

Integrating Cyber Physical Passports and Generative AI for Explainable RUL Estimation in Battery Remanufacturing

Abstract

Remanufacturing is a critical pathway for advancing circular economy goals by extending the product life of high-value components and reducing material waste. A prominent example of CE adoption is the rapid growth of electric vehicles (EVs), which has simultaneously increased the demand for remanufacturing end-of-life lithium-ion batteries. Accurate prediction of the remaining useful life (RUL) of returned batteries is essential at the inspection stage to guide reuse, replacement, or disposal decisions. However, considering that batteries may experience multiple use cycles, obtaining and interpreting the required multicycle data, and helping human workers to gain the actionable remanufacturing insights, remains a challenge.

Cyber Physical Passports (CPPs) provide a way to retain product lifecycle information such as physical attributes, manufacturing data, and components details, which are important for product RUL estimation. However, the heterogeneous and often unstructured nature of this data limits its direct applicability. Additionally, conventional AI models for RUL prediction typically yield single-point estimates (e.g., cycles to failure), which capture degradation but often fail to represent uncertainty or provide actionable context for remanufacturing decisions. Generative AI (GenAI), particularly large language models (LLMs), offers a complementary capability by analyzing diverse data formats, interpreting results into natural language, and improving human–data interaction during the decision process.

This study focuses on investigating how GenAI could expand the capabilities of traditional RUL estimation and remanufacturing decision-making. We will integrate GenAI with two AI predictive models: a decision tree model, which produces interpretable rule-based outputs, and a seq2surv model, which captures temporal degradation patterns and outputs time-to-event distributions. Using battery datasets containing features such as cycle count, discharge capacity, current, and voltage, we assess model performance with root mean square error (RMSE) and concordance index (C-index). Explainability is addressed through SHapley Additive exPlanations (SHAP) values and survival contribution scores to identify the most influential factors driving predictions.

Building on these predictive models, we will further demonstrate how fine-tuned LLMs interpret the outputs into domain-specific natural language explanations, such as clarifying why certain features contribute to observed degradation trends. We will also conduct a case study to illustrate how these explanations support decision-making in representative degradation scenarios and strengthen human-data interaction. The findings will provide a comparative assessment of interpretable and survival-based models, while demonstrating how LLMs can extend model outputs to enhance transparency, explainability, and human-data interaction in RUL estimation for battery remanufacturing.

Keywords: Circular Economy; Remanufacturing; Cyber Physical Passports; Large Language Models; Decision Tree Model; Seq2surv Model