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Degradation Stage Identification for Predictive Maintenance: A Case Study on Membrane Fouling in a Water-for-Injection System

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ABSTRACT

Predictive maintenance (PdM) refers to the use of data-driven monitoring and analytics to anticipate equipment faults before they occur, enabling maintenance to be performed proactively rather than reactively. It is critical in pharmaceutical manufacturing, where equipment failure can interrupt production, compromise product quality and trigger regulatory non-compliance. One important approach within PdM is degradation modelling, which aims to characterise the gradual deterioration of equipment performance over time to detect early signs of equipment degradation before functional failure occurs. By leveraging data-driven models to detect early signs of equipment degradation, manufacturers can reduce downtime, optimise maintenance scheduling and mitigate contamination risks.

A major challenge for industrial PdM is the scarcity of labelled degradation data: failures are rare, maintenance is predominantly preventive and systems often operate close to steady state. These characteristics limit the applicability of predictive maintenance methods such as remaining useful life prediction that require labelled degradation data.

In practice, unsupervised clustering is frequently used to create provisional degradation labels. However, clustering performance depends on the quality of feature embeddings—abstract representations learned from multivariate time-series sensor data that capture underlying process patterns. Despite advances in temporal representation learning, comparative evidence remains limited on how different embedding strategies affect degradation stage discovery in real industrial settings.

We present a systematic comparison of statistical, spectral and AI-based embedding techniques. The methods are evaluated through a case study on an industrial Water-for-Injection (WFI) system to identify degradation stages in filtration membranes, where fouling drives gradual performance decline and replacement typically occurs every six months.

Results indicate that embeddings which capture temporal dependencies and multi-scale

behaviour produce more interpretable and temporally consistent degradation clusters. Purely statistical time-domain features, while occasionally yielding early warnings, show limited robustness and poorer stage separation. Feature-level analysis identifies conductivity as a dominant degradation indicator; temperature contributes limited discriminative value. Although demonstrated on a pharmaceutical WFI system, the framework is generalisable to other continuous process industries seeking practical, data-driven degradation classification with limited labelled data.

KEY WORDS

predictive maintenance; degradation; feature embedding

BIOGRAPHY

Paul Ou is a PhD student at the School of Computing and Information Systems at the University of Melbourne, researching data-driven methods for modelling, optimising and validating digital bioprocess development as part of the ARC Digital Bioprocess Development Hub.

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