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# Exploring Industry 5.0 for remanufacturing of lithium-ion batteries in electric vehicles

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**Abstract** The growing demand for electric vehicles exacerbates concerns over the environmental implications of lithium-ion battery waste, which poses risks to both ecological systems and public health. While remanufacturing has been acknowledged as a viable, sustainable pathway for mitigating these issues, existing literature lacks a comprehensive investigation into the role of Industry 5.0 technologies in optimising this process. To achieve this goal, this study compares and evaluates the potential of different Industry 5.0 technologies and approaches to support the remanufacturing process of lithium-ion batteries. Specifically, we apply the AHP-PROMETHEE method to identify the most critical and influential Industry 5.0 prospects that should be prioritised for development and implementation. The novelty of our approach lies in the identification of critical Industry 5.0 imperatives that can enable efficient and effective remanufacturing processes. The analysis is supported by a comprehensive review of the relevant literature. The results of our study provide important implications for policymakers, battery manufacturers, and remanufacturing companies. By prioritising key Industry 5.0 technologies like digital twins, the Internet of Everything, and blockchain, this study shows that carmakers can significantly improve efficiency and sustainability in battery remanufacturing. This paper contributes to the emerging research on the integration of Industry 5.0 technologies in the remanufacturing process of lithium-ion batteries. Our next step is to explore the potential of the identified technologies in real-life applications and to evaluate their impact on the sustainability and efficiency of the remanufacturing process of lithium-ion batteries.

**Keywords** Lithium-ion batteries, Remanufacturing, Industry 5.0, Sustainability, MCDM, Automotive

## Introduction

The increasing demand for electric vehicles (EVs) has resulted in a surge in the production of lithium-ion batteries (LIBs). However, the disposal of these batteries at the end-of-life (EOL) presents significant environmental challenges due to their hazardous components, including heavy metals and toxic chemicals. To address this issue, remanufacturing has emerged as a promising solution to mitigate the environmental impact of LIB waste by recovering and restoring used batteries, thereby extending their life cycle [1]. Furthermore, remanufacturing can contribute to reducing the production of new batteries, thereby minimising the environmental impact of the LIB market [2]. However, there is a notable gap in the existing literature concerning how advanced technologies, specifically Industry 5.0 (I5.0) enablers, can optimise the LIB remanufacturing process.

Industry 5.0 (I5.0), which represents the convergence of industrial automation, digital technologies, and human worker inclusion, has the potential to revolutionise the remanufacturing process of LIBs. Leveraging I5.0 enablers such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics can enable more efficient and effective processes, leading to reduced costs and improved sustainability [3]. By embracing an I5.0 approach, remanufacturing companies can optimize their operations and minimise waste, while battery manufacturers can gain a competitive advantage by offering more sustainable products.

The purpose of this paper is to explore the potential of I5.0 for supporting the remanufacturing of LIBs from EVs. The objectives of this study are as follows:

1. Understand the current state of LIB remanufacturing and the challenges it faces.
2. Explore the potential of I5.0 technologies for enhancing the remanufacturing process.
3. Prioritise I5.0 approaches in the remanufacturing process.

By achieving these objectives, this research aims to shed light on the opportunities offered by I5.0 for improving the remanufacturing of LIBs, thereby contributing to sustainable manufacturing practices and the circular economy.

The remainder of this paper is organised as follows: section “Literature review” offers a comprehensive background on LIBs and I5.0, laying the groundwork for the subsequent analysis. Section “Methodology” outlines the methodology, detailing how the AHP-PROMETHEE method is employed to evaluate and prioritise Industry 5.0 technologies for LIB remanufacturing. Section “Results” presents the

study's findings. Finally, section "Conclusions" summarises key takeaways and suggests avenues for future research.

## Literature review

### *Remanufacturing of Lithium-ion Batteries*

The rapid growth of the EV market fosters a correspondent fast rise in battery utilisation, posing material shortages and rising material price issues, as well as EOL concerns. According to the mainstream literature, batteries used in mobility applications generally reach the end of their lifespan when their energy capacity drops to around 80% of the initial capacity after 5 to 10 years of service, although improved LIB technologies suggest that this threshold can be overcome [4]. It is estimated that, by 2030, there will be 100-200 GWh of LIBs that will end their automotive life [5]. To optimize resource use and minimise waste by applying circular economy principles, an increasing number of LIBs will become available for post-first-life applications, including re-use, remanufacturing, and recycling [6]. Re-use can include both the reapplication in electric vehicles and the repurposing for non-automotive applications (usually stationary use), while recycling allows for the return of valuable materials back into the value chain; remanufacturing is the intermediate option between the previously mentioned [7]. Remanufacturing prioritises the finished product as opposed to refurbishment or retrofit, which focus on exchanging, modernising, or repairing individual components; some studies show that remanufacturing is economically feasible, saving about 40% compared to using new batteries (see for example [8]). Remanufacturing is the process of restoring LIB so they can be used in their original (automotive) applications. To pass a remanufacturing process, the batteries must present good health (SOH) and satisfy all OEM specifications for power, energy, cycle life, etc. Refer to **Table. 1** for a brief description of remanufacturing challenges.

**Table. 1** List of LIBs remanufacturing challenges

Notation	Challenges	Options	Ref
C1	Different shapes and features hinder standardized remanufacturing.	Design for remanufacturing, considering modularity and disassembly	[6, 9]
C2	Safe handling (take-back logistics).	Labelling system, RFID	[1]
C3	Time and resources consume diagnostic and battery status tracking	Data-based machine-learning methods (cloud-based, digital twins) using existing sensor data	[7, 12]

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		Battery passport based on blockchain technology	[5]
C4	Safe and economic disassembly	Robotic disassembly with cloud computing support and human-machine hybrid mode; Virtual disassembly	[5, 13, 14]
C5	Reassembly	Original manufacturers involvement	[15]

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Diagnostic testing, partial disassembly of the battery packs, replacement of any damaged cells or modules, and final reassembly into new battery packs are the main steps in the remanufacturing of LIBs. Due to the risks involved in handling hazardous chemicals, the logistics for the removal and collection of the used LIBs towards the refurbishment centres require safe handling and storage [1].

The testing methodologies include the estimation of SOH, which is commonly done by measuring various parameters such as impedance and internal resistance. These parameters provide insights into the degradation mechanisms that occur during battery ageing [12]. Since the diagnostic step is complex and time-consuming, and to ensure that the batteries can be used to their maximum lifetime possibilities, data-based methods applying machine learning techniques (such as cloud-based methods and digital twins) to data obtained by sensors already installed in the battery systems seem to be the most advantageous methods to calculate the SOH and expected lifetime of the devices, reducing costs and improving the remanufacturing process. By making these data accessible via blockchain technology, the European Commission's plan to create a "battery passport" might be put into practice [5, 7].

The disassembling process can be split into stages, such as opening the battery pack's shell (in a controlled atmosphere to minimise oxidation at the cathodes), removing the mechanical and electrical connections between the cells, and removing auxiliary electronic components. The disassembly process is typically dangerous and calls for skilled specialists and specialised equipment. Robotic battery disassembly supported by cloud computing or a human-machine hybrid disassembly mode may reduce the chance of a human accident while simultaneously cutting remanufacturing costs [5, 13]. Moreover, virtual disassembly can help in optimising the procedures and identifying the "stopping point" of the operation that maximises profitability [14]. To address the battery type variability and standardise the remanufacturing process, it is necessary to create integrated designs for the LIBs parts that take modularity, interfaces, and disassembly into account [6, 9].

The replacement of damaged components and final reassembly are steps that remanufacturing shares with the manufacturing process, for which the original production facility could be employed. This highlights the importance of building a proper circular business model, involving the original battery manufacturers and the main stakeholders in the EV value chain [15].

## *Prospects of Industry 5.0*

To fully comprehend the benefits of I5.0, it is essential to first understand the foundation laid by Industry 4.0 (I4.0). I4.0, which was first presented in Germany, is described as the use of Cyber-Physical Systems (CPS) to gain a competitive edge in manufacturing processes [16]. It leverages digital technologies and automation to create smart factories, building upon the advancements of the internet. Key concepts include digitization, the IoT, cloud computing, robotics, automated manufacturing, and AI [17, 18].

I4.0 and I5.0 represent intertwined stages of industrial development. While I4.0 primarily focuses on technological innovation and digital transformation, I5.0 expands upon this by incorporating resilience, sustainability, and human-centricity concepts [19]. I5.0 "complements the existing I4.0 paradigm by having research and innovation drive the transition to a sustainable, human-centric, and resilient European industry", according to the European Commission [20]. It emphasises the collaboration between human workers and robots, leveraging human intelligence and creativity [21]. Furthermore, I5.0 also preserves the environment by making more precise decisions using predictive analytics and operational expertise [22], while fostering digital and green transitions [23]. I5.0 places the well-being of industry employees at the centre of production, emphasising a human-centric and sustainable approach to industrial growth [24]. Future factories should enable and empower human operators physically and intellectually, while robots assist with physically demanding tasks, cognitive systems provide decision-making advice, mixed reality enhances human vision and decision-making, and co-intelligence involves humans supporting robots and vice versa [25].

**Table. 2** provides a comprehensive list of enabling technologies for I5.0, highlighting their respective benefits and references.

**Table. 2** List of I5.0 enablers and prospects

Notation	I5.0 enabler	Prospect	References
A1	Additive Manufacturing (AM)	Precision manufacturing with minimised waste and resource optimization.	[10, 26]
A2	Predictive Maintenance (PM)	Identifies and prevents equipment issues, optimizing sustainability and efficiency.	[10]
A3	Cognitive Cyber-physical Systems (CCPS)	Real-time adaptation to demand changes, agility, and intelligence.	[10]
A4		Strengthens human cognition for safer man-machine symbiosis.	[27]
A5	Cloud Manufacturing (CM)	Global collaboration and resource sharing, decentralization, and cooperation.	[10]
A6		Strategic placement of manufacturing units and optimal location of plants near raw materials, and low costs.	[28]
A7	Collaborative Robots (Cobots)	Positive human-robot relationship, performance optimization, and risk reduction	[10, 29]

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A8	Blockchain Technology (BT)	Decentralized trust, secure transactions, transparency, and streamlined processes.	[10]
A9		Enables secure digital identities, like product life-cycle data management	[29]
A10	Virtual and Augmented Reality (VR/AR)	Improved skill development and precision in inventory management.	[28, 30]
A11		Enhances real-time information transfer and quality control providing flexible operations and technical advice.	[29, 31]
A12	Next-gen Wireless Networks (5G/6G)	Faster, more reliable, more efficient communication, and seamless connectivity.	[28, 32]
A13	Smart Wearables (SW)	Improved productivity and worker safety in a human-centric environment.	[27]
A14	Industrial Metaverse (IM)	Bridging real and virtual worlds for interaction and influence.	[33]
A15	Bio-inspired technologies (BIT)	Sustainable and smart material usage, and recyclability.	[34, 35]
A16	Digital Twin (DT)	Online emulation tool for system redesign, reconfiguration, and optimised operation.	[29]
A17	Edge Computing (EC)	Offloading tasks from the cloud to IoT devices at the network edge.	[36]
A18		Low latency, high-quality services, extensive IoT infrastructure, and integrated AI.	[37]
A19	Internet of Everything (IoE)	Holistic connectivity and total integration for efficient decision-making.	[10, 11]

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The table of enabling technologies for Industry 5.0 highlights several key insights. Firstly, Industry 5.0 requires a holistic approach to technological integration, focusing on objectives [25], which is more than early modularity approaches [38]. Secondly, Industry 5.0 uses technology to achieve sustainability and resource efficiency [39]. Lastly, Industry 5.0 combines human expertise with robotics to improve decision-making [34]. Technology integration, sustainability, and human capabilities are essential for I5.0.

## Methodology

This study introduces a model using I5.0 technology to address upcoming challenges in EV exhaust battery management within the automotive sector's circular economy. By performing an exhaustive lit review, the paper identifies primary issues in LIB remanufacturing and prospective I5.0 solutions. The AHP-PROMETHEE method is applied to prioritise the development of an I5.0 supply chain for LIB remanufacturing. The paper concludes with an analysis of the results and managerial implications.

## *Data and context of study*

During the data retrieval phase, a systematic effort was made to gather relevant information on LIBs remanufacturing and the implementation of I5.0 techniques. This approach allowed for a comprehensive understanding of the key challenges, opportunities, and risks associated with implementing remanufacturing processes for LIBs in the automotive industry, as well as the potential of I5.0 in addressing these issues. Five critical criteria were identified to assess the effectiveness of I5.0 prospects. Expert surveys were conducted, involving 7 specialists with expertise in I5.0, LIB remanufacturing, and relevant experience. The specialists evaluated and rated the identified I5.0 imperatives presented to them in a questionnaire. **Table 3** shows a brief description of expert profiles **Table 3**.

**Table 3.** Experts detailed information.

Features			Sample	Percentage
Evaluators (=7)	Role	Managing Director	1	14.300%
		SC Manager	3	42.850%
		Academic	3	42.850%
	Designation	Sustainability	2	28.575%
		Logistics	2	28.575%
		Operations	3	42.850%
	Experience	< 5 years	2	28.575%
		5 to 10 years	2	28.575%
		> 10 years	3	42.850%
	Gender	Male	4	57.150%
		Female	3	42.850%
		Other	0	00.000%

The AHP method will be employed to determine the weights of remanufacturing issues based on professional assessments, providing a foundation for analysing the effectiveness of various I5.0 schemes in addressing these challenges. The PROMETHEE approach will utilise the criterion weights to rank and evaluate different I5.0 areas of interest. The results of the analysis will assist policymakers, automakers, and stakeholders in prioritising I5.0 imperatives and developing sustainable plans for LIBs remanufacturing.

## *Hybrid AHP-PROMETHEE*

This article proposes a hybrid model that combines the Analytic Hierarchy Process (AHP) and the Preference Ranking Organization Method for Enrichment

Evaluations (PROMETHEE) to address the multi-criteria decision-making (MCDM) problem. The AHP approach, developed by Saaty [40], establishes a hierarchical model where pairwise comparisons determine the relative importance of criteria and alternatives are evaluated to calculate overall performance scores [2]. AHP excels at handling complex, multi-criteria decisions. It offers a consistency check for reliable criteria weighting and allows input from diverse stakeholders. Moreover, it's versatile, fitting various decision-making contexts.

The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) can rank and evaluate alternatives based on multiple criteria [41], incorporating both qualitative and quantitative factors [42]. PROMETHEE is ideal for prioritising multiple alternatives. It provides a complete ranking, not just the best option. The method is transparent and user-friendly, making it accessible for both research and practice. It includes PROMETHEE I for partial ranking and PROMETHEE II for complete ranking [3]. The hybrid model begins with pairwise comparisons using an evaluation matrix, followed by assigning preference functions with values from 0 to 1. The global matrix aggregates results, forming a rank [43]. A more in-depth discussion is available in the recent literature [40, 41]. Further research should also focus on integrating multi-attribute and AI-based models, such as artificial neural networks (ANN), for consistency verification [44].

## Results

The AHP analysis reveals that the criterion with the highest weight of 35.9% is C3 emphasising the significance of diagnostic testing and data-based machine-learning methods for extending the life of lithium-ion batteries. Following closely behind is the criterion of C4, with a weight of 28.3%, highlighting the importance of safe and cost-effective disassembly techniques. The criterion of C1 holds a weight of 18.9%, while C2 and C5 have weights of 9.0% and 7.9% respectively. The results of the PROMETHEE analysis provide valuable insights into the potential of 15.0 prospects for addressing the challenges of remanufacturing in the automotive sector. By using a single-vote matrix, each respondent's vote was given equal significance, allowing for a comprehensive evaluation of the prospects. The net out-ranking flow values in **Fig. 1** illustrate the relative relevance of each prospect to solving the main challenges.

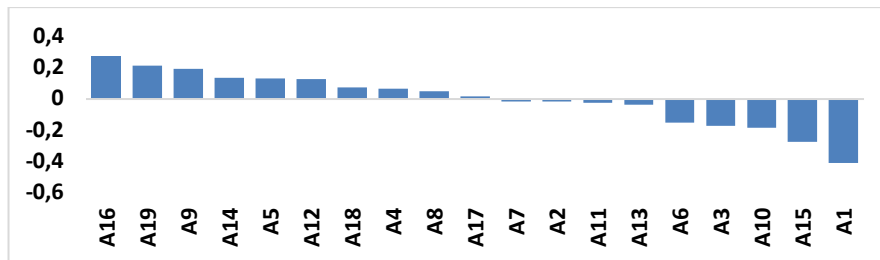


Fig. 1 Relevance of each 5.0 prospect to remanufacturing challenges

In the future of LIB remanufacturing, key I5.0 enablers such as DT, IoE, and BT will play a significant role. Among the prospects, A16 emerges as the top-ranked prospect with a significant positive net flow value of 0.3177. This suggests that the implementation of DT technology can greatly enhance the remanufacturing process by enabling online emulation, system redesign, reconfiguration, and optimised operation. It offers a powerful tool for improving efficiency and effectiveness in the battery remanufacturing domain. A19 also demonstrates a strong positive net flow, securing the second position in the rankings. This prospect emphasises the importance of holistic connectivity, integrating people, processes, information, and objects to facilitate efficient decision-making. By leveraging IoT technologies, A19 enables seamless integration and improved operational performance in the remanufacturing process. Furthermore, A9 foresees a cure and a transparent method for tracking the lifecycle of each battery. Then, A14 offers a virtual collaborative space where designers, engineers, and customers interact. This fosters innovation and accelerates problem-solving, leading to more efficient and customer-centric remanufacturing processes. A5 acts as a bridge, leveraging its global collaboration and resource optimisation capabilities, boosted by A12. By sharing resources and collaborating with other facilities, CM maximises the potential of wireless networks, enabling seamless connectivity and integration across remanufacturing operations. This synergy enables real-time data sharing, efficient diagnostics, and the life-extending of LIBs, contributing to the overall success of the remanufacturing process.

## Conclusions

The implementation of I5.0 technologies presents significant opportunities for the remanufacturing of LIBs in the automotive sector. By leveraging advancements such as DT, IoE, BT, CM, and 5G/6G, carmakers can achieve efficient and sustainable LIB remanufacturing processes. These technologies enable virtual modelling, real-time connectivity, secure data management, global collaboration, and optimised resource utilisation. The integration of these technologies improves diagnos-

tics, enhances disassembly and reassembly processes, facilitates information sharing, and supports decision-making. Through the prioritisation of I5.0 prospects, such as A16, A19, and A9, among others, carmakers can create a comprehensive and interconnected system that drives innovation, efficiency, and sustainability in LIB remanufacturing. Combining DT, IoE, and BT into LIB remanufacturing establishes an intriguing research topic. DT provides a solid foundation for predictive analytics, allowing for proactive actions that could potentially revolutionise battery diagnosis. The capabilities of IoE in process automation and real-time data capture give up opportunities for optimising disassembly and reassembly stages, cutting expenses and increasing efficiency. BT is a key technology for providing safe, transparent, and traceable data sharing, which is a prerequisite for scalable and sustainable remanufacturing practices. This research highlights the potential of I 5.0 in addressing the challenges of LIB remanufacturing and provides valuable insights for policymakers, automakers, and other stakeholders in developing sustainable strategies for the circular economy of the automotive sector. This study has indeed some limitations. The potential of I5.0 technologies in LIBs remanufacturing was assessed within a theoretical framework, lacking empirical validation. Future research could involve applying these technologies in real-world settings to assess their practical impact. Secondly, the focus of this study is primarily on the automotive sector, limiting its generalizability to other industries that also utilise LIBs. Future work could explore the implications of our findings in other sectors such as consumer electronics or renewable energy storage.

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