



Closed-Loop Supply Chains and Product Lifecycle Recovery: A Review of Advances in Sustainable Returns Management

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Abstract

Product returns have shifted from a peripheral cost of business to a defining operational and environmental problem. In 2025, retailers in the United States expected roughly 15.8 percent of annual sales, some 849.9 billion dollars in merchandise, to flow backwards through their networks, with online return rates near 19.3 percent. Regulation in the European Union has meanwhile begun treating post-consumer flows as mandated recovery obligations, through the Ecodesign for Sustainable Products Regulation, the Digital Product Passport, and the Right to Repair Directive. This review synthesises advances in closed-loop supply chain (CLSC) research with a focus on returns managed as an instrument of product lifecycle recovery rather than residual disposal. It organises the field around five interacting layers, design, information, network, decision, and market, and argues that the most consequential recent advance is item-level data infrastructure, which makes condition, provenance, and residual value legible at the moment a return is initiated, shifting the central question from where to locate recovery facilities to how to decide, at scale, what each returned unit should become. Persistent gaps include the weak empirical grounding of CLSC optimisation models, the neglect of informal recovery systems, the tension between resilience and circularity, and the near absence of validated methods for establishing whether returns management reduces environmental burden.

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1. Introduction

The linear model of production, in which materials are extracted, converted into products, sold, used, and discarded, has faced sustained challenge for three decades. What has changed recently is the point of leverage. Early circular economy scholarship concentrated on recycling infrastructure and waste policy, treating post-consumer material as something to divert from landfill. Contemporary work concentrates on the return event itself: the moment a product re-enters a firm's control while retaining substantial residual value.

This matters because value decays. A returned smartphone resold within a week may retain sixty percent of its price; the same device queued for two months is worth a fraction of that. Recovery economics are therefore inseparable from the speed of the reverse channel (Blackburn *et al.*, 2004; Guide & Van Wassenhove, 2009), a conclusion procurement research reaches from the forward direction in finding that visibility and cycle-time compression drive availability at least as strongly as unit-cost negotiation (Okonkwo *et al.*, 2021a, 2023a).

Three developments make this review timely.

First, returns have become structurally significant in scale. Retailers expected 15.8 percent of annual sales returned in 2025, totalling 849.9 billion dollars (National Retail Federation [NRF] & Happy Returns, 2025), while e-commerce returns reached an estimated 19.3 percent of online sales (NRF & Happy Returns, 2025). Returns are no longer an exception handled by customer service but a parallel supply chain at a scale comparable to the forward one, and retail analytics now treats the reverse flow as a

first-order determinant of working capital and margin (Tonoyan *et al.*, 2022b, 2023).

Second, the regulatory environment has hardened. The Ecodesign for Sustainable Products Regulation entered into force in 2024, with a 2025 to 2030 working plan identifying priority product groups (European Commission, 2025), and Directive (EU) 2024/1799 obliges producers to repair the products they sell (Council of the European Union & European Parliament, 2024a). These convert voluntary commitments into enforceable obligations with defined scopes and deadlines, mirroring compliance shifts in data protection, ESG disclosure, and trade regimes (Annan, 2022; Jones *et al.*, 2023; Ominyi & Anichukwueze, 2022a, 2022b). Third, the technological substrate has changed. Machine learning for return forecasting, computer vision for condition grading, and item-level identity for provenance have moved from prototype to deployment. Roughly 85 percent of retailers report using artificial intelligence to detect return fraud (NRF & Happy Returns, 2025), a reminder that the first commercial application of a technology is often defensive rather than restorative. Comparable diffusion appears in procurement automation, forecasting, and governance platforms (Michael & Ogunsola, 2025; Okonkwo *et al.*, 2024a, 2024d; Okoruwa *et al.*, 2025b).

2. Conceptual Foundations

A closed-loop supply chain integrates a forward channel with a reverse channel through which used, unsold, or returned products flow back for value recovery. The defining feature is coordination of both directions under a single design and control logic: a firm operating a returns depot while making no forward design decisions on the basis of recoverability has a reverse logistics operation, not a closed loop (Govindan *et al.*, 2015; Souza, 2013). Coordination is an architectural property, not an operational add-on (Okonkwo *et al.*, 2023b, 2024a, 2025). In a CLSC recovered material returns to the original producer or its authorised network; in a circular supply chain it may cascade into a different value chain. The concept remains contested (Geissdoerfer *et al.*, 2017; Kirchherr *et al.*, 2017), and recent synthesis treats the two as

complementary layers, reverse logistics facilitating recovery operationally while lifecycle management provides design oversight (Kianguebene-Koussingounina *et al.*, 2023; Michael & Ogunsola, 2024; Uduokhai *et al.*, 2024b).

Recovery options are conventionally ordered from refuse and rethink through reduce, reuse, repair, refurbish, remanufacture, and repurpose to recycle and recover energy, on the claim that preserving product architecture retains more embedded energy and labour than reducing it to material (Atasu *et al.*, 2008). The ordering is frequently misapplied: extending the life of an inefficient appliance may raise lifetime emissions relative to replacement, and reuse requiring long-distance transport may impose a burden exceeding the manufacturing burden avoided. The hierarchy is a default, and the conditions under which it inverts are among the more useful open questions in the field. Frameworks formalising these trade-offs remain rare (Okojie & Abioye, 2020).

Returns management encompasses four problems that are often conflated. Avoidance prevents returns that should not happen, and is the highest-leverage intervention and the least studied, since operations research treats return volume as exogenous (Atima *et al.*, 2022; Ogundairo & Ayivi-Donkor, 2023a, 2023b; Sanni *et al.*, 2022b). Gatekeeping decides which returns to accept and on what terms, borrowing from risk scoring developed for financial transaction monitoring (Akinola *et al.*, 2024; Azeez *et al.*, 2024; Bello *et al.*, 2025b; Fadayomi *et al.*, 2024). Disposition decides what each accepted unit becomes: restock, repair, refurbish, remanufacture, part harvest, liquidation, donation, recycling, or disposal. Recovery execution performs that decision, raising capacity, routing, scheduling, and quality control problems of the kind treated in lean process optimisation and warehouse automation (Akanbi & Sunday, 2024; Ezeugwa *et al.*, 2023). Most literature addresses only the third and fourth, because the four sit in different organisational functions with different data and incentives, and end-to-end visibility work suggests the barrier is informational before it is organisational (Nnabueze *et al.*, 2021).

Table 1: Return types differ in ways that materially affect recovery economics

Return type	Typical trigger	Residual value	Time sensitivity
Commercial returns	Buyer's remorse, fit, expectation mismatch	High, often near-new	Very high
Warranty returns	Defect within guarantee	Moderate	High
Service returns	Repair, maintenance, exchange	Moderate	Moderate
End-of-use returns	Upgrade, lease expiry, trade-in	Moderate to low	Moderate
End-of-life returns	Product failure, obsolescence	Low, material-driven	Low
Unsold inventory	Overstock, seasonal expiry	High but declining	Very high

Treating these as a single flow is a common practical error, since commercial and end-of-life returns require different facilities, inspection regimes, disposition logic, and regulatory treatment. E-commerce has skewed the mix toward the commercial category, precisely where processing speed determines recovered value (Adelanwa *et al.*, 2023; Okonkwo *et al.*, 2023a).

3. Methodology

This is a structured narrative review. A systematic review with a pre-registered protocol supports defensible claims about the distribution of a literature; a narrative review instead yields synthesis across bodies of work that use incompatible vocabularies and would not survive a single

search string. The latter suits a question spanning operations research, information systems, environmental policy, and marketing.

The field is already well served by systematic reviews at sub-domain level, including a PRISMA-guided meta-review screening 102 articles for 2012 to 2025 and a bibliometric review of 1,602 Scopus articles on CLSC pricing, which found game-theoretic models widely applied. Comparable protocols applied to lean methodology, resilience indexing, and procurement cost optimisation informed the selection approach used here (Akokodaripon *et al.*, 2023; Efobi *et al.*, 2023).

Sources were assembled from three streams: peer-reviewed operations research, operations management, and industrial

ecology; primary regulatory documents; and industry data from trade associations and returns technology providers. The third requires caution, since such statistics are often produced by firms selling returns solutions and the incentive to characterise the problem as large is obvious. Where used, these figures are attributed and their provenance noted, a concern also raised about vendor-published claims in procurement analytics (Babatope *et al.*, 2023).

Two boundaries were applied. Food and perishable chains are excluded, since shelf-life constraints dominate their recovery logic, though detection technologies developed there remain relevant to condition assessment (Olorunkosebi *et al.*, 2023). Pure waste management literature, where the product is treated only as material from the outset, is excluded except where it interfaces with product-level recovery.

4. Literature Synthesis

4.1. The Returns Problem: Scale, Cost, and Drivers

Volume. Total returns were projected at 849.9 billion dollars in 2025, with an estimated 19.3 percent of online sales returned (NRF & Happy Returns, 2025). The apparent decline in the all-channel rate from 2024 should be read carefully, because online returns rose over the same period, from 17.6 percent to 19.3 percent (NRF & Happy Returns, 2025). As channel mix shifts online, a falling blended rate is compatible with a worsening underlying problem.

Category variation is substantial and under-reported. Apparel sits far above the mean on fit uncertainty; categories with objective specifications sit well below. Models calibrated to an average rate misrepresent both tails, an aggregation hazard also documented in retail demand estimation (Akin-Oluyomi *et al.*, 2023a; Tonoyan *et al.*, 2022a).

Cost structure: The cost of a return is not the reverse of the cost of a sale. It comprises single-item reverse transport lacking outbound density economics, receipt and inspection labour, grading, repackaging, carrying cost during assessment, the value gap between original and recovered price, and refund administration. Industry estimates place per-item processing at twenty to thirty dollars, but dispersion is wide enough that a single figure has little analytical use, and simulation-based costing offers a more defensible route to category-specific estimates (Aliliele *et al.*, 2024c, 2025c; Dada *et al.*, 2024; Oluwo *et al.*, 2024).

The value gap dominates and is a function of time. This is the marginal value of time argument anchoring commercial returns research (Blackburn *et al.*, 2004): where value decays quickly, networks should be designed for speed even at the cost of transport efficiency; where decay is slow, consolidation dominates. The principle is robust but operationalised far less than cited, despite transferable machinery in route optimisation and delivery profitability modelling (Opara *et al.*, 2024; Tonoyan *et al.*, 2025). Work on quoting lead times online under contingency is a closer analogue still, since it addresses how a firm commits to a turnaround time when downstream capacity is uncertain, precisely the promise a returns operation makes when it offers an instant refund (Ekun & Muriel, 2024).

Drivers. Policy-induced demand: Liberal returns policies function as a demand instrument. Nearly 82 percent of consumers cite free returns as a major purchase consideration, up from 76 percent the previous year (NRF & Happy Returns, 2025). Leniency therefore sits inside a genuine trade-off rather than a straightforward inefficiency.

Bracketing: Ordering multiple sizes with intent to return

most makes the return channel part of the purchase process. It is rational under fit uncertainty and best addressed through avoidance rather than gatekeeping (Ogundairo & Ayivi-Donkor, 2023a, 2024b; Sanni *et al.*, 2023b; Wedraogo & Sanni, 2024).

Fraud and abuse: The 2025 industry survey found 9 percent of returns fraudulent, with growth in overstated quantities, empty box returns, and decoy returns (NRF & Happy Returns, 2025). Independent estimates run higher, at over 15 percent or 103 billion dollars in 2024 (Appriss Retail & Deloitte, 2025). The divergence reflects different definitions of abuse, and the field lacks a shared measurement standard. Returns fraud detection is a near-relative of transaction fraud, synthetic identity fraud, and financial anomaly detection, where transfer of technique has outpaced transfer of evaluation discipline (Abetoh & Atakpa, 2024; Atakpa *et al.*, 2024; Bello *et al.*, 2025a; Okoruwa *et al.*, 2025a).

Cost pressure: Retailers have begun charging for returns, citing processing costs, carrier rates, and tariff uncertainty (NRF & Happy Returns, 2025). The resulting pricing variation across comparable retailers is an unexploited source of identification for work on elasticity and avoidance.

The environmental question: The assumption that fewer returns means lower environmental impact is plausible but weakly evidenced. A return producing rapid restocking and resale may impose marginal transport burden while avoiding production of another unit; one producing liquidation, long-distance secondary transport, and disposal may be worse than no return. The environmental sign of a return depends on its disposition, and disposition-linked data has been unavailable. Attaching impact factors to individual decision gates rather than to annual totals is one tractable route, and the measurement apparatus for it already exists in emissions monitoring and ESG assurance work (Okojie *et al.*, 2023a, 2023b).

End-of-life failure is starkest in electronics. A record 62 million tonnes of e-waste was generated in 2022, up 82 percent from 2010, with only 22.3 percent documented as properly collected and recycled and an estimated 62 billion dollars of recoverable resources unaccounted for (International Telecommunication Union [ITU] & United Nations Institute for Training and Research [UNITAR], 2024). The rate is projected to fall to 20 percent by 2030, and only about 1 percent of rare earth demand is met by recycling (ITU & UNITAR, 2024). This is a recovery system losing ground, and emissions monitoring research suggests measurement infrastructure rather than method is the binding constraint (Okojie *et al.*, 2023b, 2023a; Ominyi & Anichukwueze, 2022b).

4.2. Advances in Network Design and Planning

Network configuration: CLSC network design determines where to locate collection, inspection, refurbishment, and disposal capacity and how to route flows among them. The canonical formulation is a mixed-integer program minimising cost subject to flow and capacity constraints, extended to multi-objective, multi-period, stochastic, and robust settings including carbon-constrained e-commerce networks (Govindan *et al.*, 2015; Souza, 2013). Adjacent modelling in energy and infrastructure procurement addresses similar siting, capacity, and continuity problems under regulatory constraint (Amayo *et al.*, 2024, 2025; Okonkwo *et al.*, 2024b, 2024e).

The limitation of this stream is empirical. Much published

work is validated on numerical examples with synthetic parameters, leaving models internally rigorous and externally unanchored, because firms treat returns cost data as commercially sensitive and academic incentives reward novelty over calibration. Comparative procurement studies using operational cost data show how rarely calibration is attempted (Akinleye *et al.*, 2022; Akokodaripon *et al.*, 2023). **Uncertainty:** Reverse flows are uncertain in quantity, timing, and condition simultaneously. Forward chains face the first two but rarely the third, and this quality dimension makes CLSC planning genuinely harder rather than a mirror image. Quality uncertainty propagates: it determines remanufacturing yield, hence capacity, hence configuration. Models assuming homogeneous core quality underestimate capacity and overestimate recovery rates, and the literature on network design under risk remains fragmented (Hu, 2023). Predictive vendor risk assessment offers transferable apparatus, since it also estimates a latent quality parameter from indirect signals (Akinleye *et al.*, 2023; Tonoyan *et al.*, 2024; Wedraogo *et al.*, 2025).

The resilience and sustainability tension: Resilience and sustainability objectives can conflict. Redundancy and diversified sourcing improve disruption resistance but raise resource consumption; lean circular configurations optimise material efficiency but concentrate risk (Tombido, 2025). Work on CLSC resilience has begun examining a multi-directional ripple effect, in which disruptions spread forward through production, laterally across same-tier facilities, and backward through reverse logistics. This backward channel is distinctive to closed loops and largely absent from mainstream resilience modelling, though resilience indexing, critical-infrastructure frameworks, and humanitarian logistics supply components (Adesuyi *et al.*, 2025a; Anene *et al.*, 2024; Efobi *et al.*, 2023; Ike *et al.*, 2024).

That performance degrades consistently as disruption severity rises regardless of tier count is a useful negative result: structural remedies alone are insufficient and agility matters more than topology. Post-pandemic procurement studies concur, finding supplier relationship depth outperformed supplier count as a resilience predictor (Akinleye, 2024; Akin-Oluyomi *et al.*, 2024).

Inventory and production planning with returns: Optimal policy for joint production and remanufacturing under stochastic returns depends on whether recovered and new units are substitutable and whether returns correlate with prior sales. Where correlation is strong, as it usually is with a lag, return forecasting reduces to demand forecasting with a delay distribution; where weak, the problem is much harder. The bottleneck is parameter estimation, and predictive analytics for demand and inventory holding transfers with modification (Okonkwo *et al.*, 2024c).

4.3. Disposition and Value Recovery

The disposition decision: Disposition is the pivot of returns management: every downstream cost and environmental outcome follows from it, and the decision must be made quickly, at volume, on heterogeneous units, with incomplete information.

Classical models treat it as static optimisation over condition grade, channel prices, and processing costs. Grade is itself an estimate; secondary market prices are endogenous to disposition volume, since flooding a resale channel depresses the price that justified routing there; capacity is shared, creating congestion coupling; and holding a unit preserves

option value while incurring decay. Asset valuation frameworks integrating pricing with multi-use potential offer a formal analogy (Medon & Oduleye, 2024; Tonoyan *et al.*, 2023; Walawalkar *et al.*, 2025). Recent work moves toward sequential decision formulations, though deployment lags theory, and the gap is organisational instrumentation rather than algorithmic capability (Eyetsemitan *et al.*, 2024b; Ogundairo, 2025).

Grading and inspection: Condition assessment has been the throughput bottleneck and the primary source of decision error, since manual grading is slow, costly, and inconsistent across inspectors. Core quality varies with customer usage, and computational methods such as object detection and defect identification can address the resulting uncertainty and subjective bias (Wang *et al.*, 2024).

Automated vision grading is the most consequential operational advance of the past five years because it attacks the bottleneck rather than optimising around it. Its limits matter: vision assesses surface condition well and internal condition poorly, and performs badly on the long tail where manual inspection was already most expensive. Sensor-based fault detection, non-destructive evaluation, and biosensor-assisted detection address internal condition from different directions (Atta *et al.*, 2022; Ayinde, 2025; Olorunkosebi *et al.*, 2023; Omoegun *et al.*, 2023).

Remanufacturing: Remanufacturing restores a used product to a specified performance standard with warranty comparable to new, preserving the most embedded manufacturing value. Core acquisition remains the binding constraint, since forecasting availability by quantity, timing, and condition is difficult (Zhu *et al.*, 2025). Framing condition forecasting as defect and fault prediction imports mature reliability technique into a data-poor domain (Gideon *et al.*, 2019).

Remaining barriers are largely non-technical: designs resisting disassembly, intellectual property restrictions on repair information, cannibalisation concerns, and perception of remanufactured goods as inferior. Operations research addresses the last through pricing and segmentation but treats the first three as exogenous, though work on trade secret protection suggests the intellectual property constraint is itself a policy variable (Annan, 2024).

Repair and refurbishment: Repair has received little attention relative to its position in the hierarchy and its new regulatory prominence, partly because it is often performed outside the producer's network and so falls outside the firm-centric boundary of most modelling. The changes in Section 4.5 make this untenable: a legal obligation converts repair into an in-network operation with capacity, spare parts, scheduling, and pricing decisions. Maintenance research supplies most of the apparatus, covering reactive-to-predictive transitions, reliability-centred scheduling, and ageing asset bases (Komi *et al.*, 2021; Uduokhai *et al.*, 2025b).

Recycling and material recovery: Recycling recovers material value while destroying product value. It is the option of last resort but the destination of most recovered mass, and its critical questions concern secondary material quality, separation, and the economics of materials present in small quantities per unit. Materials that are strategically critical but dispersed across many products are exactly those where recovery economics fail absent design or policy intervention. Semiconductor supply chain risk work makes the strategic dimension explicit, particularly for electric vehicle and

storage chains where substitution options are narrow (Erhimefe *et al.*, 2025; Gideon, 2025b; Komi & Ganiu, 2022). Renewable-material substitution in construction offers a contrasting case where secondary quality is more forgiving and barriers are economic rather than technical (Falegan & Aniebonam, 2022, 2024, 2025; Uduokhai *et al.*, 2024c).

4.4. Digital Enablement

Forecasting and prediction: Machine learning addresses three distinct returns problems the literature does not always separate. Predicting whether an individual order will be returned supports pre-emptive intervention such as sizing guidance; interpretability matters because restricting a customer's options carries fairness and legal implications a black-box score cannot support (Annan, 2025a; Ominyi & Anichukwueze, 2023, 2024b). Predicting aggregate volume and timing supports capacity planning and inherits the methods and failure modes of demand forecasting (Adelanwa *et al.*, 2024; Joseph *et al.*, 2025; Oziri *et al.*, 2025; Shah *et al.*, 2025). Predicting condition of arriving cores is hardest, since it depends on unobserved usage history, and interpretable early-failure prediction is the closest analogue (Komi *et al.*, 2021). Model governance is underexamined across all three: where returns models gate consequential customer-facing decisions, release criteria, bias evaluation, and drift monitoring become part of the operational system (Nwakamma *et al.*, 2024; Oyesiji *et al.*, 2024; Sanni *et al.*, 2022a).

Automated processing: Deployment evidence comes largely from industry sources and carries the provenance caveat noted in Section 3. Reported effects include a shorter interval between receipt and graded decision and higher throughput per unit of facility area, consistent with the marginal-value-of-time argument but thinly verified. Warehouse automation research shows what the physical layer of an automated returns centre looks like, addressing the high-mix handling problem through path planning, slotting optimisation, multi-agent coordination, and micro-fulfilment (Akanbi & Sunday, 2024, 2025b; Akanbi *et al.*, 2025a). Service management platform research covers the workflow layer above it (Adebayo *et al.*, 2025; Badmus *et al.*, 2025; Ladapo *et al.*, 2025; Ogbale *et al.*, 2025). Where automated systems produce contestable outcomes, human-in-the-loop architecture becomes a design requirement rather than a fallback (Ladapo *et al.*, 2022, 2024).

Digital product identity: The most structurally significant development is item-level product identity. The Digital Product Passport may include information on safety, origin, materials, repairability, environmental performance, reuse, and recycling depending on product group, with its legal basis in the Ecodesign Regulation (Council of the European Union & European Parliament, 2024b).

The implication for returns is direct and under-appreciated. Disposition has been hard because the decision-maker knows little about the unit in hand: its composition, repair history, authorised disassembly sequence, and recycler-relevant content. A passport supplies exactly this, shifting disposition from inference under ignorance toward lookup and optimisation. The nearest analogue is pharmaceutical serialisation, where item-level identity has been mandatory for a decade and traceability, chain-of-custody, data integrity, cold chain, and field authentication frameworks are documented (Aneke & Adesemoye, 2024a, 2025; Aneke *et al.*, 2023; Ussher-Eke *et al.*, 2025). Supply chain visibility

and encrypted access control research addresses the same architecture from the information systems side (Aliliele *et al.*, 2024a, 2024b, 2025b; Okoruwa *et al.*, 2024).

Implementation is being staged around a central registry of unique identifiers, with the detailed passport data held decentrally rather than in one repository (European Commission, 2025). That architecture avoids a single point of control but creates interoperability and data-availability risk over lifetimes spanning decades: a passport whose data host has ceased trading is not a passport. Data sensitivity classification and regulatory traceability frameworks address part of this, but multi-decade persistence remains unaddressed in any literature reviewed here (Adegbite *et al.*, 2024a, 2024b, 2025; Adeniyi *et al.*, 2025). Carrier durability and placement also remain unresolved, acutely so for textiles, and research on batteryless and energy-harvesting wireless devices bears directly on whether a carrier can remain readable across a product's life (Asiedu *et al.*, 2025a, 2025b; Quainoo *et al.*, 2025a, 2025b).

Distributed ledgers and digital twins: Blockchain applications in CLSC have been proposed extensively for provenance, authenticity, and multi-party coordination, including smart contract settlement, dispute resolution, cross-ledger interoperability, and collaborative data governance (Adesuyi *et al.*, 2025b; Akomolafe *et al.*, 2025b, 2025c; Olaogun *et al.*, 2025). Enthusiasm has exceeded deployment. Most proposals solve coordination problems addressable with a shared database and a governance agreement, and the genuine case, verifiable claims among parties with weak trust and no natural coordinator, is narrower than the literature suggests. Digital twins have clearer value for condition prediction but require sensing most consumer products lack; convincing applications remain in capital equipment and process environments where instrumentation already exists (Adeniji *et al.*, 2025; Ike *et al.*, 2025; Olodo *et al.*, 2025; Shittu *et al.*, 2025), with edge deployment research addressing the cost of extending them to lower-value assets (Nwakamma *et al.*, 2025; Ojukwu *et al.*, 2023, 2025; Oyesiji *et al.*, 2025).

4.5. Policy and Regulatory Drivers

Ecodesign and information requirements: The Ecodesign for Sustainable Products Regulation is the most consequential single instrument in force. It sets durability, recyclability, and recycled content requirements for products placed on the European market, introduces standardised information requirements, and bans destruction of unsold textiles and footwear (Council of the European Union & European Parliament, 2024b). The first working plan covers 2025 to 2030 with an interim review in 2028 and prioritises textiles, furniture, mattresses, tyres, iron and steel, and aluminium; textiles were designated first given their potential for lifetime extension, with a delegated act expected in 2027 (European Commission, 2025).

ESPR is framework legislation whose substantive requirements arrive through product-specific delegated acts, creating a partially predictable pipeline in which firms anticipate direction while remaining uncertain about specifics. Regulatory readiness maturity models from pharmaceutical approval pipelines offer a template for acting under scheduled uncertainty (Aneke *et al.*, 2022; Eze *et al.*, 2024a), as does work on procurement under standing regulatory constraint (Okonkwo *et al.*, 2021b).

The destruction ban deserves particular attention. Destruction

has been a common disposition for returned and overstock fashion items, chosen for brand protection and cost. Removing it forces volume into resale, donation, and recycling channels that may lack absorbing capacity, a capacity shock with a known date and an unusually clean setting for empirical work. Early warning models for medicine shortages offer methodology for anticipating channel saturation (Eze *et al.*, 2022).

The right to repair: Directive (EU) 2024/1799 is the first EU-level instrument obliging producers to repair the products they sell, inside and outside the legal guarantee. Adopted in June 2024, it must be transposed and applied from 31 July 2026, and where repair is chosen as the remedy the guarantee extends once by one year (Council of the European Union & European Parliament, 2024a). Covered products include washing machines, refrigerators, electronic displays, mobile phones, tablets, and servers, with more added as ecodesign regulations are adopted.

Two features carry operational weight. The obligation applies to products placed on the market before the application date, so the installed base generates demand from day one. And consumers choosing repair receive a 12-month warranty extension, changing the repair-versus-replace calculation for both parties. Supporting infrastructure follows a longer timeline, with a common online repair platform due by July 2027 and full operation by January 2028 (EUR-Lex, 2025).

A complication receiving little research attention is that a directive produces twenty-seven national laws rather than one. Products, obligation, and warranty extension are harmonised, but penalties are set country by country. Compliance is therefore not uniform, and comparative research on harmonising divergent national implementations is largely untapped (Annan, 2022, 2023, 2025b; Jones *et al.*, 2024a). The legislative rationale is quantified: discarded repairable items contribute 35 million tonnes of waste and 261 million tonnes of greenhouse gas emissions in the EU annually (EUR-Lex, 2025).

Extended producer responsibility: EPR shifts end-of-life cost to producers, and its extension from packaging and electronics into textiles and furniture has broadened the population of firms with mandatory obligations. The unresolved question is whether EPR induces design change. Theory says internalising end-of-life cost creates incentive for recoverable design; in practice fees are often too low and too weakly differentiated to alter design decisions, and collective compliance dilutes the individual signal. Eco-modulation is intended to address this, and evaluating whether it does is among the more policy-relevant empirical questions available, with measurement apparatus from ESG-integrated procurement research (Essandoh *et al.*, 2025; Okafor *et al.*, 2025; Sakyi *et al.*, 2024; Yeboah *et al.*, 2025).

Interaction effects: These instruments interact non-additively. Durability requirements reduce failure returns but extend the interval before end-of-life recovery. Repair obligations increase spare parts demand and shift volume from replacement sales to service revenue. Passport requirements reduce disposition uncertainty across all channels. No integrated model exists for assessing the package. Organisational readiness research on the EU Artificial Intelligence Act offers a methodological parallel for overlapping obligations on staggered timelines (Ominyi *et al.*, 2024a, 2025a, 2025b, 2025c), and trade compliance research supplies the cross-border dimension once recovered goods meet divergent classification rules (Akin-Oluyomi *et*

al., 2023b; Jones *et al.*, 2024b, 2025a, 2025b).

4.6. Consumer Behaviour and the Demand Side

Returns respond systematically to policy leniency, product information quality, price, channel, and prior return experience. Less well established is causal effect, since most work is observational and confounded by selection, a problem attribution modelling has confronted in marketing with partial solutions (Ogundairo & Ayivi-Donkor, 2023a; Sanni *et al.*, 2022b). Willingness to buy refurbished goods is the demand-side constraint on the whole system, since recovery capacity is worthless without a market for output. Acceptance is category-dependent, price-sensitive, and conditioned by warranty and certification, and manufacturer-certified refurbishment commands a premium over unbranded refurbishment of identical quality, a signalling result that pricing and valuation frameworks could formalise (Tonoyan *et al.*, 2023).

Returns fraud has moved from nuisance to material cost, and the response has been rapid technological adoption, with 85 percent of retailers deploying artificial intelligence to detect and prevent such incidents (NRF & Happy Returns, 2025). An unexamined tension follows. Fraud detection systems classify customers by predicted abuse risk and restrict options accordingly, trained on historical data, operating without transparency, and producing consequential decisions; a customer wrongly flagged has limited recourse and typically no explanation. The governance apparatus exists in adjacent domains, covering algorithmic accountability and model risk management in financial services, anti-discrimination compliance for automated decisions, responsible AI governance, and AI-assisted continuous auditing (Agu *et al.*, 2025; Akomolafe *et al.*, 2025a; Aliliele *et al.*, 2025a; Annan, 2025a). As these systems become standard, this becomes a consumer protection question rather than merely an operational one.

4.7. Business Model Innovation

Structured resale has become a substantial channel run by brands, platforms, and liquidation specialists. Its operational challenge is inventory of one: each unit is unique in condition, making pricing, listing, and matching expensive relative to unit value, so automated assessment and pricing are what make the model viable at scale and why recommerce growth has tracked grading maturity (Tonoyan *et al.*, 2022c, 2023).

Where a producer retains ownership, incentives for durability and recoverability invert, because the producer bears replacement cost. The literature is enthusiastic and the practice patchy, for structural reasons: capital intensity, accounting treatment, consumer preference for ownership, and residual value risk. Studies advocating servitisation understate these, and sustainable business model research gives a more grounded account of where the model holds (Filani *et al.*, 2023; Nnabueze *et al.*, 2023).

Third-party returns infrastructure has emerged as a distinct industry layer, since returns processing has strong scale economies, most retailers lack volume to justify dedicated automated capacity, and consolidation before line-haul restores the density economics individual shipments destroy. Reliance on third parties at peak is now common, alongside seasonal hiring and extended return windows (NRF & Happy Returns, 2025). Lean operations research on standard procedures, cycle time, and change management applies

directly to mid-sized retailers building or outsourcing this capability (Eyetsemitan *et al.*, 2023a, 2023b, 2024a, 2025).

4.8. Sector Contexts for Lifecycle Recovery

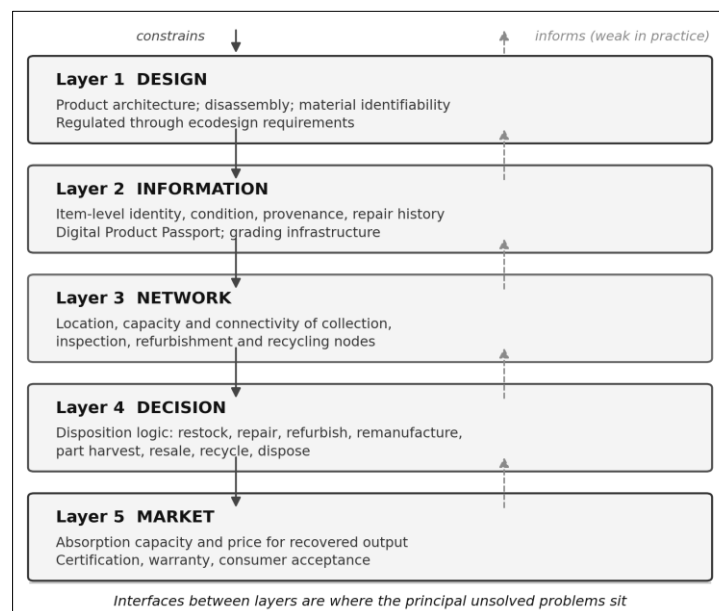
Generic CLSC models understate how much recovery logic varies by sector, and four sectors mark the range. Pharmaceutical chains have operated under item-level traceability, chain-of-custody requirements, and mandatory quality management longer than any consumer-facing sector, so they preview problems the DPP will create elsewhere, across traceability, risk-based decisions under good manufacturing practice, corrective action, data integrity, cold chain, and detection of falsified product (Aneke & Adesemoye, 2024a, 2025; Aneke *et al.*, 2023; Opara *et al.*, 2025); two lessons transfer, that mandatory identity infrastructure produces data whose governance becomes the binding problem, and that regulatory harmonisation is slow, partial, and consequential for cross-border flows (Aneke *et al.*, 2024b; Eze *et al.*, 2023, 2024a, 2024b). Electronics is where recovery economics are most favourable in principle and most disappointing in practice, combining high embedded value, rapid obsolescence, hazardous content, and critical materials in small per-unit quantities: reliability engineering determines what is technically recoverable and supply chain risk work what is strategically worth recovering (Erhimefe *et al.*, 2025; Gideon, 2025b, 2025c; Gideon & Erhimefe, 2025a), while research on data-driven maintenance shows how far forward operations have advanced relative to recovery (Olodo *et al.*, 2025). Construction inverts several standard assumptions, since value decay is slow, the recovery decision arrives decades after the design decision, and the recovering party is rarely the original producer; system

dynamics modelling of circular integration, techno-economic evaluation of renewable-material construction, and embodied carbon accounting at decision gates form the most developed strand outside consumer goods (Uduokhai *et al.*, 2024a, 2024b, 2024c, 2025a), with predictive maintenance for ageing infrastructure addressing the use-phase extension that dominates recovery value (Dagodzo & Ahiaekwe Patrick, 2022, 2023; Uduokhai *et al.*, 2025b). Distributed renewable installations and storage are becoming a major end-of-life stream on a predictable schedule, since battery degradation, inverter failure, and panel end-of-life are forecastable in a way consumer returns are not, making the sector a good testbed for recovery planning across degradation and storage performance, early failure prediction, control architecture, digital twin diagnostics, and preventive maintenance design (Atta *et al.*, 2025; Dagodzo & Ahiaekwe Patrick, 2025; Komi, 2025a; Komi & Ganiu, 2025b), with logistics optimisation connecting the use phase to the transport burden of recovery (Opara *et al.*, 2024).

5. A Layered View of Lifecycle Recovery

The literature synthesised in Section 4 is fragmented across communities that rarely cite one another: network design in operations research, disposition in operations management, traceability in information systems, ecodesign in environmental policy, returns behaviour in marketing. This section proposes an integrative model making their dependencies explicit.

The model, shown in Figure 1, treats lifecycle recovery as five nested layers. Each constrains those beneath it and returns information upward that should, but usually does not, inform the layer above.



Note. Solid arrows show constraint propagation downward; dashed arrows show information feedback upward, which the review finds weakly realised in practice.

Fig 1: The Five-Layer Model of Product Lifecycle Recovery

Layer 1: Design: Product architecture determines the feasible recovery set. Whether a unit can be non-destructively disassembled, whether materials are identifiable, and whether repair documentation exists are fixed years before the first return, and this layer is now directly regulated through ecodesign requirements.

Layer 2: Information: Item-level identity, condition,

provenance, and repair history determine the quality of every downstream decision. It is changing fastest, and it is where pharmaceutical serialisation experience is most instructive (Aneke *et al.*, 2023).

Layer 3: Network: The location, capacity, and connectivity of recovery nodes determine processing speed and cost. This layer has the most mature research base and the least recent

conceptual movement (Govindan *et al.*, 2015; Hu, 2023).

Layer 4: Decision: Disposition logic converts information into routing, and is where recovered value is realised or destroyed and the marginal value of time operates most sharply (Blackburn *et al.*, 2004).

Layer 5: Market: Demand for recovered output determines whether recovery is self-sustaining. Capacity without an absorbing market produces stockpiles, not circularity. Four propositions follow, organising the gaps in Section 6 and the agenda in Section 9.

Proposition 1 (Information dominance): Where item-level information quality is low, improvements in network configuration yield smaller gains in recovered value than improvements in information quality, because disposition error dominates processing cost. The return on passport infrastructure therefore exceeds that on facility optimisation in most settings.

Proposition 2 (Design constraint propagation): Recovery options at Layer 4 are bounded by Layer 1 decisions, so disposition optimisation cannot compensate for non-recoverable design, and regulatory intervention at Layer 1 therefore has higher leverage than at any lower layer.

Proposition 3 (Market feedback): Disposition policies ignoring secondary market absorption will over-route to resale, depressing recovered prices and inverting the assumed ranking of options. Layer 5 conditions must enter Layer 4 decision rules as endogenous variables rather than fixed prices.

Proposition 4 (Hierarchy conditionality): The recovery hierarchy holds only where use-phase impact is low relative to production impact and recovery transport distance is short. Outside these conditions it can invert, and the inversion boundary is an empirical quantity current models do not estimate.

The model is organising rather than predictive. It specifies no functional forms and is not a maturity model. Its purpose is to make explicit that the unsolved problems sit at layer interfaces, precisely where disciplinary boundaries also sit.

6. Discussion

The central finding is that returns management has been reframed rather than merely improved: a cost centre for processing unwanted goods cheaply has become the principal control point for lifecycle recovery. The three driving forces are not independent, since regulatory obligations create demand for information infrastructure and that infrastructure makes the operational scale tractable. The Digital Product Passport is the clearest instance, a regulatory instrument whose primary effect is informational, felt most acutely in the disposition decision regulation does not directly address.

The machinery needed to close several open problems already exists in adjacent fields under different names. Traceability governance is mature in pharmaceutical distribution (Aneke & Adesemoye, 2025; Aneke *et al.*, 2023). Predictive condition assessment is mature in maintenance engineering (Komi *et al.*, 2021). Algorithmic accountability is mature in financial services supervision (Aliliele *et al.*, 2025a; Ominyi & Anichukwueze, 2023, 2024b). High-mix material handling is mature in fulfilment robotics (Akanbi & Sunday, 2024, 2025b).

The CLSC literature draws on these sparingly, and the reason appears to be vocabulary rather than substance: the same structural problem is called core acquisition in remanufacturing, condition forecasting in maintenance, and

yield estimation in process engineering.

Three widely circulated claims are not well supported by the evidence reviewed. First, that reducing returns reduces environmental impact. The environmental sign of a return depends on its disposition, and disposition-linked impact data is largely unavailable; the claim may be true in aggregate but is now an assumption rather than a finding. Second, that servitisation reliably outperforms ownership on circularity grounds. The advocating literature is more enthusiastic than the practice warrants, and constraints of capital intensity, accounting treatment, and residual value risk are consistently understated (Nnabueze *et al.*, 2023). Third, that blockchain resolves multi-party coordination in recovery networks. Most proposals address problems solvable with a shared database and a governance agreement, and the genuine case is real but smaller than the volume of publication suggests.

The recognition that resilience and circularity objectives can conflict is among the more consequential recent developments (Tombido, 2025). The finding that closed-loop networks degrade consistently as disruption severity rises, regardless of tier structure, suggests topology alone is not the remedy and that agility mechanisms matter more (Efobi *et al.*, 2023; Ike *et al.*, 2024).

7. Implications

The layered framework repositions disposition, rather than network configuration, as the theoretical centre of CLSC research: the dominant tradition treats disposition as a downstream consequence of network design, whereas Proposition 1 implies the reverse dependency where information quality binds. The framework also identifies a problem class existing formulations do not address. Standard models assume condition is inferred at inspection; passport-enabled disposition inverts this, since composition, repair history, and disassembly information precede physical assessment. Inspection becomes a verification rather than an estimation decision, and its value declines as prior information improves. CLSC theory also rests on an implicit assumption of homogeneous, firm-controlled recovery that informal systems do not fit.

For firms, four implications follow. Returns should be segmented by type rather than managed as a single flow, since commercial and end-of-life returns differ in residual value, time sensitivity, inspection requirement, and regulatory treatment. Investment sequencing should favour information over facilities: where grading is manual and item history unavailable, automated condition assessment and item-level identity generate larger recovered-value gains than network reconfiguration, because they attack disposition error rather than processing cost. Speed should be a design parameter, not an operational aspiration, since for fast-decaying categories configurations sacrificing transport density for processing speed usually dominate. And producers selling into the European Union should treat the repair obligation as an immediate operations problem: because it extends to products already on the market, demand does not phase in with new sales, and spare parts, technician capacity, and repair pricing require planning now.

For regulators, instrument sequencing matters more than instrument strength. Proposition 2 implies design-stage intervention has higher leverage than downstream mandates, because it expands the feasible recovery set rather than optimising within a fixed one.

Second, information mandates appear underrated relative to

performance mandates: a passport requirement compels no recovery outcome directly but removes the informational constraint limiting recovery decisions throughout the system. Third, interaction effects are not being assessed. Durability requirements, repair obligations, destruction bans, and passport mandates interact non-additively, and no integrated modelling capacity exists to evaluate the package. Fourth, the repair obligation is harmonised in substance but not enforcement, so the compliance burden on multi-market producers is higher than the harmonised headline suggests (Annan, 2022; Ominyin & Anichukwueze, 2022a).

8. Limitations

Several limitations bound these claims. As a structured narrative review, the paper carries no pre-registered protocol, reproducible screening, or inter-rater reliability assessment, and so cannot support claims about the distribution or completeness of the literature; a different reviewer would assemble a partially different corpus. The corpus itself is heterogeneous, combining peer-reviewed research, regulatory documents, and industry reports, the last produced substantially by organisations selling returns solutions and not independently verifiable, and several sources are conceptual rather than empirical. The policy analysis is weighted toward the European Union, where binding recovery obligations are most developed, so conclusions may not generalise to jurisdictions with different enforcement capacity or market structure, and informal recovery systems are not addressed in depth despite their scale.

Several central instruments are also mid-implementation. Delegated acts under the ESPR are pending, transposition of the repair directive is incomplete, and passport infrastructure is at registry stage, so statements about their effects are anticipatory rather than evidential. The layered framework is derived from synthesis rather than validated, its propositions falsifiable but untested, and its layer boundaries analytically convenient rather than empirically demonstrated. Finally, the underlying studies use incompatible outcome measures, definitions of return, and units of analysis, so no meta-analytic aggregation was attempted and reported magnitudes are indicative rather than pooled; the divergence between fraud estimates of 9 and over 15 percent shows how far the field is from shared measurement standards.

9. Future Research Directions

9.1. Empirical Calibration

Build and share anonymised operational datasets on returns flows, disposition outcomes, and recovered value. Consortium-based sharing under confidentiality protection is the realistic path, with governance templates from cross-border payments and multi-cloud financial infrastructure (Akomolafe *et al.*, 2025b; Mbonu *et al.*, 2022). Without this the modelling literature will elaborate without converging.

9.2. Passport-Enabled Disposition

Formulate and test disposition policies exploiting item-level passport data, and characterise how optimal inspection changes as prior information improves. Pharmaceutical traceability is the best guide to what such data will and will not deliver (Aneke *et al.*, 2023).

9.3. Coupled Environmental and Operational Modelling

Integrate life cycle impact factors into disposition and network models so environmental outcome is a decision

variable rather than a post-hoc calculation, and estimate when the recovery hierarchy inverts (Proposition 4) (Okojie *et al.*, 2023a).

9.4. Repair Operations Under Mandate

Develop capacity, spare parts, and pricing models for repair obligations with retroactive scope. The 2026 transposition creates a natural experiment across member states with varying enforcement (Sunday *et al.*, 2020).

9.5. Policy Shock Studies

Exploit the destruction ban, returns fee introduction, and repair mandate transposition as identification strategies for causal work on returns behaviour and recovery capacity (Eze *et al.*, 2022).

9.6. Informal Recovery Systems

Study informal repair and recovery networks on their own terms, examining material recovery efficiency, labour conditions, and interaction with formal producer responsibility schemes (Anene *et al.*, 2024; Arumosoye & Obriki, 2024; Arumosoye *et al.*, 2025; Michael & Ogunsola, 2024).

9.7. Returns Avoidance

Study the operational and environmental effect of fit prediction, richer product representation, and returns pricing, with attention to the demand cost of friction (Ogundairo & Ayivi-Donkor, 2024a; Sanni *et al.*, 2023a, 2025; Wedraogo & Sanni, 2024).

9.8. Fairness and Contestability

Apply algorithmic accountability frameworks to returns fraud detection and disposition systems, including release gating, bias evaluation, and human-in-the-loop escalation (Ladapo *et al.*, 2024; Nwakamma *et al.*, 2024; Ominyin & Anichukwueze, 2024b).

9.9. Resilience and Circularity Trade-Off

Formalise and quantify the tension, extending resilience models to include the backward propagation channel distinctive to closed loops (Efobi *et al.*, 2023; Ike *et al.*, 2024).

9.10. Testing the Conceptual Model

Operationalise and test the four propositions in Section 5, beginning with Proposition 1, testable using firm-level variation in grading automation and item-level data availability.

10. Conclusion

Returns management has become the principal control point for product lifecycle recovery: the scale of reverse flows has made the return channel operationally comparable to the forward one, regulatory obligations have converted recovery from a choice into a requirement, and item-level information infrastructure has made fine-grained recovery decisions feasible for the first time. The research base remains uneven, with network design mature but empirically thin, disposition under-modelled, repair operations almost unstudied, and the environmental question unverified. The conceptual model locates these gaps at the layer interfaces and argues that information quality rather than physical configuration is the binding constraint. The most consequential near-term

development is therefore the Digital Product Passport, not because passports are inherently powerful but because they attack the informational constraint that has limited disposition quality since the field began.

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