Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/WC02.20250084
Published: October 14, 2025

Designing Adaptive Reverse Logistics Systems for EV Batteries Using Multi-Agent Simulation and Geospatial Intelligence

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Abstract

Collecting and tracking electric vehicle batteries for reverse logistics requires intelligent adaptive systems capable of handling uncertainty and operational complexity. This study presents a unified framework for optimizing electric vehicle battery return logistics by integrating concepts from the Dabbawala delivery model, game theory, agent-based simulation, machine learning, graph theory, geospatial analysis, and stochastic simulation. The research models a decentralized multi-agent logistics environment where collection points, sorting hubs, and transportation modes such as vans and trucks operate under strategic and resource-constrained interactions. Game theory captures competitive and cooperative behavior among agents, while agent-based modeling simulates their dynamic movements and decisions in real time across a mapped urban network. Graph theory structures the road network and optimizes routing using real geospatial data, allowing the model to evaluate distance, accessibility, and travel time across the Greater Toronto Area. Machine learning predicts demand patterns and optimizes collection routes based on historical and spatial data. Geospatial tools enhance realism by mapping collection flows and region-specific return volumes, while a bi-objective optimization model minimizing both cost and carbon emissions, guides decision making. A Pareto frontier analysis evaluates trade-offs between environmental and economic goals, and scenario based stochastic simulations evaluate the robustness of the logistics system under varying return rates and uncertainties. The proposed framework demonstrates how combining sociological logistical insights with advanced computational methods can yield scalable sustainable and intelligent reverse logistics systems for the growing electric vehicle battery recovery.

Keywords

Electric Vehicle Batteries, Geospatial Analytics, Sustainable Reverse Logistics, Stochastic Simulation and Data Driven Decision Making.

Biographies

Ibrahim Abdul Aziz holds a bachelor's degree in industrial and computer engineering from Abdullah Gül University, Türkiye, and a master's in industrial engineering from the University of Windsor, Canada. He is currently a PhD student in Industrial and Manufacturing Systems Engineering at the University of Windsor, focusing on reverse logistics, machine learning in optimization, and manufacturing systems analysis.

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Walid Abdul-Kader is a Professor of Industrial Engineering at the University of Windsor. He is also the Director of the Systems Optimization Research Laboratory in the Faculty of Engineering. His research works relate to performance evaluation of manufacturing / remanufacturing systems prone to random failure. Dr. Abdul-Kader received a bachelor's degree in industrial engineering from the University of Québec in Trois-Rivières, a master's degree in mechanical engineering from École Polytechnique de Montréal, and a PhD degree from Université Laval, Québec, Canada. His research works are published in various peer-reviewed journals in his field and cited by a worldwide audience of researchers.