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Agentic AI-Driven Reverse Supply Chains for Electric Vehicle Batteries: Digital Battery Passports, Recovery Decisions, and Quantitative Experimental Validation

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Abstract: End-of-use EV batteries pose a coordination problem: lifecycle data must become safe, timely recovery actions. This study tests a bounded agentic AI architecture in which the Digital Battery Passport (DBP) acts as shared evidence for recovery assessment, reverse logistics, material reintegration, and governance. Instead of survey evidence, we use a controlled Monte Carlo experiment: 30 matched replications, each with 1,000 generated battery-return cases, comparing human-coordinated planning, deterministic rule-based routing, and DBP-grounded agentic orchestration. Against the human baseline, agentic coordination cut mean decision-cycle time from 48.59 to 17.86 min (63.2%), lifted circular recovery yield from 81.86% to 83.55%, raised correct allocation from 79.65% to 92.70%, and reduced premature recycling from 9.44% to 4.71%. Static rules were faster in raw processing but weaker in routing quality and second-life capture. A 20-percentage-point drop in DBP completeness degraded key outcomes. These are computational results under stated assumptions, not observed industry estimates.

Keywords: Agentic artificial intelligence; Electric vehicle battery; Reverse supply chain; Digital Battery Passport; Second life; Recycling; Quantitative validation

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1. Introduction

When automotive service ends, an EV battery is not simply waste. Safety, residual condition, demand, transport feasibility, processing capacity, carbon effects, and regulation may point to reuse, repair, repurposing, remanufacturing, dismantling, or recycling. Recovery is thus a chain of linked decisions, not one disposal event [1]. Closed-loop business-model research likewise treats EV battery recovery as a coordinated circular system [2]. Digital Battery Passport (DBP) can keep lifecycle, performance, diagnostic, and sustainability records continuous across organizations [3]. At the policy level, Regulation (EU) 2023/1542 provides a formal

regulatory basis for battery lifecycle information and governance [4]. Recent studies further examine implementation challenges surrounding the EU digital battery passport [5]. Stakeholder-oriented research also identifies requirements for sustainability and circularity [6]. But a passport is evidence infrastructure, not an execution layer. It cannot by itself resolve missing records, compare routes, secure transport or capacity, or update downstream plans. Agentic AI can fill this coordination gap: software agents reason over evidence, call tools, retain context, and run multi-step workflows within set authority limits [7]. Agentic digital-twin research has also linked AI-driven decision support with supply-chain and operations management [8]. Multi-agent LLM research further explores autonomous consensus-seeking in supply chains [9]. The operational question is whether DBP-grounded agentic coordination improves recovery decisions when regimes face identical cases. Prior work has used simulation and optimization for multi-agent production planning [10]. Cooperative digital-twin and multi-agent reinforcement learning has also been applied to circular-supply-chain control [11]. Battery-passport studies have examined disassembly [12]. Experimental work has further assessed passport suitability for second-life batteries [13]. This study offers a compact quantitative comparison of three regimes. It asks: (1) under matched cases, does bounded DBP-grounded agentic orchestration improve path quality and decision efficiency over human and rule-based baselines; and (2) how sensitive are outcomes to DBP completeness?

2. Agentic AI architecture for EV battery reverse supply chains

The DBP acts as a controlled lifecycle-memory layer: identity, chemistry, state of health (SoH), safety events, inspections, maintenance, ownership, transport records, and verified recovery history. Safety-critical or legally required fields are not inferred from language-model output. Missing essential evidence triggers a documentation request or human review.

Five agents share this evidence base. The Passport Evidence Agent checks identity, completeness, and provenance. The Recovery Assessment Agent compares second-life, remanufacturing, and recycling options under hard safety constraints. The Reverse Logistics Agent verifies carrier eligibility, distance, time windows, and facility capacity. The Material Reintegration Agent links recovered materials or reusable modules to forward demand. The Governance Agent records evidence, tool use, authority boundaries, conflicts, and approvals. The output is a traceable decision-and-execution workflow, not a stand-alone recommendation. Autonomy is deliberately limited. Record retrieval, missing-document requests, route comparison, and capacity checks may be automated. Safety release, hazardous-goods classification, cross-border movement, and material transfer or disposal remain approval-gated. The aim is faster, more consistent coordination without shifting accountability away from consequential choices.

3. Quantitative validation design

The architecture was evaluated with a matched Monte Carlo experiment. Each of 30 replications contained 1,000 virtual returned batteries, and the same case stream was supplied to all three decision regimes. A fixed random seed of 20260918 supports reproduction. The parameter values are disclosed as modeling assumptions; the experiment is a controlled validation test bed, not an estimate of actual battery-return frequencies. See **Table 1**.

Table 1. Quantitative validation design and key assumptions

Element	Specification
Replications / cases	Thirty matched Monte Carlo runs; each run contains 1,000 returned-battery cases.
Battery condition	SoH drawn around a 70% mean and bounded at 40–95%; accident and thermal-abuse events determine safety status.
Network state	Case-level variation in second-life demand, remanufacturing/recycling capacity, and route distance.
DBP completeness	Lifecycle-data completeness drawn from a beta distribution and bounded between 0.45 and 1.00.
Recovery alternatives	Second life, remanufacturing, or recycling; safety constraints are applied before value-based routing.
Human baseline	Greater observation noise, incomplete logistics consideration, and longer coordination/processing time.
Rule-based baseline	Static threshold routing based on safety, SoH, demand, and remanufacturing capacity; logistics does not dynamically override the rule.
Agentic regime	DBP-informed dynamic policy with lower observation noise, explicit logistics/capacity checks, and conservative handling when critical evidence is missing.

A common reference logic determines the preferred pathway for each case. Safety is checked first. High-SoH batteries can enter second life when demand is sufficient; medium-SoH batteries can be remanufactured when capacity is available; recycling is used when higher-value routes are infeasible. Logistics or capacity constraints may override a technically attractive route. The three regimes then decide from representations of the same cases that differ in evidence completeness, observation noise, and coordination depth. This prevents the agentic regime from being defined as correct by construction.

Five outcomes are reported. Decision-cycle time measures the interval from return trigger to an executable route. Correct allocation is the share of decisions matching the reference pathway. Second-life capture records the proportion of second-life-optimal cases actually assigned there. Premature recycling is the share of non-recycling-optimal cases sent to recycling. Circular recovery yield is a normalized system-level measure of recoverable material or usable-capacity value retained by the selected route, not metallurgical process yield. Means and 95% confidence intervals are calculated across 30 matched replications.

4. Quantitative validation results and discussion

See **Table 2**.

Table 2. Quantitative validation results across 30 matched replications

Metric	Human-coordinated	Rule-based	DBP-grounded agentic
Decision-cycle time (min)	48.59 (48.39–48.79)	6.67 (6.65–6.69)	17.86 (17.80–17.92)
Circular recovery yield (%)	81.86 (81.80–81.91)	82.23 (82.17–82.29)	83.55 (83.51–83.60)
Correct allocation (%)	79.65 (79.27–80.03)	81.74 (81.33–82.15)	92.70 (92.43–92.96)
Second-life capture (%)	76.11 (75.13–77.08)	59.45 (58.17–60.73)	91.43 (90.73–92.12)
Premature recycling (%)	9.44 (9.00–9.88)	11.53 (11.07–11.98)	4.71 (4.41–5.00)

Agentic coordination substantially shortened the human process: mean decision-cycle time fell from 48.59 to 17.86 minutes, a 63.2% reduction. Deterministic rules were faster at 6.67 minutes, so the agentic advantage is not raw processing speed. Its contribution lies in combining a much shorter cycle than human coordination with better routing quality than the static rule set, which does not reconcile the same range of demand, distance, capacity, and evidence conflicts.

Pathway quality showed larger differences. Circular recovery yield was 83.55% under agentic

orchestration, compared with 81.86% for human coordination and 82.23% for rule-based routing. Correct allocation reached 92.70%, versus 79.65% and 81.74%, respectively. Second-life capture rose to 91.43%, while premature recycling fell to 4.71%. These outcomes are consistent with the architecture: DBP evidence reduces information loss, and coordinated demand, logistics, and capacity checks limit condition-only routing errors.

A DBP-completeness ablation tested this dependence directly. When average completeness was reduced by 20 percentage points, agentic decision time increased from 17.86 to 24.01 minutes; correct allocation fell from 92.70% to 88.39%; circular recovery yield fell from 83.55% to 82.90%; and second-life capture fell from 91.43% to 86.10%. Premature recycling rose from 4.71% to 9.02%. The deterioration indicates that useful lifecycle evidence, rather than the mere existence of a digital record, is central to agentic performance.

5. Implementation and governance implications

Implementation should begin with a narrow pilot, such as one battery platform, return channel, or recovery partner. The initial objective is a reliable chain from the return event to verified evidence, feasible routes, approved action, and recorded outcome. Before expanding agent authority, firms can compare data completeness, decision-cycle time, route reversals, manual interventions, circular recovery yield, and exception rates with the current process.

A pilot also requires a minimum operational data contract. Manufacturers, logistics providers, second-life operators, remanufacturers, and recyclers should align identifiers, units, timestamps, quality status, inspection validity, confidence fields, and rejection reasons. Interoperability matters because agents must interpret records produced by different organizations and information systems.

Governance should rely on an explicit authority matrix. Low-risk retrieval, missing-data requests, capacity checks, and route comparison can be delegated, whereas safety release, hazardous-goods classification, cross-border transfer, and disposal authorization should remain approval-gated until operating evidence supports broader delegation. Consequential actions should retain the evidence consulted, tool calls, alternatives considered, authorization state, and override history so that efficiency gains remain auditable [14].

6. Conclusion

This study develops and tests a bounded Agentic AI architecture for EV battery reverse supply chains. The DBP provides verified lifecycle evidence, while specialized agents coordinate assessment, logistics, material reintegration, and governance. A transparent matched computational experiment is used to examine the design through quantitative outputs generated under stated assumptions.

Under the controlled conditions, agentic orchestration shortened decision time relative to human coordination and improved circular recovery yield, allocation accuracy, second-life capture, and premature-recycling performance. Deterministic rules remained fastest in raw processing time, separating simple speed from coordinated decision quality. Performance weakened when DBP completeness was reduced. A controlled battery-level pilot using operational records is therefore the next evidentiary step; until then, the numerical results should be read as reproducible design validation rather than field performance estimates.

Disclosure statement

The author declares no conflict of interest.

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