

Reverse logistics for e-waste management: A new role for makerspaces

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Keywords

Circular economy; CReW; E-waste; Makerspaces; PURE framework; Reverse logistics

Abstract

Purpose: This paper condenses the paper's argument that e-waste reverse logistics requires a formal, scalable and economically viable network design. Design/methodology: A structured literature-based synthesis is used to develop two linked contributions: the Present-Unique-Repeatable-Environmentally-friendly (PURE) framework and the Centre for Refurbishment and Recycling of Electrical and Electronic Waste (CReW) concept. Findings: The review indicates that existing approaches emphasise recycling, policy, legal compliance and optimisation methods, but give limited attention to the operational role of makerspaces in collection, inspection, repair, disassembly and value recovery. The proposed CReW concept positions makerspaces as distributed hubs connected to central refurbishment, recycling and material recovery centres. Material passports, Industry 4.0/5.0 tools and operations research methods can improve traceability, customer participation, routing, facility location and decision-making. Practical implications: The proposed structure offers businesses, policymakers and circular economy actors a route to organise e-waste flows while balancing profitability, environmental performance and lean operations. Conclusion: A combined PURE-CReW approach provides a strategic and operational basis for formalising e-waste reverse logistics and for future quantitative modelling of facility location, routing, collection and recovery decisions.

Introduction

The rapid growth of electrical and electronic waste creates a supply chain challenge as well as a business opportunity. E-waste contains valuable metals and components, but also hazardous materials that require controlled handling. Although responsible production and consumption are embedded in the United Nations Sustainable Development Goals, many businesses continue to view e-waste collection, recycling and disposal as costly support activities rather than as sources of value.

This paper focuses on the reverse logistics of e-waste and proposes an integrated approach that balances profitability, sustainability and lean operations. Reverse logistics concerns the flow of products, materials and equipment after use, including collection, reuse, repair, recovery, remanufacturing and recycling. In e-waste systems, these flows are often fragmented: consumers store obsolete devices, informal collectors recover materials unevenly, and formal recycling is not always accessible or economically attractive.

The paper's central contribution is the combination of two ideas. First, the Present-Unique-Repeatable-Environmentally-friendly (PURE) framework provides a strategic guide for designing reverse logistics solutions. Second, the Centre for Refurbishment and Recycling of Electrical and Electronic Waste (CReW) concept provides an operational network in which makerspaces perform local inspection, disassembly, repair and maintenance, while CReW centres undertake refurbishment, recycling, cannibalisation and material recovery. This structure formalises roles that already exist informally and connects them to business-led and policy-supported circular economy systems.

The paper is guided by two research questions: RQ1: What optimisation methods are relevant to reverse logistics management of e-waste? RQ2: How can e-waste reverse logistics be organised using the makerspace concept?

Literature review

E-waste is defined here as discarded, obsolete or non-functional electrical and electronic equipment, including computers, mobile phones, refrigerators, washing machines and other consumer or business devices. Prior literature identifies e-waste as both resource-rich and risk-intensive because valuable metals may be recovered while hazardous compounds require careful processing. Core definitions and scale indicators are supported by (Materials Focus, 2023; Ahirwar and Tripathi, 2021; Anam and Syed, 2013; BBC, 2018; BBC News, 2024; Bridgens et al., 2017; Electronic waste and the Circular Economy, 2019; Electronic waste and the Circular Economy, 2020; Globe Newswire, 2025; Incineration of Electronic Waste, 2010; Joshi et al., 2020; Lee et al., 2024; Ni and Chan, 2023; Parajuly et al., 2019; Problems with e-waste, n.d.; Rautela et al., 2021; Recycle Your Electricals, n.d.).

Several studies emphasise the environmental and economic significance of e-waste recovery. Devices are frequently replaced because of damage, loss, product destruction, cosmetic preferences, limited reparability, technological obsolescence or changing consumer expectations. Small appliances and consumer electronics are particularly relevant because they are widely distributed and often stored at home rather than returned to formal recovery systems. Extending product lifecycles through repair, reuse and refurbishment can reduce the demand for virgin materials, transport, packaging and manufacturing inputs.

Circular economy research highlights the importance of reducing, reusing, repairing, refurbishing, remanufacturing and recycling products. However, many circular economy frameworks remain high-level and do not fully translate strategic sustainability goals into operational procedures. E-waste management therefore requires an approach that can move from policy ambition to physical network design, customer engagement, sorting, product assessment, repair decisions and material recovery. Circular economy and reverse-logistics interpretations are supported by (Bove and Swartz, 2016; Brown, 2020; Chang et al., 2017; Debnath and Sarkar, 2023; Elmas and Erdoğan, 2011; Ferrer and Whybark, 2000; Ellen MacArthur Foundation, 2013; H et al., 2021; Hussain et al., 2023; Jayaraman and Luo, 2007; Korra, 2022; Lai et al., 2022; Lloveras et al., 2025; Lund and Hauser, 2010; Ellen MacArthur Foundation, 2016; McFarland et al., 2013; Trojan Electronics, 2023; Zils et al., 2023).

Industry 4.0 technologies such as data-carrying devices, sensors, digital tracking, additive manufacturing and automation can support traceability and repair-oriented operations. Industry 5.0 extends this agenda by emphasising human-centric, sustainable and resilient industrial systems. Makerspaces align with this shift because they combine technical capability, community participation and flexible repair or redesign capacity. They can also support localised value creation by enabling disassembly, diagnostics, minor repairs and parts recovery before products are moved to specialist centres. Digital and Industry 4.0/5.0 enablers are supported by (Abramovici et al., 2017; Agrawal et al., 2021; Alcayaga et al., 2019; Blomeke et al., 2020; Chen, 2022; Dacre et al., 2024; Fan and Sun, 2019; Feng and Yu, 2019; Ferrer et al., 2011; Gariba et al., 2024; Ghobakhloo et al., 2023; Gu et al., 2017; John et al., 2018; Kerin and Pham, 2020; Kerin and Pham, 2019; Kumar et al., 2016; Liu et al., 2018; McKinsey & Company, 2022; Nowakowski et al., 2020; OpenAI, 2023; Rejeski et al., 2018; Rocca et al., 2020; Romero and Noran, 2017; Sarkar et al., 2025; Segovia et al., 2015; Shabur, 2024; Singh et al., 2024; Steenmans et al., 2021; Stock and Seliger, 2016; Turner et al., 2022; Yawei et al., 2017; Zwolinski et al., 2007).

Material passports are also relevant to e-waste reverse logistics. A material passport is a written or digital record describing the materials, components, lifecycle data, repair history, disassembly options and end-of-life handling requirements of a product. In an e-waste setting, material passports can improve transparency, support sorting decisions and reduce uncertainty for recyclers, manufacturers, refurbishers and consumers. Material-passport arguments are supported by (Adirorn et al., 2021; Aftab and Agliata, 2026; Atta et al., 2021; Capelleveen et al., 2023; Hagedorn et al., 2023; Hoosain et al., 2021; Jansen et al., 2022; Jensen et al., 2023; Plociennik et al., 2022; Reich et al., 2023).

Operations research has an important role in formalising e-waste systems. The literature identifies facility location, collection point allocation, routing, forecasting, capacity planning, multi-objective optimisation, mixed-integer linear programming and simulation as relevant methods. These tools can help determine where collection points, makerspaces and CRew centres should be located, how vehicles should be routed, and how costs, emissions, service time and capacity constraints should be balanced. Operations

research and optimisation evidence is supported by (Abid and Mhada, 2021; Agnudei et al., 2019; Batoo et al., 2021; Chang et al., 2021; Dekker et al., 2012; Duman et al., 2020; Duman and Kongar, 2023; Echefaj et al., 2024; Egri et al., 2021; Elia et al., 2019; Fleischmann and Minner, 2004; Gao et al., 2013; Garcia and You, 2015; Ghandi and Masehian, 2015; Goli and Golmohammadi, 2022; Gupta et al., 2021; Jassbi et al., 2011; Kannan et al., 2010; Kiris et al., 2019; Koshta et al., 2024; Malekkhouyan et al., 2021; Matsumoto, 2010; McKelvey and Neves, 2021; Min et al., 1998; Mogale et al., 2022; Muller et al., 2016; Nagy and Salhi, 2006; Nguyen and Qi, 2019; Pathak et al., 2022; Rani et al., 2020; Reddy et al., 2022; Senophiyah-Mary et al., 2019; Teodorović and Janić, 2017; Xu et al., 2022; Yerramalli and Burra, 2014; Yu and Solvang, 2017).

Research methodology

The paper uses a structured, literature-based methodology. The original review examined reverse logistics, e-waste management, circular economy frameworks, makerspaces, Industry 4.0/5.0 technologies, material passports and optimisation methods. Web of Science, Google Scholar and Scopus were used in the source paper to identify literature relevant to e-waste reverse logistics and optimisation. The review also considered industry and public-sector sources where they provided contextual evidence on e-waste volumes, repair behaviour and collection practices. Bibliometric analysis using R is deployed for the review.

The method is conceptual rather than empirical. Its purpose is not to test an implemented network but to synthesise evidence and propose a framework that can be tested later through operations research models and pilot studies. The framework-building approach is appropriate because the identified gap concerns execution: existing work discusses recycling, policy, circular economy and optimisation, but gives limited attention to how strategic sustainability goals can be deployed through a repeatable reverse logistics structure that includes makerspaces.

Findings and proposed framework

The PURE framework

The PURE framework translates the paper's strategic argument into four design principles. Present means that the problem is immediate: e-waste is increasing and requires current action rather than future-only planning. Unique means that solutions must be adapted to the specific geography, product mix, policy environment, consumer behaviour and business model. Repeatable means that the structure should be transferable across cities, sectors and product categories once adapted to local conditions. Environmentally-friendly means that decisions must reduce waste, emissions and virgin-material dependency while remaining economically viable. The framework-building logic is supported by (Campbell, 1988; Carter and Ellram, 1998; Clark et al., 2023; Fernando and Rupasinghe, 2016; Javed et al., 2021; Miller, 2020; Nanayakkara et al., 2022; Pavlopoulou, 2020; Pollard et al., 2023; Safdar et al., 2020; Saxena et al., 2023; Seuring and Müller, 2008; Stohler et al., 2018; Takacs et al., 2022; Theories and Frameworks, n.d.; Xavier et al., 2021).

PURE therefore acts as a bridge between high-level sustainability aspirations and operational implementation. It encourages firms to treat reverse logistics not as an isolated recycling activity but as part of a broader circular supply chain that includes procurement, manufacturing, distribution, use, return, repair, refurbishment, parts recovery and recycling.

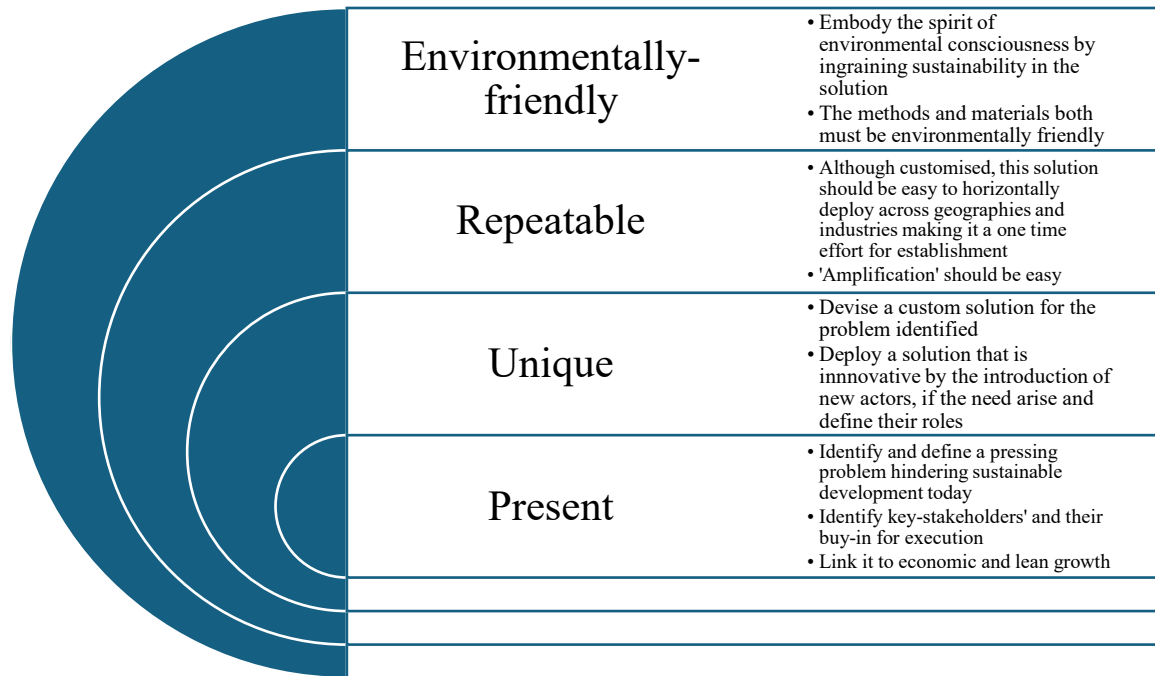


Figure 1. Proposed PURE framework for e-waste reverse logistics

The CReW concept and makerspaces

The CReW concept operationalises PURE through a network of distributed makerspaces and central CReW centres. Customers return e-waste through collection bins, take-back schemes, retail drop-off points, postal options or direct pickup. Collected products are moved first to local makerspaces where practical initial activities can occur: inspection, diagnostics, data capture, sorting, minor repair, disassembly, component harvesting and maintenance. Items requiring specialist recovery are then transported to CReW centres for refurbishment, recycling, cannibalisation or material extraction.

Makerspaces are important because they add a local and flexible layer to the reverse logistics system. They can reduce unnecessary transport to central facilities by identifying repairable or reusable items early. They can also create new revenue streams through repair services, refurbished product sales, parts recovery, training and collaboration with original equipment manufacturers. For businesses, makerspaces can complement maintenance teams, R&D units and customer service channels. For communities, they can support repair culture, skills development and circular economy participation. The makerspace and consumer-participation role is supported by (Fleischmann et al., 2016; Garai and Sarkar, 2022; Holm, 2014; Islam et al., 2021; Kerber et al., 2021; Kim and Paulos, 2011; Prendeville et al., 2017; Smith et al., 2016; Soomro et al., 2023; Vyas et al., 2023; Vyas and Vines, 2019; Yan et al., n.d.; Yan et al., 2024).

CReW centres operate as formal nodes where larger-scale decisions and processes take place. They receive flows from multiple makerspaces or collection routes, conduct more advanced refurbishment and recycling, recover materials, and redistribute products or raw materials into forward supply chains. The network therefore connects consumers, makerspaces, central recovery centres, manufacturers, retailers, recyclers and policy actors.

As shown in Figure 2, the CReW flow moves e-waste from customers to local makerspaces, then to CReW centres for cannibalisation/refurbishment, and finally to industries as recovered raw materials before re-entering forward supply chains.

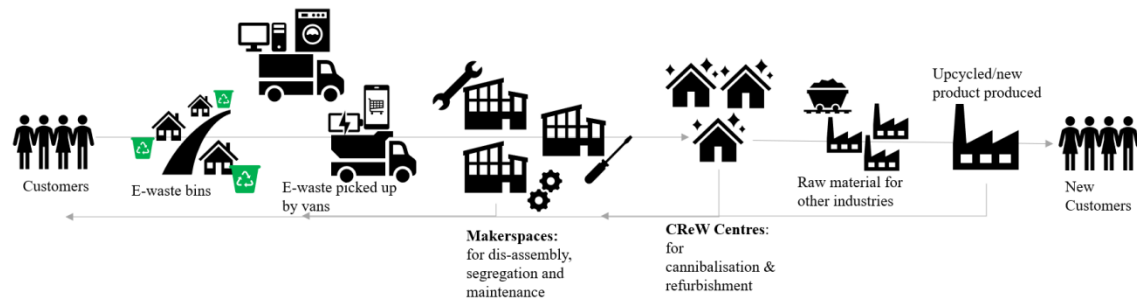


Figure 2. CReW flow of e-waste from customers to makerspaces, CReW centres and industries as raw materials

Material passports, I4.0 and I5.0

Material passports can strengthen the CReW concept by providing information on product composition, components, hazardous materials, lifecycle data, reparability, disassembly pathways and end-of-life options. This information improves decision-making at makerspaces and CReW centres, especially where handlers must choose between repair, reuse, refurbishment, recycling or disposal.

Industry 4.0 technologies can support data collection, tracking, routing and automation. Examples include QR codes, RFID, sensors, digital platforms, additive manufacturing for replacement parts, and analytics for route planning or demand forecasting. Industry 5.0 adds the human-centred dimension by emphasising collaboration between people and technologies. The combination is important because e-waste systems require technical efficiency as well as consumer trust, repair skills and local engagement.

Optimisation opportunities

The review indicates that optimisation is relevant at several points in the proposed network. Collection requires decisions on where to place bins, how to schedule pickups, whether to use vehicles, postal routes or hybrid systems, and how to minimise emissions and cost while maximising convenience. Facility location models can support decisions on where makerspaces and CReW centres should be placed relative to households, retailers, transport corridors, industrial areas and existing recycling facilities.

Vehicle routing and transshipment models can reduce travel distance, fuel use, operating cost and collection time. Forecasting models can estimate e-waste volumes and support staffing, inventory, capacity and storage decisions. Capacity planning and queueing methods can be used where repair cafes or makerspaces handle variable inflows of products. Multi-objective optimisation is particularly relevant because the system must balance cost, emissions, turnaround time, recovery rate, service quality and regulatory requirements.

Table 1. Operations Research methods relevant to e-waste reverse logistics

Application area	OR/optimisation method	Illustrative references
E-waste collection prediction, facility-location allocation and pick-up van routing	Multi-stage modelling; correlation/regression; objective functions; harmony search algorithms	Nguyen and Qi (2019); Nowakowski, Szwarc and Boryczka (2020)
E-waste prediction	Grey modelling-based forecasting; Non-linear Grey Bernoulli Model with fractional order accumulation enhanced by Particle Swarm Optimisation	Duman, Kongar and Gupta (2020); Duman and Kongar (2023)
Location of collection centres	MILP; MINLP	Nanayakkara (2022); Koshta, Patra and Singh (2024)
Location of CReW centres	MILP	Yerramalli and Burra (2014)

Application area	OR/ optimisation method	Illustrative references
JIT logistics and location-routing	Stochastic models; time windows; multiple-objective optimisation	Min, Jayaraman and Srivastava (1998)
Location-routing and transportation-location decisions	Branch-and-bound; branch-and-cut; heuristics; genetic algorithms	Nagy and Salhi (2006); Fan and Sun (2019)
Transport, inventory, facility and product recovery network design	Operations Research modelling for planning and control	Dekker, Bloemhof and Mallidis (2012)
Reverse logistics network design	Heuristic approaches; integer linear programming; stochastic modelling	Reddy et al. (2022); John, Sridharan and Kumar (2018); Yu and Solvang (2017)
Facility location in reverse logistics	Bilevel optimisation and tabu search; hybrid multi-objective optimisation combining gravity method and particle swarm optimisation	Egri, David, Kis and Kresz (2021); Chang et al. (2021)
Integrated reverse logistics location-routing	Particle swarm optimisation-multi-objective immune genetic algorithm (PSO-MOIGA)	Xu, Liu, Jiang and Lin (2022)
Vehicle routing	Exact and meta-heuristic methods with sensitivity analysis	Malekkhouyan, Aghsami and Rabbani (2021)

Discussion

The combined PURE-CReW proposal addresses the gap between strategic circular economy ambitions and operational deployment. PURE provides the logic for designing solutions that are current, tailored, scalable and environmentally sound. CReW translates that logic into a network structure with specific roles for makerspaces and central recovery facilities.

The proposal also reframes consumers as active participants in reverse logistics. Return incentives, accessible collection routes and convenient drop-off systems are necessary because e-waste flows begin with the customer's willingness to release unused or damaged products. Where customers are encouraged to return devices, they act as prosumers by supplying the circular economy with products, components and materials.

For firms, the CReW concept can support both sustainability and competitiveness. Repair, parts recovery, refurbishment and material extraction can create revenue while also reducing dependence on virgin materials. Makerspaces can generate local service value and supply product-design feedback to manufacturers. The system can therefore support circular product-service models, after-sales services and reverse supply chain learning. Wider sustainability, market and resource arguments are supported by (Agrawal et al., 2015; Dua et al., 2009; Aria and Cuccurullo, 2017; Bera and Rahut, 2024; Chung and Peng, 2008; Guchhait and Sarkar, 2025; Infinity Renewables, n.d.; J.S. et al., 2016; Kaliski, 2025; Li et al., 2023; MIT Climate Portal, 2023; Oberle et al., 2019; release, n.d.; Siddique and Rosen, 1997; Thiebaud et al., 2017; Tornese et al., 2018; Yue and Gao, 2018; Zhao et al., 2019).

The proposal does not argue that recycling alone is sufficient. A hierarchy of recovery decisions is implied: repair and reuse should be prioritised where feasible; refurbishment and remanufacturing should be used where value can be restored; component cannibalisation and recycling should follow where product-level recovery is not viable. Material passports and optimisation methods support these choices by improving information quality and decision consistency.

Conclusions, limitations and future research

This condensed paper proposes a formal reverse logistics structure for e-waste management by integrating the PURE framework with the CReW concept. The first contribution is strategic: PURE offers a concise framework for designing reverse logistics systems that are Present, Unique, Repeatable and Environmentally-friendly. The second contribution is operational: the CReW concept introduces makerspaces as local nodes for inspection, repair, disassembly and maintenance, linked to central centres for refurbishment, recycling, cannibalisation and material recovery.

The two research questions are addressed as follows. For RQ1, the review identifies facility location, routing, forecasting, capacity planning, simulation, MILP/MINLP and multi-objective optimisation as relevant methods for e-waste reverse logistics. For RQ2, the paper proposes a network in which customers return products through accessible channels, makerspaces perform local value-preserving activities, and CReW centres undertake specialised recovery and material reintegration.

It is worth mentioning that the framework is conceptual and literature-based meant for implementation. It has been tested through field implementation, quantitative modelling or stakeholder validation in the work authored by Pathak and Fatorachian (2026). This develops mathematical models for the optimal placement of makerspaces and CReW centres, evaluate routing alternatives, estimate emissions and cost trade-offs and pilot the framework with businesses, local authorities, repair cafes and consumers within UK. The key limitation is indeed the need to include legal and policy implications of the framework and CReW concept. However, is out of scope of the research at the moment. Further work should explore how to move consumer participation from a push system, where people must be persuaded to return products, to a pull system in which return, repair and reuse become convenient and desirable.

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