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Spare Parts and Material Management in Electric Vehicle Maintenance: A Multidisciplinary Review

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Abstract

Maintenance and management of spare parts for electric vehicles requires a specific approach due to high-voltage components, technological complexity, and limited availability of specialized parts. Key challenges include optimizing inventory, monitoring the life of battery systems, ensuring compatibility of parts across different vehicle models, and organizing efficient procurement, storage, and distribution. Of particular importance are safety protocols when working with high voltages, the use of specialized technical and protective materials, and environmentally friendly waste management and battery recycling. Digital solutions, including ERP and CMMS systems, IoT sensors, remote diagnostics, and predictive analytics based on artificial intelligence, enable better maintenance planning, cost reduction, and increased vehicle reliability. The paper provides an analysis of the technical, safety, environmental, and economic aspects of electric vehicle maintenance, with an emphasis on the digitalization and optimization of logistics processes. Based on the analysis, recommendations are proposed for improving the maintenance system, including the integration of advanced technologies, process standardization, and strengthening the education of service personnel. In addition, the paper identifies key research questions and outlines directions for future research—particularly in areas such as the digital integration of spare parts logistics, the environmental impact of material uses and disposal, and the role of artificial intelligence in predictive maintenance strategies. The findings suggest that the greatest improvement potential lies in combining predictive maintenance, sustainable practices, and operational cost reduction, thereby contributing to the long-term reliability and competitiveness of electric mobility.

Keywords: *electric vehicles (EV), spare parts, inventory management, digitalization of processes, vehicle maintenance, battery systems.*

1. Introduction

Electric vehicles today represent one of the key technologies in reducing greenhouse gas emissions and transitioning to sustainable transport. Their rapid development raises numerous technical and organizational issues, especially in the area of maintenance and management of the necessary resources. It is precisely spare parts and maintenance materials that play a crucial role in ensuring the safety, durability and availability of electric vehicles.

The aim of this paper is to analyze the management of spare parts and materials for electric vehicles, identify challenges in procurement, storage and distribution, and propose optimized and digitalized solutions for improving the maintenance system. The specificities of electric vehicle maintenance arise from their technological complexity: high-voltage battery systems, electric motors, inverters, advanced energy management systems (BMS), etc. Maintenance includes preventive and corrective interventions on batteries, electrical lines,

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cooling systems and software components, which requires specialized parts and materials.

The management of spare parts and materials for the maintenance of electric vehicles can be significantly improved by applying modern technologies such as predictive maintenance, digital integration, blockchain and additive manufacturing. The integration of predictive maintenance (PdM) with spare parts inventory management enables cost reduction, downtime reduction and inventory optimization through timely ordering and replacement of parts. Digital transformation requires integrated information systems and a change in organizational culture, but brings significant economic and operational benefits [1], [2]. Also, the application of advanced technologies such as blockchain technology enables reliable tracking and tracing of spare parts throughout the entire supply chain, thereby increasing transparency, security and reducing the risk of counterfeiting [3]. Additive manufacturing (3D printing) enables fast and decentralized production of spare parts, which reduces delivery time and storage costs, especially for rare or specific parts [4], [5]. Research on electric vehicles to date particularly emphasizes the importance of progress in the field of battery technologies, charging methods and energy management. Numerous authors point out that battery development is a key factor in improving the performance, safety and availability of electric vehicles [6]. Remanufacturing batteries and other key components can reduce the need for new parts, increase sustainability, and reduce costs [7], [8].

Therefore, the application of modern technologies can significantly improve the management of spare parts and materials for the maintenance of electric vehicles, bringing greater efficiency, lower costs and greater sustainability. The biggest challenges are digital integration and organizational changes, but the benefits are multiple and confirmed in practice. In doing so, it is necessary to identify critical spare parts that can be classified into critical (e.g. battery modules, inverters) and non-critical (e.g. housings, connectors). Constant monitoring of stocks is necessary with the help of software solutions such as ERP systems. They allow control of availability, shelf life and compatibility of parts, which is especially important due to the diversity of manufacturers and the need for compliance with international standards (e.g. ISO 6469, HRN EN 60903) [9].

Maintenance materials include insulating materials, coolants, protective equipment and diagnostic tools. Their properties must match the specific operating conditions of electric vehicles – resistance to high voltages, electromagnetic radiation and temperature changes. These specificities confirm that electric vehicle maintenance requires an integrated approach that combines technical, logistical and safety aspects, with a strong reliance on digitalization and process standardization.

2. Basic Components of Electric Vehicles

Electric vehicles differ from vehicles with internal combustion engines in their basic powertrain architecture, which is based on specific electrical and electronic circuits. While in conventional vehicles the internal combustion engine, fuel injection system, transmission and exhaust system play a key role, electric vehicles rely on high-voltage batteries, electric motors, inverters, power converters and energy management systems. These circuits are interconnected into an integrated system that enables high energy conversion efficiency, reduced emissions and simpler maintenance compared to conventional vehicles. Such technical differences require a different organization of spare parts, different safety procedures and specific maintenance materials.

In addition, the drive architecture of electric vehicles also includes new safety requirements (e.g. handling of high-voltage systems), advanced cooling technologies, digital connectivity with the charging infrastructure, as well as software tools for monitoring and optimizing performance. This makes electric vehicles not only an alternative form of transport, but also an example of the application of high technology and digitalization in the automotive industry. The key components that form the basis of their drive and technical structure are presented below. The comparison clearly shows that electric vehicles introduce challenges in the areas of energy components and digital monitoring (Table 1). These vehicles consist of several key technological components including batteries, electric motor, control electronics, power converters and charging systems. Each of these components is the subject of intensive development to increase the efficiency, safety and range of the vehicle.

Table 1. Comparison of certain EV components with SUS vehicles.

Component	Electric vehicles (EV)	Internal combustion vehicles (ICE)
Drive system	Electric motor + inverter + battery	Internal combustion engine
Transmission system	Simple – often no gearbox	Complex – manual or automatic gearbox
Maintenance	Digitally driven, software linked	Mechanical, more frequent servicing
Sources of failure	Electronic and battery components	Mechanical systems and combustion

High-voltage batteries – The battery is the main source of energy and the most important part of an electric vehicle. Lithium-ion batteries are most commonly used due to their high energy density and long lifespan, with different chemical configurations being used (e.g. NCA – lithium-nickel-cobalt-aluminum, LFP – lithium-iron-phosphate). The battery system is modular, which allows the replacement of individual modules during maintenance. In addition to lithium-ion, new generations of batteries are also being developed, such as solid electrolyte and sodium-ion batteries.

Electric motor – Converts electrical energy into mechanical work and drives the vehicle. Permanent magnet synchronous motors (PMSMs) are most commonly used, which are characterized by high efficiency, compact construction, and induction motors, which have lower production and maintenance costs.

Inverter – Converts direct current from the battery into alternating current required for the operation of the electric motor. In addition, it allows the regulation of engine speed and torque, thus significantly affecting the performance and energy efficiency of the vehicle.

Battery Management System (BMS) – Represents an electronic system for monitoring and optimizing battery operation. It continuously monitors key parameters such as voltage, current, temperature and capacity, ensuring safety, optimal charging and discharging, and extending the battery's lifespan.

Power converters and inverters – Provide the various voltage and current levels required to power the vehicle’s propulsion and auxiliary systems. DC-DC converters enable the conversion of high-voltage battery energy into lower voltages for electronic and safety systems.

Charging systems – Include on-board chargers integrated into the vehicle, as well as off-board chargers within the fast or wireless charging infrastructure. These systems allow flexibility in different charging scenarios and directly affect the usability of electric vehicles.

In addition to the above components, EVs most often include cooling systems that ensure temperature control of the battery, electric motor and inverter. Liquid cooling systems are most often used, which prevent overheating and enable stable operation of components under various operating conditions. Also, in addition to the powertrain, electric vehicles contain a number of auxiliary systems, including air conditioning, energy management systems, safety functions and communication modules for connecting to the infrastructure and smart transport networks.

3. Specifics of Eletric Vehicle Maintenance

Electric vehicle maintenance requires a tailored approach due to their technical complexity, the presence of high-voltage systems and the specific materials used in construction and operation. Unlike vehicles with internal combustion engines, where mechanical failures and replacement of conventional consumable parts dominate, the focus of maintenance for electric vehicles is on electronic and power components, software support and safety procedures.

The three main types of electric vehicle maintenance include:

- **Preventive maintenance** – carried out periodically to prevent failures. It includes visual inspections, software upgrades, cooling system checks and insulation checks.
- **Corrective maintenance** – refers to interventions after a failure occurs, such as replacing battery modules, repairing inverters or regenerating connectors.
- **Predictive maintenance** – is based on the analysis of data collected by sensors and monitoring systems (e.g. BMS). This approach allows the timely identification of components that show signs of degradation, thus minimizing the risk of unplanned downtime.

Therefore, the specificities of electric vehicle maintenance arise from their technological complexity and safety requirements. Successful maintenance requires an integrated approach that includes preventive, corrective and predictive strategies, while ensuring the supply of critical materials and optimizing logistics processes. Digital connectivity through BMS and advanced software platforms enables timely intervention and cost reduction, while recycling and remanufacturing contribute to the sustainability and environmental friendliness of the entire system.

3.1. Safety requirements

Special attention should be paid to the safety aspects of electric vehicle maintenance. Working on high-voltage systems (>400 V) requires compliance with international occupational safety standards and the implementation of specialized procedures. Specialized education and interactive tools (e.g. 3D diagnostics) reduce dependence on experts and accelerate troubleshooting [10], [11]. Standardization of safety protocols and adaptation of workshops to the specificities of EVs are necessary to protect personnel and vehicles, given the high-voltage systems and specific risks [12].

Based on the above, key safety requirements can be identified, which include:

1. use of personal protective equipment (dielectric gloves, protective visors, insulating tools),
2. definition of the work area as an electrical safety zone, with clearly marked signs and access protocols,
3. training of service personnel and possession of specialized certificates (e.g. ECE R100, EN 50110),
4. standardization of safety protocols adapted to the specificities of EVs.

The application of these measures represents the foundation for the safe exploitation and long-term preservation of the functionality of electric vehicles.

3.2. The role of BMS in maintenance

Battery Management System (BMS) is one of the most important elements in the maintenance of electric vehicles because it allows continuous monitoring and optimization of the battery system. BMS monitors key parameters such as voltage, current, temperature and capacity, thus ensuring safety, stability and optimal operating conditions of the battery (Table 2). Based on the collected data, the system enables precise diagnostics of the condition and prediction of the moment when intervention will be required, which significantly contributes to the application of predictive maintenance. This is especially important because optimizing battery charging (e.g., adjusted charging profiles during idle time) significantly reduces degradation and extends battery life [13], [14], [15].

Table 2. BMS functions and their contribution to electric vehicle maintenance.

BMS Function	Description	Contribution to the maintenance of EV
Voltage and current monitoring	Continuously measures the values of battery cells and modules	Prevents overcharging and deep discharge, preserves battery life
Temperature monitoring	Detects overheating and uneven heat distribution	Reduces the risk of thermal runaway and extends system reliability
Cell balancing	Equalizes the voltage between cells in a pack	Ensures even battery operation and longer battery life
State of Health (SoH)	Assesses battery health and capacity	Enables planning of preventive and predictive interventions
Remaining Life Estimation (SoE, RUL)	Predicts the duration until the next service need	Helps optimize costs and reduce unexpected failures
Integration with platforms	Connects to fleet management and service systems	Enables remote monitoring and centralized maintenance planning

Modern BMS systems connect to centralized service platforms and fleet management solutions, enabling remote performance monitoring and service activity planning. Such integration contributes to reducing costs, reducing downtime and extending the lifespan of battery modules, which represent the most expensive and technically sensitive component of electric vehicles. In this way, BMS not only optimizes battery operation, but also becomes a key tool for efficient and sustainable management of the entire maintenance process.

4. Spare Parts Management

Electric vehicle (EV) spare parts management is a complex process that involves parts classification, warehousing and logistics, and addressing procurement and management challenges. Unlike conventional vehicles, EVs require specialized parts with high technological value, which introduces additional complexities in inventory planning, quality control, and ensuring continuous availability.

The management of spare parts and materials for electric vehicle (EV) maintenance faces challenges such as unpredictable demand, high inventory costs, and the need for rapid service. Modern technologies, including predictive maintenance, digital integration, block chain, additive manufacturing (3D printing), and remanufacturing, offer solutions for optimizing inventory, reducing costs, and increasing the reliability of maintenance systems [5], [7], [16], [17], [18], [19]. The integration of these technologies enables more accurate consumption forecasts, supply chain transparency, and sustainability through a circular economy. Research shows that digital transformation and innovative approaches can significantly improve the efficiency and cost-effectiveness of EV spare parts management, but also require changes in organizational culture and infrastructure.

Therefore, managing spare parts and materials for electric vehicles requires addressing unique challenges related to critical materials, battery life cycles, supply chain risks, and inventory optimization. Effective management must take into account limited material availability, warranty requirements, quality variations, and the need for sustainability.

Key requirements for managing spare parts and materials include critical materials supply and recycling issues [20], [21], inventory planning [22], [23], remanufacturing [7], [24], supplier quality management [25] and reliability [23], [26].

Critical Materials Supply and Recycling – Electric vehicles rely heavily on materials such as lithium, cobalt and silicon, making security of supply and recycling essential. The development of closed supply chains and incentives for recycling batteries and other components are becoming key to ensuring material availability and reducing environmental impact.

Inventory Planning – Managing spare parts inventories, especially those required for warranty repairs, must take into account variable and time-varying demand, which depends on fluctuations in sales and failure rates. Advanced forecasting models and planning strategies within a limited time horizon are essential to minimize costs and meet warranty obligations.

Remanufacturing and renewable parts – Remanufacturing batteries and other components of electric vehicles can significantly reduce the need for new materials and contribute to sustainability. This process requires investment in appropriate infrastructure, as well as user trust in remanufactured parts, which depends on their price and expected lifespan.

Quality and supplier management –Spare parts from different suppliers can vary in quality and delivery time. Joint optimization of maintenance schedules and inventory policies, taking into account the quality of suppliers, is crucial to achieve a balance between reliability, costs and the risk of shortages.

Reliability and sufficiency – Accurate calculation of the required spare parts sets must include equipment reliability, sufficiency level and operational requirements. Diagnostic tools and robust forecasting models improve reliability and contribute to more cost-effective maintenance.

4.1. Classification of spare parts

Efficient classification of parts enables inventory optimization, cost rationalization and timely response to maintenance needs. EV spare parts can be classified into:

- **Original Parts (OEM)** – made by the vehicle's manufacturer; highly compatible and reliable, but usually more expensive.
- **Replacement parts** – produced by third-party manufacturers according to technical specifications; generally, more affordable, but may vary in quality and lifespan.
- **Remanufactured parts** – refurbished and tested components that offer a compromise between cost and reliability, especially important for battery modules.
- **Specialized EV parts** – such as electrical connectors, inverter units, thermal sensors or

BMS modules, which have no equivalents in SUS vehicles.

In addition to this basic classification, multi-criteria methods are used in practice that take into account criticality, demand, price, delivery time, remanufacturing capability, and suitability for additive manufacturing (Table 3). Such models, such as the Dominance-based Rough Set Approach (DRSA), enable more precise categorization and inventory optimization through a combination of data analysis and expert validation.

Table 3. Criteria for classifying spare parts for electric vehicles.

Criterion	Description / Methodology	Reference
Criticality	Impact of a part on vehicle functionality and safety	[26], [27]
Demand (ADI, CV^2)	Analysis of demand interval and variability based on historical data	[27]
Price and consumption	Unit price and annual consumption of parts	[26]
Delivery time	Average procurement time and delays in the supply chain	[26]
Remanufacturing	Possibility of renewal and reuse of components (e.g. batteries)	[7]
Additive manufacturing	Suitability for production via 3D printing	[28]

For the classification of spare parts for electric vehicles, a combination of criticality, demand, price, lead time and remanufacturing analysis, with the application of multi-criteria methods and validation through expertise and data, is recommended. This approach enables inventory optimization and system sustainability.

4.2. EV spare parts and materials management strategies

The management of spare parts and materials for electric vehicle (EV) maintenance faces challenges such as unpredictable demand, high inventory costs and the need for rapid service. The procurement of spare parts for electric vehicles takes place in the context of global supply chains, which are particularly susceptible to disruptions and uncertainties. The most common challenges include delivery delays, fluctuations in raw material prices and growing demand for specialized EV components. Such bottlenecks in supply channels can cause significant downtime in vehicle maintenance, increase costs and reduce the availability of key parts.

In order to mitigate these risks, it is recommended to develop more sustainable and resilient procurement strategies. Among the most important solutions are the localization of production and strengthening regional supply networks, increasing the use of recycled and remanufactured components and establishing strategic partnerships with certified suppliers to ensure stability and continuity of supplies. In this way, the procurement process becomes more resilient to external shocks and contributes to greater reliability of the electric vehicle maintenance system.

Spare parts management for electric vehicles faces a number of specific challenges that significantly affect maintenance efficiency and vehicle reliability. Limited availability of parts is a result of specific technical requirements and a small number of manufacturers, which increases the risk of shortages and extended downtime. An additional problem is the rapid technological evolution in the electric vehicle sector, which causes the obsolescence of certain components in a relatively short period of time and imposes the need for constant adjustment of procurement and logistics strategies. A special challenge is the safety risks when handling high-voltage components, as they require additional training and certification of personnel, which generates new costs and increases the complexity of management.

The solution to these challenges is possible through the integration of predictive analytics tools and digital platforms, which enable more precise planning and optimization of inventories. Table 4 shows certain strategies for managing spare parts and materials for EVs. Such an approach reduces the risk of shortages, increases the level of safety in working with specialized components and ensures more efficient management of the entire maintenance process. In this way, spare parts management becomes more resilient, safer and more aligned with the demands of the dynamic electric vehicle market.

Table 4. Spare parts and materials management strategies for EVs.

Strategy / requirement	Description
Critical materials supply and recycling	Ensuring the availability of lithium, cobalt, silicon and other resources through closed supply chains and encouraging the recycling of batteries and components.
Inventory and warranty requirements optimization	Using advanced forecasting and inventory planning models to reduce costs and secure parts for warranty repairs.
Remanufacturing and renewable parts	Remanufacturing and reusing renewable batteries and components, while developing infrastructure and strengthening customer trust.
Quality and supplier management	Integrated maintenance planning and inventory management taking into account variations in quality and delivery times of parts.
Spare kit reliability and sufficiency	Precise determination of required spare parts kits based on system reliability, operational requirements and diagnostic data.

4.3. EV spare parts management challenges

Storage of spare parts for electric vehicles requires the application of specific conditions that ensure their reliability and durability. Particularly sensitive components, such as battery modules, must be stored in air-conditioned warehouses to prevent degradation due to changes in temperature and humidity. Digital inventory tracking using RFID technology and IoT sensors allows precise control of availability and shelf life, thus minimizing the risk of unplanned shortages or parts obsolescence. Inventory planning within service networks is increasingly based on historical data on failures, regional specificities and seasonal fluctuations in demand, which contributes to the optimization of logistics processes.

The logistics segment in the EV sector increasingly relies on digital platforms and predictive models, which enable cost reduction, more precise distribution planning and significantly reduced vehicle downtime. For example, the integration of predictive maintenance and inventory optimizes parts ordering and replacement [4], [16], [17]. On the other hand, remanufacturing reduces the need for new parts [7], [29], and additive manufacturing reduces storage costs [4], [5]. In this way, storage and logistics become an integral part of an intelligent electric vehicle maintenance system.

Managing the procurement, storage and distribution of spare parts for electric vehicles faces a number of challenges arising from the specific technical and logistical requirements of this technology. In addition to the classic problems in the supply chain, an additional layer of complexity is brought by the need for specialized warehouses, environmental standards and ensuring a reliable supply of critical materials. Key challenges and issues in parts procurement include dependence on critical materials [30], [31] and the complexity of supply networks [32]. The procurement of key components for electric vehicles is largely conditioned by the availability of rare and critical materials such as lithium, cobalt, nickel and rare earths. Their production is geographically concentrated, which increases the risks of shortages and price volatility. An additional challenge is the complexity of supplier networks, as the localization and flexibility of suppliers is required for high-tech components, which increases vulnerability to disruption. Also, the lack of expertise and capacity of individual suppliers slows down development and increases costs, because new technologies require specialized knowledge and infrastructure.

The storage of batteries and other electrical components requires special storage conditions for safety and environmental reasons (e.g. fire protection, temperature control) [30], [33]. Also, waste management and recycling of batteries and electronic components represents a logistical and environmental challenge, requiring new processes and investments [31], [33]. Electrical batteries and other specific components require special storage conditions for safety and environmental reasons, including temperature control, fire protection and prevention of material degradation. In addition, the disposal and recycling of batteries and electronic components represent a significant logistical and environmental challenge, requiring the development of new processes, regulations and investments in infrastructure.

The need for sustainable distribution models (e.g. returns and parts remanufacturing) increases the complexity of logistics and requires new technologies and processes [33], [34]. Electric vehicles in logistics require route optimization due to limited range and the need for charging stations, which affects distribution efficiency. Also, the distribution of spare parts increasingly relies on green and circular supply chains, which include return, recycling and remanufacturing of components. Although these models increase sustainability, they simultaneously require more complex logistics and new technological processes. Additionally, electric vehicles used in logistics require careful route planning due to limited range and availability of charging stations, which directly affects costs and distribution efficiency.

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The need for sustainable distribution models (e.g. return and remanufacturing of parts) increases the complexity of logistics and requires new technologies and processes [33], [34]. Electric vehicles in logistics require route optimization due to their limited range and the need for charging stations, which affects the efficiency of distribution. Also, the distribution of spare parts increasingly relies on green and circular supply chains, which include the return, recycling and remanufacturing of components. Although these models increase sustainability, they simultaneously require more complex logistics and new technological processes. Additionally, electric vehicles used in logistics require careful route planning due to limited range and availability of charging stations, which directly affects costs and distribution efficiency.

5. Digitalization and Technological Solutions in EV Maintenance Management

Digital transformation is a key for improving the process of electric vehicle maintenance and spare parts management. The integration of software platforms, IoT technologies, artificial intelligence (AI), digital twins and advanced algorithms enables greater transparency, predictability and efficiency in all segments of the value chain. By applying the above technologies (Table 5), digital transformation enables predictive maintenance, performance optimization and more efficient spare parts management [19], [35], [36], [37]. These solutions contribute to reducing costs, shortening vehicle downtime and increasing safety, while at the same time supporting the principles of sustainability through the application of circular and green logistics models.

Therefore, modern technologies enable significant improvements in the management of spare parts and materials for EV maintenance. Predictive maintenance and digital integration reduce costs and increase efficiency, but require changes in organizational culture and infrastructure. Specific challenges that stand out include the need for standardization, investments in infrastructure and personnel education.

Table 5. Digital and technological solutions in EV maintenance.

Technology / Methodology	Application in EV maintenance	Contribution / Benefits
ERP and CMMS systems	Monitoring of inventory, service orders, costs and schedules	Data centralization, better coordination, error reduction
Fleet management platforms	Using data from BMS, GPS and sensors	Optimization of service interventions, preventive inspections
OTA software updates	Remote installation of new versions and security patches	Fewer physical service visits, faster interventions
IoT sensors	Monitoring of temperature, voltage, vibration and wear of parts	Automated notifications, reduced downtime, higher reliability
Artificial intelligence (AI)	Analysis of failure data, predictive maintenance	Failure prediction, inventory optimization, cost reduction
Optimization Algorithms	Route planning, warehouse and distribution locations	Lower logistics costs, faster delivery, sustainability
WMS and ERP integration	Digitalization of warehouse and purchasing processes	Complete synchronization and automation of logistics flows

5.1. Software solutions

Key software solutions for the management of spare parts for electric vehicles include advanced inventory management systems, predictive analytics, blockchain for parts tracking and integrated information systems. For electric vehicles, the integration of software and electronics through advanced ICT architectures enables better connectivity, automation and efficiency in spare parts management, especially in the context of connected and autonomous vehicles [26], [38].

ERP (Enterprise Resource Planning) and CMMS (Computerized Maintenance Management Systems) systems enable real-time inventory, service orders, costs, and maintenance schedules. ERP systems enable centralized management of data on materials, procurement, inventory, and suppliers, leading to standardization, error reduction, and more efficient procurement and inventory planning. In the automotive industry, ERP implementation enables real-time parts tracking, reduced inventory levels, faster delivery, and better control over production processes, which is especially important for complex electric vehicle supply chains [20], [39].

CMMS (Computerized Maintenance Management Systems) are essential for monitoring the maintenance and life cycle of electric vehicle components, especially batteries. Digitalization and data integration enable timely maintenance, diagnostics, and failure prediction, thereby extending the life of components and reducing the cost of unplanned downtime [40]. Advanced functions include big data analysis and the application of machine learning to optimize battery maintenance and safety.

The implementation of these systems contributes to centralized management and better coordination between service centers and suppliers. Fleet management platforms additionally use vehicle data (BMS, GPS, sensors) to optimize service interventions, plan preventive inspections, and reduce operating costs. Of particular importance is the integration of the aforementioned systems, which enables data centralization, optimization of procurement and inventory, predictive maintenance, etc. [39], [40], [41]

In addition, electric vehicles introduce new capabilities through over-the-air (OTA) software updates, which significantly reduce the need for physical visits to service centers. These solutions significantly improve electric vehicles by enabling faster, safer and more flexible introduction of new functionalities, fixes and improvements without the need for a service center visit [42], [43], [44], [45], [46]. In addition, electric vehicles introduce new capabilities through over-the-air (OTA) software updates, which significantly reduce the need for physical visits to service centers. These solutions significantly improve electric vehicles by enabling faster, safer and more flexible introduction of new functionalities, fixes and improvements without the need for a service center visit

5.2. IoT and sensor technologies

IoT and sensor technologies significantly improve the management of parts and maintenance of electric vehicles through real-time monitoring, predictive maintenance and optimization of the performance of batteries and other key components. Built-in sensors in electric vehicles monitor key parameters such as temperature, voltage, vibration and the degree of wear of components [47], [48], [49]. The collected data is sent to cloud platforms, where it is analyzed and visualized, allowing users and workshops to gain insight into the condition of the vehicle at any time. The data can be automatically sent to service systems, which allows automated notification of service personnel about necessary interventions. In this way, IoT solutions ensure greater reliability and cost reduction by connecting real-time data with logistical and operational decisions.

IoT solutions also enable the creation of so-called digital twins, enabling real-time monitoring of the condition of vehicles and components, which leads to timely detection of failures and reduced downtime [35], [50], [51], [52], [53]. For example, digital twins and IoT sensors enable real-time monitoring of component health, prediction of remaining life, and optimization of maintenance, especially for batteries and fuel cells [36], [53]. Their application is not limited to monitoring, but also includes simulation of different load scenarios, thereby optimizing maintenance and extending the life of critical components. By integrating with IoT sensors and BMS systems, digital twins become a predictive maintenance tool that connects real-world data with future performance models. This allows service centers and manufacturers to make informed decisions, reduce maintenance costs, and increase the reliability of electric vehicles. Thus, IoT enables centralized monitoring and management of electric vehicle fleets, optimization of energy consumption, planning of parts replacement and more efficient management of spare parts inventory. Analysis of sensor data enables early detection of potential failures (e.g. overheating, overcharging, short circuit), thus preventing more serious failures and reducing maintenance costs.

5.3. Artificial Intelligence (AI) in maintenance

The application of AI algorithms and machine learning brings significant improvements in the field of predictive maintenance and inventory management. By analyzing historical failure data, it is possible to predict future needs for part replacement, while optimization algorithms help to increase reliability, reduce costs and the risk of shortages. For example, the application of AI and machine learning enables predictive maintenance, early detection of failures and optimization of service schedules, thereby reducing costs and downtime [54], [55], [56]. AI and machine learning also improve the accuracy of predicting the required maintenance and extend the life of key components, especially batteries and motors [19], [37], [55], [56], [57], [58]. In this way, AI contributes to making decisions that balance safety, costs and availability of parts.

The application of digital technologies in the maintenance of electric vehicles is becoming a key factor in improving the efficiency, safety and economy of the entire process. Modern solutions, from ERP and CMMS systems, through IoT sensors and OTA updates, to artificial intelligence and optimization algorithms, enable integrated monitoring and management of all phases of maintenance – from planning and procurement to diagnostics and logistics. These technologies not only reduce costs and downtime, but also increase reliability and contribute to the development of sustainable and green supply chains. The table shows the most important digital and technological solutions and their contribution to the maintenance of electric vehicles.

5.4. Optimization and digitalization of logistics processes

Optimization of the procurement, storage and distribution processes of spare parts is based on the integration of innovative logistics models and advanced algorithms. Key approaches include:

- Innovative supply chain models – circular and green supply chains, reverse logistics, and lean and agile approaches that enable waste reduction and rapid adaptation to changes in demand [34].
- Distribution and storage optimization – application of mathematical models and heuristic algorithms (e.g. ant colony optimization, simulated annealing) to plan optimal routes and locations of distribution centers [59], [60].
- Process digitalization – introduction of real-time tracking systems, IoT sensors and integration of WMS (Warehouse Management Systems) with ERP platforms, thus achieving full synchronization and automation of logistics flows [34].

Optimization and digitalization of processes in maintenance and logistics of spare parts for electric vehicles requires the application of advanced methods that connect procurement, storage and distribution with digital tools and predictive models. These approaches enable cost reduction, faster adaptation to changes in demand, and greater transparency in operations. By combining lean and agile supply chains, IoT technologies, route optimization algorithms, and new concepts such as blockchain and digital twins, an integrated system is formed capable of ensuring reliable and sustainable support for the maintenance of electric vehicles.

Table 6 shows the key methods and technologies for process optimization and digitalization. The key methods and technologies for process optimization and digitalization in electric vehicle maintenance include various approaches that connect procurement, warehousing, and distribution with modern digital tools.

Table 6. Key methods and technologies for process optimization and digitalization.

Method / Technology	Application in the process	Potential contribution
Lean and agile supply chains	Procurement, warehousing and distribution	Fast adaptation to demand, waste reduction
Route optimization (AI, heuristics)	Distribution and logistics planning	Lower transportation costs, shorter delivery times
Bi-level programming	Determining distribution center locations	Balancing storage and distribution costs
IoT and digital analytics	Real-time inventory monitoring and optimization	Greater transparency, reducing the risk of shortages
Blockchain	Monitoring the supply chain and authenticity of parts	Data security, transparency and reducing counterfeiting
Digital twins	Simulation of maintenance and logistics processes	Predictive planning, reducing downtime and costs
Predictive analytics	Forecasting failures and supply needs	Just-in-time procurement, reducing storage costs
Automated robotic systems (AGV/AMR)	Handling parts in warehouses and distribution centers	Faster processing, reducing errors and operating costs

The application of lean and agile supply chains allows faster adaptation to market changes and waste reduction, while route optimization algorithms significantly reduce distribution costs and delivery times. Bi-level programming helps determine the optimal locations of distribution centers, balancing storage and transportation costs. In parallel, IoT and digital analytics ensure real-time inventory tracking, which increases transparency and reduces the risk of shortages. The combination of these methods achieves greater efficiency, lower costs, and better sustainability of the maintenance system.

The most effective approaches involve a combination of innovative logistics models, advanced optimization algorithms, and digital technologies for process monitoring and automation. These solutions enable greater sustainability, faster adaptation to market changes, and reduced overall costs, while ensuring high reliability and safety in the maintenance of electric vehicles.

6. Safety, Environmental and Economic Aspects of Electric Vehicle Maintenance

Electric vehicle maintenance involves much more than technical interventions and spare parts management. It is a complex process that includes safety requirements, environmental responsibility and economic aspects. The safety dimension stems from the need to work with high-voltage systems and specialized equipment, while the environmental aspect includes battery recycling, waste management and the implementation of sustainable service processes. At the same time, the economic dimension refers to maintenance costs, long-term savings and resource optimization. By combining these elements, it is possible to view electric vehicle maintenance as an integrated system, in which technical efficiency goes hand in hand with sustainability and economic profitability.

6.1. Safety aspects of maintenance

Maintenance of electric vehicles requires strict adherence to safety procedures due to the presence of high-voltage systems, specialized materials, and complex electronic components. Unlike vehicles with internal combustion engines, where risks predominantly arise from fuel and mechanical failures, the greatest danger for electric vehicles comes from electric shock, battery overheating, and possible chemical reactions within the battery cells. Therefore, safety aspects are a fundamental component of any maintenance process. EV maintenance requires special attention due to the high voltages, specific battery risks, and the lack of universal standards. The most important safety aspects include protection against electric shock, prevention of fire and thermal runaway of batteries, proper management of high voltages, and constant monitoring of the condition of the battery and components [12], [61], [62].

Working with high-voltage systems requires specific precautions, as electric vehicles generally use batteries with voltages ranging from 300 V to over 1200 V. Specialized training, the use of insulated tools and protective equipment, and clear marking of high-voltage parts are required [61], [63]. Before any service intervention, it is necessary to deactivate the system using a safety switch (service plug), which prevents contact with live parts. In addition, the Battery Management System (BMS) constantly monitors the battery status and has the ability to automatically shut down in the event of a fault, overload or collision, which significantly reduces the risk of accidents.

The use of appropriate personal protective equipment (PPE) is mandatory for all interventions on electric vehicles. Service personnel must use insulating gloves in accordance with the HRN EN 60903 standard, protective suits and helmets with visors, as well as insulating shoes intended for work under voltage. The workplace must be equipped with insulating partitions and protective covers for components not subject to intervention, in order to minimize the risk of accidental contact.

Currently, there is no universal standard for working on EVs, and it is recommended to adopt best practices from existing guidelines for electrical installations and emergency interventions [12], [64]. However, safety protocols and international standards play a key role in protecting personnel and infrastructure. Vehicles and components must comply with standards such as ISO 6469 and HRN EN 61482-1-2, which prescribe battery tests for overcharging, short circuit, humidity, fire, impact and immersion in water. In addition, high-voltage cables in EVs are always clearly marked with orange color and accompanying warnings to further reduce the risk.

Electric vehicle maintenance safety is based on understanding high voltages, fire risks and the importance of constant battery monitoring. Specialized training, the use of appropriate equipment, the implementation of advanced monitoring systems and the adoption of the best security procedures are key. Education and continuous training of service personnel is an indispensable element of the security system. Service technicians must be familiar with vehicle electrical diagrams, safe voltage deactivation procedures and first aid measures in case of electric shock. Only certified technicians, trained according to international standards, can perform complex interventions on high-voltage components of electric vehicles.

Ultimately, the safety aspects of electric vehicle maintenance require an integrated approach that combines technical protection measures, appropriate equipment, clearly defined protocols and ongoing training of service personnel. This framework represents the basis for minimizing risks and ensuring the reliable exploitation of electric vehicles in practice.

6.2. Environmental aspects of maintenance

Electric vehicle maintenance includes not only technical and safety procedures, but also a series of activities aimed at protecting the environment and rational use of resources. Therefore, EV maintenance has significant environmental aspects that differ from traditional internal combustion vehicles. The greatest advantages are the reduction of greenhouse gas emissions during driving and lower maintenance costs, but there are challenges related to the production and recycling of batteries, as well as dependence on electricity sources. Environmental aspects are particularly evident in battery recycling, disposal of technical waste, the application of sustainable service processes and the education of all participants in the maintenance chain.

EVs are known to have significantly lower emissions of CO2 and other pollutants during driving, especially when powered by renewable energy sources [65], [66]. However, equal attention must be paid to the environmental aspects of spare parts management. Electric motors and systems require less maintenance and have fewer moving parts, which reduces the need to replace oil, filters and other consumables [65], [67]. However, it is necessary to take into account specific issues such as battery recycling and disposal of other waste generated from replacing parts.

Battery recycling is the most important segment of environmentally responsible maintenance. Battery production and maintenance have a high environmental footprint due to the exploitation of metals (lithium, cobalt, nickel) and energy consumption. Recycling and reuse of batteries (second-life) can significantly reduce the overall impact [68], [69]. Lithium-ion batteries contain valuable metals such as lithium, cobalt and nickel, which can be reused in the production of new cells. Specialized companies carry out battery disassembly and processing according to strict environmental standards, thereby reducing the need for mining and the CO_2 emissions associated with the production of new batteries. This significantly reduces the overall environmental footprint of electric vehicles.

Waste management also plays a key role. During service and maintenance activities, technical waste such as oil, filters, coolants and electronic components is generated. These materials are classified as hazardous waste and must be disposed of according to applicable regulations, with precise records and controls. An increasing number of service centers apply certified waste treatment methods to minimize environmental impact and ensure compliance with regulatory frameworks.

Sustainable service processes represent a modern approach to reducing resource consumption and emissions. The introduction of digital service orders reduces paper consumption, while energy-efficient tools and LED lighting in workshops contribute to reducing energy consumption. Some manufacturers additionally offer carbon-neutral service packages in which emissions are offset through tree planting or investments in renewable energy projects.

Environmental responsibility education is essential for both service technicians and vehicle owners. Service personnel are trained in the proper handling of waste and materials, while customers are informed about sustainable practices. Examples include regular maintenance that extends the life of vehicles and batteries, reducing the need for premature replacements and reducing the overall environmental impact.

The environmental aspects of electric vehicle maintenance are more favorable in the use phase, but challenges remain in the production and recycling of batteries, as well as depending on the source of electricity. Further advances in battery technology, recycling and the transition to renewable energy sources are key to the sustainability of EVs. The environmental aspects of electric vehicle maintenance are thus an integral part of the concept of sustainable mobility, combining technical efficiency with the reduction of negative environmental impacts.

6.3. Economic aspects of maintenance

Electric vehicle maintenance and spare parts management has specific economic and cost challenges and advantages compared to internal combustion vehicles. The main economic benefits of EVs are lower maintenance costs, but batteries and spare parts inventory management are key cost items. Thus, the maintenance costs of electric vehicles are on average lower than the maintenance costs of vehicles with internal combustion engines, which results from their simpler mechanical structure. Electric vehicles do not have engine oil, filters, spark plugs, clutch or complex gearboxes, which significantly reduces the need for regular replacements and service interventions [67], [70]. Also, the use of regenerative braking extends the service life of the brakes, which further reduces the frequency and costs of their maintenance. However, the biggest cost challenge is the batteries, whose failure or replacement significantly increases the total costs [70], [71].

Unlike classic vehicles, with electric vehicles, major services are rarely needed, while the main costs are related to periodic checks of the electrical and cooling systems. The biggest potential expenses are associated with the battery, which is the most expensive component of a vehicle, although its lifespan is typically long and can be extended with proper maintenance and advanced energy management systems.

In addition to regular service costs, there is also a significant difference in energy costs. Electric vehicles consume electricity, the equivalent cost per kilometer of which is many times lower than the fuel consumption of conventional vehicles. This results in significant financial savings during operation, especially for vehicles used for intensive driving or in fleets.

When looking at the long-term total cost of ownership, electric vehicles show significant advantages over vehicles with internal combustion engines. Although the initial purchase price and the costs of specialized maintenance may be higher, the savings on regular services and energy lead to an overall more favorable economic balance over the vehicle's life cycle.

In conclusion, electric vehicles require specific investments in staff training and service infrastructure, but at the same time offer lower operating costs and long-term savings, which makes them more competitive and profitable in the context of sustainable transport. The management of spare parts inventories for EVs requires optimization due to high storage costs and uncertainty about failures, especially batteries [22], [70], [71].

7. Recommendations and Future Research Directions

The analysis of maintenance and spare parts management for electric vehicles shows that the biggest challenges are related to high safety requirements, specialized materials and complex logistics processes. At the same time, digitalization and technological innovations open up space for significant improvements, especially through the introduction of predictive approaches and the integration of digital solutions. Improving the maintenance system requires a combination of advanced technologies, optimization of organizational processes and strengthening of safety standards.

Technological innovations offer new opportunities for predictive maintenance. The application of artificial intelligence and machine learning enables early detection of failures and optimization of service schedules, while digital twins and IoT sensors contribute to monitoring the condition of components in real time. It is especially important to highlight the optimization of battery charging and advanced BMS functions, which directly extend the lifespan of battery systems and reduce the risk of costly interventions.

Organizational and safety aspects are equally important. Standardization of safety protocols and adaptation of workshops to the specifics of EV technology are the basis for protecting personnel and assets. Specialized training of technicians, the use of interactive diagnostic tools and the development of certification programs contribute to greater safety and efficiency. In parallel, the development of charging infrastructure and better availability of spare parts remain key factors for reducing costs and increasing system reliability.

Environmental and economic aspects further confirm the need to introduce a circular economy, remanufacturing and recycling. Such models not only reduce overall costs, but also significantly contribute to the sustainability and reduction of the ecological footprint of electric vehicles.

7.1. Recommendations for improving EV maintenance

Successful maintenance of electric vehicles requires a combination of technological solutions, organizational measures and strategic initiatives. The recommendations that follow are aimed at strengthening reliability and safety, reducing costs and increasing sustainability through digitalization and standardization of processes. Their implementation ensures more efficient management of spare parts and materials in the long term, while at the same time strengthening the environmental responsibility and competitiveness of service networks.

Based on the conducted analyses, the following key recommendations were identified:

- Implementation of digital inventory management systems, including tracking serial numbers and technical specifications of parts.
- Establishment of partnerships with certified suppliers and continuous updating of technical documentation.
- Development of predictive maintenance based on data from BMS and sensor systems.
- Organizing regular staff training on safety protocols and working with high-voltage systems.

- Introducing incentives for service centers that invest in equipment and education, and expanding local production of parts and batteries to reduce dependence on imports.
- Promoting environmental awareness among users through information campaigns and transparent maintenance data.

The greatest potential for further progress lies in digitalization, the application of predictive technologies, and the strengthening of safety and education standards. Their implementation leads to more reliable, safer, and more economical electric vehicle maintenance systems.

7.2. Open research questions

Although digitalization, predictive models and new logistics strategies have already significantly improved the maintenance of electric vehicles, numerous questions remain open and represent the basis for future research. A particular challenge is the integration of different technologies (e.g. predictive maintenance, blockchain, 3D printing) into a single and interoperable system. The long-term economic and environmental sustainability of the application of remanufacturing and the circular economy has also been insufficiently investigated, although these models are expected to significantly reduce costs and the ecological footprint. In addition, organizational and infrastructural barriers continue to slow down the wider application of digital solutions, as they require a change in business culture and significant investments in infrastructure.

Further research should focus on addressing a number of challenges (Table 7), with an emphasis on standardizing processes, ensuring interoperability of technologies and empirically measuring their long-term effects. This would lay a solid foundation for reliable, sustainable and cost-effective maintenance management of electric vehicles. Therefore, modern technologies offer significant potential for improving the management of spare parts and materials for the maintenance of electric vehicles, but further research is needed for their optimal integration and standardization.

Table 7. Key open research questions.

Research question / challenge	Rationale	Recommendations for future research directions
How to integrate multiple modern technologies (e.g. predictive maintenance, block chain, 3D printing) into a single EV spare parts management system?	Integration can bring synergistic effects, but requires standardization and interoperability of different solutions.	Develop methodological frameworks and interoperability standards for the combination of multiple technologies in a single digital ecosystem.
What are the long-term economic and environmental impacts of remanufacturing and circular economy in the EV sector?	Sustainability and cost reduction are key, but empirical data on the long-term impacts of these models are lacking.	Conduct longitudinal studies measuring the economic and environmental benefits of remanufacturing and recycling in different contexts.
How to overcome organizational and infrastructural barriers to digital transformation in spare parts management?	Changing organizational culture and significant investments in infrastructure represent the biggest obstacles.	Analyze successful implementation examples, develop change management guidelines, and identify financial support models.
How can digital tools and simulation technologies (e.g., digital twins) improve safety protocols and training of service personnel?	Safety when working with high-voltage systems remains a critical challenge, and new technologies offer potential tools for risk reduction.	Explore the effectiveness of digital twins and VR/AR technologies in training personnel and simulating critical situations.
How to ensure reliable and cost-effective availability of spare parts in conditions of global disruptions in supply chains?	Limited availability and price fluctuations cause delays and increase in maintenance costs.	Test models of local production, additive technology (3D printing), and regional supply networks.
What is the optimal way to use data from BMS and fleet management systems for predictive maintenance?	The data exists, but the question is how to best use it for reliable failure forecasts and resource optimization.	Develop advanced algorithms and standardized procedures for integrating BMS data into predictive maintenance models.

8. Conclusion

Maintenance and management of spare parts for EVs is a complex challenge involving technical, safety, logistical, environmental, and economic aspects. Analysis shows that electric vehicles offer clear advantages over internal combustion engine vehicles, particularly due to their simpler mechanical structure, lower operating costs, and smaller ecological footprint. However, unique features such as high-voltage systems, advanced battery technologies, and limited spare parts availability demand an integrated approach based on digitalization, standardization, and ongoing training of service personnel.

The greatest progress in EV maintenance is achieved through digitalization, a predictive approach and strengthening safety and education standards. The implementation of these recommendations leads to more reliable, safer and more economical electric vehicle maintenance systems. Practical recommendations highlight the implementation of predictive maintenance, improving inventory tracking and management systems, strengthening safety protocols, and developing charging infrastructure. Additionally, environmental aspects – through battery recycling, responsible waste management, and the introduction of sustainable service processes – confirm the importance of the circular economy and green solutions in this sector.

This paper highlights key research questions for future studies, including:

- How to integrate modern technologies (e.g., predictive maintenance, blockchain, 3D printing) into a unified spare parts management system?
- What are the long-term economic and environmental impacts of remanufacturing and circular economy in the EV sector?
- How to address organizational and infrastructural challenges in the digital transformation of maintenance and parts logistics?

In conclusion, the development of EV maintenance is geared towards greater reliability, safety and cost-effectiveness, with a strong reliance on digital technologies and sustainable practices. Future research should focus on the integration of innovative solutions and their standardization to ensure the long-term sustainability and competitiveness of electric mobility.

Declaration of Competing Interests

The authors declare that there are no known competing financial interests or personal relationships that could influence the work reported in this paper..

Declaration of Data Availability

Additional materials and data used in this research are available upon request. For access, please contact the corresponding author at [fuad.k@ipi.ba].

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