Predictive Maintenance of Complex Systems using Data-Driven Approaches and Digital Twins

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Context & Objectives:

Starting from a given physical asset or a complex industrial system, a Digital Twin (DT) representation consists in twinning, thanks to virtualization techniques, the different physical components, the relevant flows, and the environment in which the physical asset is evolving. This DT will rely on different and heterogenous data collected from many deployed sensors on the physical asset and will propose data driven models (see [1]) to achieve given objectives and offer some services, while providing the physical system with rationale feedback.

Given such a complex system and its DT, we need to plan the predictive maintenance and its dynamic grouping based on heterogenous data collected in near real time (see [2], for example).

Moreover, it is well known that the collected data in our DT will be impacted by many uncontrollable factors (missing data, errors, unstable sensors, etc.) making it uncertain. Hence, and to handle with this uncertainty, this thesis will investigate mathematical modelling based on optimization under uncertainty (stochastic optimization, chance-constrained optimization, distributionally robust optimization (DRO), etc.) to propose scalable predictive maintenance under uncertainty. Moreover, the optimization will take into account carbon footprint, production and resource limitation constraints to be jointly considered in the description of our problem. The solutions provided by the digital twin will be used as feedback to the physical asset (use-case) to reconfigure or modify the maintenance plans accordingly.

After validating the theoretical results mentioned above, we propose to illustrate them using at least one industrial use-case which will show and highlight the important role of the DT in constrained and data-driven predictive maintenance of complex systems.

Scientific challenges to investigate:

We will use existing Key Health Indicators (such as Remaining Useful Life) to evaluate the degradation level of a given physical asset or complex system. We will focus on methods from optimization under uncertainty to propose robust solutions for predictive maintenance subject to different constraints, such as resource limitation, environmental constraints, etc.

The role of the collected data is key for predictive maintenance planning and optimization. Indeed, we will use data-driven optimization techniques to establish efficient predictive maintenance plans that meet the above-mentioned constraints. Hence, we propose to investigate Model Predictive Control (MPC) approaches to build solid mathematical formulations and models using the heterogenous data and the control techniques we will develop. We will investigate smart approaches based on the new paradigm of "Predict-then-Optimize" (see [4] and [5] for more details) to improve the accuracy of the predictive model while looking to minimize the decision error instead of a classical loss function (such as MSE, for example). Furthermore, we will show the importance of these new methods in the era of predictive maintenance and digital twins and illustrate how they are improving existing results in the literature.

Applications using Digital Twins:

All the results of the thesis will be demonstrated on a technological DT pipeline covering the data collection, data-driven models (stochastic optimization under constraints, predict-then-optimize, etc.) and visualization of the data and of the decisions. We can rely on the deployment of open-source DT solutions and technologies (see reference [3] for instance).

References:

[1] Towards Model-Driven Digital Twin Engineering: Current Opportunities and Future Challenges, F. Bordeleau, et al., 2020
[2] Digital Twin for maintenance: A literature review: I. Errandonea et al., 2020
[3] DT tools : https://grafana.com/docs/grafana/latest/dashboards/
[4] Toon Vanderschueren, Tim Verdonck, Bart Baesens, Wouter Verbeke, Predict-then-optimize or predict-and-optimize? An empirical evaluation of cost-sensitive learning strategies, Information Sciences, Volume 594, 2022, Pages 400-415, ISSN 0020-0255, https://doi.org/10.1016/j.ins.2022.02.021
[5] A.N., Elmachtoub et al, Smart "Predict, then Optimize", Management Science Volume 68 Issue 101, January 2022, pp 9–26

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