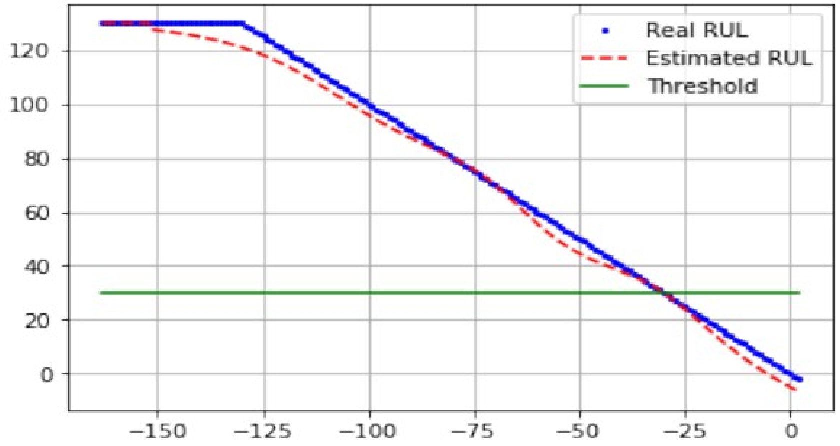
White paper

How to design Predictive Maintenance of Dynamic Systems using Artificial Intelligence

ABSTRACT
AN APPROACH TO PREDICTIVE MAINTENANCE USING MACHINE LEARNING

The question to which PdM -Predictive Maintenance answers is:
which is the most suitable time to maintain the system and avoid premature substitution of components, reducing downtime operations to the minimum, and at the same time keeping system's reliability and performances at their optimal levels?
The answer comes from data mining techniques applied to the failure analysis and detection problem.
The ML-machine learning algorithms allow for the estimation of the systems' remaining useful life (RUL).



PdM is also called Condition Based Maintenance since RUL is estimated real-time on the basis of the involved condition indicators. These are physical parameters representing the health status of the system.

Common application fields for PdM process are:

- **electrical engines**
- **internal combustion engines**
- **industrial machinery**
- **medical devices**
- **consumer product with mechanical components (i.e. washing, cooling, cooking)**

This document outlines the possible routes for the development of a **predictive maintenance application** for embedded systems. The aim is to suggest a choice between possible approaches to the problem, and outline a road-map for the prototyping development phases.

FUNDAMENTALS ON PREDICTIVE MAINTENANCE

For industrial equipment, machinery and mechanical devices, product reliability is a majorconcern.
In the last decades we witnessed the change of the maintenance techniques' paradigm: from reactive to preventive at first, and from preventive to predictive at last.

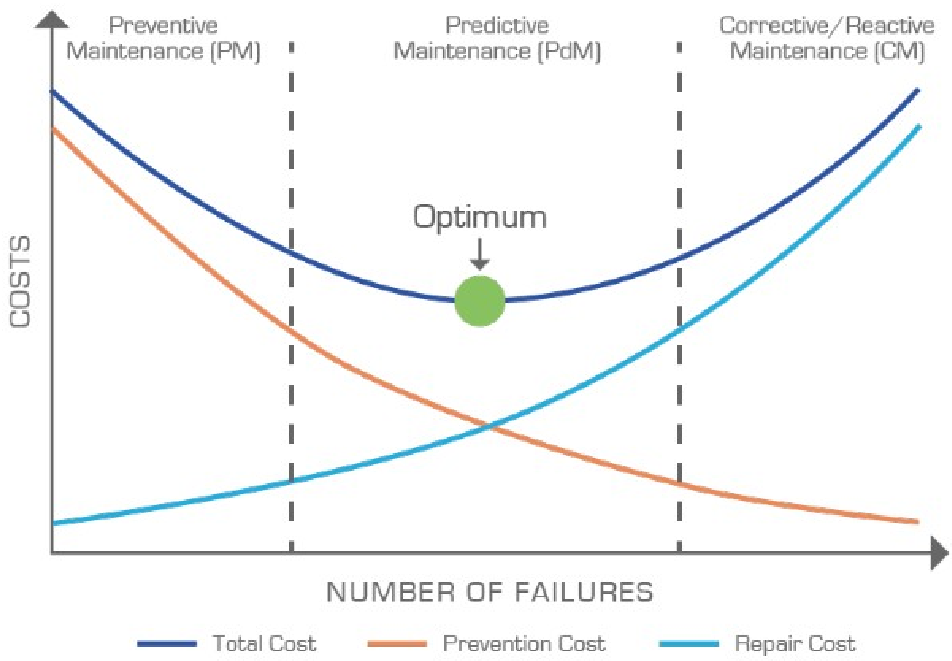
Reactive maintenance
Reactive maintenance (RM) acted after the system's failure, leading to unsustainable downtime.
Furthermore, acceptable reliability levels were granted by designing oversized products.
For instance, this paradigm is used today in the household appliances sector.

Preventive maintenance
Preventive maintenance (PvM) aims to keep the system's health levels above critical thresholds by scheduling maintenance operations on a regular basis. These techniques avoid downtime operations, but at the same time lead to increased and sometimes unaffordable costs.
This paradigm is used in the car inspection and in the HVAC sectors, where maintenance is scheduled on a yearly or two-years basis.

Predictive maintenance
What if our product/system needs to:

- grant high **reliability?**
- act in an **extremely competitive business?**

In this case Predictive Maintenance (PdM) solutions add value to the product/system in termsof both reliability and costs.



DESIGNING A PREDICTIVE MAINTENANCE APPLICATION

With the expression predictive maintenance application we mean:

an embedded system (hardware and software) designed for the real-time estimation of a time-dependent continuous variable related to the remaining useful life (RUL) of the system.

The main components of such an application are:

- embedded sensors apparatus
- electronic core system (application manager)
- software application for data processing and RUL estimation

Which approach to follow when developing a PdM application for embedded system?

1. A straight **analytical** (i.e theoretical-deductive) approach is feasible whenever the mathematical mapping between the input variables (sensors outputs) and the application's output variable (RUL) is known a priori.

2. A straight **statistical-inductive** approach is feasible whenever a very big amount of data is available, holding information regarding the seeked mapping between the input variables and the output variables too (we name it Big-And-Stupid-Data, jointly with the application of DataMining techniques).

For the modeling of a physical system (industrial equipment, tooling or machinery, mechanical devices) with statistical algorithms (machine learning) we recommends adopting a mixed approach or a synthesis of 1 and 2, a theoretical-statistical approach.

When designing a system or product including a PdM application with the theoretical-statistical approach, a **bidirectional know-how** sharing among development teams is necessary.

A **theoretical-statistical approach** is available, which hold information of consideration each of the possible

understanding of the physical system Data).
feasible whenever data samples (or datasets) are both a healthy and degraded system, taking into sources of failure.
Here the starting point is an working principle (we name it Small-But-Meaningful-Data).

- from the system design team to the PdM application development team: to create awareness on the working principle of the product/system, on the way the sub-systems interact with each other, on the possible failure modes, on the constraints regarding the sensors apparatus intrusiveness level
- from the PdM application development team to the system design team: to share the experience on the predictive analytical models in terms of algorithms design and valuation metrics, useful techniques and strategies for the dataset acquisition, know-how regarding the possibilities made available by the predictive
- maintenance algorithms (relating to failure classification and RUL regression).

PdM APPLICATION, A DEVELOPMENT WORKFLOW

When designing the PdM Application, the recurrent development steps are as described below.
For each step, a typical interaction among "System Developer Team" and "PdM Application Team" is suggested.

Understanding of the physical model of the system (system and sub-systems interaction modes)	
Purpose: The product designer describes the working principle of the overall system and of its sub-systems. Furthermore, the product designer depicts the nominal working condition of the product/system (healthy condition characterization) and the main parameters suitable for its assessment (torque, rpm, voltage, temperature, pressure are common examples).	Interaction: Technology trasfer: System Design Team > PdM Application team Mode: Face to face workshop

Outline and definition of the predictive purpose: which are the condition indicators representing the system status? which output shall the application estimate?	
Purpose: Verify the sensors apparatus consistency (input). Definition of the condition indicators for the health status characterization (middle-input). Definition of the output variable and of its unit of measure (output).	Interaction: Joint analysis Mode: Face to face workshop

Understanding of the possible operating conditions of the product/systems	
Purpose: The product designer describes the different operating conditions of the product/system. The team determines the way the different OCs affect the measuring system.	Interaction: Technology trasfer: System Design Team > PdM Application team Joint Analysis Mode: Face to face workshop

Predictive algorithm choice	
Purpose: The team outlines the main features of the predictive algorithm depending on the desired output. Bluewind involves the product designer in the understanding of the main blocks of the algorithm and of their relationship.	Interaction: Technology trasfer: PdM Application team > System Design Team. Mode: remote meeting

Sensors apparatus design optimization	
Purpose: Design and optimize the sensors embedded system	Interaction: Joint analysis. Mode: Face to face workshop or remote meeting

PdM APPLICATION: PROTOTYPE DEVELOPMENT STEPS

Phases 2-4 are subject to an iterative process for the AI/ML algorithm's hyper-parameter optimization.

Dataset acquisition	
Purpose: Acquisition of a meaningful dataset	Mode: measurements at the lab and teams periodic alignment.

Data pre-processing and condition indicator calculation	
Purpose: **PdM Application Team** defines the most suitable training algorithm based on the available dataset. Bluewind executes the training and shares the know-how and the results with the product designer.	Mode: Statistical analysis at the **PdM Application Team** and alignment to System Design Team.

Algorithm training	
Purpose: **PdM Application Team** defines the most suitable training algorithm based on the available dataset. Bluewind executes the training and shares the know-how and the results with the product designer.	Mode: Statistical analysis at the **PdM Application Team** and alignment to System Design Team.

Algorithm Validation	
Purpose: PdM Application Team defines the metrics for the algorithm evaluation and for the hyper-parameters optimization. Furthermore PdM Team verifies the compliance with the target resources constraints.	Mode: Statistical analysis at the **PdM Application Team** and alignment to System Design Team.

CONCLUSIONS

We explored the domain of the development of a predictive maintenance application for embedded systems. Possible approaches to the problem were listed and a road-map for the prototyping development phases was described and motivated.
At Bluewind we strongly believe that working with Machine Learning on data collected from a process requires that a focused understanding of the process itself is not only suggested but also needed in order to develop the correct solution.
Here by describing correctness we must take into account the need for the Machine Learning algorithm to be executed in the field and not only on infinite-resources cloud computation engines.
The described path to a solution for a predictive maintenance application is what we learned as a best effort for a consistent, measurable and deployable development.

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