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END-OF-LIFE VEHICLE RECYCLING IN THE CONTEXT OF THE CIRCULAR ECONOMY

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ABSTRACT

This paper synthesises, from an industrial engineering management perspective, the recycling of end-of-life vehicles (ELVs) within the European transition towards a circular economy. The study integrates three levels of analysis: the theoretical foundations of Life Cycle Assessment (LCA) under ISO 14040 and ISO 14044, the European and Romanian legal and institutional framework built around Directive 2000/53/EC and its national transposition and an applied case study carried out at an authorised ELV collection and treatment centre in Romania, where the complete technological flow — reception, de-pollution, dismantling, sorting and recovery — is analysed for a representative vehicle (Volkswagen Golf IV). The results show that a properly organised treatment centre can reach recovery rates above 90%, approaching the EU target of 95% set by Directive 2000/53/EC. The application of quality-management tools allows critical points of the technological flow to be identified and corrective measures to be substantiated, leading to reduced hazardous-liquid losses, improved traceability of reusable parts, and shorter average vehicle processing time. The paper also offers a comparative view of emerging challenges — automotive shredder residue (ASR) and electric-vehicle battery recycling and puts forward recommendations for digitalising traceability and optimising sorting processes.

KEYWORDS: end-of-life vehicles, circular economy, life cycle assessment, automotive recycling, quality management, environmental pollution

1. Introduction

End-of-life vehicle (ELV) recycling has become a fundamental component of the global sustainable development strategy, particularly in the context of a continuously expanding automotive industry that generates substantial volumes of waste and places considerable pressure on natural resources. Each year, approximately 12–15 million vehicles reach the end of their service life within the European Union alone [8], representing not only a significant waste stream but also an important secondary source of recoverable and recyclable materials - including steel, aluminium, copper, glass, and plastics - which can be reintroduced into the economic cycle. This process contributes to reducing the consumption of virgin raw materials and mitigating environmental impacts.

From a management perspective, ELV recycling is closely aligned with the principles of the circular economy, which promote efficient resource utilization, product life extension, and the minimization of waste disposal. The implementation of efficient collection, treatment, and recovery systems contributes not only to environmental protection but also to the development of a more resource-efficient and sustainable industrial model. This perspective is increasingly supported by recent international literature, which recognizes ELV management as an emerging research field situated at the intersection of industrial engineering, waste management, and environmental policy [10, 14].

Romania has aligned its national legislative framework with European Union regulations through the transposition of Directive 2000/53/EC on End-of-Life Vehicles [3]. The directive establishes clear responsibilities for vehicle manufacturers and economic operators involved in the collection and treatment of ELVs, imposing strict environmental, safety, and traceability requirements. Consequently, automotive recycling can no longer be regarded solely as a waste disposal activity, but rather as a complex industrial process requiring rigorous planning, substantial infrastructure investments, and compliance with well-defined technical and organizational standards.

The present study aims to analyse the recycling process of end-of-life vehicles from the perspective of industrial engineering management, focusing on:

- the theoretical foundations of Life Cycle Assessment (LCA) and circular economy principles applied to the automotive sector;
- the European and Romanian legal and institutional framework governing ELV management;
- the organization and technological workflow of authorized collection and treatment facilities;
- an applied case study illustrating how these principles are implemented in the day-to-day activities of an authorized recycling operator. The primary objective is to highlight opportunities for improving both the operational efficiency and environmental performance of ELV recycling processes, thereby contributing to the achievement of national and European recycling targets.

2. Theoretical Framework of End-of-Life Vehicle Recycling

2.1. Life Cycle Assessment (LCA) According to ISO 14040 and ISO 14044 Standards

Life Cycle Assessment (LCA) is one of the most widely recognized methodologies for evaluating the environmental impacts associated with products, processes, and services throughout their entire life cycle, from raw material extraction to final disposal ("cradle-to-grave"). The methodological framework for LCA is internationally standardized through ISO 14040, which establishes the principles and general framework, and ISO 14044, which specifies the technical requirements and methodological guidelines for conducting LCA studies, emphasizing transparency, consistency, and comparability of results [1, 2].

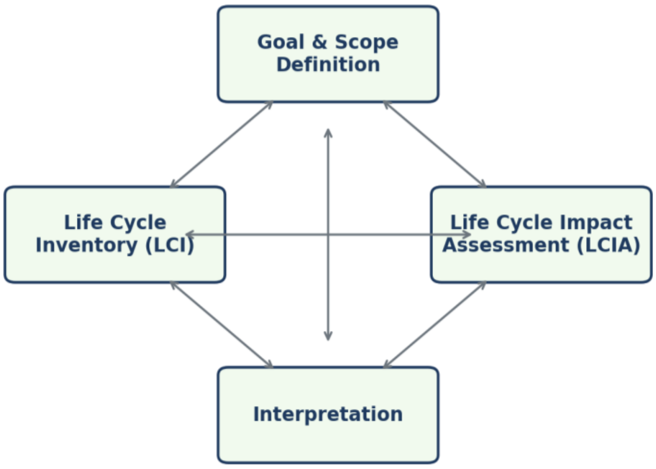

Fig. 1. *Methodological Framework of Life Cycle Assessment According to ISO 14040 and ISO 14044*

A standard LCA study comprises four interrelated phases: goal and scope definition, life cycle inventory (LCI) analysis, involving the quantification of input and output flows, life cycle impact assessment (LCIA), and interpretation of the results [1, 2]. These four phases are not strictly sequential but are connected through an iterative interpretation process, as illustrated in Figure 1.

In the automotive industry, the application of Life Cycle Assessment (LCA) is essential because vehicles are complex products characterized by high consumption of materials, energy, and natural resources. Their environmental impact is not limited to the use phase but also extends to the stages of raw material extraction, manufacturing, maintenance, and end-of-life management. Consequently, validated LCA studies are increasingly regarded as a "market passport" for automotive manufacturers, providing transparent, standardized, and comparable information on the environmental performance of vehicles throughout their entire life cycle [1, 2].

By applying the LCA methodology, different technological scenarios and design alternatives can be systematically evaluated, ranging from material selection and manufacturing processes to end-of-life vehicle (ELV) treatment and recycling strategies. This approach provides an objective scientific basis for environmental management decisions, sustainable product development, and the formulation of circular economy and sustainability policies.

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2.2. Vehicle Life Cycle

The life cycle of a vehicle encompasses all stages through which it passes, beginning with design and manufacturing, continuing through the use and maintenance phases, and concluding with end-of-life management and recycling (Figure 2). Decisions made during the design stage have a direct influence on the vehicle's recyclability, production costs, and long-term environmental impact. This principle is widely recognized in the scientific literature as Design for Recycling (DfR) or Eco-design, emphasizing the integration of environmental considerations into product development from the earliest design phases [13].

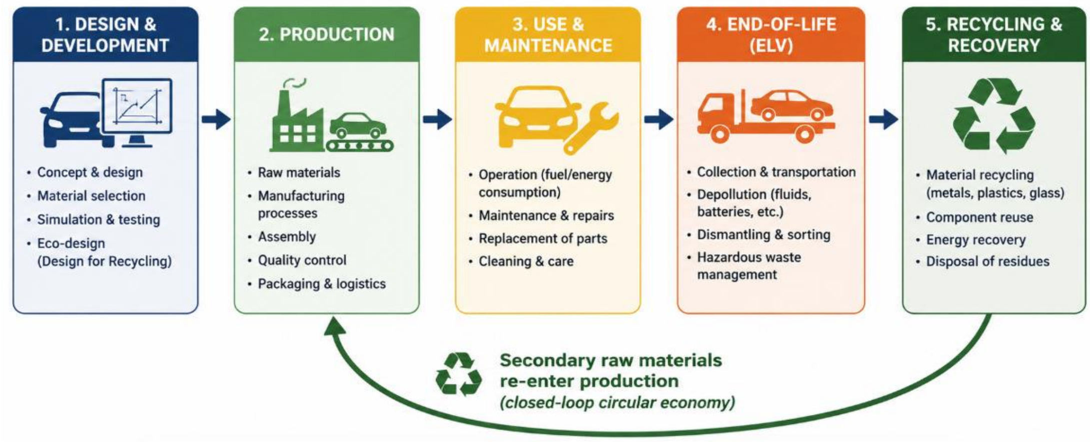

Fig. 2. *Life Cycle Stages of a Motor Vehicle, Including the Closed-Loop Reintegration of Secondary Raw Materials into the Production Process.*

The vehicle life cycle comprises the following stages:

• Design and development – during this stage, the vehicle's structural characteristics, material selection, and technological solutions are defined. Decisions made at this phase have a direct influence on the vehicle's future recyclability, resource efficiency, and overall environmental performance.

• Production – involves complex industrial manufacturing processes characterized by significant consumption of energy and raw materials, as well as the generation of emissions and industrial waste.

• Use and maintenance – the longest phase of the vehicle life cycle, encompassing fuel or energy consumption, pollutant emissions, routine maintenance, and the replacement of worn or damaged components.

• End-of-life (ELV) – the stage at which the vehicle is no longer functional or economically viable for continued operation. The vehicle is transferred to an authorized treatment facility, where a Certificate of Destruction (CoD) is issued in accordance with the applicable regulatory requirements.

• Recycling and recovery – the final stage of the life cycle, during which the vehicle undergoes depollution, dismantling, and material separation. Recoverable materials are recycled and reintroduced into the production cycle as secondary raw materials. According to European legislation, at least 95% of the average vehicle weight must be recovered, of which a minimum of 85% must be achieved through material recycling [3].

2.3. Circular Economy Applied to the Automotive Industry

The circular economy is a sustainable development model that aims to keep materials and resources in productive use for as long as possible through reuse, recycling, remanufacturing, and recovery, thereby minimizing waste generation and reducing pressure on natural resources. Unlike the traditional linear economic model ("take–make–consume–dispose"), the circular economy promotes the closing of product life cycle loops by reintegrating secondary materials into economic and industrial processes, thus improving resource efficiency and supporting long-term sustainability (Figure 3) [7, 9].

At the European Union level, the Second Circular Economy Action Plan (CEAP), adopted in March 2020 as a key component of the European Green Deal, identifies the automotive sector as one of the priority value chains, alongside electronics, batteries, packaging, textiles, and construction, owing to its significant potential for circularity [7, 9]. This strategic direction has recently been reinforced through a provisional agreement between the

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European Parliament and the Council on a new regulation governing the circularity of vehicle design, manufacturing, and end-of-life vehicle (ELV) management. The proposed regulation introduces mandatory targets for recycled plastic content in new vehicles - at least 15% within six years and 25% within ten years after its entry into force - as well as design requirements aimed at facilitating component dismantling by authorized treatment facilities [8].

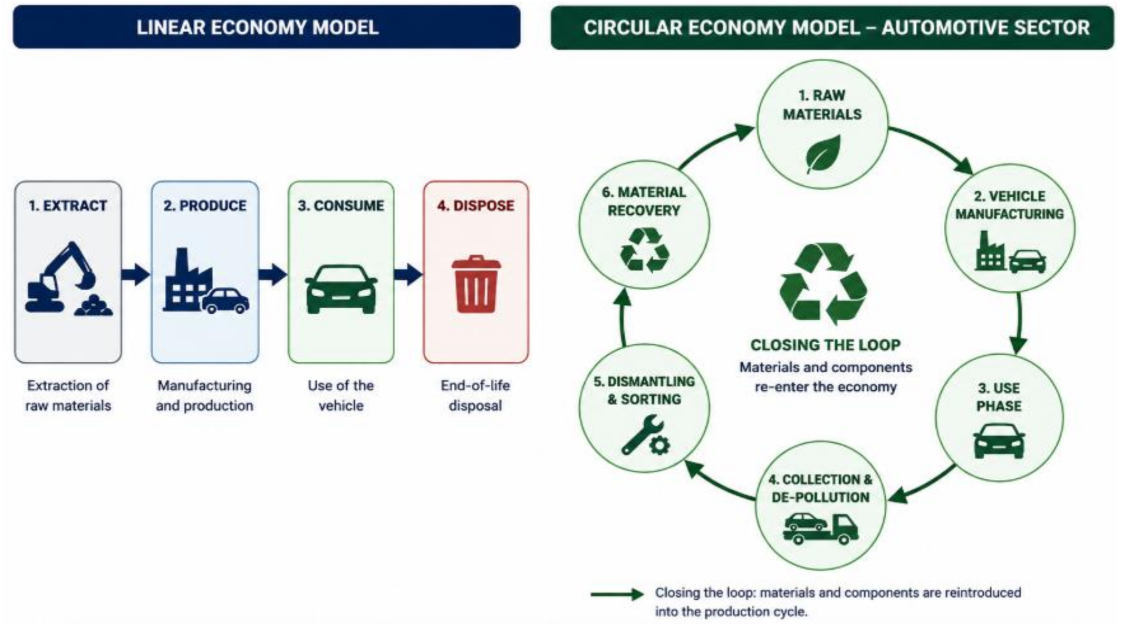

***Fig. 3**. Comparison between the Linear Economy Model and the Circular Economy Model Applied to the Automotive Industry*

End-of-life vehicles (ELVs) constitute an important source of recoverable secondary raw materials. The average material composition of a passenger vehicle (Figure 4) shows that ferrous metals account for the largest proportion of the total vehicle mass, followed by plastics, non-ferrous metals, rubber, glass, and a heterogeneous residual fraction known as Automotive Shredder Residue (ASR) [17-18, 22]. The environmental impacts associated with these materials differ considerably. In particular, the recycling of ferrous and non-ferrous metals provides substantial energy savings compared with the production of primary metals, thereby significantly reducing the climate impact and resource consumption of the automotive sector [29, 30, 32].

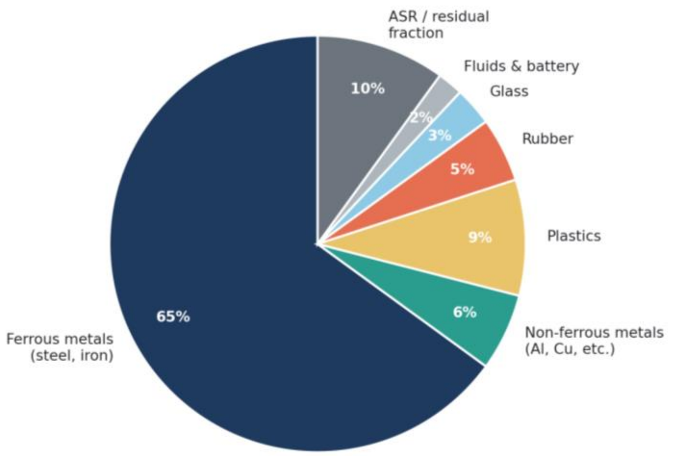

***Fig. 4.** Estimated Average Material Composition of an End-of-Life Vehicle, Expressed as a Percentage of Total Vehicle Weight*

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A clear definition of the terminology used in the field is essential for a rigorous analysis. Recycling refers to the process of converting waste materials into secondary raw materials that can be used in the manufacture of new products. Reuse involves the direct use of products or functional components without substantial industrial processing. Recovery encompasses both material recycling and energy recovery from non-recyclable waste, while treatment refers to the complete set of operations including depollution, dismantling, sorting, and preparation of materials for recycling or environmentally sound disposal [3, 4].

A comprehensive understanding of the vehicle life cycle, combined with the principles of the circular economy and the application of the ISO 14040 and ISO 14044 Life Cycle Assessment (LCA) standards, provides the theoretical foundation for end-of-life vehicle (ELV) recycling. The integration of these concepts enables the reduction of environmental impacts, improves resource and economic efficiency, and supports the transition toward a more sustainable and circular automotive sector.

3. Legal and Institutional Framework in Romania and the European Union

The collection, treatment, and recycling of end-of-life vehicles (ELVs) are governed by a comprehensive legal framework established at both the European Union and national levels. This regulatory framework aims to prevent the adverse environmental impacts associated with end-of-life vehicles, promote the efficient use of natural resources, and clearly define the responsibilities of all stakeholders involved in the management of vehicles reaching the end of their service life.

3.1. European Legislation

Directive 2000/53/EC on End-of-Life Vehicles constitutes the principal European legislative instrument governing the management of ELVs [3]. Its primary objective is to prevent waste generation from vehicles while promoting the reuse, recycling, and recovery of vehicle components and materials. Among its key provisions are restrictions on the use of hazardous substances in vehicle manufacturing - including lead, mercury, cadmium, and hexavalent chromium, except in specifically regulated applications - the obligation for vehicle manufacturers to ensure the free take-back of end-of-life vehicles, and the establishment of quantitative targets for reuse, recycling, and recovery.

The final target, applicable since 1 January 2015, requires a minimum reuse and recovery rate of 95% of the average vehicle weight, of which at least 85% must be achieved through reuse and material recycling, while the remaining fraction may be fulfilled through energy recovery [3, 17, 18, 22].

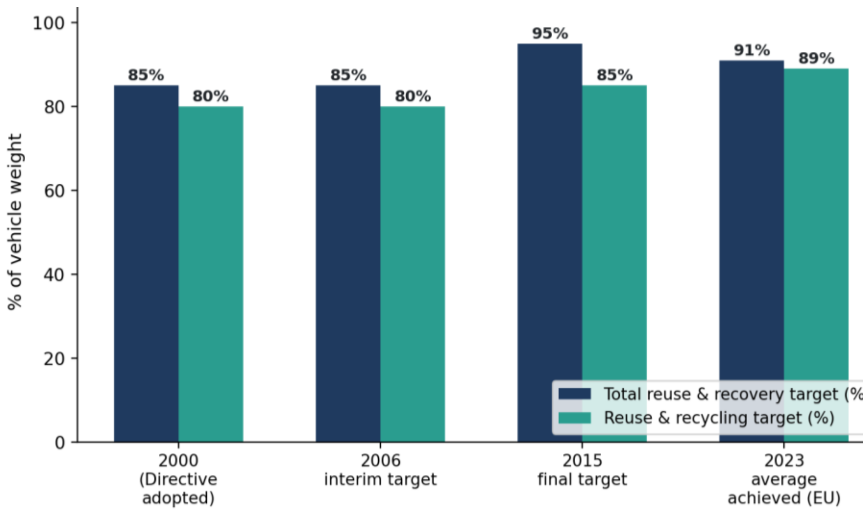

***Fig. 5.** Evolution of European End-of-Life Vehicle (ELV) Recovery and Recycling Targets Compared with the Average Recovery Rate Achieved*

The evolution of these regulatory targets, together with the average recovery rates achieved across the European Union, is presented in Figure 5. As illustrated, a persistent gap exists between the mandatory 95% recovery target and the actual average recovery performance, estimated at approximately 89–91%. According to the scientific literature, this discrepancy is primarily attributed to the difficulty of recovering the Automotive Shredder Residue (ASR) fraction, a heterogeneous waste stream that continues to be disposed of predominantly in landfills due to the limited availability of

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economically and technically viable recovery technologies [17, 18, 21].

The European regulatory framework has been substantially strengthened in recent years through the Second Circular Economy Action Plan (CEAP, 2020) [7, 9] and, more recently, through a provisional agreement (2025) between the European Parliament and the Council of the European Union on a new Regulation on Vehicle Circularity. This regulation will progressively replace Directive 2000/53/EC and introduce design requirements aimed at improving vehicle dismantlability, mandatory recycled-content targets for plastics, steel, and aluminium, as well as a strengthened Extended Producer Responsibility (EPR) framework [8].

In addition, Regulation (EC) No. 1907/2006 (REACH) governs the Registration, Evaluation, Authorisation and Restriction of Chemicals used in automotive components. The REACH Regulation has direct implications for vehicle depollution operations and the management of hazardous waste generated during the treatment of end-of-life vehicles, ensuring a higher level of environmental and human health protection throughout the recycling process [6].

3.2. National Legislation

Romania has transposed the European regulatory requirements through Law No. 212/2015 on the Management of Vehicles and End-of-Life Vehicles (ELVs) [4] and Government Emergency Ordinance No. 92/2021 on Waste Management [5]. These legislative acts establish the responsibilities of vehicle owners, manufacturers, and economic operators involved in the collection, treatment, recovery, and recycling of end-of-life vehicles, while also defining the minimum technical requirements applicable to authorized collection and treatment facilities.

The national legislation further specifies the requirements regarding the location and infrastructure of authorized treatment facilities, the mandatory equipment necessary for depollution and dismantling operations, the documentation required upon vehicle handover - including the Certificate of Destruction (CoD), the Vehicle Registration Certificate, and the Vehicle Handover Report - as well as the reporting obligations imposed on operators with respect to the competent environmental authorities.

3.3. Authorities Responsible for the Authorization and Supervision of ELV Recycling Facilities

The legal operation of an authorized end-of-life vehicle (ELV) collection and treatment facility requires the involvement of several public authorities, each exercising specific regulatory, authorization, monitoring, and enforcement responsibilities. The main institutions and their respective roles are summarized in Table 1.

From the perspective of industrial engineering management, the systematic planning of the authorization process is essential for optimizing the time, costs, and resources required to establish an end-of-life vehicle (ELV) collection and treatment facility. Each of the authorities listed in Table 1 requires specific documentation and compliance inspections, while the logical sequence of obtaining the necessary permits—urban planning approval → RAR technical authorization → environmental permit → water management permit (where applicable) → operating authorization—has a direct influence on the overall duration and efficiency of the investment project.

Table 1. *The main institutions and their respective roles in authorization and supervision of ELV Recycling Facilities*

Authority	Main Responsibilities	Issued Document / Authorization
Romanian Automotive Registry (RAR)	Technical authorization of vehicle dismantling and treatment activities	ELV Treatment Authorization issued by RAR
Environmental Protection Agency (EPA)	Assessment of environmental impacts and verification of environmental protection infrastructure	Environmental Permit (typically valid for five years)
Romanian Waters National Administration – ANAR	Regulation of water resource use and wastewater discharge	Water Management Permit
Inspectorate for Emergency Situations (ISU)	Verification of compliance with fire prevention and fire safety regulations	Fire Safety Approval / Fire Safety Permit
Local Municipality / Local Public Administration	Verification of compliance with urban planning regulations and issuance of the operating approval	Urban Planning Certificate and Operating Approval

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4. Organization of Automotive Recycling Facilities and Technological Workflow

4.1. Site Selection and Minimum Infrastructure Requirements

The selection of an appropriate site for an end-of-life vehicle (ELV) collection and treatment facility must consider several technical and regulatory factors, including accessibility for heavy vehicles, the minimum distance from residential areas, the availability of essential utilities (water supply, sewerage, and three-phase electrical power), the required site area (typically 1.000–2.000 m², depending on the treatment capacity), and the applicable urban planning and land-use regulations. Furthermore, the facility should not be in flood-prone areas, protected environmental zones, or in the vicinity of drinking water sources.

The minimum mandatory infrastructure includes an impermeable reinforced concrete platform resistant to aggressive chemical substances, a hazardous liquid collection system for waste oils, fuels, brake fluid, antifreeze, refrigerants, and battery acids, dedicated storage areas for untreated and depolluted ELVs, reusable components, and non-recoverable waste, as well as the technical equipment required for dismantling operations, such as vehicle lifts or ramps, fluid extraction systems, dismantling tools, and containers for the separate collection of recyclable materials.

5. Technological Workflow for End-of-Life Vehicle Recycling

The technological workflow of end-of-life vehicle (ELV) recycling comprises the sequence of organized operations through which a vehicle is received, treated, and recovered in accordance with safety regulations and applicable legal requirements.

Fig. 6. *Technological Workflow of an Authorized End-of-Life Vehicle (ELV) Treatment Facility*

The process includes successive stages of collection, storage, depollution, dismantling, material sorting, and resource recovery (Figure 6), with the primary objectives of minimizing environmental impacts, maximizing resource efficiency, and achieving the recycling and recovery targets established by European and national legislation.

5.1. Collection and Traceability of End-of-Life Vehicles

The collection of end-of-life vehicles (ELVs) may be carried out through several channels, including direct handover by the vehicle owner (the most common method, in exchange for a Certificate of Destruction), government incentive schemes promoting vehicle fleet renewal (e.g., the "Rabla" scrappage program), partnerships with automotive repair workshops and dealerships, or vehicle collection services for non-operational vehicles directly from the owner's premises.

Upon delivery, the vehicle owner is required to provide an identity document, the vehicle registration certificate, the vehicle identification document, and a vehicle handover protocol. In return, the authorized treatment facility issues a Certificate of Destruction (CoD), which is a mandatory document for the deregistration of the vehicle from the records of the Romanian Automotive Registry (RAR) and the Directorate for Driving Licences and Vehicle Registration (DRPCIV).

Traceability - the process through which the movement and treatment of a vehicle are monitored and documented from its reception until the completion of all treatment operations - is essential for preventing the illegal abandonment of vehicles, ensuring accurate reporting of recycled quantities, and fulfilling the obligations established under the Extended Producer Responsibility (EPR) framework. An increasing number of authorized treatment facilities are implementing digital traceability systems, enabling the electronic registration of each vehicle, the integration of supporting documentation, and the automatic generation of reports required by public authorities. These systems improve operational efficiency while ensuring regulatory compliance.

5.2. Depollution, Dismantling, and Material Sorting

Depollution constitutes the first mandatory stage of the treatment process. It involves the removal of all hazardous substances and fluids, including the remaining fuel in the tank, engine oil, transmission oil, brake fluid, power steering fluid, and engine coolant, as well as the recovery of refrigerants from air-conditioning systems. In addition, the battery - which contains sulfuric acid and lead - together with airbags, seatbelt pretensioners, filters, and other potentially hazardous components, must be safely removed before further processing. All extracted fluids are required to be stored in properly labelled, leak-proof containers in accordance with environmental regulations.

The dismantling stage aims primarily at recovering reusable components, such as engines, alternators, mirrors, windows, and alloy wheels, which can subsequently be marketed as second-hand spare parts, thereby reducing the demand for newly manufactured components produced from virgin raw materials. Components that cannot be reused are subsequently sorted according to material type - including ferrous and non-ferrous metals, plastics, rubber, glass, and electrical cables - to facilitate their efficient recycling and recovery.

5.3. Material and Energy Recovery: The Challenge of Automotive Shredder Residue (ASR)

Following the sorting process, the recovered materials are delivered to authorized recycling facilities. Ferrous and non-ferrous metals are transported to specialized smelters, plastics are processed by polymer recycling facilities, while rubber and glass are directed to dedicated recycling or recovery streams.

Metal recycling provides substantial energy savings compared with primary production from virgin raw materials. Aluminium recycling can reduce energy consumption by up to 95% compared with primary aluminium production from bauxite, copper recycling saves approximately 85%, while steel recycling typically reduces energy requirements by 60–75%, depending on the recycling technology employed (Figure 7) [29-30, 32].

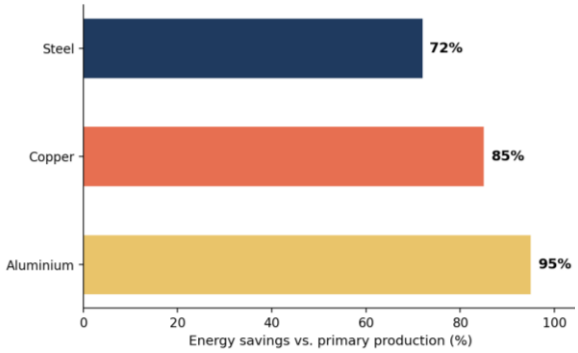

Fig. 7. *Energy Savings Achieved through the Recycling of Metals Recovered from End-of-Life Vehicles Compared with Production from Primary Raw Materials*

The fraction that cannot be recovered through mechanical sorting—Automotive Shredder Residue (ASR)—accounts, according to the scientific literature, for approximately 20–25% of the mass of a vehicle and represents the main barrier to achieving the 95% recovery target established by Directive 2000/53/EC [17, 18, 21, 22]. ASR has a heterogeneous composition, consisting of plastics, rubber, glass, textiles, foams, and metallic dust, which makes its separation and recovery using conventional technologies difficult [24, 33]. Consequently, it is currently disposed of predominantly in landfills [18, 22]. Post-shredder technologies (PSTs), based either on additional mechanical separation or on thermal treatment for energy recovery, are considered in the scientific literature to be the main solution for closing this recovery gap [17, 21].

5.4. An Emerging Challenge: Recycling of Electric Vehicle Batteries

The expansion of the electric vehicle fleet is generating a new category of waste that affects the conventional technological workflow of automotive recycling: lithium-ion batteries. Recent studies indicate that the current recycling rate of these batteries remains low, estimated at 5–10% worldwide, mainly due to the lack of standardized methods for assessing battery condition, the high costs associated with collection and transportation (since batteries are classified as hazardous waste), and the fragmented regulatory framework [23-27]. The materials recovered through battery recycling, including lithium, cobalt, nickel, and manganese, can reduce the carbon footprint of new batteries by up to 40% while decreasing dependence on critical primary raw materials, whose extraction is often associated with significant environmental and geopolitical risks

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[28]. The new European Batteries Regulation establishes mandatory recycled-content targets (at least 6% lithium and nickel and 16% cobalt by 2031) [28], which will require authorized ELV treatment facilities to progressively develop specific expertise and procedures for the safe dismantling of traction batteries, separate from the conventional depollution process.

6. Case Study: Recycling Centre

To illustrate how the theoretical principles and legal requirements presented above are implemented in practice, an end-of-life vehicle (ELV) collection and treatment centre in Romania was analysed. The facility operates in the field of waste collection and recovery, including recyclable materials originating from end-of-life vehicles. The site benefits from convenient access to the road transport network, facilitating the collection and transportation of vehicles from private individuals, economic operators, and other entities.

6.1. Application of the ELV Guideline Stages

The analysed centre implements each stage specified in the ELV Best Practice Guidelines. Vehicle collection is carried out either directly at the facility or through the company's own fleet. Each vehicle is registered in the record system and its documentation is verified before the Certificate of Destruction is issued. Depollution is performed on an impermeable platform equipped with a leakage collection system and an oil separator, where all hazardous fluids are removed and batteries and airbags are dismantled. Dismantling and material sorting are carried out by qualified personnel using dedicated equipment, including vehicle lifts, presses, and power tools. Reusable components are cleaned, labelled, and stored in a covered area, while non-reusable components are sorted according to material type. The sorted materials are delivered to authorized recycling companies, and hazardous waste is periodically transferred to specialized operators for neutralization and disposal.

Through this organization, the centre achieves a recovery rate exceeding 92%, which is reported annually to the Environmental Protection Agency, approaching the European target of 95% [3].

6.2. Practical Example: Workflow of a Volkswagen Golf IV

To illustrate the application of the ELV guideline at the individual vehicle level, the treatment process of a Volkswagen Golf IV, equipped with a 1.4-1.6 L gasoline engine complying with the Euro 3 emission standard, was analysed. The vehicle had an unladen weight of approximately 1.150 kg, was more than 20 years old, in non-operational condition due to major engine failure and severe body corrosion and did not have a valid periodic technical inspection.

Upon reception, the owner's documents and the vehicle documentation were verified, after which the centre issued the Certificate of Destruction. The depollution process consisted of removing the residual fuel, lubricating oils, and technical fluids, together with the battery and pyrotechnic components. During dismantling, several components in good condition - including the engine, radiator, and alloy wheels - were recovered for resale as second-hand spare parts, while other components, such as the windshield, side windows, and interior upholstery, were separated for glass recycling and textile/composite recycling streams, respectively. Non-ferrous metals and end-of-life tyres were also separated for dedicated recovery processes. The overall treatment of this individual vehicle confirmed that a recovery rate exceeding 90% can be achieved through the combination of complete depollution, dismantling focused on component reuse, and appropriate material sorting.

6.3. Quality Management in the ELV Treatment Process

To identify and correct operational deficiencies, the analysed centre applies the PDCA (Plan–Do–Check–Act) continuous improvement cycle.

The risks associated with the main operations of the technological workflow - depollution, dismantling, sorting, and storage - were evaluated based on the criteria of severity, probability of occurrence, and defect detectability. Among the risks identified as having high priority were the incomplete removal of brake fluid, the accidental mixing of plastic and metallic materials during the sorting process, and the improper storage of used batteries.

The causes of the identified non-conformities were determined, making it possible to move from the simple identification of symptoms (for example, hazardous liquid leaks) to the identification of their underlying causes (such as the absence of standardized inspection procedures). Based on this analysis, solutions, devices, and procedures for error prevention by design were proposed, including liquid presence sensors in collection containers, colour-coded trays for the visual sorting of plastic and metal components, and labelled containers with lockable lids for the storage of used batteries.

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Table 2. *Quality Management in the ELV Treatment Process*

Process Stage / Identified Risk	Observed Non-conformity	Proposed Solution	Type of Control
Fluid removal (depollution)	Incomplete removal of brake fluid	Liquid presence sensor in the collection container	Automatic detection
Component sorting	Accidental mixing of plastic and metal components	Colour-coded trays according to material type	Visual guidance
Storage of used batteries	Improper or non-sealed storage	Labelled containers with lockable lids	Physical and visual inspection

6.4. Recommendations and Evaluation of the Impact of the Proposed Improvements

Based on the analysis performed, the following recommendations were formulated to optimize the process: the introduction of QR codes on reusable components, connected to a centralized database, in order to improve traceability; periodic training of personnel regarding dismantling and sorting procedures; equipping the facility with automatic optical systems for the accurate sorting of materials; the complete digitalization of the traceability system, including the automatic generation of reports for the competent authorities; and the definition of key performance indicators (KPIs) specific to each stage of the process, including processing time, recovery rate, hazardous liquid loss rate, and reusable component traceability.

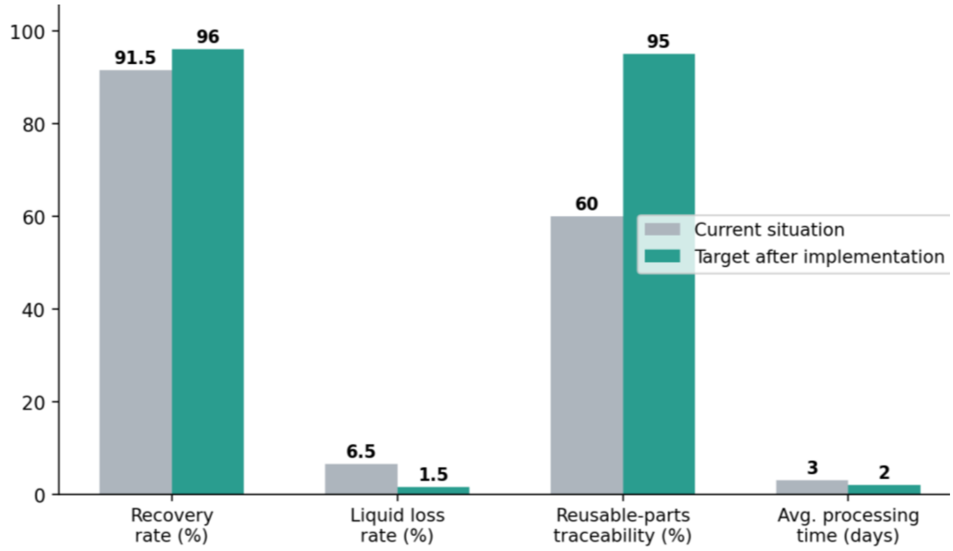

Fig. 8. *Key performance indicators of the case study before and after the implementation of the proposed improvement measures*

The evaluation of the impact of these measures, summarized in Figure 8, indicates the potential to increase the recovery rate from 91–92% to more than 95%, reduce the hazardous liquid loss rate from 5–8% to below 2%, improve the traceability of reusable components from approximately 60% to 95%, and reduce the average processing time per vehicle from 3 days to 2 days.

These results confirm that an integrated quality management approach can lead to sustainable long-term performance from economic, environmental, and operational safety perspectives.

7. Discussion: An International Comparative Perspective

Placing the Romanian case study within a broader international context reveals both common features and significant differences compared with other markets. Within the European Union, the gap between the regulated recovery target of 95% and the actual average recovery rate achieved (89–91%) is mainly attributed to the difficulty of recovering Automotive Shredder Residue (ASR), a finding confirmed by studies conducted in the United Kingdom and the Netherlands, where investments in post-shredder technologies (PSTs) remain essential for achieving the final recovery target [17-18, 21].

In Asia, a comparative analysis of China and Japan shows an expected increase in recycling rates from approximately 90% to 98% over the coming years, supported by a combination of strict regulations, technological advances, and increased public awareness regarding resource recovery [13]. In emerging economies, such as India, Malaysia, and other developing countries, the literature identifies structural barriers - including the informality of the recycling sector, ambiguous legislation concerning vehicle deregistration, and the lack of authorized treatment infrastructure - as the main obstacles to the development of a functional circular economy in the automotive sector [10-12, 16]. These findings support the idea that the success of ELV recycling depends not only on the existence of an appropriate legal framework but also on the institutional capacity to implement and consistently enforce it.

Compared with these contexts, the case study conducted at the Romanian recycling centre indicates a level of compliance and operational performance comparable to European best practices, with a recovery rate exceeding 92%, significantly above the minimum legal threshold of 85% and approaching the European target of 95%. This performance supports the argument that the rigorous implementation of legal requirements, combined with quality management tools, can partially compensate for the technological limitations associated with the recovery of the ASR fraction by maximizing reuse and material recycling in the stages preceding shredding.

One area of research and industrial practice that will become increasingly important during the next decade is the recycling of electric vehicle batteries, a field in which the current recovery rate remains considerably below its technical potential due to the technological, economic, and regulatory barriers identified in the recent literature [23-27]. In the future, authorized ELV treatment centres will need to integrate specific procedures for the safe dismantling of traction batteries, separate from the conventional depollution process applied to internal combustion engine vehicles. This development will require additional investments in equipment, personnel training, and specific authorizations.

8. Conclusions and recommendations

The recycling of end-of-life vehicles (ELVs) represents an essential component of the transition towards a circular economy and a sustainable automotive sector, playing a major role in reducing environmental impacts, conserving natural resources, and improving economic efficiency. In the context of the continuous growth of the vehicle fleet and the increasing number of vehicles reaching the end of their service life, their proper management has become a priority at both the European and national levels.

The analysis carried out in this study highlighted the following main aspects:

• ISO 14040 and ISO 14044 provide the methodological framework for Life Cycle Assessment (LCA), enabling the identification of the stages with the greatest environmental impact and supporting the adoption of technical and organizational solutions aimed at reducing resource consumption and pollutant emissions.

• The legal and institutional framework in Romania is harmonized with the requirements of the European Union, particularly through the transposition of Directive 2000/53/EC, which establishes clear recycling and recovery targets, as well as specific responsibilities for economic operators, public authorities, and vehicle manufacturers.

• The technological workflow of an authorized treatment facility - including collection, depollution, dismantling, sorting, and recovery - makes it possible to recover a significant proportion of the vehicle mass, particularly ferrous and non-ferrous metals, thereby reducing the demand for primary raw materials and the climate impact associated with industrial production processes.

• The case study conducted at the recycling centre demonstrated the practical implementation of the ELV guidelines in an authorized facility, showing that, through complete depollution, dismantling focused on reuse, and appropriate material sorting, a recovery rate exceeding 90% can be achieved, approaching the European target.

• The integration of quality management tools into the management of the ELV treatment process contributes to the continuous improvement of performance, the reduction of environmental risks, and the enhancement of operational efficiency.

• The emerging challenges facing the sector - the recovery of Automotive Shredder Residue (ASR) and the recycling of electric vehicle batteries - remain the principal technological and regulatory barriers to achieving full circularity targets, requiring additional investments in post-shredder technologies and traction battery recycling infrastructure.

The recommendations formulated in this study focus on optimizing material sorting through automatic optical systems, fully digitalizing traceability using QR codes and centralized databases, and increasing the reuse of components through the systematic cataloguing and commercialization of recovered parts. The implementation of these measures can generate multiple benefits, including reduced operating costs, increased revenues from the recovery of materials and reusable components, and improved compliance with environmental requirements.

In conclusion, the recycling of end-of-life vehicles represents not only a legal obligation but also a strategic opportunity for the development of a more efficient, responsible, and sustainable automotive sector. Through the integrated application of Life Cycle Assessment (LCA) standards, circular economy principles, and appropriate technical and quality management practices, recycling centres can make a significant contribution to environmental protection, resource conservation, and the sustainable development of the automotive industry, both in Romania and throughout the European Union.

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