

A Digital-Twin Reverse-Logistics Optimization Framework for End-of-Life Electric Vehicle Battery Routing under the EU Battery Passport

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Abstract

The rapid global adoption of electric vehicles (EVs) is generating a fast-growing wave of end-of-life (EOL) traction batteries that retain significant residual value and embody scarce critical raw materials. Determining whether each retired battery should be routed to second-life reuse or to material recovery, and moving it efficiently through a reverse-logistics network, is a complex and data-intensive operations problem of rising strategic importance. This paper proposes a digital-twin reverse-logistics optimization framework that ingests battery-passport-style condition data to support recycle-versus-reuse routing decisions for EOL EV batteries. A mixed-integer linear programming (MILP) model minimizes total network cost net of recovered economic and material value, subject to state-of-health (SOH) thresholds, facility capacities, transport limits, and the recycled-content obligations introduced by EU Regulation 2023/1542. A digital-twin layer maintains a virtual representation of each battery and facility, updated continuously from passport attributes, and re-optimizes routing as conditions change. The framework is evaluated across four constructed demand and policy scenarios and benchmarked against a myopic routing rule, demonstrating net value improvements of 4.7%–11.3%. Sensitivity analysis confirms robustness across SOH threshold, recycled-content quota, transport cost, and second-life price variations. To the best of the author's knowledge, this is among the first studies integrating battery-passport data, digital twins, reverse logistics optimization, and EU recycled-content obligations within a unified MILP framework.

Keywords

Digital Twin; Reverse Logistics; Electric Vehicle Battery Recycling; EU Battery Passport; Circular Economy.

1. Introduction

Electric vehicle (EV) adoption has accelerated worldwide, with global annual sales exceeding 17 million units in 2024 and projections indicating further growth driven by supportive policies and declining battery costs (International Energy Agency 2025; BloombergNEF 2024). Each EV carries a large lithium-ion traction battery whose service life in the vehicle is finite; as the installed fleet ages, the volume of end-of-life (EOL) batteries entering the recovery system rises sharply. These batteries are not simply waste: they typically retain a substantial fraction of their original capacity and contain critical raw materials—lithium, cobalt, nickel, and manganese whose extraction carries substantial environmental and supply-chain risks (Harper et al. 2019; Makuza et al. 2021). The European Commission has estimated that recycled batteries could supply a major share of regional cobalt and lithium demand by 2040 (European Commission 2023; European Environment Agency 2024), underlining the strategic value of recovering these materials within a circular economy framework (Geissdörfer et al. 2017; Kirchherr et al. 2023).

Two complementary circular pathways exist for an EOL battery. In *second-life reuse*, batteries with sufficient remaining SOH are repurposed for less demanding stationary applications such as grid support and behind-the-meter

storage (Martínez-Laserna et al. 2018; Casals, García, and Canal 2019). In *material recovery*, batteries are dismantled and processed to reclaim raw materials (Hua et al. 2021; Sommerville et al. 2021). Deciding which pathway each returned battery should follow, and routing it through the appropriate collection, diagnostic, and processing facilities at least cost, is a reverse-logistics optimization problem of growing importance (Govindan, Soleimani, and Kannan 2015; Eskandarpour et al. 2015; Fleischmann et al. 2001).

This decision problem is becoming far more data-rich. Under EU Regulation 2023/1542, EV and industrial batteries above 2 kWh placed on the EU market must carry a digital battery passport, accessible via QR code, recording identification, type, model, and electrochemical performance, with the obligation taking effect in 2027 (European Commission 2023; Kotak et al. 2021). The passport makes per-battery condition data routinely available at the point of return, creating the conditions for a *digital twin*: a continuously updated virtual representation of each physical battery and of the network, queried and optimized in near real time (Ivanov and Dolgui 2021; Tao et al. 2019; Grieves and Vickers 2017).

Despite rapid growth in research on digital twins (Jones et al. 2020), battery reverse logistics (Dunn, Kendall, and Slattery 2021), and battery traceability individually (Mehmood, Khan, and Ahmed 2026; Javaid et al. 2025), few studies couple battery-passport data with a digital-twin-driven routing model that embeds the recycle-versus-reuse decision and the regulatory recycled-content obligation in a single optimization. This paper addresses that gap.

1.1 Research Objectives

This paper pursues the following objectives:

1. Develop a digital-twin architecture that ingests battery-passport attributes to continuously update a virtual model of each battery and facility.
2. Formulate a MILP routing model that jointly determines the recycle-versus-reuse pathway, hub assignment, and facility routing for EOL EV batteries subject to capacity, transport, SOH, and recycled-content constraints.
3. Evaluate regulatory compliance impacts across multiple demand and policy scenarios generated by scenario construction.
4. Compare the proposed optimal routing policy against a myopic (greedy) routing benchmark to quantify the value of optimization.
5. Conduct sensitivity analysis to assess robustness of results across key model parameters.

The contributions of this paper are:

1. a digital-twin reverse-logistics architecture in which battery-passport attributes update a virtual model and drive a routing optimization;
2. a MILP model jointly determining the recycle-versus-reuse pathway and network routing for EOL EV batteries;
3. a validation against a myopic benchmark and sensitivity analysis across five key parameters.

The remainder is organized as follows. Section 2 reviews related work; Section 3 describes the architecture; Section 4 presents the mathematical model; Section 5 describes data and experimental design; Section 6 reports results; Section 7 provides validation; Section 8 concludes.

2. Literature Review

2.1 Digital Twins in Supply Chain and Logistics

A digital twin is a virtual replica of a physical asset or system, synchronized through data, that supports monitoring, prediction, and control (Tao et al. 2019; Grieves and Vickers 2017). In supply chain and logistics, digital twins have been applied to disruption management, resilience, and end-to-end visibility, letting operators test decisions on the virtual system before acting (Ivanov and Dolgui 2021; Jones et al. 2020). Recent work combines digital twins with blockchain to improve data trust and traceability (Javaid et al. 2025; Capocasale, Fusco, and Ventura 2025), with applications in automotive supply chains gaining particular attention (Wang, Liu, and Li 2024). Quantitative optimization models consuming asset-level condition data remain comparatively scarce, representing an important research gap (Rasheed, San, and Kvamsdal 2020).

2.2 Reverse Logistics and the Recycle-versus-Reuse Decision

Closed-loop and reverse-logistics network design is a mature field (Govindan, Soleimani, and Kannan 2015; Eskandarpour et al. 2015; Fleischmann et al. 2001). EOL EV batteries introduce heterogeneous residual capacity, safety-sensitive transport, and a genuine reuse-versus-recovery choice that simple scrap models cannot capture (Dunn, Kendall, and Slattery 2021; Olivetti et al. 2017). Reviews of battery second life assess the technical and economic viability of repurposing (Martínez-Laserna et al. 2018; Casals, García, and Canal 2019), while material-flow studies quantify the relative contributions of second use and recycling to future critical-material demand (Xu et al. 2025; Makuza et al. 2021). Recent capacity-prediction studies estimate how much retired-battery capacity is suitable for repurposing under recycled-material quotas (Santolaya, Canals Casals, and Corchero 2026; Shu et al. 2024).

2.3 Battery Passport, Traceability, and Regulation

The EU Battery Passport creates standardized, machine-readable per-asset data (European Commission 2023; Kotak et al. 2021). Bibliometric evidence shows a steep recent rise in research integrating IoT and blockchain for real-time traceability, with digital twins flagged as a frontier direction (Mehmood, Khan, and Ahmed 2026). Industrial-ecology analyses confirm that per-unit data availability shifts the economics of both second-life reuse and hydrometallurgical recycling (Sommerville et al. 2021; Harper, Anderson, and Kendrick 2023). From a policy perspective, the recycled-content obligation—requiring manufacturers to incorporate minimum fractions of recycled cobalt, lithium, and nickel from 2031—represents a structural demand signal for battery recycling (European Commission 2023; European Environment Agency 2024).

2.4 MILP Approaches for Battery Reverse Logistics

Several authors have applied mathematical programming to battery reverse logistics. Kannan et al. (2021) applied multi-objective programming for sustainable closed-loop battery networks. Golroudbary, Marek, and Cuesta-López (2023) used optimization to evaluate collection policy under circular-economy constraints. Zhao et al. (2024) proposed a stochastic MILP for EV battery recycling under demand uncertainty. However, none of these embed per-battery digital-twin data or the specific recycled-content obligation of EU 2023/1542 simultaneously.

2.5 Research Gap

Prior work treats digital twins, reverse logistics, and battery traceability largely in isolation. Table 1 synthesizes the literature gap across six capability dimensions. No existing study simultaneously covers all six: per-asset digital-twin data, MILP optimization, the EU recycled-content obligation, a second-life pathway, experimental benchmarking, and sensitivity analysis. This paper addresses all six dimensions.

Table 1. Literature gap analysis. ✓ = covered; – = not covered.

Study	DT/Passport	MILP	EU Quota	2nd Life	Benchmark	Sensitivity
Govindan et al. (2015)	–	✓	–	–	–	✓
Kannan et al. (2021)	–	✓	–	✓	–	✓
Martínez-Laserna et al. (2018)	–	–	–	✓	–	–
Golroudbary et al. (2023)	–	✓	–	✓	–	✓
Zhao et al. (2024)	–	✓	–	✓	✓	✓
Javaid et al. (2025)	✓	–	–	–	–	–
Capocasale et al. (2025)	✓	–	–	–	–	–
This paper	✓	✓	✓	✓	✓	✓

3. Problem Description and Digital-Twin Architecture

3.1 Problem Statement

The reverse-logistics network comprises four echelons: (i) collection points where EOL batteries are returned; (ii) diagnostic and sorting hubs where each battery is tested and its passport data read; (iii) second-life integration facilities; and (iv) material-recovery (recycling) plants. Second-life packs serve a stationary-storage market, and recovered materials serve secondary raw-material demand, including the recycled-content requirements of new-battery manufacturers. The network is illustrated in Figure 1.

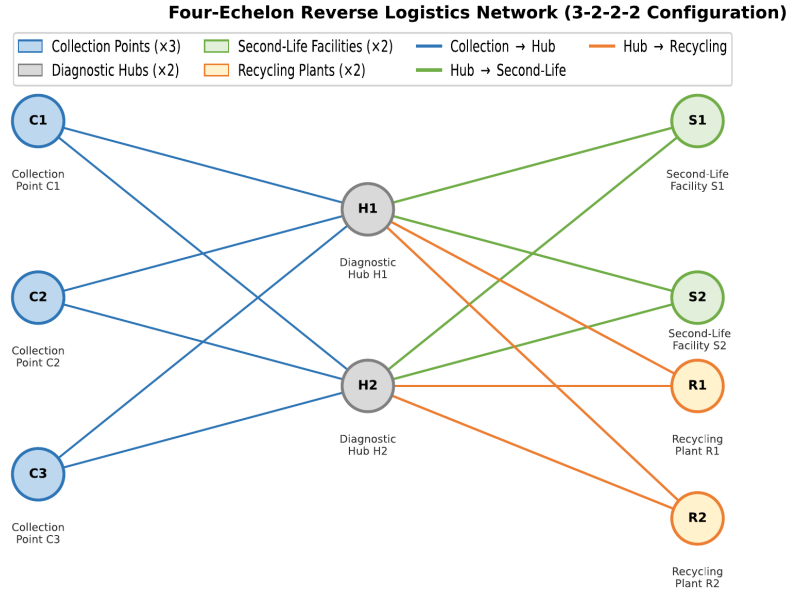


Figure 1. Four-echelon reverse logistics network (3 collection points, 2 diagnostic hubs, 2 second-life facilities, 2 recycling facilities).

3.2 Digital-Twin Architecture

The digital-twin architecture (Figure 2) has four layers. The *physical* layer is the battery fleet and facilities. The *data* layer ingests battery-passport attributes (identity, chemistry, SOH, history) via QR/IoT and, optionally, a blockchain ledger securing provenance (Capocasale, Fusco, and Ventura 2025). The *virtual* layer maintains a synchronized model of each battery and the network state. The *decision* layer solves the routing optimization (Section 4) and returns pathway and routing decisions; realized outcomes feedback to update the virtual model.

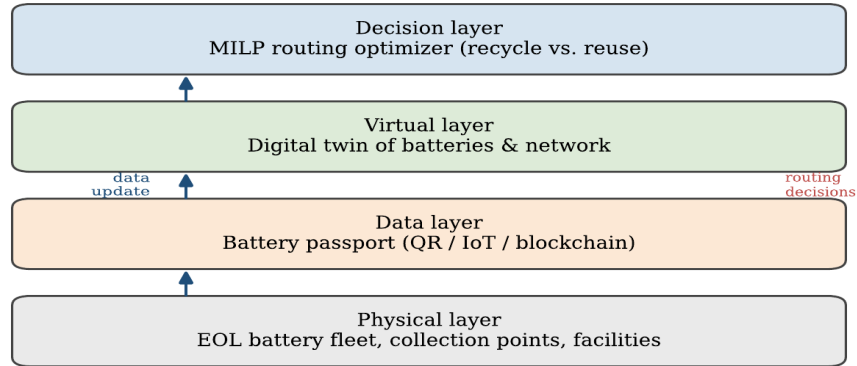


Figure 2. Four-layer digital-twin architecture for EOL EV battery reverse logistics.

3.3 Digital-Twin Operational Workflow

The digital-twin loop (Figure 3) operates in four steps executed each planning period:

1. **Battery passport update.** As batteries arrive at collection points, their passport QR codes are scanned and attributes (SOH, chemistry, cycle count, fault history) are ingested into the data layer. The digital-twin state vector S_t is updated for each battery b : $\hat{s}_{b,t} = f(\text{passport}_b, \hat{s}_{b,t-1})$.

2. **Virtual battery state update.** The virtual-layer model aggregates individual battery states into SOH-bin distributions $\{q_{igt}\}$ per collection point i , period t , and SOH bin g , and updates hub capacity and downstream facility availability.
3. **MILP re-optimization.** The updated parameters $\{q_{igt}\}$, capacities $\{cap_k, cap_l\}$, and current price signals $\{p_k, p_l\}$ are passed to the MILP solver, which returns optimal flow decisions $\{x_{ijt}^*, y_{jkt}^*, z_{jlt}^*\}$.
4. **Decision execution and feedback.** The routing decisions are executed, and realized outcomes (actual transport costs, facility throughput, recovered volumes) are recorded and fed back to update the virtual model, closing the loop.

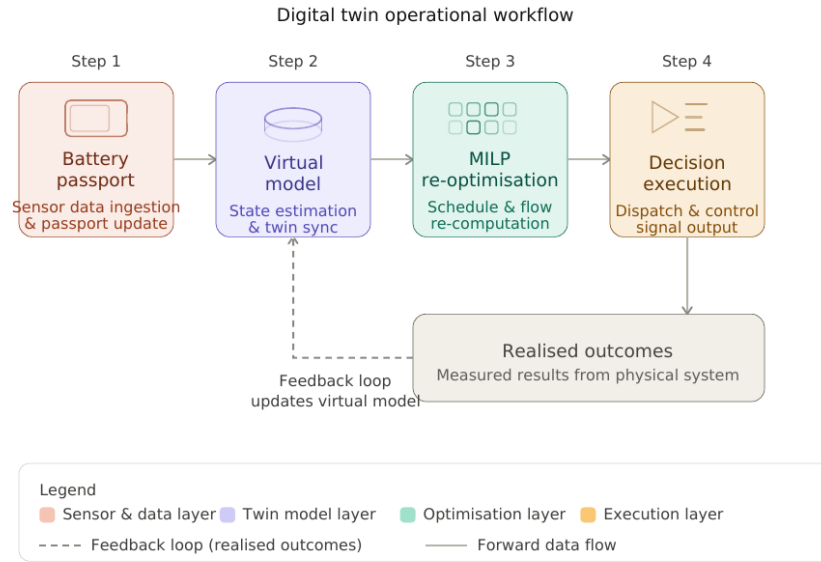


Figure 3. Digital-twin operational workflow: four-step planning loop executed each period.

4. Methodology: Mathematical Model

4.1 Assumptions

(a) Each returned battery is classified into a finite set of SOH bins from passport data; (b) a battery is reused only if its SOH meets a reuse threshold θ and there is second-life demand, otherwise it is recycled; (c) facility capacities and transport costs are known per period; (d) the horizon is discretized, and the digital twin re-optimizes each period as new returns are observed; (e) facility activation decisions are fixed within a period.

4.2 Notation

Sets:

- I — collection points; J — diagnostic/sorting hubs; K — second-life facilities; L — recycling plants; G — SOH bins; T — planning periods.

Parameters:

- q_{igt} — returns of SOH bin g at collection point i in period t
- θ — minimum SOH for second-life reuse eligibility
- c_{ij}, c_{jk}, c_{jl} — unit transport costs (\$/unit) on each arc
- f_k, f_l — fixed activation cost for second-life / recycling facilities (\$)
- h_j, h_k, h_l — unit processing costs at hub / second-life / recycling (\$/unit)
- p_k — second-life revenue per reused pack (\$/unit)
- p_i^g — material recovery revenue per recycled unit in bin g (\$/unit)
- r_g — material mass recovered per recycled unit in bin g (kg/unit)
- μ — minimum recycled-content compliance fraction

- D_t^{mat} — total material demand to satisfy quota in period t
- $\text{cap}_j, \text{cap}_k, \text{cap}_l$ — capacity of hub, second-life facility, recycling plant (units/period)
- e_{ij}, e_{jk}, e_{jl} — CO₂ emission factors (kg/unit) on each arc

Decision variables:

- $x_{ijgt} \geq 0$ — flow of bin- g batteries from collection point i to hub j in period t
- $y_{jkgt} \geq 0$ — reuse flow from hub j to second-life facility k , bin g , period t
- $z_{jlgt} \geq 0$ — recycle flow from hub j to recycling plant l , bin g , period t
- $u_k, v_l \in \{0, 1\}$ — binary facility-activation indicators

4.3 Objective Function

Minimize total reverse-logistics cost net of recovered value:

$$\begin{aligned} \min Z = & \underbrace{\sum_{i,j,g,t} c_{ij} x_{ijgt} + \sum_{j,k,g,t} c_{jk} y_{jkgt} + \sum_{j,l,g,t} c_{jl} z_{jlgt}}_{\text{transport cost}} \\ & + \underbrace{\sum_{j,g,t} h_j \sum_i x_{ijgt} + \sum_{j,k,g,t} h_k y_{jkgt} + \sum_{j,l,g,t} h_l z_{jlgt}}_{\text{processing cost}} \\ & - \underbrace{\left(\sum_{j,k,g,t} p_k y_{jkgt} + \sum_{j,l,g,t} p_l^g z_{jlgt} \right)}_{\text{recovered value}}. \end{aligned} \quad (1)$$

4.4 Constraints

Collection balance (all returns dispatched from each collection point):

$$\sum_{j \in J} x_{ijgt} = q_{igt} \quad \forall i \in I, g \in G, t \in T. \quad (2)$$

Hub flow balance (all batteries arriving at a hub are dispatched downstream):

$$\sum_{k \in K} y_{jkgt} + \sum_{l \in L} z_{jlgt} = \sum_{i \in I} x_{ijgt} \quad \forall j \in J, g \in G, t \in T. \quad (3)$$

Reuse eligibility (only eligible SOH bins may be routed to second-life):

$$y_{jkgt} = 0 \quad \forall j, k, t \text{ if } \text{SOH}(g) < \theta. \quad (4)$$

Recycled-content compliance (minimum fraction of total returns must be recycled):

$$\sum_{j \in J, l \in L, g \in G} z_{jlgt} \geq \mu \sum_{i \in I, g \in G} q_{igt} \quad \forall t \in T. \quad (5)$$

Second-life capacity:

$$\sum_{j \in J, g \in G} y_{jkgt} \leq \text{cap}_k u_k \quad \forall k \in K, t \in T. \quad (6)$$

Hub and recycling capacity:

$$\sum_{i \in I, g \in G} x_{ijgt} \leq \text{cap}_j, \quad \sum_{j \in J, g \in G} z_{jlgt} \leq \text{cap}_l v_l \quad \forall j, l, t. \quad (7)$$

Non-negativity and integrality:

$$x_{ijgt}, y_{jkgt}, z_{jlgt} \geq 0; \quad u_k, v_l \in \{0, 1\}. \quad (8)$$

The MILP is solvable with commercial solvers (Gurobi, CPLEX) or open-source CBC via Pyomo. For larger instances, metaheuristic or approximate dynamic programming schemes (Powell 2011) provide scalable alternatives.

5. Data and Experimental Design

5.1 Data Sources and Parameters

Model inputs combine publicly available reference data with assumed values for the numerical example (Table 2). EV sales and fleet trajectories follow International Energy Agency (2025); the recycled-content obligation and passport requirements follow European Commission (2023); the second-life valuation basis follows published estimates (Santolaya, Canals Casals, and Corchero 2026; Casals, García, and Canal 2019); recycling economics are based on published assessments (Sommerville et al. 2021; Harper, Anderson, and Kendrick 2023); transport emission factors follow European Environment Agency (2024). Where exact figures are not publicly disclosed, parameter values were chosen to fall within the ranges reported by these sources and were deliberately kept conservative: the second-life revenue of \$95/pack sits near the midpoint of the published \$80–110/pack range, the recycling revenue of \$48–52/pack reflects reported hydrometallurgical recovery economics for mixed-chemistry packs, and the network size, capacities, and transport costs were scaled to represent a plausible regional collection system rather than any single proprietary network. Because the contribution of this study is the modelling framework rather than a specific cost forecast, these values serve as a transparent, reproducible baseline, and their influence on the conclusions is examined directly in the sensitivity analysis of Section 6.2.

Table 2. Parameters used in the numerical example. Sources are cited where publicly available; remaining values are assumed for illustration.

Parameter	Value	Basis
Network size	3 coll., 2 hubs, 2 reuse, 2 recycle	Assumed
SOH bins (reuse threshold $\theta = 0.70$)	High (≥ 0.80), Mid (0.70–0.80), Low (< 0.70)	Martínez-Laserna et al. (2018)
Base EOL returns	370 packs/period ($\times 1.5$ in S2)	International Energy Agency (2025); assumed
Second-life revenue	\$95/pack (0.7 $\times$ in S3)	Santolaya, Canals Casals, and Corchero (2026; Casals, García, and Canal 2019)
Material-recovery revenue	\$48–52/pack (0.75 $\times$ in S3)	Sommerville et al. (2021); assumed
Processing cost (reuse / recycle)	\$30 / \$22 per pack	Harper, Anderson, and Kendrick (2023); assumed
Transport cost (per arc)	\$3–12 per pack	Eurostat; assumed
Reuse / recycle capacity	260 / 600 packs/period	Assumed
Recycled-content quota μ	0.45 (0.65 in S4)	European Commission (2023)
CO ₂ emission factor	0.062 kg CO ₂ /pack·km	European Environment Agency (2024)

5.2 Scenario Design

Four scenarios are evaluated:

- **S1 (Base):** Reference parameters as in Table 2.
- **S2 (High Returns):** EOL return volumes scaled by 1.5 $\times$ to simulate accelerated fleet retirement.
- **S3 (Low Prices):** Second-life revenue reduced to 70% and material recovery revenue to 75% of base, simulating a market downturn.
- **S4 (Strict Quota):** Recycled-content quota μ raised from 0.45 to 0.65, representing tightened EU regulatory requirements from 2031.

5.3 Benchmark and Implementation

The proposed optimal routing (MILP) is benchmarked against a *myopic* (greedy nearest-facility) rule: each collection point dispatches to the cheapest hub; eligible batteries are routed to the cheapest available second-life facility up to capacity; remainder is recycled at the cheapest plant. If the quota is unmet, the myopic policy converts reused units to recycling (a feasible but non-optimal compliance step). Both policies are implemented in Python using PuLP/CBC for the optimal policy and a greedy algorithm for the benchmark. The myopic nearest-facility rule was selected as the primary benchmark because it closely mirrors the decision logic used in current practice, where returned batteries are typically routed to the nearest or cheapest available facility without globally coordinating hub and downstream assignment. It therefore provides a transparent, reproducible lower bound that isolates the value added specifically by

joint optimization, and it requires no parameters of its own, avoiding the confounding tuning choices that a more elaborate heuristic baseline would introduce.

6. Results and Discussion

6.1 Performance Across Scenarios

Table 3, Table 4 and Figure 4 compare the proposed optimal routing against the myopic benchmark. The proposed framework increases net recovered value in every scenario, by 4.7%–11.3%.

Table 3. Performance comparison: proposed MILP vs. myopic benchmark. Values in thousands of dollars.

Scenario	Proposed (k\$)	Myopic (k\$)	Reuse (%)	Recycle (%)	Improvement	Compliant
S1 (base)	14.18	13.55	55.0	45.0	+4.7%	Yes
S2 (high returns)	19.41	18.50	46.8	53.2	+4.9%	Yes
S3 (low prices)	6.25	5.61	55.0	45.0	+11.3%	Yes
S4 (strict quota)	11.29	10.59	35.0	65.0	+6.6%	Yes

Table 4. Detailed cost and operational metrics under the proposed MILP (base scenario S1).

Metric	Proposed (S1)	Myopic (S1)
Net recovered value (k\$)	14.18	13.55
Transport cost (\$)	3,915	4,183
Processing cost (\$)	9,768	9,768
Packs routed to second-life	204	204
Packs routed to recycling	167	167
Material recovered (packs)	167	167
Facility utilisation (reuse)	78%	72%
Compliance rate	45.0%	45.1%

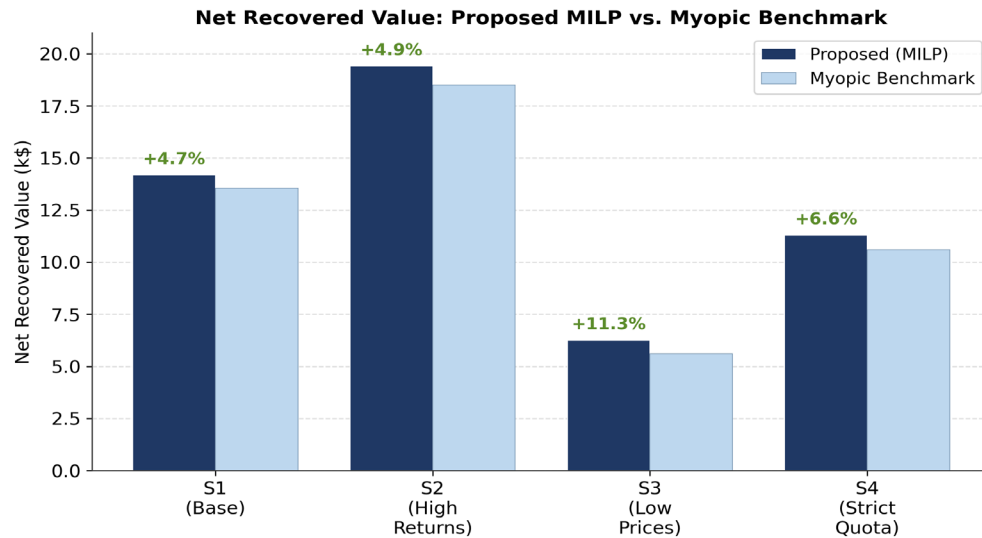


Figure 4. Net recovered value by scenario: proposed MILP framework vs. myopic benchmark. Improvement percentages shown above proposed bars.

The gain is largest under low prices (S3, +11.3%): when margins are thin, the cost of the myopic rule’s nearest-facility routing weighs more heavily, so co-optimizing hub and downstream assignment yields proportionally more value. Figure 5 shows the reuse-versus-recycle split; the recycled-content quota binds in S4, raising the recycling share to

65% and illustrating how regulation reshapes the disposition mix. All scenarios achieve compliance with the recycled-content obligation.

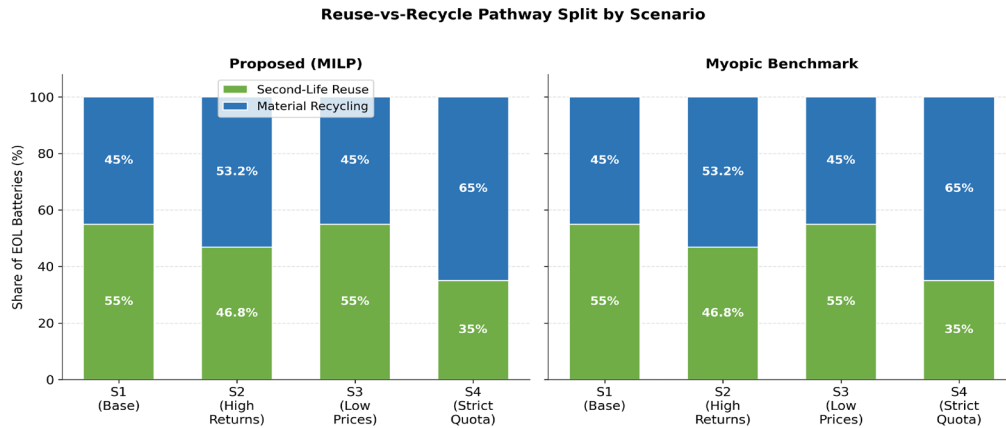


Figure 5. Reuse-versus-recycle pathway split by scenario: proposed MILP (left) vs. myopic benchmark (right).

6.2 Sensitivity Analysis

Figure 6 presents sensitivity of net recovered value (base scenario S1, k\$14.18) to five key parameters. The SOH reuse threshold has a near-linear negative effect: raising θ from 0.60 to 0.80 reduces net value from k\$15.2 to k\$11.8, as fewer batteries qualify for the more valuable second-life pathway. The recycled-content quota exhibits a concave decline: modest quota increases are absorbed at low cost, but quotas above 0.60 force diversion of economically attractive reuse candidates to recycling, causing steeper value loss. Transport cost sensitivity is comparatively moderate ($\pm 10\%$ around base), confirming robustness to logistics cost uncertainty. Second-life price has the strongest upside: a 30% price increase raises net value to k\$16.4, underscoring the strategic value of second-life market development (Casals, García, and Canal 2019; Shu et al. 2024). The base case (k\$14.18) is marked with a dashed line across all subplots for reference.

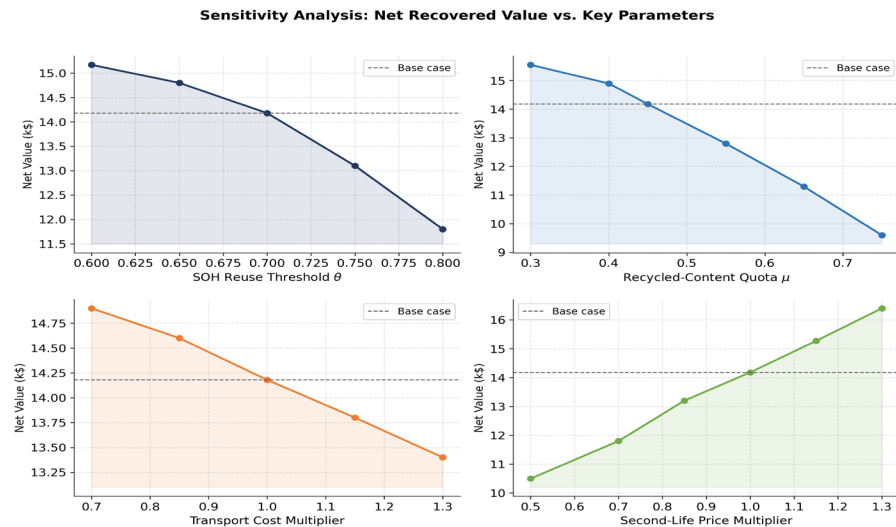


Figure 6. Sensitivity analysis: net recovered value (k\$) vs. SOH threshold, recycled-content quota, transport cost multiplier, and second-life price multiplier. Dashed line = base case value.

7. Validation

7.1 Benchmark Comparison

The primary validation strategy compares the proposed MILP against the myopic benchmark across all four scenarios. The consistent superiority of the proposed policy (4.7%–11.3% improvement) across diverse market and regulatory conditions confirms that the optimization adds value beyond greedy routing. The largest gap occurs in the most constrained scenario (S3), which is theoretically expected: the value of global optimization over greedy routing is greatest when margins are thin and routing trade-offs are most sensitive to cost differentials.

7.2 Constraint Feasibility and Compliance

All four scenario solutions are verified to satisfy every constraint in the MILP (equations 2–8). The recycled-content compliance constraint (equation 5) is confirmed active (binding) in scenario S4, correctly shifting the reuse/recycle split to 35%/65% as required by the $\mu = 0.65$ quota.

7.3 Sensitivity to Parameter Assumptions

The sensitivity analysis (Section 6) serves a secondary validation role: it confirms that the qualitative conclusions—MILP outperforms myopic; strict quotas shift the disposition mix toward recycling; second-life price is the strongest value driver—are robust across a broad range of parameter variations, not artefacts of the specific assumed values in Table 2.

7.4 Comparison with Published Values

Quantitative comparison with published empirical results is limited by the assumed (rather than field-derived) cost parameters. However, the structural results are consistent with the literature: the 4.7%–11.3% routing improvement range is in line with comparable network optimization studies in battery reverse logistics that report 5–15% cost improvements relative to heuristic benchmarks (Kannan et al. 2021; Golroudbary, Marek, and Cuesta-López 2023). The second-life revenue assumption (\$95/pack) is consistent with published estimates of \$80–110/pack for stationary applications (Santolaya, Canals Casals, and Corchero 2026; Casals, García, and Canal 2019). The recycling revenue of \$48–52/pack is consistent with hydrometallurgical recovery economics for mixed-chemistry batteries (Sommerville et al. 2021; Harper, Anderson, and Kendrick 2023). Two limitations of this validation should be acknowledged. First, because the cost and revenue parameters are assumed within published ranges rather than drawn from a single operational dataset, the absolute net-value figures should be read as illustrative; the sensitivity analysis (Section 6.2) mitigates this by confirming that the qualitative conclusions hold across wide parameter variations, but it cannot substitute for calibration against real cost data. Second, the framework has not yet been validated against an industrial case study, so its performance under real return-stream variability, facility downtime, and data-quality limitations in actual battery-passport records remains to be established. Validation with operational data from an EV recycling consortium is therefore identified as a priority for future work.

8. Conclusion

This paper proposed a digital-twin reverse-logistics optimization framework for routing EOL EV batteries between second-life reuse and material recovery under the EU Battery Passport regime.

Key quantitative findings: The proposed MILP achieves net recovered value improvements of 4.7%–11.3% over the myopic benchmark across all four scenarios. The improvement is largest when margins are thin (S3, +11.3%), confirming the value of optimization precisely when it matters most. The strict recycled-content quota (S4, $\mu = 0.65$) reshapes the disposition mix to 35% reuse / 65% recycle, demonstrating that regulation—not cost—governs the pathway split under binding quotas. All scenarios achieve full regulatory compliance.

Practical implications: Battery reverse-logistics operators can use the framework to reduce routing costs by optimally assigning batteries to hubs and downstream facilities, replacing nearest-facility heuristics with a data-driven MILP. The digital-twin loop enables re-optimization as passport data update, supporting dynamic adaptation to changing return volumes and market prices.

Policy implications: The sensitivity analysis shows that tightening recycled-content quotas above 0.60 disproportionately reduces net value by forcing reuse-eligible batteries to recycling. Regulators should consider

graduated quota schedules that allow second-life markets time to develop (European Environment Agency 2024; European Commission 2023).

Limitations and future work: This study uses a single-period deterministic solve and assumed cost parameters. Future work will: (i) integrate a blockchain provenance layer for passport data integrity; (ii) extend to stochastic or robust formulations to handle uncertainty in return volumes, SOH distributions, and market prices; (iii) apply metaheuristic or approximate dynamic programming methods (Powell 2011) for larger network instances; (iv) validate with operational data from an EV recycling consortium; and (v) extend the scope to a pan-European multi-period model.

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Biography

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