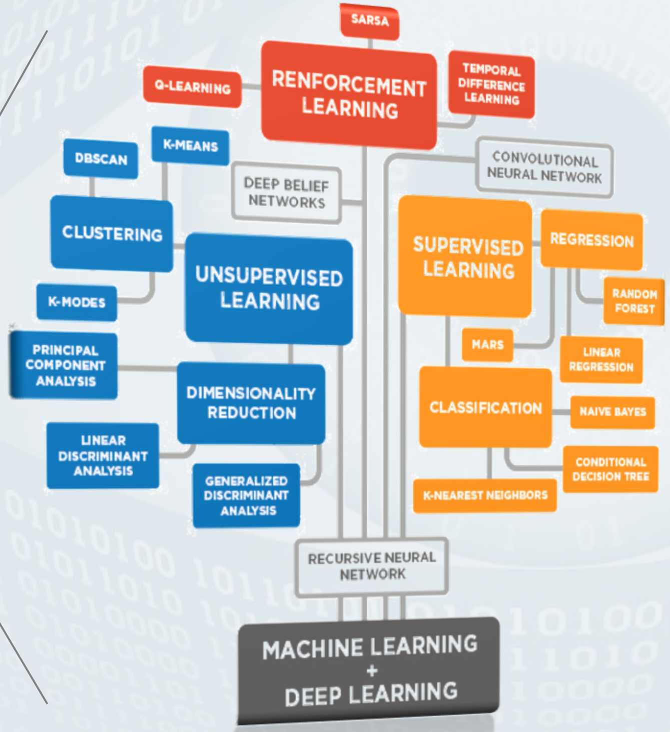
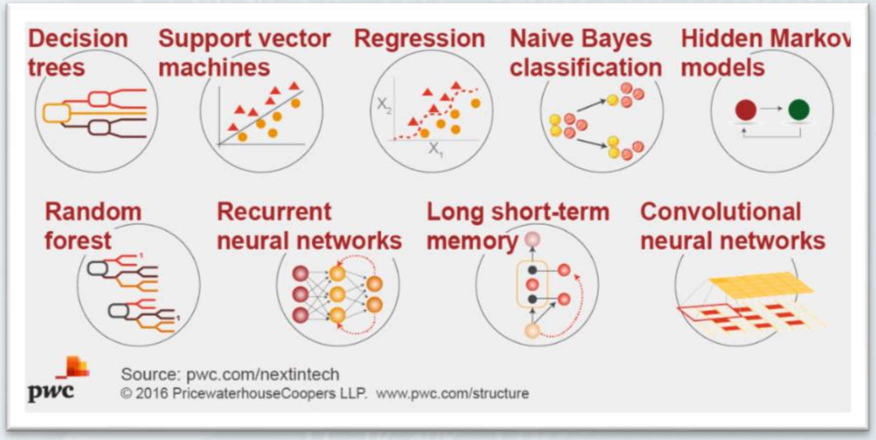
Artificial Intelligence –
Machine Learning
Techniques







Machine learning algorithms build a mathematical model based on sample data, known as "training data", in order to make predictions or decisions without being explicitly programmed to do so. [Source: Wikipedia]

Machine learning techniques for virtual sensing (VS)
Example: Load estimation - Drive shaft torque

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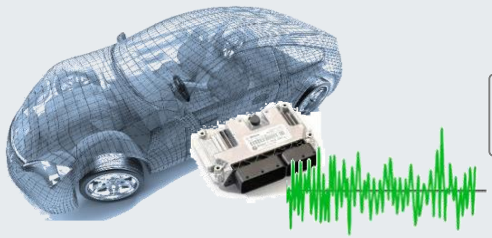
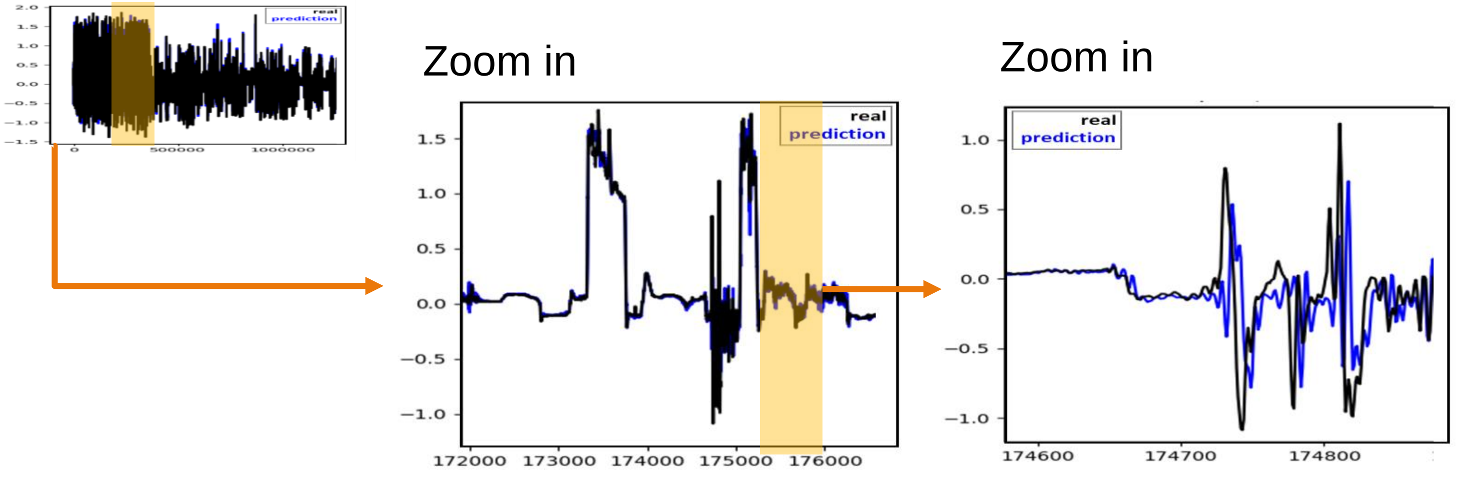
TARGET - Load estimation based on onboard vehicle CAN data
→ Expand limited information to detailed insight



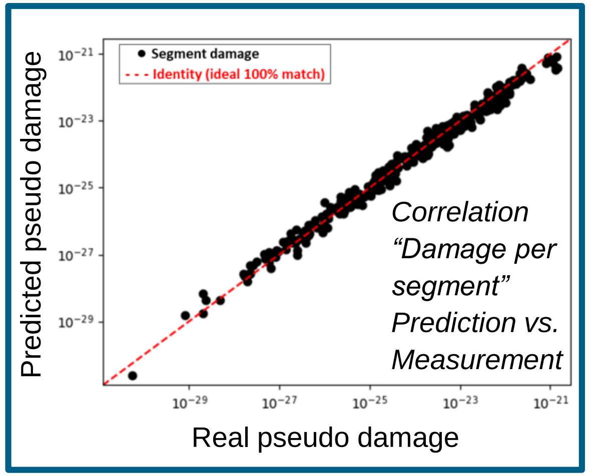
Input CAN Data → Prediction model → **Output** Load

Challenges
- Feature extraction – "Load indicators"
- Regression model with damage cost function
- Model performance (Accuracy + Cost)

Load prediction result example: Time series plot *(Measurement vs. Prediction)*



Segment damage scatter plot (Real vs. Prediction)



Machine learning techniques for virtual sensing (VS)
Workflow example

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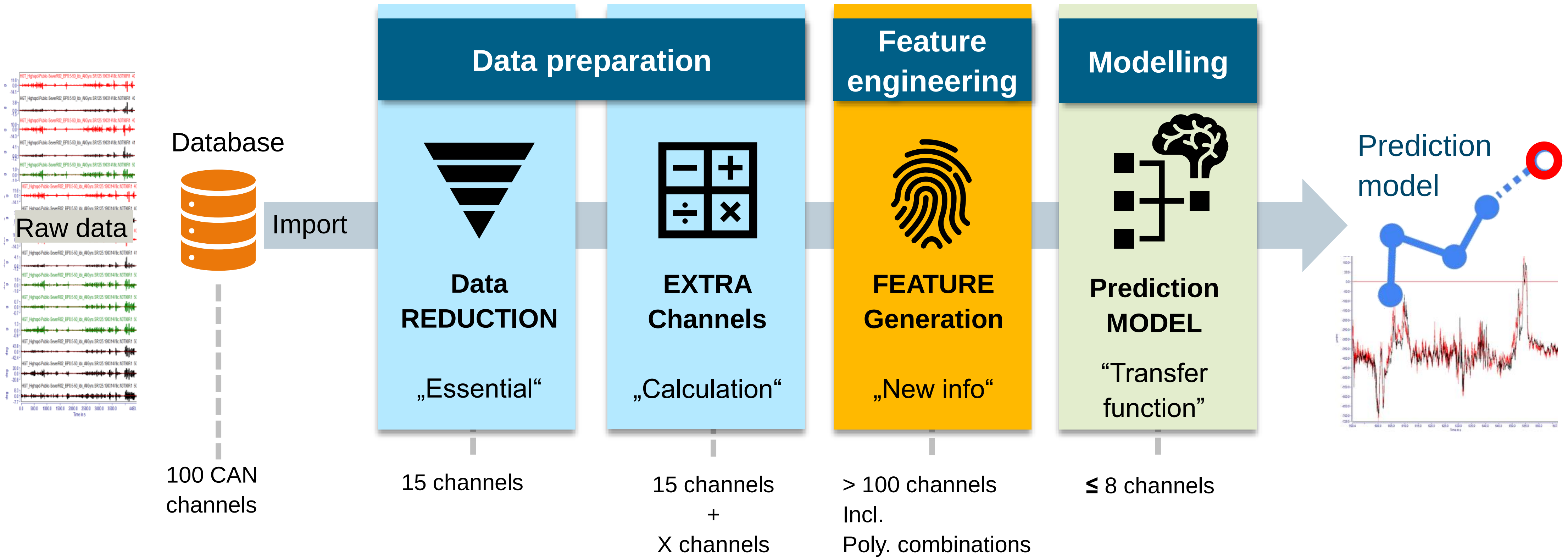


FEATURE ENGINEERING
- Preparing the proper input dataset
- Improving the performance of machine learning models.

Requires domain knowledge
“What? Why? How?”

- PHM Solutions
- Condition Monitoring
- Data science
- Digital twin
- RUL estimation
- Edge device

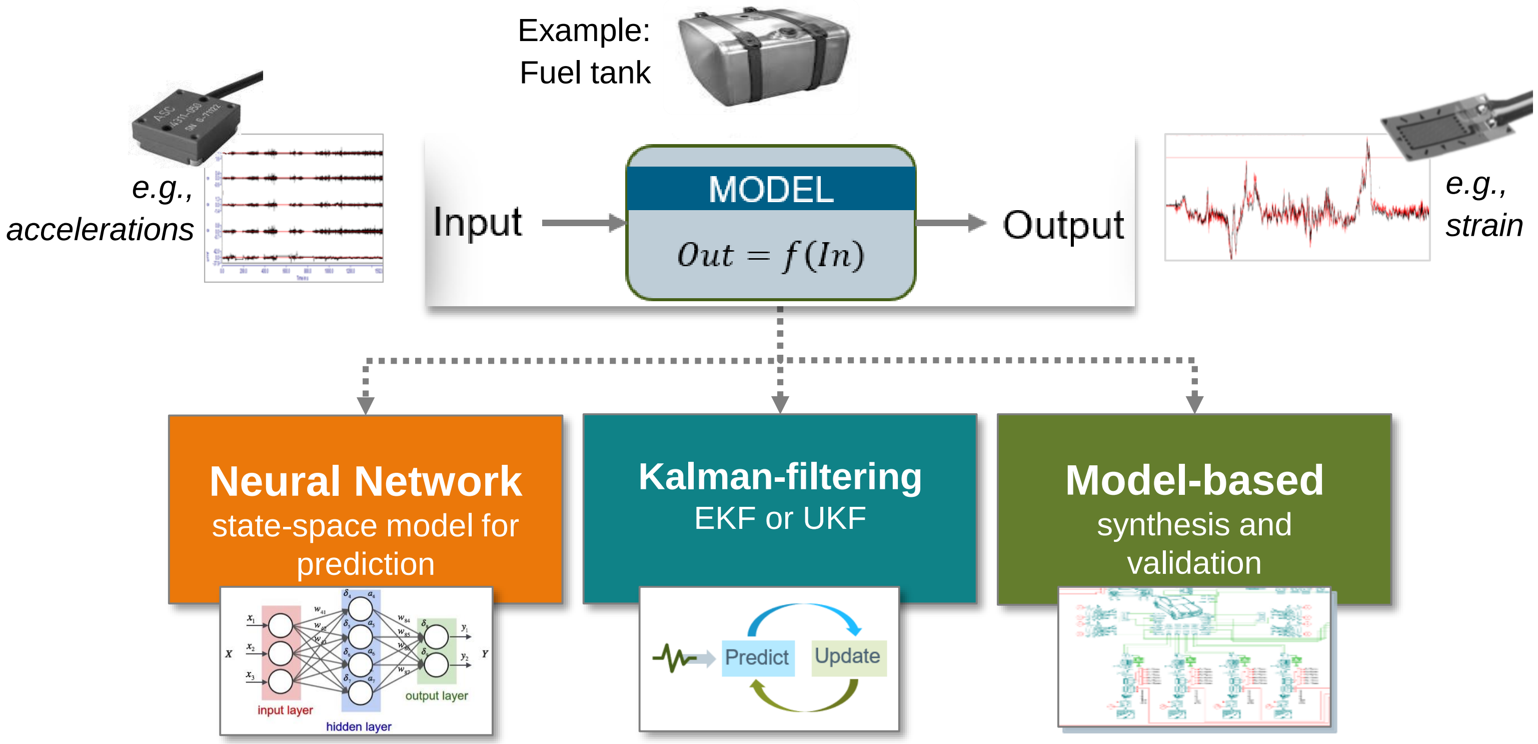
Virtual Sensing

Virtual Sensors in addition to Measured Variables

Virtual sensing

Techniques to provide access to difficult-to-measure quantities

→ Combine a reduced set of measurements and a real time model to virtually sense variables



CAE simulation and Digital twin
Enable health assessment and fault diagnostics

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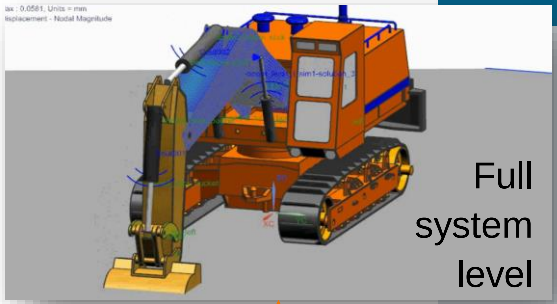
Replicate and follow the system operation and state by using CAE models → Perform virtual measurements

Real-world

Physics

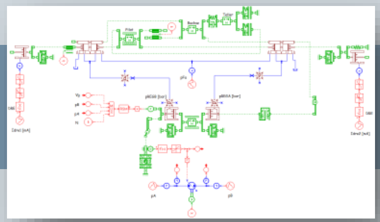
Data

IoT

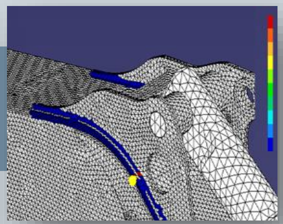


Full system level

CAE simulation (functional virtual model)



Subsystem level



Component level

"DIGITAL TWIN – Model of a released product "

Challenge
- Modelling and rendering of the physics
- Input data – from CAD to component properties
- Effort and computational time

Benefits
- Get insight on operation – monitor system state
- Virtual sensing – extend information
- What-if-analysis – Failure analysis etc.

Application example – MBD (Model based analysis)
From customer to simulation

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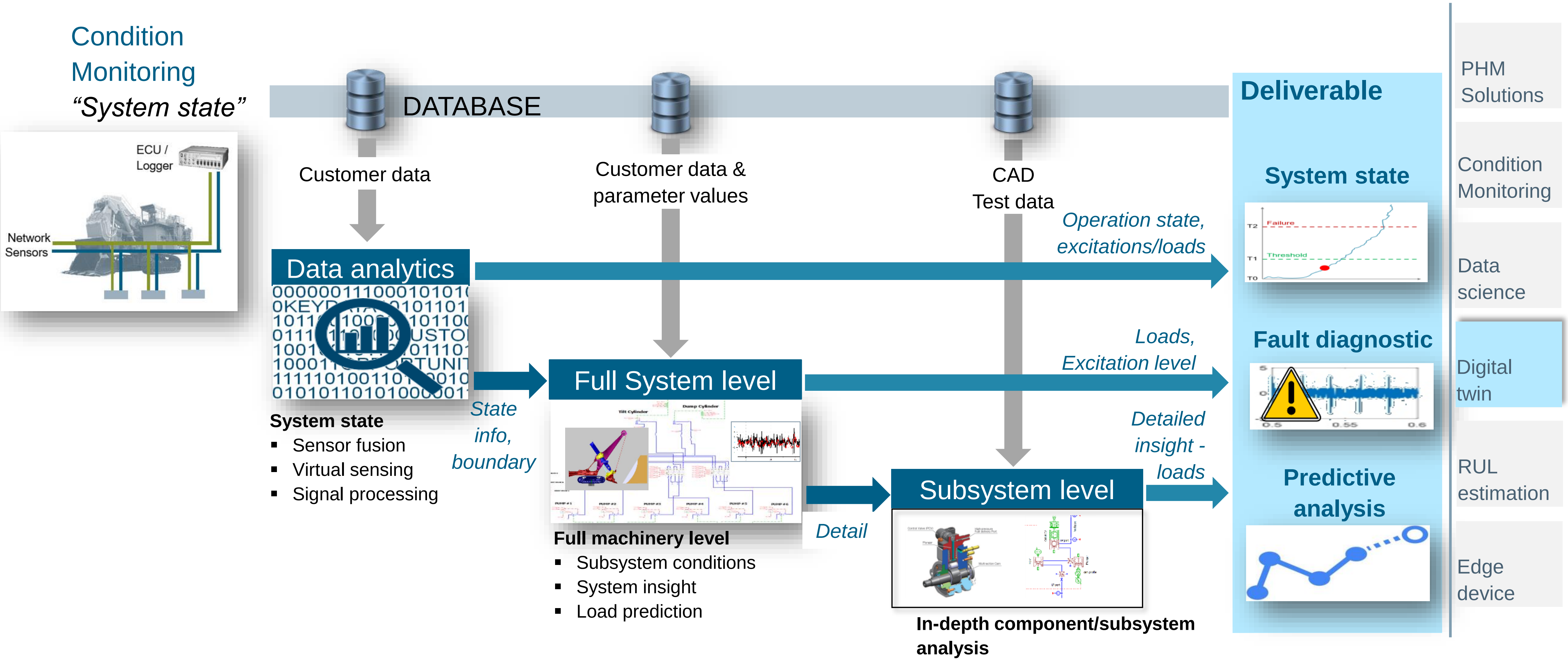

RUL Estimation models for predictive maintenance

How long will it last?

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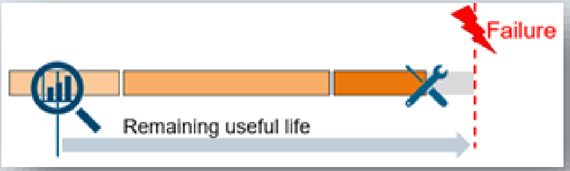
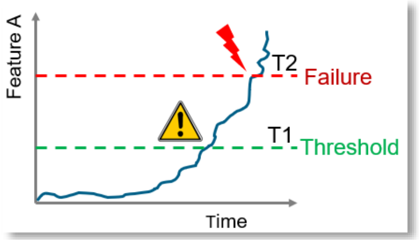
The problem of RUL:



(1) estimation of present state
(2) estimation of future state
(3) RUL computation

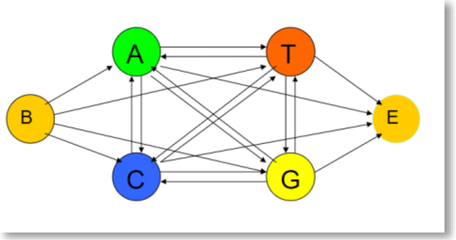
Data uncertainties
- Measurement errors (sensors, data reduction,…)
- Analysis model parameter inaccuracies
- Uncertainty of future usage

Historical data

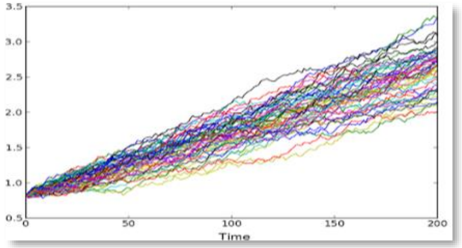


Methods examples to tackle uncertainties

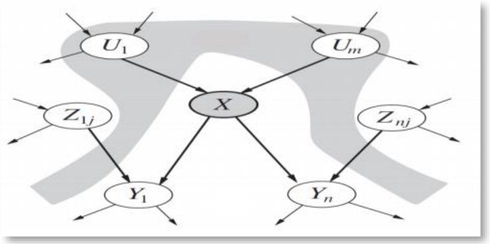
Hidden-Markov chain



Monto-carlo simulation



Bayesian network



Remaining useful lifetime prediction depends on the boundaries:

Given data
- Historical failure data
- Record duration

Application case
- Physics complexity
- Degradation model
- Operation condition

PHM Solutions
Condition Monitoring
Data science
Digital twin
RUL estimation
Edge device

Embedded solutions
Model Order Reduction & Artificial intelligence

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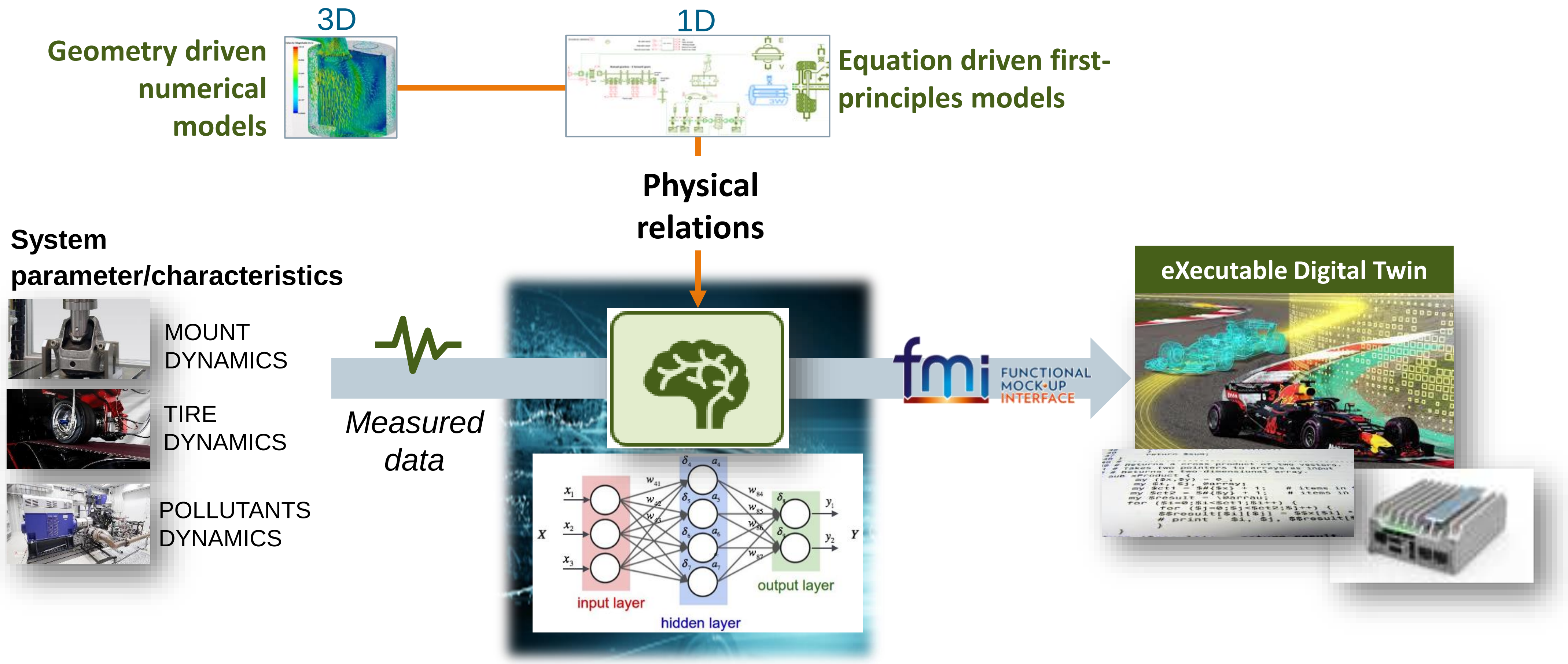

AI to combine physics and data and create physically relevant eXecutable Digital Twins (xDT)

- PHM Solutions
- Condition Monitoring
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- RUL estimation
- Edge device

Application example – Oil degradation

Estimation of Long Time Scale Physical Properties

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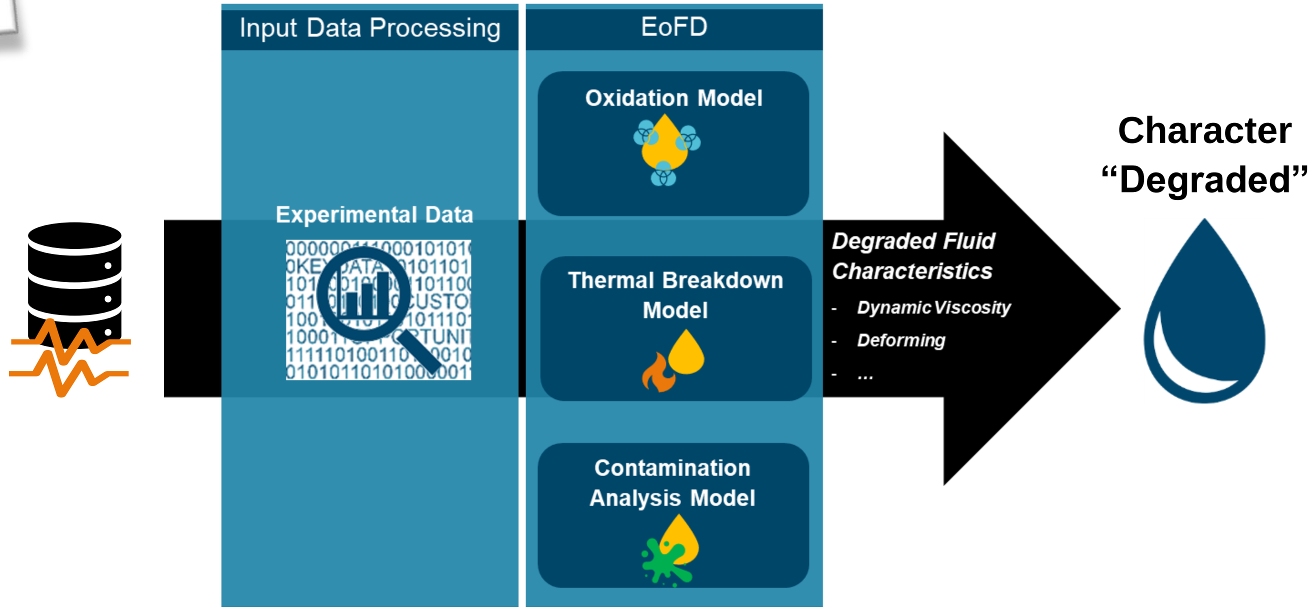
TARGET: surrogate model for oil degradation estimation

CHALLENGE:

- Long time scale phenomenon like Fluid degradation are highly complex and non-linear with many contributing factors in a typical vehicle system
- Limited data and long lead time for data acquisition
- Lack of standard physics based model available to synthesize the long time scale phenomenon for training ML algorithm
- Needs deep expertise of the domain to design effective Machine Learning (ML) model

SOLUTION:

- ML based Estimator of Fluid Degradation (EoFD) estimates the level of degradation of a fluid
- EoFD has multiple modules each trained to capture a particular cause of fluid degradation
- Intelligent fusion of ML with innovative data sampling techniques

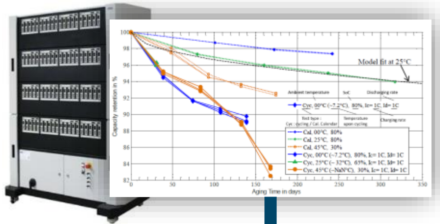


Application example - Battery health assessment
Fusion approach combine Test, 1D and 3D

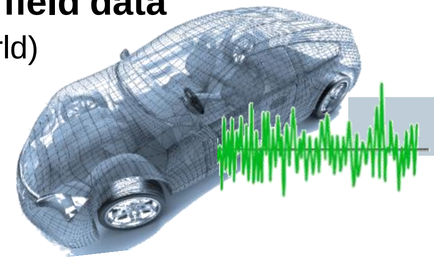
TARGET: Battery lifetime prediction

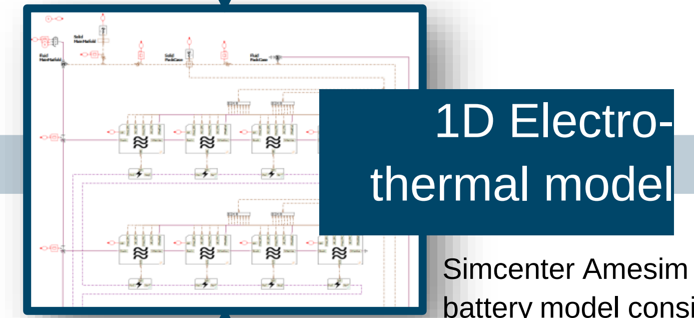
- Complex electro-thermal battery model incl. cell ageing
- High simulation performance by “3D-transformation” into 1D

Degradation model
(Test/AI)



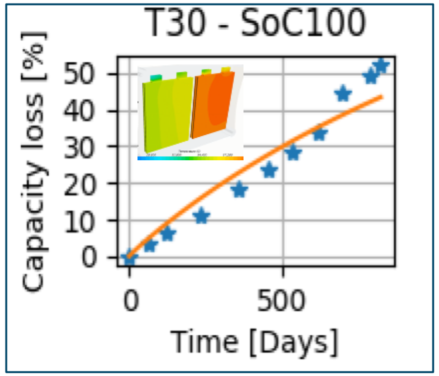
Vehicle field data
(Real-world)





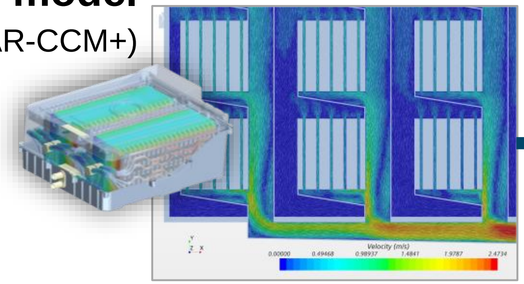
Simcenter Amesim – 1D battery model considering electro-thermal behavior and cell ageing model

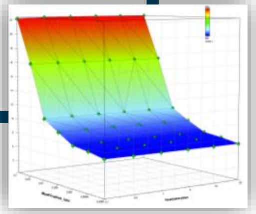
Remaining battery lifetime



3D-Thermal model
(STAR-CCM+)

3D steady state model to provide node properties and information (heat capacity, thermal conductance values)





Nodalisation & Tabular data

Health management and component lifetime
How to address this challenge?

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The challenges
of health management

What happened?

Why did it happen?

What will happen?

Health history

State assessment

State prediction

Condition Monitoring

Data analytics

Digital twin

Solutions
to overcome the challenges

Capture usage conditions
- Virtual sensing
- Embedded solution

Develop insight and foresight
- Advanced data analytics
- Machine learning
- Estimation models

Virtual measurements
- Develop virtual sensors
- Load predictions

Domain know-how | Context know-how | Analytics Know-how

Thank you! Want to know more?

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Read more

Explore, share and learn

Watch videos

Contact the expert