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From Pathways to Portfolios: A Multi-Criteria Investment Approach to Circular EV Battery Innovation

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Abstract

This study develops an investment portfolio of circular innovation projects in the electric vehicle battery sector within the context of the sustainable transformation of the automotive industry. The central research problem concerns the allocation of limited investment resources across alternative circular pathways while simultaneously accounting for economic performance, investment risk, and social and environmental effects. The theoretical and methodological foundation of the study was established through a structured literature search organized in accordance with the PRISMA 2020 framework. A total of 5110 records published between 2010 and 2026 were identified in Scopus; following deduplication and thematic screening, 656 publications were retained for subsequent systematization. Based on the literature analysis, five classes of circular innovation projects were identified: battery diagnostics and lifetime extension; repair, refurbishment, and remanufacturing; reuse and second-life applications; collection, disassembly, and reverse logistics; and recycling and material recovery. A multi-criteria portfolio model was developed to evaluate these alternatives jointly, incorporating economic performance, investment risk, social effects, and environmental effects. The scenario-based application showed that the individual optima for the respective criteria do not coincide. The economically preferred combination includes lifetime extension, remanufacturing, and recycling, whereas the compromise solution consists of second life, reverse logistics, and recycling/material recovery. Sensitivity analysis showed that second life and recycling/material recovery remain part of the compromise portfolios under changes in the assumed investment constraint. The findings support a shift from selecting a single circular pathway toward forming a portfolio of complementary innovation directions, enabling the alignment of economic, social, and environmental sustainability priorities and creating conditions for the sustainable innovative development of automotive enterprises.

Keywords: circular economy; electric vehicle batteries; circular innovation; investment portfolio; multi-criteria optimization; second life; reverse logistics; recycling; sustainability; sustainable innovation development; PRISMA 2020

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1. Introduction

The automotive industry is undergoing a structural transformation driven by the combined effects of technological innovation, transport decarbonization, digitalization, and the transition toward more resource-efficient models of production and consumption. The proliferation of electric vehicles is one of the most visible manifestations of this transformation. However, the shift from internal combustion engine vehicles to electric mobility is changing not only vehicle technology architecture but also the structure of value chains within the automotive industry. Battery systems are becoming increasingly important, while their production, use, and end-of-life management create new technological, economic, and environmental challenges for automotive enterprises and other actors within the associated industrial ecosystem. Under these conditions, the innovative development of automotive enterprises is becoming increasingly linked to the formation of sustainable industrial systems based on improved resource efficiency, closed material loops, and the preservation of economic value across different stages of the product life cycle.

Particular importance is attached to the management of batteries after the end of their first use in electric vehicles. The residual technical and economic value of batteries creates opportunities to move from a linear "production–use–disposal" model toward a circular system encompassing diagnostics and lifetime extension, repair, refurbishment, reuse, repurposing for stationary energy storage applications, recycling, and the reintegration of recovered materials into production processes. A systematic analysis of the literature indicates that these pathways have already developed into a distinct field of research: alongside recycling, substantial attention is devoted to second-life applications, reuse and repurposing, remanufacturing, reverse logistics, and closed-loop supply chains.

At the same time, circular battery management is increasingly moving beyond a purely environmental or technological perspective. Existing studies show that the implementation of circular battery pathways requires changes in business models, inter-organizational relationships, value creation and value capture processes, reverse flows, and interactions among automotive manufacturers, battery companies, recyclers, energy firms, and public institutions [1–12]. In particular, the transition toward second-life, remanufacturing, and closed-loop models may generate new products and services, reshape production and logistics processes, foster new partnerships, and create additional revenue streams. Circular projects in the EV battery sector can therefore be regarded not only as instruments for improving resource efficiency and reducing waste but also as mechanisms of sustainable innovation-driven transformation for automotive enterprises and related industrial value chains.

In this study, enterprise innovative development is understood as the outcome of interconnected technological, product, process, organizational, business-model, and environmental changes arising from the development and implementation of circular innovation projects. This perspective shifts the research focus from an individual battery recycling technology toward a broader question: how can a portfolio of projects related to lifetime extension, reuse, refurbishment, recycling, and material recovery influence the development trajectory of an enterprise and its position within the emerging circular ecosystem of the automotive industry?

However, the implementation of such transformation requires substantial financial resources. Alternative circular projects differ in terms of cost, expected returns, implementation timelines, technological and market risks, environmental and social outcomes, and their capacity to preserve the material value of batteries. Studies examining the economic viability of recycling, remanufacturing, and second-life projects indicate that outcomes depend considerably on project scale, logistics, supply chain configuration, labor intensity, the

technologies employed, and market conditions [4,13–16]. Consequently, the environmental desirability of a circular project does not in itself imply investment attractiveness.

This issue becomes particularly important under conditions of constrained investment resources. An enterprise or investor must decide not only whether an individual project is economically viable but also which projects should be included in an investment portfolio and how capital should be allocated among competing alternatives. This level of decision-making differs fundamentally from the traditional techno-economic assessment of a single project. It requires the simultaneous consideration of returns, risk, and non-financial outcomes, as well as the reconciliation of the interests of different participants in the circular battery ecosystem.

In this context, portfolio allocation of investment capital across alternative innovation projects becomes especially relevant. Investment decisions related to circular EV battery projects are made under resource constraints and in the presence of differences in project cost, expected return, technology-cycle duration, and risk. These conditions provide a methodological basis for applying a portfolio perspective to the financing of circular innovation projects in automotive enterprises and for treating investment capital as a resource that enables the corresponding transformation.

At the same time, reliance exclusively on financial criteria when selecting such projects may result in decisions that are inconsistent with the logic of circular and sustainable transformation. Existing studies apply multi-objective optimization, multi-criteria decision-making (MCDM), game theory, mathematical programming, and Pareto optimization to the selection of recycling technologies, the design of closed-loop supply chains, the organization of battery collection systems, and the identification of optimal end-of-life pathways [17–22]. Recent research is gradually expanding the range of criteria considered and increasingly incorporates environmental and social effects alongside economic outcomes. Nevertheless, the principal objects of optimization remain technologies, logistics networks, collection modes, or individual end-of-life pathways rather than portfolios of circular innovation projects at the enterprise level.

The systematic literature review conducted in accordance with the PRISMA 2020 framework further clarified this research gap. The analysis of the retained literature corpus showed a high prevalence of studies focused on economic assessment, management, and decision-making, whereas studies directly integrating circularity, investment portfolio formation, and enterprise innovative development were considerably less common.

The existing literature can be grouped into several relatively distinct research streams. The first focuses on recycling, second life, reuse, remanufacturing, and environmental performance assessment. The second addresses circular business models, stakeholder interaction, and the innovation-driven transformation of value chains. The third concentrates on economic feasibility, investment decision-making, and multi-criteria optimization. However, the integration of these streams within a unified investment decision-making framework remains limited. No integrated approach was identified in the reviewed corpus for forming an investment portfolio of circular innovation projects in automotive enterprises in which economic performance, investment risk, social effects, and environmental effects are considered simultaneously when allocating limited investment resources across different circular pathways.

Against this background, the aim of this study is to develop a multi-criteria approach to forming an investment portfolio of circular innovation projects in the EV battery sector that reconciles economic performance, investment risk, social effects, and environmental effects under conditions of limited investment resources. The implications of the resulting portfolio decisions for the sustainable innovative development of automotive enterprises are subse-

quently interpreted through the substantive characteristics of the selected circular pathways and the associated technological, process, organizational, and business-model changes.

To achieve this aim, the study addresses the following research objectives: to systematize the main types of circular innovation projects in the EV battery sector; to identify the criteria used for their economic, social, and environmental assessment; to adapt a portfolio approach to the allocation of investment capital among alternative circular projects; to develop a multi-criteria project-selection model incorporating returns, risk, social outcomes, and environmental outcomes; to conduct a scenario-based application of the model; and to interpret the implications of the resulting portfolio decisions for the sustainable innovative development of the enterprise.

The scientific contribution of the study is threefold. First, circular EV battery projects are conceptualized as pathways of sustainable innovation-driven transformation for automotive enterprises, associated with technological, process, organizational, business-model, and environmental changes. Second, the investment perspective on the circular economy is extended by shifting from the assessment of the economic viability of individual projects toward portfolio formation under capital constraints. Third, economic performance, investment risk, social effects, and environmental effects are integrated within a single decision-making framework. Circularity is embedded in the substantive content of the investment alternatives rather than introduced as an independent optimization criterion, while the relationship between the resulting portfolio solutions and sustainable innovative development is addressed through substantive interpretation. The contribution of the study therefore does not lie in introducing a new optimization algorithm. Rather, it lies in reformulating circular EV battery investment as a portfolio-level decision problem and integrating circular innovation pathways, constrained investment allocation, and sustainable enterprise development within a single analytical framework. More specifically, the methodological distinction of the present study lies in the level and structure of the decision problem rather than in the optimization algorithm itself. Existing MCDM studies in the EV-battery field predominantly rank individual technologies, end-of-life pathways, collection modes, or supply-chain configurations, while conventional portfolio models generally assume a predefined set of comparable investment projects. In contrast, the present framework first derives a set of circular innovation project classes from the structured literature analysis and then treats these heterogeneous circular pathways as competing and complementary objects of constrained portfolio selection. The model therefore connects pathway classification, portfolio formation, and multi-dimensional sustainability assessment within a single decision sequence. This should be understood as a methodological adaptation and integration of established tools to a different decision object, rather than as the introduction of a new optimization method.

Accordingly, this study advances the existing discussion on the circular transformation of the battery ecosystem from the question of "which battery management pathway is the most effective?" toward a broader managerial question: "which combination of circular innovation projects provides the most balanced investment decision in terms of economic performance, risk, social effects, and environmental effects, and what conditions can such a portfolio create for the sustainable innovative development of an automotive enterprise?" Addressing this question provides the foundation for the subsequent sections of the study.

2. Literature Review

To establish the theoretical foundation of the study, a structured search of the scientific literature was conducted in accordance with the PRISMA 2020 framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). This approach ensured a transparent sequence of record identification, deduplication, and screening and provided a

reproducible basis for the subsequent thematic analysis of research on circular applications of electric vehicle batteries [23].

The search was conducted in the Scopus database using three complementary search streams. The first stream provided broad coverage of research on the circular life cycle of EV batteries; the second focused on the investment, economic, and managerial dimensions of relevant projects; and the third addressed innovation, enterprise transformation, and the development of circular business models. In total, 5110 records were identified. After the removal of 1557 duplicate records, 3553 unique publications remained for screening. Following the assessment of titles, abstracts, and keywords, 2897 publications that did not meet the thematic relevance criteria were excluded, while 656 publications were retained for further thematic assessment.

The detailed search queries, inclusion and exclusion criteria, deduplication procedure, and subsequent screening process conducted in accordance with PRISMA 2020 are presented in Section 3. In the present section, the search results are used primarily to systematize the major research streams and to identify the research gap addressed by this study. Importantly, the 656 publications represent the analytical corpus retained after title, abstract, and keyword screening rather than the final number of studies included following full-text eligibility assessment.

To structure the literature review, the following research questions were formulated:

- RQ1. Which circular pathways are addressed at different stages of the electric vehicle battery life cycle?
- RQ2. Which economic, environmental, and social indicators are used to evaluate the corresponding circular projects?
- RQ3. How are circular projects associated with technological, product, process, organizational, and business-model innovations within enterprises?
- RQ4. How is the economic viability of circular EV battery projects assessed, and how are investment decisions formulated under resource constraints?
- RQ5. Which multi-criteria decision-making and optimization methods are applied to the selection of alternative circular solutions?
- RQ6. What research gaps remain in integrating investment decision-making, circularity, and the innovative development of automotive enterprises?

The distribution of publications that passed the initial thematic screening indicates a substantial acceleration in the development of this research field. Prior to the mid-2010s, relevant studies were relatively scarce, whereas since 2020 there has been a sustained increase in scholarly interest in second-life applications, recycling, closed-loop supply chains, and circular business models for electric vehicle batteries.

The strongest full-year growth occurred during 2023–2025: the number of publications in the analyzed corpus increased from 85 in 2023 to 123 in 2024 and 130 in 2025. A further 123 publications had been indexed in 2026 as of 16 August 2026. Because the 2026 observation covers only a partial year, it should not be directly compared with the complete annual counts for previous years. The annual publication dynamics of the records retained after thematic screening are presented in Figure 1.

2.1. Circular Pathways Across the Electric Vehicle Battery Life Cycle

The results of the literature synthesis indicate that research on the circular life cycle of electric vehicle batteries extends well beyond end-of-life recycling. The literature identifies a range of interconnected pathways aimed at preserving and recreating value, including lifetime extension, diagnostics, repair, refurbishment, remanufacturing, reuse, repurposing, second-life applications, recycling, and the reintegration of recovered materials into production processes.

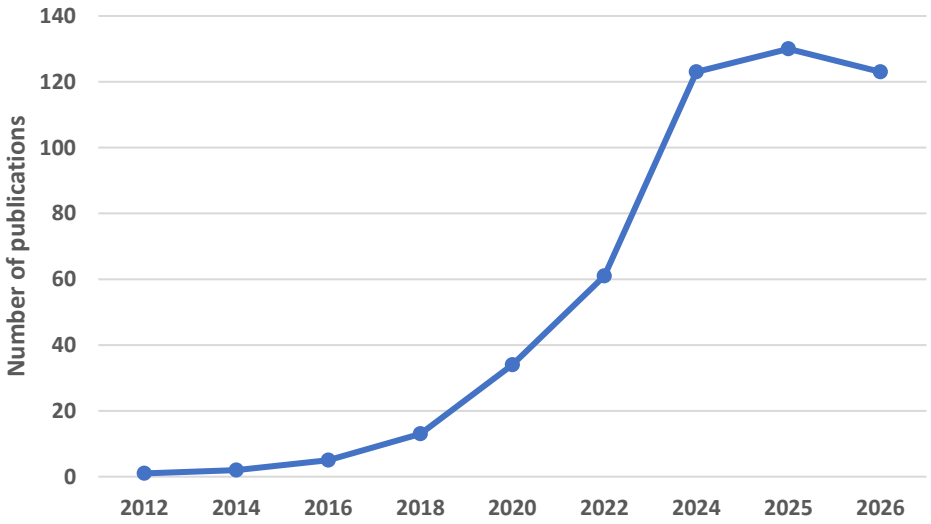


Figure 1. Dynamics of Publications on Circular EV Battery Research. Note: The figure presents publications retained after screening based on titles, abstracts, and keywords (n = 656).

Recycling is the most extensively represented pathway in the analyzed corpus, with 526 publications. A substantial body of research also addresses end-of-life management (308 publications), second life (212), reuse/repurposing (189), reverse logistics and closed-loop systems (122), disassembly/collection (108), remanufacturing/refurbishment (90), and life extension/diagnostics (51). These categories are not mutually exclusive, as a single publication may address several circular pathways simultaneously. The distribution of publications across the principal circular pathways is summarized in Figure 2.

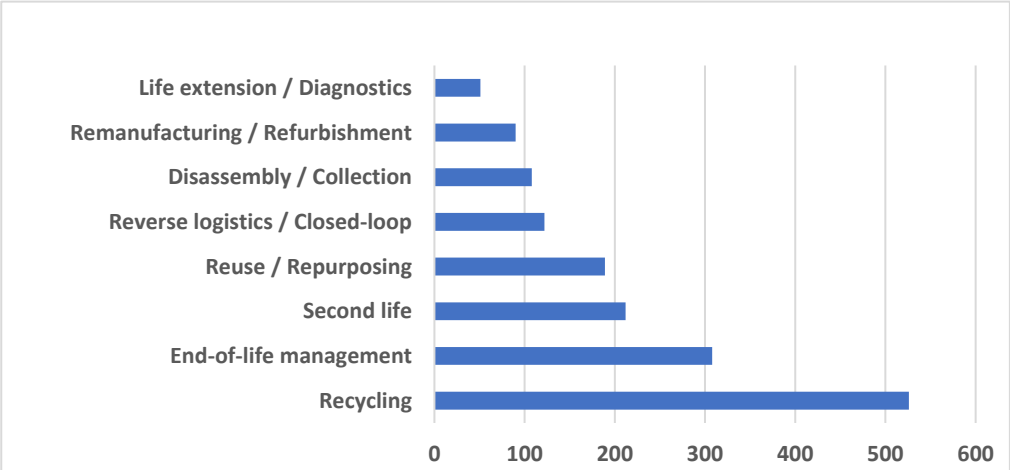


Figure 2. Main Circular Pathways in EV Battery Research. Note: The categories overlap; a single publication may be assigned to multiple circular pathways.

This structure of the literature confirms that circularity within the battery ecosystem should not be understood as a single end-of-life treatment process but rather as a set of alternative managerial and technological pathways spanning the battery life cycle.

Olsson et al. [1] consider second-life EV batteries not only as a means of reducing waste generation but also as a driver of changes in the value chain itself. The authors show that the transition toward second-life applications requires new business models, inter-organizational collaboration, and the overcoming of organizational and cognitive barriers.

Reinhardt et al. [2,3] demonstrate that battery reuse can generate economic, environmental, and social value simultaneously, although existing business models often remain

primarily focused on economic benefits. Their subsequent work develops the concept of sustainable business model archetypes, providing a framework for combining economic value creation with environmental and social outcomes.

At the same time, the literature indicates that there is no universally optimal end-of-life pathway. Wang et al. [17], using multi-objective optimization, examine the trade-off between the first and second life of batteries and identify a set of Pareto-efficient solutions. Seika and Kubli [21] analyze repurposing and recycling as competing alternatives and show that regulatory support for one pathway can affect the economic conditions under which the other develops.

Accordingly, the answer to RQ1 is that the circular EV battery ecosystem is formed by a combination of several interconnected pathways, creating a need for selection and resource allocation among alternative circular options.

2.2. Circular Business Models and the Innovative Development of Enterprises

The second stream of the literature reflects a gradual shift in research attention from battery treatment technologies toward the enterprise and its business model.

Albertsen et al. [5], in their analysis of the practices of European vehicle manufacturers, show that repair, refurbishment, and repurposing are implemented through different organizational models, with the degree of manufacturer involvement and the nature of interactions among value-chain participants playing a significant role.

Wrålsen et al. [6] identify government regulation, financial viability, and the involvement of key stakeholders—particularly public authorities and vehicle manufacturers—as important factors shaping the development of circular business models.

The study by Chirumalla et al. [7] is particularly relevant, as it conceptualizes a circular business opportunity as the outcome of multi-stakeholder circular business model innovation. The authors distinguish the stages of initiation, ideation, testing, and implementation and associate the development of a new business model with the simultaneous creation of value for firms, partners, society, and the environment.

Schulz-Mönninghoff et al. [8] shift the analysis to the level of business processes within automotive enterprises and demonstrate that material circularity depends on coordinated changes in product development, supply chains, production, end-of-life management, and business models. This is particularly important for the present study because it indicates that circular transition cannot be confined to the environmental function of the enterprise. Its implementation requires changes across multiple elements of the management system.

In recent studies, this perspective has increasingly been developed through an ecosystem approach. Chirumalla et al. [9] identify different circular business model archetypes and forms of collaboration within the EV battery ecosystem; Toorajipour et al. [10] analyze the challenges and enablers associated with implementing second-life business models at the ecosystem level; and Furtado et al. [11] demonstrate the context-specific nature of their development. In a more recent study, Xu et al. [12] propose a comprehensive typology of circular business models for the battery closed-loop supply chain, including battery leasing, remanufacturing, repurposing, recycling, repairing, refurbishing, and technology-led models.

Accordingly, circularity becomes a source not only of reduced resource losses but also of new products, processes, technologies, partnerships, and mechanisms of value creation. On this basis, circular EV battery projects can be interpreted as instruments of enterprise innovation-driven transformation. The main innovation-related changes associated with the identified circular project types are summarized in Table 1.

Table 1. Relationship between Circular EV Battery Projects and Areas of Enterprise Innovation.

Circular Project	Nature of Innovation-Related Changes Identified in the Literature
Life extension/diagnostics	Technological and process innovations; new service models
Repair/refurbishment	Technological, process, and service-related changes
Remanufacturing	Technological restructuring of production processes; changes in the supply chain
Second-life applications	New products and markets; new business models; cross-industry partnerships
Recycling	Technological innovations; closed-loop production; new forms of interaction between OEMs and recyclers
Material recovery	Process and environmental innovations; reintegration of secondary materials into production
Closed-loop/reverse logistics	Organizational and supply-chain innovations
Circular business models	Changes in value creation, value delivery, and value capture mechanisms

Note: The table does not imply that all types of innovation are inherently present in each project; rather, it reflects the areas of change that are directly traceable in the selected literature.

Within the corpus of 656 publications, the thematic tag innovation was identified in 142 studies, compared with 470 publications tagged as business/management, 515 as economic, and 395 as decision/optimization. This distribution indicates that innovation-related issues are clearly present within the research field but remain less prominent than the economic and managerial dimensions.

Moreover, the specific term innovative development is used only rarely in relation to enterprises within the selected corpus, whereas more specific categories such as business model innovation, technological innovation, process innovation, innovation ecosystem, and collaborative innovation occur more frequently. This leads to an important intermediate conclusion regarding RQ3: although the literature provides substantial insight into individual forms of innovation associated with the circular transition, it addresses them far less often as an integrated process of enterprise innovative development.

2.3. Economic Viability and Investment Decision-Making for Circular Projects

The third stream of the literature focuses on the economic assessment of circular EV battery projects. Existing studies show that the environmental desirability of a circular solution does not, in itself, guarantee its economic viability.

Li et al. [4] examine a cost-effective supply chain for EV battery remanufacturing and demonstrate the potential for increased profitability under an appropriately configured closed-loop supply chain. Lander et al. [14] show that the financial viability of recycling depends on transportation costs, labor costs, battery architecture, and the recycling technology employed.

Lieskoski et al. [16] demonstrate that alternative second-life utilization pathways differ in their economic performance: more extensive battery disassembly may reduce project attractiveness because of the high labor intensity associated with diagnostics and disassembly. Chaianong et al. [15] further show that the economic performance of recycling facilities depends on scale, battery chemistry, technological development, and market volatility.

Particularly relevant to the present study is the work of Schulz-Mönninghoff and Evans [13], which examines the economic viability of a real-world battery repurposing project. The authors identify several conditions necessary for project viability, including the development of a product platform, the analysis of multiple value-creation streams,

the management of residual resource value, quality assurance, monitoring of downstream markets, access to capital, and the implementation of pilot projects.

Thus, the literature provides a relatively well-developed basis for assessing whether an individual circular project is economically viable. A substantially less developed question, however, concerns how limited investment resources should be allocated across multiple alternative circular innovation projects.

This distinction is central to RQ4. Economic feasibility assessment addresses the viability of an individual project, whereas portfolio investment decision-making requires identifying which combination of projects should be financed under capital constraints and competing objectives related to economic performance, risk, environmental effects, and social effects. In the reviewed literature, these two decision problems are predominantly addressed separately.

2.4. Multi-Criteria Decision-Making and Optimization

The fourth stream of the literature reflects a gradual transition from conventional cost assessment toward multi-criteria decision-making models. Within the selected corpus, 395 publications exhibit a decision- and/or optimization-oriented focus.

The methods applied include multi-objective optimization, multi-criteria decision-making (MCDM), game theory, mathematical programming, Pareto optimization, scenario analysis, system dynamics, and robust optimization. Wang et al. [17] use multi-objective optimization to determine the transition point between the first and second life of EV batteries. Bhuyan et al. [18] apply a multi-stakeholder, multi-criteria decision-making approach to evaluate the battery recycling industry, while Zhang et al. [19] and Chen et al. [20] employ game-theoretic and policy-oriented models to analyze the organization of collection and recycling systems for retired EV batteries.

Recent models increasingly incorporate economic, environmental, and social objectives simultaneously. Çakır and Serdarasan [22] propose a multi-objective approach to the design of a circular supply chain for EV batteries, reflecting a broader shift from conventional cost minimization toward sustainability-oriented decision-making.

At the same time, the stakeholder perspective is becoming more prominent. Yao et al. [24], examining interactions between electric vehicle manufacturers and battery recyclers, show that innovation outcomes depend on the structure of technological interaction and incentives for cooperation. More recent studies extend this logic to the level of innovation ecosystems and governance [25].

However, the object of optimization is still most often a recycling technology, recycling network, collection mode, facility location, end-of-life pathway, reverse logistics system, or the transition point to a battery's second life. Considerably less attention is given to a set of alternative innovation projects at the enterprise level considered as an investment portfolio. Accordingly, the answer to RQ5 is that the necessary mathematical tools are already well established in the literature, but they are applied primarily to technological and logistics decisions and much less frequently to portfolio investment decisions.

Accordingly, the present study adopts established multi-criteria optimization tools as decision-support instruments and does not claim algorithmic novelty. The research contribution is instead associated with the formulation of the decision problem, the portfolio-level object of selection, and the integration of circular innovation with investment allocation and sustainable enterprise development.

2.5. Systematization of the Research Gap

At the final stage of the review, the findings from the individual research streams were compared and synthesized. This systematization makes it possible to distinguish

well-developed combinations of research components from those in which integration remains limited. The resulting synthesis of the research gap is presented in Table 2.

Table 2. Research Gap Matrix.

Combination of Research Streams	Representation in the Analyzed Corpus	Conclusion
Circularity + environmental assessment	High	A substantial body of LCA and sustainability studies has been established
Circularity + economic assessment	High	Cost and techno-economic models are widely represented
Circularity + business/management	High	Circular business models and supply-chain approaches are actively developing
Circularity + policy/governance	Medium–high	Considerable attention is devoted to EPR, regulation, and stakeholder coordination
Circularity + MCDM/optimization	Medium	These methods are actively applied to technologies, networks, and circular pathways
Circularity + innovation	Medium	The literature predominantly addresses individual technological and business-model innovations
Circularity + investment allocation	Low	Assessment of individual projects dominates over capital allocation across alternatives
Circularity + investment portfolio	Very Low	Portfolio-based approaches remain limited
Circularity + innovative development of enterprises	Low	Innovation is examined in a fragmented manner, while an integrated enterprise development trajectory is rarely formalized
Investment portfolio + circularity + enterprise innovative development	No integrated approach identified	Potential research gap addressed by the present study

The results of the systematization indicate that the existing literature provides a relatively detailed account of technological pathways such as recycling, second life, reuse, and remanufacturing, as well as the development of closed-loop supply chains and circular business models, the environmental and economic assessment of individual projects, and the application of multi-criteria methods to the selection of technological and logistics solutions.

At the same time, three research streams remain largely disconnected. The first concerns circularity and sustainability assessment; the second focuses on business model innovation and the innovation-driven transformation of enterprises; and the third addresses economic assessment, investment decision-making, and optimization. Their integration within a single analytical framework remains considerably less developed.

Accordingly, the research gap addressed in this study can be formulated as follows: despite the growing body of research on circular business models, second-life and recycling projects, economic assessment, and multi-criteria optimization, the analyzed literature does not reveal an integrated approach to forming an investment portfolio of circular innovation projects for automotive enterprises that simultaneously accounts for economic performance, investment risk, social effects, and environmental effects when allocating limited capital across alternative circular pathways. The relationship between such portfolio decisions and

the sustainable innovative development of enterprises also remains weakly formalized in the existing literature and therefore requires separate substantive interpretation.

This gap provides a logical transition to the subsequent original contribution of the study: circular EV battery projects are treated as mechanisms of enterprise innovative development, investment financing is considered a means of providing the resources required for the corresponding transformation, and the multi-criteria portfolio model is used as an instrument for selecting and reconciling alternative projects.

3. Materials and Methods

3.1. Research Design and PRISMA 2020-Based Literature Search Procedure

The research design combines a structured analysis of the scientific literature with subsequent economic and mathematical modeling of investment decisions. In this study, the literature corpus is used not only to characterize the state of the research field but also as the basis for identifying classes of circular innovation projects, defining the dimensions of their assessment, and formulating the investment portfolio problem. Accordingly, the study is implemented in four interrelated stages: (1) identification and thematic screening of publications; (2) classification of circular project alternatives and the criteria used to assess them; (3) development of a multi-criteria investment portfolio model; and (4) scenario-based comparison and robustness assessment of the resulting decisions.

To structure and transparently report the search and screening stages of the review, the study follows the PRISMA 2020 framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), while the search strategies are documented with reference to the PRISMA-S recommendations for reproducible reporting of literature searches [23,26]. In the present study, PRISMA 2020 is used specifically as a framework for documenting the identification and screening stages rather than as an independent method of substantive literature analysis.

The literature search and bibliographic data export were conducted in the Scopus database on 16 August 2026. The search period covered 2010–2026. Prior to export, restrictions were applied by language and document type: only English-language publications classified as Articles or Reviews were included in the working dataset. The exported records contained, among other fields, publication titles, abstracts, author and indexed keywords, DOI information, and Scopus EIDs, enabling deduplication and thematic screening on a unified bibliographic basis.

To improve search coverage, three complementary search streams were employed. The first was designed to provide broad coverage of research on the circular life cycle of EV batteries; the second focused on economic, investment, and optimization-related aspects; and the third addressed innovation, enterprise transformation, and circular business models. The use of multiple search streams was intentional: their partial overlap increased the likelihood of identifying relevant publications, while duplicate records were subsequently removed during the deduplication stage. The exact search strings are presented in Table 3.

A total of 5110 records were exported across the three search streams: 3477 from Stream A, 1278 from Stream B, and 355 from Stream C. Because the search streams partially overlapped, deduplication was performed prior to substantive screening. Scopus EID was used as the primary identifier and was available for all 5110 exported records. After the removal of 1557 duplicate records, a dataset of 3553 unique publications was obtained for thematic screening.

Screening was conducted on the basis of titles, abstracts, author keywords, and indexed keywords using predefined relevance criteria. A publication was retained in the analytical corpus only if all three of the following conditions were met: (1) electric vehicle or automotive batteries constituted the central object of the study; (2) at least one circu-

lar life-cycle pathway was addressed, including lifetime extension, repair, refurbishment, remanufacturing, reuse/repurposing, second life, collection and disassembly, reverse logistics/closed-loop systems, recycling, or material recovery; and (3) the study included at least one analytical dimension relevant to the objectives of the article, namely an economic/financial, managerial, regulatory, innovation-related, socio-environmental, or decision-making and optimization dimension.

Table 3. Scopus Search Strategies.

Search Stream	Purpose	Scopus Search String
Stream A—Circular EV Battery Core	Broad coverage of the circular life cycle of EV batteries	TITLE-ABS-KEY((“electric vehicle*” OR “electric mobility” OR electromobility) AND (batter* OR “lithium-ion batter*” OR “Li-ion batter*”) AND (“circular economy” OR circularity OR recycl* OR reuse OR repurpos* OR “second life” OR “second-life” OR refurbish* OR remanufactur* OR repair* OR “material recovery” OR “closed-loop”)) AND PUBYEAR > 2009 AND PUBYEAR < 2027
Stream B—Investment and Decision-Making	Identification of investment, financial, and optimization-oriented studies	TITLE-ABS-KEY((“electric vehicle*” OR “electric mobility” OR electromobility) AND (batter* OR “lithium-ion batter*”) AND (“circular economy” OR circularity OR recycl* OR reuse OR repurpos* OR “second life” OR remanufactur*) AND (invest* OR financ* OR “venture capital” OR “green finance” OR portfolio OR “investment decision*” OR “project selection” OR optim* OR “multi-objective” OR “multi-criteria” OR MCDM)) AND PUBYEAR > 2009 AND PUBYEAR < 2027
Stream C—Innovative Development	Identification of publications on innovation, enterprise transformation, and circular business models	TITLE-ABS-KEY((“electric vehicle*” OR “EV batter*” OR “electric vehicle batter*”) AND (“circular economy” OR circularity OR “circular business model*” OR “closed-loop” OR “second life” OR repurpos* OR remanufactur* OR recycl*) AND (innovation OR “business model innovation” OR “process innovation” OR “product innovation” OR “organizational innovation” OR eco-innovation OR “technological innovation” OR “enterprise development” OR “firm development” OR transformation)) AND PUBYEAR > 2009 AND PUBYEAR < 2027

Publications were excluded if EV or automotive batteries were not the central object of analysis; if they focused primarily on materials chemistry or individual technological processes without an economic, managerial, or assessment dimension; if they addressed charging, battery management systems, or control algorithms without a connection to the circular life cycle; if they focused on primary raw-material extraction without linking it to subsequent battery circularity; or if circularity primarily concerned non-battery vehicle components. The final distribution of exclusion reasons is presented in Table 4.

As a result of the thematic screening, 2897 of the 3553 unique publications were excluded, while 656 publications were retained as the analytical corpus for subsequent thematic systematization and for establishing the methodological basis of the model. This corpus was used to identify the principal circular pathways, groups of assessment criteria, and research streams presented in Section 2.

Table 4. Reasons for Excluding Publications at the Title/Abstract Screening Stage.

Reasons for Excluding Publications	*n*
EV/automotive batteries are not the central object of the study	1231
Predominantly technical research on battery chemistry or individual processes without the required analytical dimension	388
The circular/end-of-life pathway is not a central focus of the study	366
No economic, managerial, policy-related, innovation-related, or assessment dimension is present	317
Insufficient direct relevance following title/abstract screening	251
Charging, battery management systems (BMS), or control studies without a circularity focus	238
Battery operation or diagnostics without a link to a circular project	54
Primary raw-material extraction without a connection to battery circularity	40
Closed-loop concepts refer to engineering control rather than circularity	8
Circularity concerns non-battery vehicle components	4

The figure of 656 does not represent the final number of studies that underwent full-text eligibility assessment. Rather, it refers to the corpus that passed a standardized screening procedure based on bibliographic information, titles, abstracts, and keywords. Accordingly, in the present study these publications are referred to as the analytical corpus or records retained for thematic assessment, rather than as final included studies. This distinction avoids overstating the extent to which the PRISMA procedure was completed and ensures transparency regarding the screening stages that were actually conducted.

Thus, Section 3.1 establishes a reproducible sequence for constructing the literature base of the study: 5110 records identified → 1557 duplicates removed → 3553 unique publications screened → 2897 records excluded → 656 publications retained for thematic assessment. These results are subsequently used as the basis for classifying circular innovation projects and their assessment criteria in Section 3.2.

3.2. Multi-Criteria Model for Forming an Investment Portfolio of Circular Innovation Projects

The results of the systematic literature review showed that circular management of electric vehicle batteries encompasses a set of interconnected pathways, including lifetime extension, battery refurbishment and reuse, second-life applications, the organization of reverse flows, recycling, and the reintegration of recovered materials into production processes. Within the analyzed corpus, the most extensively represented research areas include recycling, end-of-life management, second life, reuse/repurposing, reverse logistics/closed-loop systems, remanufacturing/refurbishment, and life extension/diagnostics.

For the subsequent modeling stage, these pathways were consolidated into five groups of circular innovation projects. The resulting classification of circular innovation project classes is presented in Table 5.

The identified groups are subsequently treated as categories of innovation projects among which investment resources are allocated. This formulation makes it possible to integrate the technological dimension of the circular battery life cycle with the problem of selecting among alternative investment options. The mathematical model is constructed sequentially: economic, social, and environmental outcomes are assessed first, after which a multi-criteria portfolio of specific innovation projects is formed.

Table 5. Classes of Circular Innovation Projects.

Code	Project Group	Description
J_1	Diagnostics and lifetime extension	Assessment of battery condition and remaining useful life; solutions aimed at extending the battery's service life
J_2	Repair, refurbishment, and remanufacturing	Repair, refurbishment, and restoration of the battery or its individual components
J_3	Reuse and second-life applications	Reuse, repurposing, and application of batteries after the end of their automotive service life
J_4	Collection, disassembly, and reverse logistics	Collection, sorting, disassembly, reverse logistics, and the organization of closed-loop return flows
J_5	Recycling and material recovery	Recycling, material recovery, and the reintegration of secondary resources into production processes

To construct the model, a set of basic assumptions is introduced concerning the participants in market interactions, the set of projects, products and resources, and the relevant constraints. The outcomes of innovation projects are considered across three interrelated dimensions: economic (F_E), social (F_C), and environmental (F_G). Their combined impact is represented by the integral effect I.

The economic effect is defined as:

$$F_E = \Sigma_{i=1}{}^{m} \alpha_i{}^{m} x_i{}^{m} \gamma_i{}^{m} \rightarrow max \quad (1)$$

the social effect as:

$$F_C = \Sigma_{j=1}{}^{n} \beta_j{}^{n} y_j{}^{n} \rightarrow max \quad (2)$$

the environmental effect as:

$$F_G = \Sigma_{k=1}{}^{w} \varphi_k{}^{w} y_k{}^{w} \rightarrow max \quad (3)$$

and the overall result is defined as:

$$\mathrm{I} = F_E + F_C + F_G \quad (4)$$

The integral effect I is used as an analytical representation of the combined economic, social, and environmental outcomes and is not treated as an independent scalar objective in the subsequent portfolio optimization. At the portfolio-formation stage, the individual criteria are considered separately and subsequently reconciled through the multi-criteria decision procedure.

Thus, the model is designed to achieve economic, social, and environmental outcomes simultaneously and belongs to the class of linear multi-criteria models.

The objective functions are supplemented by a system of constraints. The minimum allowable implementation volume of an innovation solution is specified by the condition:

$$\alpha_i{}^{m} \geq d_i{}^{m} \quad (5)$$

the market constraints are expressed as:

$$D_j{}^{min} \leq y_j{}^{n} \leq D_j{}^{max} \quad (6)$$

and the non-negativity condition is given by:

$$\alpha_i{}^{m} \geq 0 \quad (7)$$

The dependence of the volume of innovative products on the resources used is defined as:

$$\alpha_i{}^m = \delta_1 z_i + \delta_2 f_i + \cdots + \delta_p h_i \quad (8)$$

Taken together, the system of constraints accounts for the availability and use of material, energy, labor, financial, and information resources, as well as constraints associated with environmental impacts. The environmental component of the model makes it possible to incorporate such outcomes as the rational use of natural resources, material and energy productivity, waste reduction, and improvements in resource efficiency.

Equations (1)–(8) define the general economic, social, environmental, and resource dimensions of the modeling framework. In the scenario-based application developed below, these dimensions are not estimated from a single enterprise-level production dataset. Instead, they are operationalized through standardized project-level indicators derived from the published evidence. Accordingly, the reduced portfolio model used in Section 4.2 should be interpreted as an operationalization of the general framework rather than as a direct numerical solution of the full production-resource block represented by Equations (1)–(8).

This is particularly important for the purposes of the present study: circularity is not introduced as an additional mathematical function and is not treated as an independent optimization criterion. Instead, it is embedded in the substantive characteristics of the projects under consideration and in the environmental outcomes incorporated into the model. Accordingly, second-life, reuse, remanufacturing, recycling, and material recovery projects are evaluated within the already established economic, social, and environmental dimensions, without artificially expanding the mathematical framework.

The next stage concerns the formation of the investment portfolio itself. The need for a portfolio-based decision arises because innovation projects differ in their orientation, cost, expected return, and level of risk, while the amount of available investment capital is limited. The portfolio approach therefore makes it possible to select not an individual project but a set of projects that jointly satisfies the specified criteria.

For a project of type (i) within direction (j), an integer decision variable d_{ij} is introduced, taking the value 1 if the project is included in the investment portfolio and 0 otherwise. The economic criteria include the maximization of portfolio economic performance and the minimization of portfolio risk.

The multi-criteria formulation of the portfolio problem is given by:

$$F(d) = \Sigma_{j=1}{}^n \Sigma_{i=1}{}^m r_{ij} d_{ij} \rightarrow max \quad (9)$$

$$U(d) = \Sigma_{j=1}{}^n \Sigma_{i=1}{}^m u_{ij} d_{ij} \rightarrow min \quad (10)$$

$$S(d) = \Sigma_{j=1}{}^n \Sigma_{i=1}{}^m s_{ij} d_{ij} \rightarrow max \quad (11)$$

$$L(d) = \Sigma_{j=1}{}^n \Sigma_{i=1}{}^m l_{ij} d_{ij} \rightarrow max \quad (12)$$

where F_d denotes the aggregate economic performance of the investment portfolio, U_d denotes aggregate portfolio risk, S_d represents the aggregate social effect, and L_d represents the aggregate environmental effect. The parameters r_{ij}, u_{ij}, s_{ij}, and l_{ij} characterize, respectively, the economic performance, risk, social effect, and environmental effect associated with project i within direction j.

In the baseline formulation, the criterion values of the selected project classes are aggregated additively. This assumption is introduced to maintain a transparent and tractable reduced-form portfolio model under the limitations of the available empirical data. It does not imply that circular project classes are technologically or operationally independent. In practice, important complementarities may exist: diagnostics can support routing decisions among reuse, remanufacturing, and recycling pathways, while reverse logistics provides enabling infrastructure for several downstream circular options. These interaction effects

are not estimated explicitly in the present scenario-based application because comparable quantitative estimates of cross-project synergies are not available for all project-class pairs.

A natural extension of the model would introduce pairwise interaction terms. For example, an extended economic-performance function may be written as $F(d) = \sum_j F_j d_j + \sum_{j<k} \gamma_{jk}^F d_j d_k$, where γ_{jk}^F captures a positive synergy or a negative substitution effect between project classes j and k. Analogous interaction terms can be introduced for the social and environmental criteria. Such an extension would transform the reduced additive formulation into an interaction-aware portfolio model, but its empirical implementation requires reliable estimates of the corresponding cross-project effects.

The objective functions are supplemented by the following portfolio constraints:

$$\sum_{i=1}^{m} q_{ij} d_{ij} \le Q_j + \lambda_j, \mathrm{j} = 1, \ldots, n. \quad (13)$$

$$\sum_{i=1}^{m} q_{ij} d_{ij} \ge Q_j - \lambda_j, \; j = 1, \ldots, n. \quad (14)$$

$$\sum_{j=1}^{n} \sum_{i=1}^{m} q_{ij} d_{ij} \le V_0 \quad (15)$$

$$d_{\mathrm{ij}} \in \{0,1\} \quad (16)$$

where q_{ij} denotes the amount of investment resources required to finance project $i$within direction j; Q_j represents the target amount of investment resources allocated to direction j; λ_j denotes the allowable absolute deviation from the target allocation for direction j; and V_0 represents the total amount of available investment resources.

In this formulation, $U(d)$ represents an aggregate portfolio risk criterion rather than a covariance-based measure of financial portfolio diversification.

Thus, the model simultaneously accounts for compliance with the specified investment portfolio structure, the limited availability of total investment resources, and the discrete nature of the decision to include a particular project in the portfolio.

The criteria of maximizing economic performance and minimizing portfolio risk primarily reflect the economic interests of internal participants in the investment process.

At the same time, the formation of the innovation project portfolio incorporates social and environmental outcomes that reflect the interests of external stakeholders. The simultaneous use of these criteria requires the identification of a compromise solution, since a portfolio that is optimal with respect to one criterion may not be optimal with respect to the others.

The method of successive concessions is used to reconcile the criteria. Its logic consists of transforming the multi-criteria problem into a single-criterion problem by establishing a dominant criterion and incorporating the remaining criteria into the system of constraints. A certain deterioration in the individual optimal values of selected criteria is allowed, making it possible to generate a set of efficient solutions and select the final investment portfolio from among them.

The use of a common relative concession for the constrained criteria is intended as a neutral baseline decision rule rather than as a direct representation of empirically elicited stakeholder preferences. Comparable quantitative preference weights for investors, firms, employees, regulators, and other stakeholders are not available for the project classes considered. Applying the same relative tolerance to risk, social, and environmental criteria therefore avoids introducing unsupported differences in their admissible deterioration while retaining economic performance as the principal objective. At the same time, this assumption implies that heterogeneous stakeholder preferences are not explicitly represented in the baseline solution. Such preferences can be incorporated through criterion-specific concession levels or alternative weighting schemes, and their influence is examined below through an alternative multi-criteria aggregation rule.

The resulting portfolio simultaneously accounts for economic performance, portfolio risk, social effects, and environmental effects, thereby enabling the reconciliation of the

interests of different stakeholder groups. The model retains its multi-criteria nature and can be used to allocate investment resources across circular innovation projects belonging to different directions.

In the context of the present study, the objects of portfolio selection are projects associated with different stages of the circular life cycle of electric vehicle batteries. The circular specificity of the model is therefore determined not by introducing an additional mathematical function but by the substantive content of the investment alternatives, which include lifetime extension, refurbishment, second life, reverse logistics, recycling, and material recovery. The relationship between the resulting portfolio decision and the sustainable innovative development of the enterprise is subsequently interpreted on the basis of the substantive characteristics of the selected project classes and the technological, process, organizational, and business-model changes identified in the literature; no separate objective function for innovative development is introduced into the model.

For clarity, the mathematical framework used in this study consists of three analytically distinct levels. First, Equations (1)–(8) define the conceptual level of the model by describing the economic, social, environmental, and resource dimensions of circular innovation activity. This level provides the general structure of the framework but is not estimated numerically in the present study because a homogeneous enterprise-level dataset on production volumes, resource use, and project-specific constraints is not available.

Second, Equations (9)–(16) define the portfolio-selection level. At this level, circular innovation alternatives are represented as discrete investment choices evaluated according to economic performance, risk, social effect, and environmental effect under limited investment resources. This formulation provides the mathematical link between the general sustainability dimensions introduced in Equations (1)–(8) and the portfolio decision problem.

Third, the computational experiment in Section 4.2 represents a reduced operationalization of the portfolio model. Because the available literature does not provide a homogeneous set of comparable parameters for several individual projects within each circular direction, each of the five project classes is represented by one aggregated alternative. Accordingly, the project-level index is collapsed, and the decision variable is written as $d_j \in \{0,1\}$, where $j = 1,\ldots,5$. The corresponding class-level parameters are denoted by F_j, U_j, S_j, and L_j, representing economic performance, risk, social effect, and environmental effect, respectively.

Not all constraints of the general portfolio formulation are activated in the numerical experiment. In particular, direction-specific target-allocation constraints are not imposed because empirically justified target shares are unavailable, and the full production-resource constraints of Equations (1)–(8) are not numerically estimated because comparable enterprise-level resource data are absent. The reduced experiment therefore retains the binary selection logic, the overall investment-resource constraint, and the four evaluation criteria while using standardized class-level parameters derived from published evidence. These simplifications are deliberate consequences of the available empirical base rather than omitted elements of the computational procedure. The results should therefore be interpreted as a scenario-based test of the portfolio-selection logic rather than as a numerical solution of the complete enterprise-level model.

4. Results

4.1. Formation of the Analytical Dataset for Circular Innovation Projects

The quantitative application of the developed multi-criteria model is aimed at identifying a rational structure for allocating investment resources across alternative circular innovation pathways in the electric vehicle battery sector. Consistent with the objective of the study, the object of modeling is not the investment portfolio of a specific automotive enterprise but rather a scenario-based financing structure for the main classes of circular

innovation projects. This makes it possible to assess how investment priorities change when economic performance, risk, social effects, and environmental effects are considered simultaneously.

J_1—battery diagnostics and lifetime extension;

J_2—repair, refurbishment, and remanufacturing;

J_3—reuse, repurposing, and second-life applications;

J_4—collection, disassembly, and reverse logistics;

J_5—recycling and reintegration of recovered materials into the production cycle.

Thus, the modeling problem is not concerned with choosing among individual companies or geographically dispersed projects. Rather, it seeks to determine the financing structure across J_1–J_5 generated by a multi-criteria investment decision.

The quantitative results reported in published studies and documented industry cases were used to parameterize the computational model. In this context, real-world projects serve as empirical reference points for identifying the economic, risk-related, social, and environmental characteristics of the corresponding types of circular activity. At the same time, indicators from different projects were not combined in a manner that would create an artificial "real-world project" that does not actually exist in practice.

This approach reflects the characteristics of the available open empirical evidence. Published studies provide relatively comprehensive information for particular groups of indicators: techno-economic studies report costs, revenues, net present value (NPV), internal rate of return (IRR), and payback periods; sustainability studies provide life-cycle assessment (LCA) and social life-cycle assessment (S-LCA) indicators; and research on closed-loop supply chains and reverse logistics reports uncertainty and risk estimates. However, a unified open dataset containing comparable economic, risk, social, and environmental indicators for the same real-world enterprise or project is virtually unavailable. Accordingly, published cases are used in this study not as direct elements of a single investment portfolio but to calibrate the scenario characteristics of the J_1–J_5 project classes.

The main quantitative reference points used to construct the analytical dataset are presented in Table 6.

For class J_1, published studies indicate that extending battery service life can simultaneously reduce total life-cycle costs and environmental impacts. The economic effect of this direction arises primarily from postponing battery replacement, making fuller use of the material value already embedded in the battery, and reducing the need to manufacture a new battery. The main sources of uncertainty include the actual degradation rate, operating conditions, temperature exposure, and the reliability of remaining-useful-life assessments [27].

For class J_2, studies of EV battery remanufacturing provide the quantitative basis and demonstrate that financial outcomes depend substantially on the quality of returned batteries. Changes in the proportion of components suitable for restoration affect the amount of additional components required, process costs, and final profitability. Remanufacturing may therefore generate substantial economic benefits while remaining highly sensitive to uncertainty in the characteristics of the incoming battery stream [28].

Class J_3 is characterized by the most developed empirical evidence base. Published studies of second-life systems report initial investment requirements, NPV, IRR, levelized cost of storage (LCOS), and the sensitivity of economic outcomes to battery parameters. Individual commercial cases indicate lower initial investment compared with systems using new batteries and simultaneously report reductions in embodied emissions. Second life can therefore be regarded as a pathway combining financial attractiveness with the extension of the useful life of an already manufactured battery [29].

Table 6. Empirical Reference Points for Parameterizing Circular Innovation Project Classes.

Class	Investment Direction	Economic Reference Points	Main Sources of Uncertainty	Social and Environmental Reference Points
J_1	Diagnostics and lifetime extension	Extending battery service life can reduce total life-cycle costs	Operating conditions, state of health (SOH), degradation, temperature conditions	Reduced need for premature battery replacement and lower life-cycle impacts
J_2	Repair, refurbishment, and remanufacturing	Published scenarios indicate substantial variability in costs and profitability depending on the condition of returned batteries	Quality of returned batteries, SOH, need for cell replacement, component costs	Reduced demand for newly manufactured components and preservation of battery functional value
J_3	Reuse and second-life applications	Real-world cases report lower initial investment compared with new battery systems; NPV, IRR, and LCOS are commonly used	Acquisition cost of retired batteries, SOH, degradation rate, discount rate, operation and maintenance (O&M) costs	Reduced embodied emissions and extension of the useful service life of batteries
J_4	Collection, disassembly, and reverse logistics	Economic performance depends on network configuration, the volume of return flows, and transportation and operating costs	Collection rate, transportation distances, condition of returned batteries, uncertainty of return flows	Reduction in uncontrolled handling of end-of-life batteries and facilitation of their return to the circular system
J_5	Recycling and material recovery	Costs depend substantially on battery chemistry, recycling technology, and the market value of recovered materials	Secondary-material prices, recovery rate, technological efficiency, processing volume	Reduced demand for primary materials, recovery of critical resources, and mitigation of associated environmental and social impacts

For class J_4, the infrastructure component of the circular system is of central importance. The economics of reverse logistics depends on the density and configuration of the collection network, transportation distances, the volume of returned batteries, and their allocation among subsequent circular pathways. Accordingly, investment performance in this direction is strongly affected by the scale of return flows and uncertainty regarding collection rates. At the same time, second-life, remanufacturing, and recycling projects cannot operate reliably without the corresponding infrastructure. J_4 therefore performs an enabling function within the circular battery ecosystem [30].

For class J_5, published techno-economic and life-cycle studies demonstrate that recycling performance depends on battery chemistry, recovery rates, the technology employed, and the market value of recovered materials. Unlike reuse-oriented scenarios, the primary outcome of recycling is the recovery of the battery's material value and its reintegration into the production cycle. The social and environmental effects of this direction are associated with reducing the demand for primary raw-material extraction, decreasing waste generation, and mitigating part of the impacts arising at the upstream stages of the battery value chain [31].

The comparison leads to an important conclusion for the subsequent optimization: none of the J_1–J_5 directions exhibits an unconditional advantage across all criteria simulta-

neously. A pathway with relatively high potential financial performance may also involve greater uncertainty; an environmentally preferable alternative may require substantial initial investment; and reverse-logistics infrastructure projects may generate lower direct returns while remaining essential for the operation of other elements of the circular system.

The presence of these trade-offs provides the rationale for applying a multi-criteria portfolio model rather than selecting a single "most efficient" battery management pathway.

An important limitation of the study is the heterogeneity of the underlying quantitative evidence. The published studies considered use different currencies, project scales, time horizons, and units for measuring environmental and social effects. Their absolute values are therefore not interpreted as directly comparable characteristics of a single real-world investment portfolio. Instead, they are used as empirical bounds and reference points for constructing scenario parameters for the corresponding project classes.

Consequently, the quantitative experiment is scenario-based rather than corporate-empirical in nature. Its purpose is to examine the behavior of the developed model under different combinations of characteristics of circular investment pathways, with parameters remaining within the ranges and relationships documented in the published literature.

This analytical dataset provides a direct basis for addressing the central research question: how does the allocation of investment resources across J_1–J_5 change when the decision-making priority shifts sequentially among maximizing economic performance, minimizing risk, improving social outcomes, improving environmental outcomes, and subsequently identifying a compromise solution?

Based on the analytical dataset developed in this section, Section 4.2 determines the individual optimal solutions for economic performance, risk, social effects, and environmental effects and then constructs a compromise multi-criteria portfolio. This makes it possible to identify the combination of circular innovation pathways J_1–J_5 and the corresponding structure of investment resource allocation that, under the specified scenario conditions, balances economic, social, and environmental outcomes and creates conditions for the sustainable innovative development of an automotive enterprise.

4.2. Results of Multi-Criteria Investment Portfolio Formation

The calculations presented in this subsection are scenario-based and use the reduced form of the multi-criteria model described in Section 3.2. They do not reproduce the actual portfolio of a specific automotive enterprise and should not be interpreted as estimates of real monetary capital shares. Each class J_1–J_5 is represented by a single aggregated investment alternative, while published empirical studies are used solely to calibrate the parameters of these classes. All additional assumptions underlying the computational experiment are stated explicitly and are separated from the original empirical evidence.

For consistency with the notation introduced in Section 3.2, the computational experiment uses d_j as the binary class-selection variable and F_j, U_j, S_j, and L_j as the corresponding class-level criterion values.

The economic and environmental criteria were derived from relative improvements explicitly reported for the corresponding circular pathways. For J_2, where the source reports ranges, the midpoint of the published interval was used; this calculation is shown separately. For J_4, the economic and environmental reference values were obtained from different studies addressing the same class of reverse-logistics solutions and are therefore treated as class-level parameters rather than as characteristics of a single real-world project.

The economic and environmental indicators reported in Table 7 were derived from independent studies that differ in functional units, reference conditions, system boundaries, time horizons, project scales, and assessment methodologies. Therefore, their original percentage values are not interpreted in this study as directly comparable empirical measurements

of a single real-world investment portfolio. Instead, they are used as literature-calibrated relative scenario indicators reflecting the direction and approximate magnitude of favorable change reported for the corresponding class of circular projects. The subsequent normalization is used only to transform these relative indicators onto a common dimensionless scale within each criterion; it does not eliminate the methodological heterogeneity of the underlying studies or make different functional units and system boundaries empirically equivalent. Accordingly, the normalized values should be interpreted as scenario-based comparative scores rather than as directly comparable empirical measures of economic or environmental performance.

Table 7. Initial Economic and Environmental Reference Values for the Scenario Experiment.

Class	Economic Reference Value, %	Calculation/Source	Environmental Reference Value, %	Calculation/Source
J_1	27.0	−27% life-cycle cost [27]	25.0	−25% carbon footprint [27]
J_2	31.12	(25.61 + 36.63)/2 [32]	33.71	(29.27 + 38.15)/2 [32]
J_3	23.30	−23.3% initial investment vs. new [29]	41.20	−41.2% embodied emissions![29]
J_4	16.0	≥16% economic effort![33]	4.10	−4.1% environmental carbon cost [34]
J_5	44.0	−44% costs [35]	37.0	−37% GWP [35]

Note: The economic and environmental indicators are not parameters of a single real-world corporate portfolio. They are used as literature-calibrated scenario parameters for the five classes of circular investment pathways.

Because the reported indicators have been expressed as relative favorable changes with a common direction of preference, min–max normalization was applied separately within the economic and environmental criteria to transform the literature-calibrated scenario values to the dimensionless interval [0; 1]:

$$F_j = (E_j - E_{min})/(E_{max} - E_{min}),$$

$$L_j = (G_j - G_{min})/(G_{max} - G_{min}).$$

For the economic criterion, $E_{min} = 16.00\%$ and $E_{max} = 44.00\%$. For example, for J_1:

$$F_{J1} = (27.00 - 16.00)/(44.00 - 16.00) = 0.3929.$$

For the environmental criterion, $G_{min} = 4.10\%$ and $G_{max} = 41.20\%$. For example, for J_2:

$$L_{J2} = (33.71 - 4.10)/(41.20 - 4.10) = 0.7981.$$

A unified quantitative measure of investment risk obtained using the same methodology is not available in the open literature for all five project classes. Accordingly, the risk indicator in the scenario experiment is not interpreted as an empirical probability of loss, a variance-based measure, or a statistical measure of volatility. Instead, it is used as an ordinal scenario proxy reflecting the degree of documented uncertainty in economic performance.

The baseline coding distinguishes between a neutral uncertainty category (0.5) and an elevated uncertainty category (1.0). The value 0.5 should not be interpreted as an empirical estimate of "medium risk"; rather, it is used as a neutral placeholder when the available evidence documents uncertainty but does not provide a sufficiently comparable basis for assigning a higher relative risk level. The value 1.0 is assigned only where the available evidence indicates a qualitatively stronger downside risk. In particular, J_2 is

assigned a value of 1.0 because the published remanufacturing scenario reports a change in profit from +USD 1.584 million to −USD 0.961 million as the quality of returned batteries deteriorates, demonstrating a transition from profitability to loss [28]. For J_1, J_3, J_4, and J_5, the baseline value of 0.5 is retained because the available sources document uncertainty or sensitivity but do not provide directly comparable evidence supporting classification in the elevated-risk category.

This coding is therefore a scenario assumption rather than an empirical risk measurement, and its influence on the portfolio result is examined explicitly through sensitivity analysis.

$$U = (0.5; 1.0; 0.5; 0.5; 0.5).$$

For the social criterion, the only indicator for which quantitative estimates could be obtained across several relevant circular pathways was employment creation potential. According to the European Commission Impact Assessment, the second-life market may generate approximately 2000 full-time equivalent jobs (FTEs) by 2030; additional collection/recovery activities may generate approximately 3100 FTEs; and recycling and material recovery may generate 2168–3272 new jobs by 2030. For J_1 and J_2, no comparable quantitative employment estimates were identified in the selected calibration base. This is not interpreted as the absence of a social effect but rather as the absence of a comparable estimate [36].

Because the portfolio calculation requires a complete numerical matrix, the missing employment-based social-proxy values for J_1 and J_2 were conservatively set to 0 in the baseline scenario. This value should be interpreted solely as a lower-bound imputation reflecting the absence of comparable quantitative employment evidence in the selected calibration base and not as evidence that these project classes generate no social benefits or employment effects. The influence of this assumption is therefore examined separately through sensitivity analysis.

For the baseline calculation of J_5, the midpoint of the published range was used:

$$Jobs_{J5} = (2168 + 3272)/2 = 2720.$$

The social indicator was normalized by dividing by the maximum published value of 3100 FTEs:

$$S_j = Jobs_j/3100.$$

$$S = (0.0000; 0.0000; 0.6452; 1.0000; 0.8774).$$

Employment estimates were obtained from the European Commission Impact Assessment [36]. These values refer to the market/policy level and are used only as class-level social proxies rather than as expected employment effects for a specific enterprise. The resulting standardized criterion values for the five project classes are summarized in Table 8.

The published sources use incomparable monetary scales and functional units, including USD/km, USD/kWh, EUR/kg, and infrastructure-network costs. Therefore, the absolute q_{ij} values cannot be combined into a single monetary budget without introducing artificial conversions. To isolate the effects of the criteria themselves, one standardized investment unit $q_j = 1$ is assigned to each class. The total resource is $V_0 = 3$, meaning that, in the baseline setting, three of the five classes are selected simultaneously:

$$q_j = 1; V_0 = 3; \Sigma d_j = 3; d_j \in 0,1.$$

This condition means that the calculation primarily identifies the composition of the preferred combination of circular pathways under equal assumed capital intensity. It does not permit the 33.3% shares to be interpreted as empirically estimated monetary allocations for a real enterprise. Estimating actual capital shares would require a homogeneous corporate CAPEX dataset for all J_1–J_5, which is not available in the open empirical base.

Table 8. Final Standardized Matrix for Classes J_1–J_5.

Class	Economic Effect	Risks	Social Proxy	Environmental Effect
J_1	0.3929	0.5000	0.0000	0.5633
J_2	0.5400	1.0000	0.0000	0.7981
J_3	0.2607	0.5000	0.6452	1.0000
J_4	0.0000	0.5000	1.0000	0.0000
J_5	1.0000	0.5000	0.8774	0.8868

Accordingly, the equal-unit assumption should be understood as a neutral baseline for comparing portfolio composition rather than as an assumption that the five project classes require equal amounts of real capital. Its purpose is to avoid introducing undocumented class-specific CAPEX estimates into the baseline calculation. Because unequal capital intensity may nevertheless affect the feasible set of portfolio combinations, the robustness of the result to this assumption is examined separately below.

With five classes and three selected directions, there are exactly 10 admissible combinations:

$$C(5,3) = 5!/(3!\cdot 2!) = 10.$$

Because all combinations contain the same number of classes and the same standardized budget, average criterion values are used for comparison. Using sums would produce an identical ranking. The complete set of admissible three-component portfolios and their corresponding criterion values is presented in Table 9.

Table 9. Complete Enumeration of Admissible Three-Component Portfolios.

Portfolio	F	U	S	L
$J_1 + J_2 + J_3$	0.3979	0.6667	0.2151	0.7872
$J_1 + J_2 + J_4$	0.3110	0.6667	0.3333	0.4538
$J_1 + J_2 + J_5$	0.6443	0.6667	0.2925	0.7494
$J_1 + J_3 + J_4$	0.2179	0.5000	0.5484	0.5211
$J_1 + J_3 + J_5$	0.5512	0.5000	0.5075	0.8167
$J_1 + J_4 + J_5$	0.4643	0.5000	0.6258	0.4834
$J_2 + J_3 + J_4$	0.2669	0.6667	0.5484	0.5994
$J_2 + J_3 + J_5$	0.6002	0.6667	0.5075	0.8950
$J_2 + J_4 + J_5$	0.5133	0.6667	0.6258	0.5616
$J_3 + J_4 + J_5$	0.4202	0.5000	0.8409	0.6289

The table can be verified by direct recalculation. For example, for portfolio $J_1 + J_2 + +J_5$:

$$F = (0.3929 + 0.5400 + 1.0000)/3 = 0.6443,$$

$$U = (0.5000 + 1.0000 + 0.5000)/3 = 0.6667.$$

The maximum economic result, F* = 0.6443, is achieved by portfolio $J_1 + J_2 + J_5$. The minimum risk, U* = 0.5000, is achieved by four portfolios excluding J_2: $J_1 + J_3 + J_4$, $J_1 + J_3 + J_5$, $J_1 + J_4 + J_5$, and $J_3 + J_4 + J_5$. The maximum social result, S* = 0.8409, corresponds to portfolio $J_3 + J_4 + J_5$. The maximum environmental result, L* = 0.8950, is achieved by portfolio $J_2 + J_3 + J_5$. Thus, the individual optima do not coincide, confirming the existence of a conflict among the criteria. The resulting criterion-specific optima are summarized in Table 10.

Table 10. Individual Optima by Criterion.

Criterion	Optimal Value	Optimal Portfolio/Set	Interpretation
max F	0.6443	$J_1 + J_2 + J_5$	Maximum economic performance
min U	0.5000	$J_1 + J_3 + J_4$; $J_1 + J_3 + J_5$; $J_1 + J_4 + J_5$; $J_3 + J_4 + J_5$	Minimum scenario-based risk
max S	0.8409	$J_3 + J_4 + J_5$	Maximum employment proxy
max L	0.8950	$J_2 + J_3 + J_5$	Maximum environmental effect

In accordance with the successive-concessions logic presented in Section 3.2, the scenario experiment treats risk, social, and environmental outcomes as constrained criteria and determines the minimum common concession level at which at least one portfolio simultaneously satisfies the corresponding constraints for U, S, and L. Economic performance is then retained as the principal objective for evaluating the feasible compromise solution.

$$U(d) \leq (1 + \alpha)U^*,$$

$$S(d) \geq (1 - \alpha)S^*,$$

$$L(d) \geq (1 - \alpha)L^*.$$

For each admissible combination, the minimum concessions required for the three constrained criteria are calculated separately:

$$\alpha_U = max[0; U/U^* - 1],$$

$$\alpha_S = max[0; 1 - S/S^*],$$

$$\alpha_L = max[0; 1 - L/L^*],$$

$$\alpha_{req} = max(\alpha_U; \alpha_S; \alpha_L).$$

This operation does not modify the objective functions of the model. It is used solely as a transparent rule for identifying the minimum required common concession within the finite set of 10 admissible combinations. The concession requirements calculated for all admissible portfolio combinations are reported in Table 11.

Table 11. Required Common Concession for Each Portfolio Combination.

Portfolio	α_U	α_S	α_L	α_{req}	F
$J_3 + J_4 + J_5$	0.0000	0.0000	0.2973	0.2973	0.4202
$J_2 + J_3 + J_4$	0.3333	0.3478	0.3303	0.3478	0.2669
$J_2 + J_4 + J_5$	0.3333	0.2558	0.3725	0.3725	0.5133
$J_2 + J_3 + J_5$	0.3333	0.3964	0.0000	0.3964	0.6002
$J_1 + J_3 + J_5$	0.0000	0.3964	0.0874	0.3964	0.5512
$J_1 + J_3 + J_4$	0.0000	0.3478	0.4177	0.4177	0.2179
$J_1 + J_4 + J_5$	0.0000	0.2558	0.4599	0.4599	0.4643
$J_1 + J_2 + J_4$	0.3333	0.6036	0.4929	0.6036	0.3110
$J_1 + J_2 + J_5$	0.3333	0.6522	0.1626	0.6522	0.6443
$J_1 + J_2 + J_3$	0.3333	0.7442	0.1205	0.7442	0.3979

The minimum value of α_{req} is 0.2973, or 29.73%, and is achieved by portfolio $J_3 + J_4 + J_5$. For this portfolio:

$$U = 0.5000 = U^*, \text{ therefore } \alpha_U = 0;$$

$$S = 0.8409 = S^*, \text{ therefore } \alpha_S = 0;$$

$$\alpha_L = 1 - 0.6289/0.8950 = 0.2973.$$

Accordingly, the minimum common concession is $\alpha^* = 0.2973$, and the compromise portfolio in the baseline scenario is $J_3 + J_4 + J_5$. Its characteristics are F = 0.4202, U = 0.5000; S = 0.8409; L = 0.6289. The economic result of this portfolio is 34.77% below the individual maximum F*, which represents the quantitative cost of moving from the purely economic optimum toward a solution that preserves the best values for the risk and social criteria while accepting a limited loss in environmental performance.

The economic trade-off also depends on the admissible concession level. At the minimum feasible level, $\alpha^* = 0.2973$, the compromise portfolio is $J_3 + J_4 + J_5$, with an economic-performance score of $F = 0.4202$. As the admissible concession increases, portfolios with stronger economic performance become feasible: $J_2 + J_4 + J_5$ is preferred at $\alpha = 0.3725$, followed by $J_2 + J_3 + J_5$ at $\alpha = 0.3964$. The purely economic optimum $J_1 + J_2 + J_5$ becomes feasible only at a substantially higher concession level of $\alpha = 0.6522$. This pattern shows that the economic cost of the compromise decreases as greater deviations from the individual social, environmental, and risk optima are accepted.

As a complementary robustness check, the portfolio ranking was also evaluated using a weighted-sum approach based on the same standardized economic, risk, social, and environmental criteria. With equal weights assigned to all four criteria, the alternative procedure reproduced the baseline compromise portfolio $J_3 + J_4 + J_5$. The result changed when the relative importance of the criteria was altered: greater emphasis on economic or environmental performance shifted the preferred solution to $J_2 + J_3 + J_5$, whereas a stronger social priority retained $J_3 + J_4 + J_5$. This comparison indicates that the baseline solution is consistent with a balanced preference structure but is not invariant to stakeholder priorities.

Because the two most debatable calibration components, scenario-based risk and the employment proxy, are not derived from a unified primary dataset, the robustness of the compromise combination was tested under alternative assumptions. First, the risk values for J_3 and J_5 were increased from 0.5 to 1.0, representing a more conservative interpretation. Second, the social proxy for J_5 was calculated separately using the lower and upper bounds of the published range of 2168–3272 jobs. In both cases, the composition of the three-component compromise portfolio remained unchanged: $J_3 + J_4 + J_5$.

Because the baseline distinction between $U_2 = 1.0$ and $U_j = 0.5$ for the remaining project classes is itself a scenario assumption, an additional one-way sensitivity test was performed for the risk score of J_2. The value of U_2 was varied over the interval from 0.5 to 1.0, while the risk scores of the other four classes were held constant at 0.5. Across the entire tested range, the compromise portfolio remained $J_3 + J_4 + J_5$, and the minimum common concession remained $\alpha^* = 0.2973$. Thus, the baseline portfolio composition is not driven by assigning the maximum scenario-based risk score to remanufacturing. This result does not validate 1.0 as an empirical risk estimate; rather, it demonstrates that the portfolio selection is robust to the full range of plausible values between the neutral and elevated categories used in the scenario coding.

The effect of changing the conditional budget constraint was also examined by selecting two, three, and four classes out of five while maintaining equal standardized investment units. The results are presented in Table 12.

Across all three budget settings, J_3 (second life) and J_5 (recycling/material recovery) remain part of the compromise combination. J_4 (reverse logistics) enters the solution when $V_0 = 3$, while J_1 (lifetime extension) is added when the conditional budget increases to four investment units. This allows J_3 and J_5 to be interpreted as the most robust core of the resulting scenario-based solution, whereas the inclusion of infrastructure and lifetime-extension pathways depends on the amount of available conditional resources.

Table 12. Sensitivity of the Compromise Portfolio Composition to the Conditional Budget Size.

Conditional Budget V_0	Number of Financed Classes	Compromise Composition	Minimum Common Concession α^*
2	2	$J_3 + J_5$	0.1890
3	3	$J_3 + J_4 + J_5$	0.2973
4	4	$J_1 + J_3 + J_4 + J_5$	0.2457

To examine whether the baseline result depends on the assumption of equal capital intensity across project classes, an additional permutation-based stress test was performed. Because comparable class-specific CAPEX data are not available, no empirical cost ranking was imposed. Instead, five standardized capital-intensity multipliers of 0.50, 0.75, 1.00, 1.25, and 1.50 were assigned across J_1–J_5 in all 120 possible permutations. These multipliers are centered around the baseline value of 1.00 and are used solely to introduce controlled heterogeneity in conditional investment requirements; they should not be interpreted as estimates of actual CAPEX ratios. The conditional budget was held at $V_0 = 3$, and the portfolio size was retained at three project classes in order to isolate the effect of heterogeneous capital requirements from the separate budget-size effect examined in Table 12.

The baseline compromise portfolio $J_3 + J_4 + J_5$ remained the preferred solution in 72 of the 120 permutations (60.0%). At the level of individual project classes, J_5 was retained in 116 scenarios (96.7%) and J_3 in 112 scenarios (93.3%), whereas the identity of the third component varied more substantially with the assumed capital intensities. These results support the interpretation of J_3 and J_5 as the more robust core of the scenario-based solution while also confirming that the complete portfolio composition is sensitive to differences in relative investment requirements. The stress test therefore does not remove the need for actual project-level CAPEX data, but it demonstrates explicitly that relaxing the equal-unit assumption does not eliminate the main structural finding of the analysis.

To further assess whether the portfolio result is driven by the heterogeneous magnitudes of the economic and environmental effects reported in different studies, an additional robustness test was performed using rank-based scaling (Table 13). In this alternative specification, the absolute distances between the reported percentage effects were disregarded, and only the ordinal position of each project class within the corresponding criterion was retained. The five classes were assigned equally spaced scores of 0, 0.25, 0.50, 0.75, and 1.00 from the least to the most favorable alternative. This procedure deliberately removes information on the magnitude of differences between studies while preserving their relative ordering and therefore provides a conservative test of whether the baseline portfolio structure depends on the specific numerical values derived from heterogeneous sources.

Table 13. Robustness of Portfolio Results to Alternative Scaling of Economic and Environmental Indicators.

Scaling Approach	Economic Optimum	Environmental Optimum	Compromise Portfolio	Minimum Common Concession, α^*
Baseline min–max normalization	$J_1 + J_2 + J_5$	$J_2 + J_3 + J_5$	$J_3 + J_4 + J_5$	0.2973
Rank-based scaling	$J_1 + J_2 + J_5$	$J_2 + J_3 + J_5$	$J_3 + J_4 + J_5$	0.2222

For the economic criterion, the ordering of the project classes was $J_4 < J_3 < J_1 < J_2 < J_5$, resulting in rank-based scores of 0.00, 0.25, 0.50, 0.75, and 1.00, respectively. For the environmental criterion, the ordering was $J_4 < J_1 < J_2 < J_5 < J_3$, resulting in rank-based scores of 0.00, 0.25, 0.50, 0.75, and 1.00, respectively. The risk and social-proxy values were

kept unchanged so that the test isolated the effect of alternative scaling of the economic and environmental indicators.

A separate sensitivity analysis was conducted for the missing employment-based social-proxy values of J_1 and J_2. Because no comparable evidence was available to justify different numerical estimates for these two classes, a symmetric interval assumption was used, with $S_1 = S_2 = s$ and s varied from 0 to 1.0. Five scenario values were examined: 0, 0.25, 0.50, 0.75, and 1.00.

The results show that the baseline compromise portfolio $J_3 + J_4 + J_5$ is retained when the imputed social-proxy values for J_1 and J_2 are 0 or 0.25. When the assumed values increase to 0.50 or above, the compromise solution changes to $J_1 + J_3 + J_5$. Thus, the identity of the third portfolio component is sensitive to the treatment of missing social data. Importantly, however, J_3 (second-life applications) and J_5 (recycling/material recovery) remain in the compromise portfolio across all tested social-proxy scenarios, indicating that these two classes constitute a more robust core of the scenario-based solution.

The rank-based specification produced the same criterion-specific economic and environmental optima as the baseline model and, importantly, retained $J_3 + J_4 + J_5$ as the compromise portfolio. The minimum common concession decreased from 0.2973 under min–max normalization to 0.2222 under rank-based scaling, but the composition of the selected portfolio did not change. This result indicates that the structural composition of the baseline compromise solution is not solely an artifact of the numerical distances between heterogeneous percentage effects reported in the source studies. At the same time, the test does not eliminate the underlying differences in functional units, system boundaries, reference conditions, or assessment methodologies. It should therefore be interpreted as a robustness check of the scenario-based decision outcome rather than as evidence that the underlying empirical indicators are fully comparable.

Finally, to assess the simultaneous rather than one-factor-at-a-time influence of the main calibration uncertainties, an integrated robustness test was conducted by combining the alternative specifications examined above. Economic and environmental criterion values were independently represented using either the baseline min–max or rank-based scaling; the missing social-proxy values for J_1 and J_2 were varied across 0, 0.25, 0.50, 0.75, and 1.00; three alternative risk specifications were considered; and the five standardized capital-intensity coefficients of 0.50, 0.75, 1.00, 1.25, and 1.50 were distributed across the project classes in all 120 possible permutations. This resulted in 7200 combined scenarios. For each scenario, the feasible portfolio set and the compromise solution were recalculated rather than holding the baseline optimum fixed.

The integrated analysis confirms that the full three-component portfolio is more sensitive to joint uncertainty than suggested by the individual one-factor tests. The baseline configuration $J_3 + J_4 + J_5$ was selected in 2456 of the 7200 scenarios (34.1%), while $J_1 + J_3 + J_5$ was the second most frequent solution (28.6%). At the level of individual project classes, however, J_5 was retained in 90.3% of all scenarios and J_3 in 87.7%, compared with 46.0% for J_1, 40.7% for J_4, and 35.3% for J_2. Thus, simultaneous variation in the principal calibration assumptions confirms that the identity of the third component can change, whereas second-life applications J_3 and recycling/material recovery J_5 remain the most persistent elements of the portfolio. The robustness claim is therefore restricted to this structural core rather than to the exact baseline three-class configuration.

In the baseline scenario, the compromise portfolio $J_3 + J_4 + J_5$ combines three functionally sequential elements of the circular battery life cycle: the reuse of residual functional value through second-life applications, the infrastructure required for battery return and routing through reverse logistics, and the subsequent recovery of material value through recycling and material recovery. This combination should not be interpreted as a universal

investment recommendation and does not imply that a real enterprise should allocate capital equally among the three directions at 33.3%/33.3%/33.3%. The equal shares result from the standardized condition $q_j = 1$ and were introduced solely to enable comparison among project classes in the absence of homogeneous CAPEX data.

Accordingly, the results of Section 4.2 should be interpreted as a literature-calibrated scenario experiment demonstrating which pathways retain relative preference under multi-criteria selection and how the economic, risk, social, and environmental criteria conflict with one another. Determining the actual monetary financing structure of a specific automotive enterprise would require a corporate dataset containing comparable q_{ij},r_{ij},u_{ij},s_{ij} и l_{ij} values for all projects under consideration. This limitation does not affect the assessment of the model logic, but it restricts the direct transferability of the calculated conditional capital shares to specific investment programs.

Thus, under the specified scenario conditions, the multi-criteria formulation produces a different solution from the one obtained by maximizing economic performance alone. The purely economic optimum is represented by $J_1 + J_2 + J_5$, whereas the minimum-compromise configuration is $J_3 + J_4 + J_5$. This finding confirms that incorporating risk, social outcomes, and environmental outcomes can alter financing priorities for circular innovation and supports a shift from searching for a single "best" end-of-life solution toward selecting a coordinated combination of complementary circular pathways.

5. Discussion

The results confirm that the choice of a circular pathway for electric vehicle batteries cannot be based on a single performance criterion. Economically preferred solutions do not coincide with those that deliver the strongest social or environmental outcomes, while minimizing investment risk also leads to a different portfolio structure. This implies that, in transitioning toward a circular model, an automotive enterprise should not focus on selecting a single "best" battery management option but rather on combining several complementary pathways. In the scenario-based experiment, the compromise solution integrates projects related to battery reuse and second-life applications, the development of reverse logistics, and subsequent recycling with the reintegration of recovered materials into the production cycle. This configuration reflects a sequential logic of value preservation: first, the residual functional potential of the battery is utilized; second, its return to the circular system is ensured; and finally, the material value of the resources contained in the battery is recovered. At the same time, this result should be interpreted as a consequence of the specified scenario conditions rather than as a universal investment structure applicable to all automotive enterprises.

The additional sensitivity analysis of the missing social-proxy values further qualifies this result. When low social-proxy values were assumed for J_1 and J_2, the baseline compromise portfolio $J_3 + J_4 + J_5$ was retained. However, under moderate and higher assumed values, the third component changed from J_4 to J_1, resulting in $J_1 + J_3 + J_5$. Thus, the inclusion of reverse logistics in the baseline compromise solution is sensitive to the treatment of missing social data. By contrast, J_3 and J_5 remained in the compromise portfolio across all tested scenarios and can therefore be interpreted as the more robust core of the scenario-based solution.

The findings extend the conclusions of the systematic literature review. The analysis showed that existing studies predominantly address individual circular battery life-cycle pathways, including recycling and material recovery, reuse and second-life applications, refurbishment and remanufacturing, reverse logistics, and lifetime extension [1–22,24,25]. A substantial share of the literature is devoted to assessing the economic or environmental performance of a specific technology, comparing alternative battery management options,

or optimizing individual elements of closed-loop supply chains [14–22]. Such approaches make it possible to identify the advantages of particular solutions, but they provide a more limited answer to the managerial question of how constrained investment resources should be allocated across multiple circular pathways. The portfolio formulation proposed in this study extends this perspective. The object of decision-making is not an individual technology but a set of interconnected circular innovation projects evaluated simultaneously in terms of economic performance, risk, social effects, and environmental effects.

In contrast to studies in which multi-criteria optimization is applied primarily to the selection of a specific technology, network configuration, or end-of-life trajectory, the proposed approach shifts the object of optimization to portfolio-level allocation across alternative circular innovation project classes relevant to automotive enterprises.

Accordingly, the novelty of the proposed approach is associated with the object and structure of the decision problem rather than with the optimization technique itself. Established multi-criteria tools are applied here to a different managerial problem: the coordinated allocation of constrained investment resources across complementary circular innovation pathways.

In this way, the study establishes a link among circularity, the allocation of investment resources, and sustainable innovative development—a relationship that remains only weakly represented in the systematically analyzed body of literature.

From the perspective of enterprise innovative development, the identified compromise structure also has distinct economic significance. Battery reuse and second-life projects create opportunities for the development of new products, services, and business models, allowing enterprises to extract additional value from batteries after the end of their initial automotive use [1–3,7,9–12]. The development of reverse logistics requires organizational and process changes, the establishment of stable return flows, and new forms of interaction with suppliers, recyclers, energy companies, and other participants in the value chain [19,22,30,33,34]. Recycling and material recovery are associated with technological innovation, resource efficiency, and reduced dependence on primary raw materials [14,15,18,20,22,24,25,31,35]. Taken together, these pathways constitute not a set of isolated environmental initiatives but an interconnected system of technological, process, organizational, and business-model transformations. In practical terms, this implies a transition from project-by-project financing of separate environmental initiatives toward the strategic management of a portfolio of interconnected circular innovations. Portfolio financing of circular projects can therefore be regarded as a mechanism for creating the conditions for sustainable innovative development, in which resource efficiency, economic performance, and environmental sustainability are integrated within a unified trajectory of business transformation.

At the same time, the findings are subject to several limitations that should be taken into account when interpreting the results. The quantitative application was conducted not on confidential data from a specific automotive enterprise but within a scenario-based modeling framework calibrated using quantitative findings from published studies. The underlying sources differ in project scale, time horizon, and the methods used to assess economic, social, and environmental outcomes; therefore, their absolute values were not interpreted as directly comparable characteristics of a single real-world investment portfolio. For several pathways, the open literature also does not provide fully comparable measures of investment risk and social effects, which required the use of standardized scenario-based estimates. For this reason, the resulting portfolio structure should be interpreted primarily as a test of the proposed multi-criteria selection mechanism and as an illustration of the trade-offs among competing investment objectives.

The capital-intensity stress test further showed that unequal conditional investment requirements can affect the identity of the third portfolio component, although J_3 and J_5 remained highly persistent across the tested permutations.

The additional rank-based robustness test further showed that the compromise portfolio $J_3 + J_4 + J_5$ remains unchanged when the absolute magnitudes of the literature-derived economic and environmental effects are removed and only their ordinal ranking is retained. This increases confidence in the structural robustness of the scenario-based portfolio result with respect to the scaling of heterogeneous source indicators. However, it does not eliminate the underlying differences in functional units, system boundaries, reference conditions, and assessment methodologies; therefore, validation using a homogeneous enterprise-level dataset remains necessary.

The comparison with the weighted-sum model also indicates that the compromise portfolio is partly preference-dependent. The baseline $J_3 + J_4 + J_5$ configuration was reproduced under balanced criterion weights, whereas stronger economic or environmental preferences shifted the solution toward $J_2 + J_3 + J_5$. Therefore, the common-concession solution should be interpreted as a transparent neutral-reference compromise rather than as a unique portfolio independent of stakeholder preferences.

The integrated robustness analysis further demonstrates that uncertainty should be interpreted jointly rather than criterion by criterion. When economic and environmental scaling, social-proxy assumptions, risk specifications, and conditional capital requirements were varied simultaneously, the exact three-class configuration changed across scenarios, whereas J_3 and J_5 remained the most persistent components. This result narrows the robustness claim of the study from a fixed portfolio composition to a robust structural core.

Future research should focus on applying the model to data from specific automotive enterprises, incorporating actual project-level investment parameters and cash flows, refining the assessment of risk and social effects, and accounting for regional differences in regulation, logistics, energy costs, and secondary-material prices.

6. Conclusions

The systematization of research on the circular life cycle of electric vehicle batteries shows that the transition toward circularity in the automotive industry is developing simultaneously across several pathways, including battery lifetime extension, refurbishment, reuse and second-life applications, reverse logistics, recycling, and the reintegration of recovered materials into production processes. Existing studies, however, tend to examine these pathways separately, focusing on technological performance, environmental impacts, economic feasibility, or the organization of closed-loop supply chains. Considerably less attention has been paid to the allocation of limited investment resources across several circular pathways simultaneously. This gap provided the basis for shifting the focus of the present study from selecting an individual battery management option toward forming a portfolio of circular innovation projects.

Based on the systematic literature review, five classes of circular innovation projects were identified, and a multi-criteria model for their investment selection was developed. The model simultaneously incorporates economic performance, investment risk, social effects, and environmental effects under conditions of limited investment resources. This approach makes it possible to view circular projects not merely as environmental or technological initiatives but as interconnected pathways of enterprise innovative development that compete for investment capital while generating different combinations of financial and non-financial outcomes.

The scenario-based application of the model demonstrated that changes in decision-making priorities lead to changes in investment portfolio composition. A portfolio designed

to maximize economic performance does not coincide with solutions that are optimal from a social or environmental perspective. This confirms that there is no universally preferable circular investment pathway; the choice depends on the outcomes prioritized by the enterprise. The multi-criteria reconciliation mechanism produced a compromise combination comprising battery reuse and second-life applications, reverse logistics, and recycling with material recovery. Under the specified scenario conditions, this combination provides the most acceptable balance among economic, risk-related, social, and environmental characteristics.

The sensitivity analysis further showed that the third component of the compromise portfolio depends on assumptions concerning missing social-effect data, whereas second-life applications and recycling/material recovery remained present across all tested social-proxy scenarios. These two directions should therefore be regarded as the more robust core of the scenario-based portfolio, while the inclusion of reverse logistics or lifetime-extension projects is more sensitive to the underlying calibration assumptions.

The resulting portfolio has important implications for understanding the sustainable innovative development of automotive enterprises. Battery reuse creates opportunities for new products, services, and business models; reverse logistics requires organizational and process changes throughout the value chain; and recycling and material recovery are associated with technological innovation, resource conservation, and reduced dependence on primary raw materials. Within the scenario-based framework of this study, the portfolio results indicate that combining complementary circular pathways can create conditions for technological, process, organizational, and business-model changes associated with the sustainable innovative development of automotive enterprises. This interpretation is derived from the substantive characteristics of the selected project classes and should not be treated as a direct quantitative measurement of enterprise innovative development. The principal scientific contribution of the study therefore lies not in proposing a new optimization technique but in reformulating circular EV battery investment as a portfolio-level decision problem that combines complementary circular innovation project classes with economic, risk, social, and environmental criteria and links the resulting portfolio decisions to the sustainable innovative development of automotive enterprises.

The proposed approach may be applied to the development of investment programs by automotive enterprises, battery companies, investors, and other actors within the circular battery ecosystem. At the same time, the quantitative results are derived from a scenario-based application of the model using parameters calibrated from published studies rather than data from a specific enterprise. The resulting portfolio structure should therefore not be interpreted as a universal investment recommendation. Further development of the approach should focus on its application to corporate datasets, the use of actual project-level capital expenditures and cash flows, refinement of investment risk and social-effect indicators, and the incorporation of sectoral and regional conditions affecting the implementation of circular projects.

The findings indicate that effective circular transformation of the battery ecosystem should be based not on the selection of a single battery management pathway but on the formation of a balanced portfolio of complementary innovation projects. Such an approach makes it possible to account for differences in economic performance, risk, social effects, and environmental effects across alternative pathways and, in doing so, to integrate circular-economy instruments into the strategic management of sustainable innovative development in the automotive industry.

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