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Reverse Logistics Network Design for Waste Electrical and Electronic Equipment (WEEE) in Emerging Market Economies: A Historical Case Study of Greater Shanghai, China

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Abstract: The sustainable management of waste electrical and electronic equipment (WEEE)—also referred to as e-waste or e-scrap—is a major policy issue in emerging market economies like China. This study explores the initial phase of practical eco-innovation policy implementation, elucidating the foundational challenge of techno-organizational infrastructure development for environmentally sound WEEE recovery and disposal in China. A discrete mixed-integer linear programming model for WEEE reverse logistics network design is introduced and applied to the historical real-world case of Greater Shanghai. The computational results offer scenario-based insights into the cost-optimal determination of facility locations for regional WEEE treatment from a multi-staged network system perspective, illuminating underlying cost structures and the intricate contextual factors shaping location solutions. This facilitates the derivation of strategic locational recommendations for integrated network system design. The study concludes by pointing to societal challenges involved in practical eco-innovation policy enforcement toward achieving (more) holistically sustainable WEEE recovery and disposal in China.

Keywords: waste electrical and electronic equipment (WEEE), recycling, reverse logistics network design, mixed-integer linear programming (MILP), China

1. Introduction

Critical global environmental challenges, including climate change, resource depletion, and biodiversity loss, underscore the urgent need for dedicated structural changes in our socio-economic systems to foster sustainable development and transformation. In this context, the management of waste electrical and electronic equipment (WEEE), also known as e-waste or sometimes e-scrap, has increasingly emerged as a focal concern. WEEE remains the most rapidly growing waste stream worldwide. The use of electrical and electronic equipment (EEE) has been proliferating widely, resulting in ever-increasing volumes of discarded appliances on a global scale [1, 2]. In addition, WEEE comprises an increasingly diverse and expanding range of appliances containing hazardous substances that can harm terrestrial, aquatic, and aerial environments as well as humans and animals if not treated in a technically appropriate manner [2–4]. WEEE recovery and disposal pose significant challenges to sustainable waste management, particularly in the context of less developed emerging market economies. Here, informal-economy waste systems typically reign supreme over the formal economy in unregulated “daisy chains” of legal and illegal activities. While formal activities are governed by responsible compliance and safety standards, WEEE is informally collected, traded, processed, and ultimately discarded by small/micro firms, groups, or even individuals with a primary—if not sole—focus on economic viability. Short-term financial gains are usually prioritized over compliance and safety considerations [3, 5–7].

In China, the essentially profit-driven WEEE recovery and disposal within the informal economy have not only caused serious damage to the environment and human health [8–10]. Crude recycling practices are also associated with considerable losses of valuable secondary raw materials [11]. China’s remarkable economic growth and rising affluence have arguably enhanced domestic consumption while shortening the utilization phase of EEE [12], thereby progressively increasing the per-capita WEEE generation over time [13, 14]. In addition, China has long been a major destination for illegal WEEE exports originating from high(er)-income countries, albeit with decreasing volumes nowadays [15].

In light of this compelling situation, the development of waste management strategies across central, provincial, county, and township levels has become a key policy focus for promoting eco-innovation in China. The so-called “Chinese WEEE directive,” which was issued on February 25, 2009, and became effective on January 1, 2011, has laid the regulatory foundation intended to pave the way toward (more) environmentally sustainable WEEE recovery and disposal through mandatory formalization [16]. However, the practical implementation of the stipulated WEEE management legislation also imposes substantial requirements for infrastructure development on the ground, both in technical and organizational terms. Specifically, formalization entails establishing centralized reverse logistics systems for formal WEEE recovery and disposal, including the locational siting and installation of new recycling facilities in accordance with mandated compliance and safety standards.

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The present study aims to shed light on this intriguing transformative initial phase of practical policy implementation toward eco-innovation in industry from 2009 to 2010, emphasizing the developmental challenge of formalizing WEEE recovery and disposal in emerging market economies like China. It seeks to develop and apply a locational decision-support system to determine and analyze the cost-optimal configurational design of reverse logistics networks for formal WEEE recycling within the Chinese context using the historical real-world case of Greater Shanghai in 2009/2010. The location modeling approach elucidates the optimized network configuration of a regional reverse logistics system for WEEE recovery and disposal by locating recycling facilities across various case scenarios. Specifically, the optimization results provide analytical insights into cost structures and how different scenario-parametric factors shape the locational configuration of reverse logistics networks in practice, highlighting pertinent implications for integrated network design.

The remainder of this paper is structured as follows. Section 2 offers a conceptual outline of WEEE recovery and disposal. Section 3 presents a methodological introduction to quantitative location planning, focusing on reverse logistics network design. Section 4 delves into reverse logistics network design for WEEE recovery and disposal in the historical context of Greater Shanghai. A discrete location optimization approach based on mixed-integer linear programming (MILP) is proposed to establish the cost-optimal configuration of a multi-staged reverse logistics system for formal WEEE treatment, adapted to the Chinese context. The MILP model is then applied to the practical case of Greater Shanghai, focusing on the circumstances and data available as of early 2009. Section 5 provides concluding remarks, emphasizing societal challenges of eco-innovation policy enforcement in the pursuit of holistically sustainable WEEE recovery and disposal in China.

2. WEEE Recovery and Disposal

WEEE is generally understood as disposed EEE, encompassing all associated components, subassemblies, and consumables present at the time of disposal [17]. Managing WEEE recovery and disposal is inherent to advancing a circular economy [18–20]. Although reuse, servicing, and remanufacturing can extend the utilization lifespan of EEE [18, 20, 21], both the appliances and their components eventually become non-reusable waste, with recycling remaining as the final recovery option [22]. The recycling stage involves manual dismantling (i.e., breaking down appliances into components and separating hazardous and valuable materials), upgrading valuable material fractions (i.e., applying mechanical and/or metallurgical treatment), refining (i.e., reintegrating the recovered materials into their lifecycle), and disposal [23]. A reverse logistics infrastructure must accommodate all "reverse activities" involved in accumulating and distributing appliances for recovery, executing recovery processes, and distributing recovered and residual items to various demand points [24, 25]. Accordingly, optimally locating recycling facilities depends on the location of upstream supply options as well as of downstream sales market and disposal options.

3. Network Design in Reverse Logistics

Reverse logistics network design is an emerging field of study characterized by a growing number of location models and corresponding case applications. There is a diverse array of research designs and methodological optimization approaches, depending on the particular modeling context [26]. Many—if not predominantly most—studies leverage MILP-based techniques to address the discrete nature of location decisions, relying on a finite location solution space for large-scale mathematical optimization [27–29], including those related to WEEE reverse logistics.

Krikke et al. [30] designed a reverse logistics network for copier recycling based on MILP optimization. The optimization model determines locations for processing facilities and the associated inter-facility commodity flows. The study reported by Shih [31] proposes an MILP formulation to optimize the infrastructure design and flows within a reverse logistics network for waste home appliances and computers in Taiwan. The location model minimizes total costs, including transport costs, operating costs, fixed costs for new facilities, final disposal costs, and landfill costs. Walther [32] applied an MILP model to a case study on the design of a material flow network for sustainable WEEE recovery and disposal in Lower Saxony, Germany. Queiruga Dios [33] developed an MILP-based approach for the strategic planning of a return system for large household appliances in Spain. The model accommodates several capacity classes and integrates decisions regarding the location and allocation of appliances and material fractions. Gomes et al. [34] established a WEEE recovery network in Portugal using an MILP model to simultaneously select the optimal locations for collection and sorting centers. Alumur et al. [35] introduced an MILP approach for designing a multi-period reverse logistics network. The profit-maximization model is applied to a reverse logistics case study focused on washing machines and tumble dryers in Germany. Qiang and Zhou [36] presented an MILP model that enables robust reverse logistics network design for WEEE under recovery uncertainty. Ozgur Polat and Gungor [37] used MILP to facilitate WEEE closed-loop supply chain network design and management, considering different quality and damage levels of returned products. Gharibi and Abdollahzadeh [38] advanced a multi-objective multi-stage MILP model to design a WEEE reverse logistics network for integrated after-sales services.

Methodologically, a very widely adopted MILP-based optimization approach for designing (reverse) distribution systems is the warehouse location problem (WLP), sometimes also referred to as the facility location problem (FLP). In its most general form, this problem involves identifying optimal locations for (warehouse) facilities that, together with transportation logistics, vehicles, and supporting infrastructure, form a network system [39]. A primary optimization objective of classical WLP model formulations is to determine the number and locations of (warehouse) facilities that minimize the total sum of facility location installation costs and transport costs between facility locations [40]. Along these lines, WLP optimization supports the combined quantitative planning of facility locations, inter-facility item flows, and transport routes based on a given traffic system. It also accommodates the inclusion of existing facility infrastructure within a specified set of alternative location options deemed eligible for installation.

In general, the practical application of location modeling is complicated by the challenge of decreased realism, typically requiring simplifications and parametric assumptions that may not fully capture the complexities of real-world situations and dynamics [41]. Sensitivity analysis can be used as a powerful tool for reducing uncertainty and fostering confidence in a location model because it provides contextual insights into the planning problem and assesses the robustness of the optimization results [42–44]. A standard approach to sensitivity analysis in location modeling involves addressing uncertainty through the incorporation of meaningful case scenarios [41]. In particular, this extends to MILP-based location optimization techniques [38, 45–49].

Overall, employing scenario-based MILP modeling to methodologically address WLPs appears well suited for the location planning problem at hand. It provides an effective optimization approach for network design by enabling integrated location-allocation decisions. Moving forward, the basic WLP model needs to be adapted and operationalized into a network-based reverse logistics system that is tailored to the specific planning context of WEEE recovery and disposal in China and Greater Shanghai, respectively. In particular, this involves developing diverse case scenarios capturing relevant variations in cost parameters and the distributional characteristics of WEEE masses and item flows for sensitivity analysis.

4. Reverse Logistics Network Design for WEEE Recycling in Greater Shanghai

The conceptual-analytical development and practical application of MILP modeling for reverse logistics network design are intricately shaped by the planning context. It is important to recall that the present context refers to the historical situation in China prior to the enforcement of the "Chinese WEEE directive" in 2011, focusing on the case of Greater Shanghai in 2009/2010. Modeling requirements are derived accordingly.

4.1. WEEE recovery and disposal in China

In response to emerging environmental challenges, China has adopted an increasingly proactive economic approach that seeks to weave ecological responsibility and stewardship into its broader mission for societal advancement [50]. An integral part of China's green growth strategy has been the promotion of circular economy development for resource recovery and conservation [51], legally initiated in line with the enactment of the "Chinese WEEE directive" in 2009. This newly introduced WEEE management legislation has complemented a series of related laws and regulations, bolstering a more robust regulatory approach by aligning centralized WEEE recovery and disposal with environmental standards and national socio-economic development priorities [52–54].

The key legal provisions of the "Chinese WEEE directive" were designed to improve ecological outcomes in both WEEE management and related EEE manufacturing. These provisions comprise restrictions on the use of specific toxic and hazardous materials in EEE, regulations governing WEEE imports, institutional strategies for pollution prevention and control during WEEE treatment, licensing requirements for the collection and treatment of WEEE, and the assignment of obligatory financial and organizational responsibilities for WEEE management to EEE importers and manufacturers. Although such dedicated reform efforts have established a crucial foundation for environmentally sustainable WEEE management in China, notable challenges remained. These challenges included various regulatory interpretations due to vague definitions of legal terms and provisions, difficulties in ensuring consistent policy enforcement across regions, the need for developing and maintaining up-to-date technology and infrastructure to effectively handle evolving WEEE, and the requirement to formalize informal WEEE recovery and disposal systems. Indeed, the prevailing informal economy in China had received only minor strategic policy attention up to that point [55].

The informal WEEE economy in China was deeply entrenched, having grown over many years within well-adapted interconnected systems. WEEE was considered an economically important and valuable resource, particularly for the more deprived strata of the Chinese population [56, 57]. In addition to illegal imports, widespread informal collection networks secured the vast majority of WEEE supplies from domestic sources [55, 58], posing fierce competition to the market success of formal WEEE management businesses. Licensed recycling plants faced considerable profitability challenges due to shortages in WEEE feed streams and disproportionately higher investment and operational costs for environmentally effective machinery and equipment [59, 60]. As such, WEEE recovery and disposal in China essentially took place in the long shadow of the informal economy, with the number of small-scale recycling sheds continuing to increase [61].

The Chinese domestic WEEE pool can be categorized by end-of-life options into appliances eligible for direct reuse, those intended for recovery, and those temporarily stored before being directed toward either option. WEEE designated for recovery can be further distinguished into appliances meant for either reconditioning and reuse or manual dismantling. Dismantled components may also be reconditioned, and the remainder is either recycled or discarded. Extracted WEEE material fractions, such as copper, silver, and aluminum, are utilized as secondary raw materials across various production industries [53, 61, 62]. The reuse of second-hand appliances results in time-lagged increases in the domestic WEEE pool in subsequent periods, as shown in Figure 1 [53, 61, 62].

4.2. MILP model formulation for reverse logistics network design in the Chinese context

Reverse logistics for WEEE recycling in China can be conceptualized as a multi-stage process. Initially, WEEE is collected and transferred to recycling facilities for treatment. After processing, appliances, components, materials, and residues are eventually transferred to subsequent facilities for further recovery and disposal. In operational practice, the recycling process may span multiple treatment tiers, involving primary and downstream secondary processing facilities. Given the early stage of development of China's formal recycling industry, the location model should support the emergence and expansion of lower-capital WEEE business models, offering recovery alternatives at primary processing facilities. This particularly involves formalizing informal-economy activities through licensing, accommodating their straightforward integration into the formal recycling infrastructure in compliance with legal requirements. Likewise, the notable Chinese domestic market for the reuse of appliances and components should be taken into account. In this conceptual light, the MILP model shall incorporate the locations of facilities for WEEE collection, processing, further recovery, reuse, and disposal; the WEEE masses at the collection stage; and the different recovery options available at different reverse logistics network stages.

The conceptual system boundary defined for the MILP model encompasses three distinct recovery levels. At the appliance recovery level, the five main types of large WEEE well documented in China at the time are considered: washing machines, refrigerators, TV sets, personal computers, and air conditioners, all with their associated peripherals. At the component recovery level, appliance parts are regarded as intermediary goods. At the material recovery level, material fractions are categorized as ferrous metal (i.e., WEEE material fraction I), non-ferrous metal (i.e., WEEE material fraction II), non-metal (i.e., WEEE material fraction III), and residues (i.e., WEEE material fraction IV).

Figure 1
Structure of China's domestic WEEE value chain

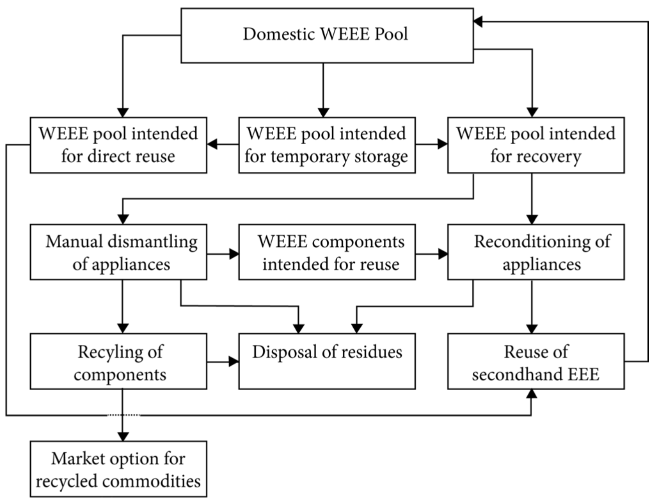
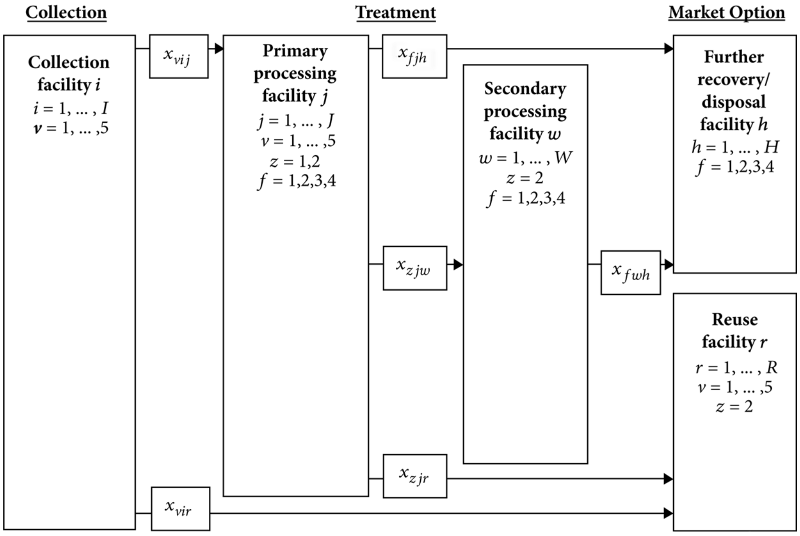


Figure 2
WEEE item flows of the MILP model formulation



The MILP model integrates various WEEE item flows, detailing the transfer and processing of appliances, components, and materials across the different stages of the reverse logistics network. It includes an upstream collection stage as the source, a midstream treatment stage, and downstream sales markets and disposal options as the sink, along with various alternative recovery options. At the initial collection stage, two basic recovery alternatives exist: (a) appliances suitable for reuse are directed to reuse facilities and/or (b) appliances are directed to primary processing facilities for treatment; primary processing facilities are licensed and authorized to treat large WEEE appliances. At the primary processing stage, three basic recovery alternatives can be exercised after dismantling appliances into components: (a) well-functioning components are directed to reuse facilities; (b) components receive final treatment, with the resulting material fractions being directed to further recovery and disposal facilities; and/or (c) components are directed to secondary processing facilities for further treatment; secondary processing facilities are not (yet) licensed to treat large WEEE appliances but are authorized only for certain components. At the secondary processing stage, components receive further treatment. The resulting material fractions are directed to recovery and/or disposal facilities. The final market option stage involves facilities for further recovery, disposal, and reuse: (a) further recovery facilities provide material conditioning, treating ferrous metal, non-ferrous metal, and non-metal materials (i.e., WEEE material fractions I, II, and III, respectively); (b) disposal facilities conduct the disposal and incineration of residues (WEEE material fraction IV) and the incineration of non-metal material (i.e., WEEE material fraction III) for energy recovery; and (c) reuse facilities manage items across all types of appliances and components.

Figure 2 illustrates the WEEE item flows across the reverse logistics network facility stages as represented in the MILP model. To mathematically formulate the WLP, the following set of indices, system parameters, and variables is used:

Indices

- i Collection facilities $i = 1, ..., I$
- h Further recovery/disposal facilities $h = 1, ..., H$
- r Reuse facilities $r = 1, ..., R$
- j Candidate locations of primary processing facilities $j = 1, ..., J$
- w Candidate locations of secondary processing facilities $w = 1, ..., W$
- v WEEE appliance types $v = 1, 2, 3, 4, 5$: $v = 1$ for refrigerators; $v = 2$ for air conditioners; $v = 3$ for TV sets; $v = 4$ for personal computers; $v = 5$ for washing machines
- z WEEE component types z=1,2: z=1 for components processed in-house at primary processing facilities j; z=2 otherwise
- f WEEE material fractions $f = 1, 2, 3, 4$: $f = 1$ for ferrous metal fractions; $f = 2$ for non-ferrous metal fractions; $f = 3$ for non-metal material fractions; $f = 4$ for residues

System parameters and variables

- c_{vij} Transport costs for the transport of WEEE appliance type v from collection facility i to primary processing facility j [€/t]
- c_{fjh} Transport costs for the transport of WEEE material fraction f from primary processing facility j to further recovery/disposal facility h [€/t]
- c_{zjw} Transport costs for the transport of WEEE component type z from primary processing facility j to secondary processing facility w [€/t]
- c_{fwh} Transport costs for the transport of WEEE material fraction f from secondary processing facility w to further recovery/disposal facility h [€/t]
- c_{vir} Transport costs for the transport of WEEE appliance type v from collection facility i to reuse facility r [€/t]
- c_{zjr} Transport costs for the transport of WEEE component type z from primary processing facility j to reuse facility r [€/t]
- e_{vi} Mass of feed stream of WEEE appliance type v of collection facility i [t/a]
- e_{zj} Mass of feed stream of WEEE component type z of primary processing facility j [t/a]
- e_{zw} Mass of feed stream of WEEE component type z of secondary processing facility w [t/a]
- q_{vir} Proportion of reusable commodities of WEEE appliance type v at collection facility i; $q_{vir} \in [0,1]$
- q_{zjr} Proportion of reusable commodities of component type z at primary processing facility j; $q_{zjr} \in [0,1]$
- a_{zv} Proportion of WEEE component type z within WEEE appliance type v; $a_{zv} \in [0,1]$

a_{fz} Proportion of WEEE material fraction *f* within WEEE component type *z*; $a_{fz}\in[0,1]$

Cap_j Processing capacity of primary processing facilities j [t/a]

Cap_w Processing capacity of secondary processing facilities w [t/a]

Cap_{hf} Processing capacity of further recovery/disposal facility *h* for WEEE material fraction *f* [t/a]

Cap_{rvz} Processing capacity of reuse facility *r* for WEEE appliance type *v* and WEEE component type *z* [t/a]

d_j Investment-dependent costs for installation of primary processing facilities j [€/a]

d_w Investment-dependent costs for installation of secondary processing facilities w [€/a]

x_{vij} Mass of WEEE appliance type *v* transported from collection facility *i* to primary processing facility j [t/a]

x_{vir} Mass of WEEE appliance type *v* transported from collection facility *i* to reuse facility *r* [t/a]

x_{fjh} Mass of WEEE material fraction *f* transported from primary processing facility j to further recovery/disposal facility *h* [t/a]

x_{zjw} Mass of WEEE component type z transported from primary processing facility j to secondary processing facility w [t/a]

x_{zjr} Mass of WEEE component type z transported from primary processing facility j to reuse facility *r* [t/a]

x_{fwh} Mass of material fraction *f* transported from secondary processing facility *w* to further recovery/disposal facility *h* [t/a]

y_j Binary variable: $y_j = 1$, if primary processing facility j is installed; $y_j = 0$ otherwise

y_w Binary variable: $y_w = 1$, if secondary processing facility *w* is installed; $y_w = 0$ otherwise

The WLP is mathematically formulated as follows:

Minimize $F(x, y) =$

$$\sum_{v=1}^{V}\sum_{i=1}^{I}\sum_{j=1}^{J}c_{vij}x_{vij} + \sum_{v=1}^{V}\sum_{i=1}^{I}\sum_{r=1}^{R}c_{vir}x_{vir} + \sum_{f=1}^{F}\sum_{j=1}^{J}\sum_{h=1}^{H}c_{fjh}x_{fjh} + \sum_{z=1}^{Z}\sum_{j=1}^{J}\sum_{w=1}^{W}c_{zjw}x_{zjw} + \sum_{z=1}^{Z}\sum_{j=1}^{J}\sum_{r=1}^{R}c_{zjr}x_{zjr} + \sum_{f=1}^{F}\sum_{w=1}^{W}\sum_{h=1}^{H}c_{fwh}x_{fwh} + \sum_{j=1}^{J}d_jy_j + \sum_{w=1}^{W}d_wy_w \quad (1)$$

subject to

$$\sum_{j=1}^{J}x_{vij} + \sum_{r=1}^{R}x_{vir} = e_{vi} \;\; for \;\; i = 1,\ldots,I; v = 1,2,3,4,5 \quad (2)$$

$$\sum_{r=1}^{R}x_{vir} = q_{vir}\, e_{vi} \;\; for \;\; i = 1,\ldots,I; v = 1,2,3,4,5 \quad (3)$$

$$\sum_{j=1}^{J}x_{vij} = (1 - q_{vir})e_{vi} \;\; for \;\; i = 1,\ldots,I; v = 1,2,3,4,5 \quad (4)$$

$$\sum_{v=1}^{V}\sum_{j=1}^{I}x_{vij} \le Cap_jy_j \;\; for \;\; j = 1,\ldots,J \quad (5)$$

$$\sum_{h=1}^{H}x_{fjh} + \sum_{w=1}^{W}x_{zjw} + \sum_{r=1}^{R}x_{zjr} = e_{zj} \;\; for \;\; f = 1,2,3,4; \;\; J = 1,\ldots,J; \;\; z = 1,2 \quad (6)$$

$$a_{zv}\sum_{v=1}^{V}\sum_{i=1}^{I}x_{vij} = e_{zj} \;\; for \;\; j = 1,\ldots,J; \;\; v = 1,2,3,4,5; \;\; z = 1,2 \quad (7)$$

$$\sum_{h=1}^{H}x_{fjh} = a_{fz}e_{zj} \;\; for \;\; f = 1,2,3,4; \;\; j = 1,\ldots,J; \;\; z = 1 \quad (8)$$

$$\sum_{r=1}^{R}x_{zjr} = q_{zjr}e_{zj} \;\; for \;\; j = 1,\ldots,J; \;\; z = 2 \quad (9)$$

$$\sum_{w=1}^{W}x_{zjw} = (1 - q_{zjr})e_{zj} \;\; for \;\; j = 1,\ldots,J; \;\; z = 1,2 \quad (10)$$

$$\sum_{j=1}^{J}x_{zjw} \le Cap_wy_w \;\; for \;\; n = 1,2; \;\; w = 1,\ldots,W; \;\; z = 2 \quad (11)$$

$$y_j + y_w \le 1 \;\; for \;\; J \cap W \quad (12)$$

$$\sum_{h=1}^{H}x_{fwh} = e_{zw} \;\; for \;\; f = 1,2,3,4; \;\; w = 1,\ldots,W; \;\; z = 1 \quad (13)$$

$$\sum_{j=1}^{J}x_{zjw} = e_{zw} \;\; for \;\; w = 1,\ldots,W; \;\; z = 2 \quad (14)$$

$$\sum_{h=1}^{H}x_{fwh} = a_{fz}e_{zw} \;\; for \;\; f = 1,2,3,4; \;\; w = 1,\ldots,W; \;\; z = 2 \quad (15)$$

$$\sum_{j=1}^{J}x_{fjh} + \sum_{w=1}^{W}x_{fwh} \le Cap_{hf} \;\; for \;\; f = 1,2,3,4; \;\; h = 1,\ldots,H \quad (16)$$

$$\sum_{i=1}^{I}x_{vir} + \sum_{j=1}^{J}x_{zjr} \le Cap_{rvz} \quad for \;\; r = 1,\ldots,R; \;\; v = 1,2,3,4,5; \;\; z = 2 \quad (17)$$

$$y_j \in \{0,1\} \;\; for \;\; j = 1,\ldots,J \quad (18)$$

$$y_w \in \{0,1\} \;\; for \;\; w = 1,\ldots,W \quad (19)$$

$$x_{vij} \ge 0 \;\; for \;\; i = 1,\ldots,I; \;\; J = 1,\ldots,J; \;\; v = 1,2,2,3,4,5 \quad (20)$$

$$x_{fjh} \ge 0 \;\; for \;\; f = 1,2,3,4; \;\; h = 1,\ldots,H; \;\; j = 1,\ldots,J \quad (21)$$

$$x_{zjw} \ge 0 \;\; for \;\; j = 1,\ldots,J; \;\; w = 1,\ldots,W; \;\; z = 2 \quad (22)$$

$$x_{fwh} \ge 0 \;\; for \;\; f = 1,2,3,4; \;\; h = 1,\ldots,H; \;\; w = 1,\ldots,W \quad (23)$$

$$x_{vir} \ge 0 \;\; for \;\; i = 1,\ldots,I; \;\; r = 1,\ldots,R; \;\; v = 1,2,3,4,5 \quad (24)$$

$$x_{zjr} \ge 0 \;\; for \;\; j = 1,\ldots,J; \;\; r = 1,\ldots,R; \;\; z = 2 \quad (25)$$

In the mathematical WLP formulation, Equation (1) specifies the objective function aimed at minimizing the combined total costs of transporting items (i) from collection to primary processing facilities, (ii) from collection to reuse facilities, (iii) from primary processing to further recovery/disposal facilities, (iv) from primary processing to secondary processing facilities, (v) from primary processing to reuse facilities, and (vi) from secondary processing to further recovery/disposal facilities. In addition, the WLP minimization accounts for investment costs associated with installing (vii) primary processing and (viii) secondary processing facilities.

Equation (2) defines recovery options at collection facilities, maintaining a balanced inflow and outflow of appliances. In this context, Equations (3) and (4) establish the appliance masses to be transported to reuse and/or primary processing facilities. Equation (5) mandates that primary processing facilities operate within processing capacity limits. Equations (6) to (10) govern the full delivery of appliances and components treated at primary processing facilities to further recovery/disposal, secondary processing, and/or reuse facilities as components and material fractions. Equation (11) requires secondary processing facilities to be supplied within capacity limits. Equation (12) ensures that candidate locations are suitable for the installation of either primary or secondary processing facilities but not both. Equations (13) to (15) specify recovery options at secondary processing facilities, balancing component inflows from primary processing facilities with material fraction outflows to further recovery/disposal facilities. Equations (16) and (17) present constraints on processing capacities, establishing upper limits on the material fractions designated for recovery and disposal as well as on the appliances and components designated for reuse. Equations (18) and (19) determine integrality and guarantee that decision variables take on binary integer values. Equations (20) to (25) enforce that all variables representing WEEE masses remain non-negative.

4.3. MILP model application for reverse logistics network design in Greater Shanghai

4.3.1. Case study specification

Greater Shanghai is located on the east coast of China, covering a total land area of 6,340.5 km^2. The metropolitan region was organized into 19 administrative divisions. A large-scale survey estimated the population of long-term residents at 17.78 million by the end of 2005 [63].

There are certain system boundaries defining the conceptual-analytical scope of the Shanghai case study. The MILP model application for reverse logistics network design in Greater Shanghai emphasizes developing a foundational techno-organizational infrastructure for environmentally sound WEEE recovery and disposal. Thus, the focus is on determining the number and locations of primary processing facilities, omitting secondary processing facility locations. The integration of alternative recovery options at secondary processing facilities is represented as a decrease in treatment process outputs from primary processing facilities based on respective in-house processing ratios. Following previous studies by Kovačić and Bogataj [64] and Walther and Spengler [65], WEEE treatment is simplified using an input-output approach that balances the inflow and outflow of items at primary processing facilities. Interactions between primary processing facilities remain unconsidered. Cost calculations are limited to the key network system costs of primary processing facility installation and transportation, excluding other variables or fixed cost items.

The case study also involves certain suppositions concerning the different stages of the reverse logistics network. An illustrative overview of the facilities and their locations considered at the different stages of the reverse logistics network is provided in Table A1. At the collection stage, it is assumed that a comprehensive collection system covering all 19 administrative divisions is in place and capable of handling all generated WEEE masses. Given that only nine collection points existed in the urban center of Shanghai, an area-wide collection infrastructure is provisionally installed for case study purposes, adding 10 fictitious collection facilities in the remaining adjacent administrative divisions of central Shanghai. The geographic locations of these fictitiously installed collection facilities are deemed to align with the center of gravity of administrative divisions.[1] At the treatment stage, the set of candidate locations for primary processing facilities includes both already existing facilities (i.e., developed candidate locations) and those considered for potential new installations (i.e., undeveloped candidate locations). To map out the undeveloped candidate locations for new facility installations, Greater Shanghai is overlaid with a virtual grid. This grid partitions the target area into 480 squares, each with an edge length measuring 5.25 km. Geographically, the undeveloped locations are pinpointed at the intersections of the diagonals of these squares.[2] As a result, a total of 248 candidate locations for primary processing facilities, including four developed candidate locations, qualify for consideration in MILP optimization. At the market option stage, reuse and further recovery/disposal are designated as demand options. Although the locations of reuse facilities are not explicitly accounted for, reuse activities are implicitly incorporated by proportionately decreasing the masses of appliances and components available for processing at primary processing facilities. For processed material flows, nine existing facility locations for secondary raw materials are included, with ferrous and non-ferrous metal fractions being combined into a single metal cluster. In addition, three existing facilities for environmentally applicable energy recovery and disposal serve as demand locations for residues and non-metal material fractions, encompassing both hazardous and non-hazardous constituents.

4.3.2. Case scenarios and data

Diverse case scenarios are developed and employed to evaluate robustness and to illuminate key contextual factors influencing the locational configuration of the reverse logistics network system. These case scenarios involve assumptions regarding cost parameters and the distributional characteristics of WEEE masses and item flows.

1) Spatial distribution and masses of the WEEE feed stream

In the absence of public data for Greater Shanghai, it is broadly assumed that urban households in major developed areas exhibit similar WEEE characteristics [66]. Using 2010 data on average WEEE generation rates for Beijing [67], a per-capita WEEE feed stream generation of 5.86 kg is estimated for the Shanghai case study, totaling 105,000 t, of which approximately 70% or 73,000 t is ultimately recoverable for treatment (input scenario 1). The spatial distribution of the WEEE feed stream involves aligning the per-capita WEEE generation within each administrative division with the corresponding regional collection facility, taking into account the average distribution among appliance types. An overview of the WEEE feed stream considered for input scenario 1 is available in Table A2 [53, 62, 63]. The respective allocation of appliances is determined by the average proportion that each appliance type holds within the overall WEEE mass, based on data from China for the year 2010 [53].

To evaluate locational robustness against variations in WEEE generation, the WEEE masses considered for input scenario 1 are universally increased by 50%. This increase results in 110,000 t being proportionately allocated (input scenario 2).

2) Distribution and masses of WEEE flows

Appliance reuse initiated at the collection stage is implicitly addressed by varying the WEEE masses designated for treatment. At the processing stage, appliances are either completely processed in-house

[1] The center of gravity of administrative divisions is estimated using Google Earth by manually modeling the territorial shapes of the divisions and deriving centroids from polygonal geocoordinates.

[2] Candidate locations are deemed eligible when situated on solid ground within the Greater Shanghai area. For location determination purposes, geocoordinates of undeveloped candidate locations, fetched from Google Earth, are converted to km and extrapolated over the virtual grid; no adjustments are made to latitude and longitude values because any potential differences from original values are minor and practically negligible.

into material fractions at primary processing facilities (flow scenario 1) or partially redirected downstream to secondary processing and reuse facilities as components (flow scenario 2). Both flow scenarios are derived by calculating the proportions of material fractions for each appliance and component type. In flow scenario 2, the downstream recovery of components reduces the material fraction output at primary processing facilities. Due to limited Chinese operational data, this is informed by empirical average proportions of redirected component types that are not completely processed in-house in Japan [68].[3] An overview of the scenario-based proration of WEEE material flows can be found in Table A3 [68–70].

3) Cost parameters

Transport costs are incurred when transferring WEEE items across the subsequent facility stages of the reverse logistics network.[4] The average transport costs for WEEE items in Greater Shanghai are estimated at 0.15 € per t per km.[5] It is assumed that WEEE transfers are operated at full transport runs under this scenario (transport scenario 1) and double transport costs of 0.30 € per t per km account for partial empty transport runs (transport scenario 2). Moreover, there are investment-dependent costs associated with new facility installations. The assumed costs are 705,512 €/a for a primary processing facility having a capacity of 15,000 t/a (plant design scenario 1) and 1,069,356 €/a for a capacity of 30,000 t/a (plant design scenario 2). For plant design scenario 2, the cost calculation follows that reported by Queiruga Dios [33], applying an economies of scale coefficient of 0.6. A detailed breakdown of investment-dependent facility installation costs for plant design scenario 1 can be found in Table A4 [33, 71].

4) Summary of case scenarios

Overall, the Shanghai case study considers 19 locations for regional collection facilities, including 9 existing and 10 fictitiously installed facilities, 248 candidate locations eligible for primary processing facilities, comprising 4 existing and 244 potential new facility installations, and 9 locations for existing further recovery/disposal facilities across 16 scenarios. The two base scenarios consist of A) complete in-house processing (flow scenario 1) and B) partial in-house processing (flow scenario 2). Each base scenario is further divided into subscenarios based on variations in processing capacities (plant design scenarios 1 and 2), WEEE input volumes (input scenarios 1 and 2), and transport costs (transport scenarios 1 and 2) (see Table 1).

4.3.3. Computational results

LINGO 8.0, a comprehensive software tool designed to address complex linear, non-linear, and integer optimization problems, was used to build and computationally solve the MILP model. The solver relies on a branch-and-bound search algorithm as the core technique for finding global optima. The computation required over 193.22 million iterations to produce the optimization results. These results elucidate the network-based determination of locations for primary processing facilities, taking into account the associated costs incurred for cost-optimal facility installation and inter-facility transportation. Transport costs include those from collection to primary processing facilities (i.e., transport costs 1) and those from primary processing to further recovery/disposal facilities (i.e., transport costs 2).

Table 1
Parametric overview of case scenarios

Base scenarios and subscenarios	Plant design
A) Complete in-house processing	
A 1) Complete in-house processing	15,000 t/a
A 1.1) Transport: 0.15 €/tkm, input: 73,000 t/a	
A 1.2) Transport: 0.15 €/tkm, input: 110,000 t/a	
A 1.3) Transport: 0.30 €/tkm, input: 73,000 t/a	
A 1.4) Transport: 0.30 €/tkm, input: 110,000 t/a	
A 2) Complete in-house processing	30,000 t/a
A 2.1) Transport: 0.15 €/tkm, input: 73,000 t/a	
A 2.2) Transport: 0.15 €/tkm, input: 110,000 t/a	
A 2.3) Transport: 0.30 €/tkm, input: 73,000 t/a	
A 2.4) Transport: 0.30 €/tkm, input: 110,000 t/a	
B) Partial in-house processing	
B 1) Partial in-house processing	15,000 t/a
B 1.1) Transport: 0.15 €/tkm, input: 73,000 t/a	
B 1.2) Transport: 0.15 €/tkm, input: 110,000 t/a	
B 1.3) Transport: 0.30 €/tkm, input: 73,000 t/a	
B 1.4) Transport: 0.30 €/tkm, input: 110,000 t/a	
B 2) Partial in-house processing	30,000 t/a
B 2.1) Transport: 0.15 €/tkm, input: 73,000 t/a	
B 2.2) Transport: 0.15 €/tkm, input: 110,000 t/a	
B 2.3) Transport: 0.30 €/tkm, input: 73,000 t/a	
B 2.4) Transport: 0.30 €/tkm, input: 110,000 t/a	

1) Base scenario A) – Complete in-house processing

In scenario A 1), the results indicate that transport costs significantly contribute to total costs. Increases in total costs can be attributed to both rising transport rates and growing masses of WEEE for treatment. Transport costs appear to double across the transport scenarios. Additional investment-dependent costs arise from new processing facility installations due to expanding processing capacity requirements. Notably, transport costs 2 surpass transport costs 1 as a result of increasing WEEE input (see Figure 3).

In all subscenarios A 1), the four developed candidate locations with existing primary processing capacities are part of the solution. The locational network structure is robust against transport rate increases in any of the subscenarios (see Figure 4 [72]). In input scenario 1, two new primary processing facilities are installed under both transport scenarios at the same locations. A similar pattern is observed in input scenario 2, where four new facilities are identically located. In contrast, the volume of the WEEE input appears to exert a substantial influence on the configurational network structure. Beyond necessitating additional processing capacities, the configuration of the facility locations in input scenario 2 omits all locations identified in input scenario 1.

The results of scenario A 2) provide cost insights that are comparable to those of scenario A 1). While economic scale effects generally bring about lower total costs, increasing the processing capacity to 30,000 t/a exhibits only a slight effect on the overall cost structure (see Figure 5).

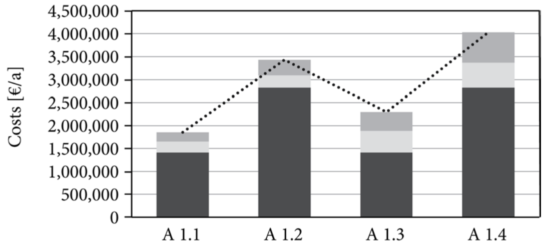
Again, all four existing primary processing facilities at developed candidate locations are included in the location solutions for scenario

[3] Average proportions are derived from insights gained during the 2001 implementation of the Japanese Home Appliance Recycling Law, thereby reflecting somewhat comparable early-stage conditions in process flows and material balances.

[4] Inter-facility transport distances between locations are determined using Google Maps based on pairwise fetching of geocoordinates of respective location constellations.

[5] The assumption regarding transport costs for WEEE items is grounded in local transportation experience in Beijing, acknowledging the similarity of urban conditions in Shanghai (personal communication, January 6, 2009; personal consultation with a firm representative of Huaxing Group Environmental Industry Development).

Figure 3
Cost structure of subscenario A 1)



	A 1.1	A 1.2	A 1.3	A 1.4
Transport costs 2	203,026	332,543	406,052	665,086
Transport costs 1	238,390	272,672	476,781	545,345
Installation costs	1,411,024	2,822,048	1,411,024	2,822,048
Total costs	1,852,440	3,427,263	2,293,857	4,032,479

Figure 4
Location solutions of subscenario A 1)

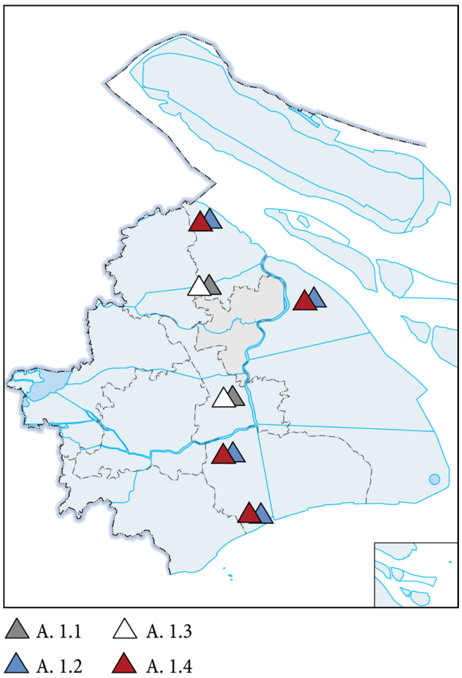
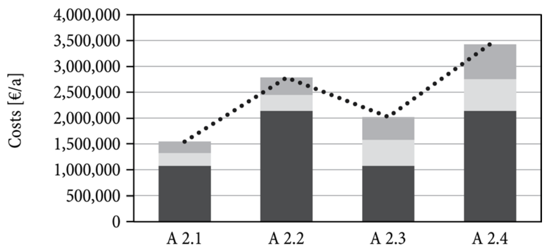


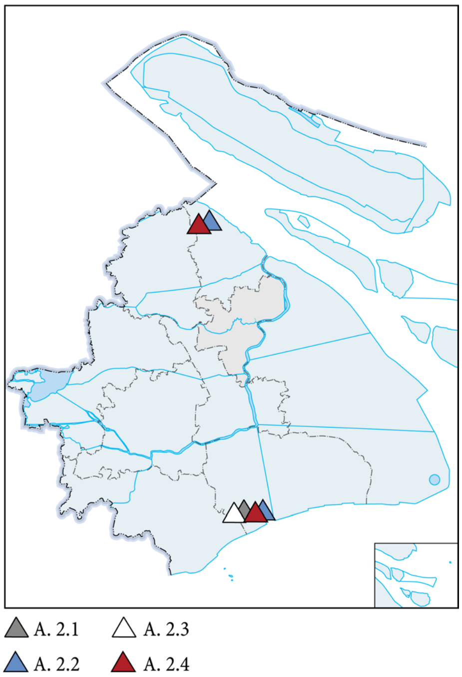
Figure 5
Cost structure of subscenario A 2)



	A 2.1	A 2.2	A 2.3	A 2.4
Transport costs 2	220,617	337,904	441,235	675,808
Transport costs 1	253,715	306,685	507,431	613,370
Installation costs	1,069,356	2,138,712	1,069,356	2,138,712
Total costs	1,543,688	2,783,301	2,018,022	3,427,890

A 2). However, changes in the network configuration occur for new facility installations. As processing capacities increase and, hence, the required number of new facilities decreases, the optimal undeveloped

Figure 6
Location solutions of subscenario A 2)



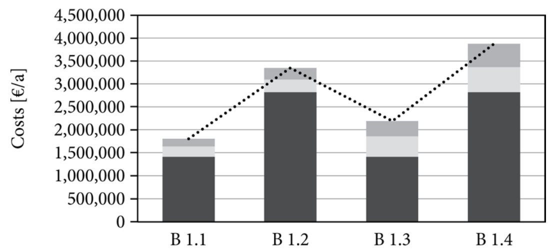
locations in input scenario 1 shift from the central and upper northern areas to the far southern area. In input scenario 2, increasing WEEE feed stream prompts the installation of new processing capacities in the far northern and southern areas. While the processing capacities in the north-eastern and upper southern areas designated in scenario A 1) are consolidated, both the far southern and northern locations are robustly retained (see Figure 6 [72]).

2) Base scenario B) – Partial in-house processing

Scenarios grounded in partial in-house processing incorporate the integration of downstream recovery options. Conceptualized as a process output decrease at primary processing facilities, not all downstream WEEE item flows to the market option stage are considered. Although this renders direct cost comparisons across the base scenarios A) and B) impracticable, the overall cost structure of scenario B 1) reveals substantial similarity with scenario A 1), except for transport costs 2 (see Figure 7).

All four developed candidate locations with existing primary processing facilities remain integral to the location solution. Consistent with scenarios A 1) and A 2), scenario B 1) demonstrates that location

Figure 7
Cost structure of subscenario B 1)



	B 1.1	B 1.2	B 1.3	B 1.4
Transport costs 2	166,109	255,839	332,219	511,679
Transport costs 1	224,003	271,744	448,007	543,488
Installation costs	1,411,024	2,822,048	1,411,024	2,822,048
Total costs	1,801,136	3,349,631	2,191,250	3,877,215

solutions are robust across both transport scenarios because variations in transport rates do not cause configurational changes in the network. Similarly, the sensitivity of the optimal locations is mainly associated with changes in WEEE input and plant design. This highlights the dual influence of downstream treatment on the locational network configuration, shaped by processing capacity constraints. When compared with scenario A 1), the optional integration of downstream recovery in scenario B 1) leads to new primary processing facility installations in the northeastern and far southern areas in input scenario 1. In contrast, the robustness of the locations identified as optimal in input scenario 2 becomes evident because increasing WEEE input requires additional new facility installations only in the far northern and upper southern areas (see Figure 8 [72]).

As observed in scenarios A 1) and A 2), economies of scale result in lower total costs in scenario B 2) relative to scenario B 1). The cost structure of scenario B 2) is comparable to that of scenario B 1). It is also essentially similar to that of scenario A 2), excluding transport costs 2 (see Figure 9).

Scenarios A 2) and B 2), along with all related subscenarios, yield identical location solutions. Accordingly, the optimal locational network configuration appears nearly independent of process output when processing capacities are larger. Remarkably, locations also demonstrate robustness against WEEE input variations, regardless of the number of new primary processing facilities being installed (see Figure 10 [72]).

Figure 8
Location solutions of subscenario B 1)

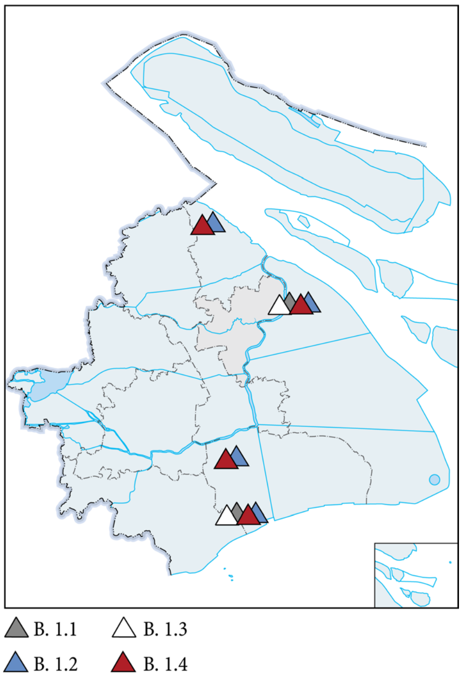
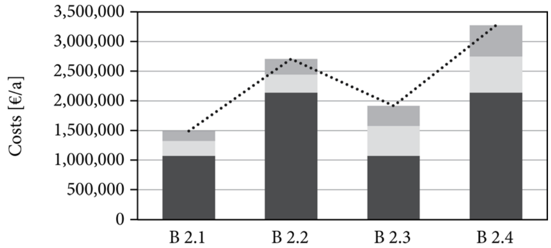


Figure 9
Cost structure of subscenario B 2)



	B 2.1	B 2.2	B 2.3	B 2.4
Transport costs 2	169,395	261,114	338,791	522,229
Transport costs 1	253,258	305,990	506,518	611,980
Installation costs	1,069,356	2,138,712	1,069,356	2,138,712
Total costs	1,492,009	2,705,816	1,914,665	3,272,921

4.3.4. Discussion

In the 16 case scenarios considered, the four developed candidate locations with existing processing capacities are included in any location solution due to major savings in facility installation costs. From a set of 244 undeveloped candidate locations, only 6 are identified as optimal, with varying frequency distributions across scenarios (see Table 2).

Optimal locations are almost exclusively spatially distributed along the central vertical axis of Greater Shanghai, extending from the far north to the far south. Only one optimal location is situated in the upper north-eastern area (see Figure 11 [72]).

In principle, prioritizing the identified optimal locations and their immediate surrounding areas for initial facility installation considerations seems advisable. However, the computational results clearly demonstrate that the optimality of the locations can vary widely across different case scenarios. It becomes evident that variations in WEEE input are associated with differences in both the number and spatial distribution of facilities, leading to significant cost differentials. While the volumes of WEEE feed stream significantly shape the robustness of location solutions, variations in transport costs have notably no impact on the locational network configuration. There is also rather minor sensitivity regarding the masses of WEEE process outputs from primary processing facilities. It shows that the influence of downstream recovery options largely stems from the factors of WEEE input and plant design. Increasing processing capacities not only reduces the number of facility locations required, thereby affecting the locational network structure, but also contributes to cost efficiency. Total network cost reductions can be achieved by realizing economies of scale because the savings from decreased facility installation costs consistently outweigh the resulting increases in transport costs across all case scenarios.

Figure 10
Location solutions of subscenario B 2)

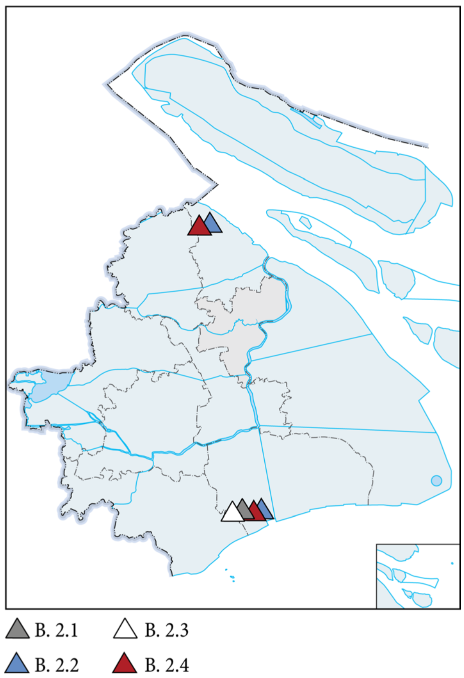
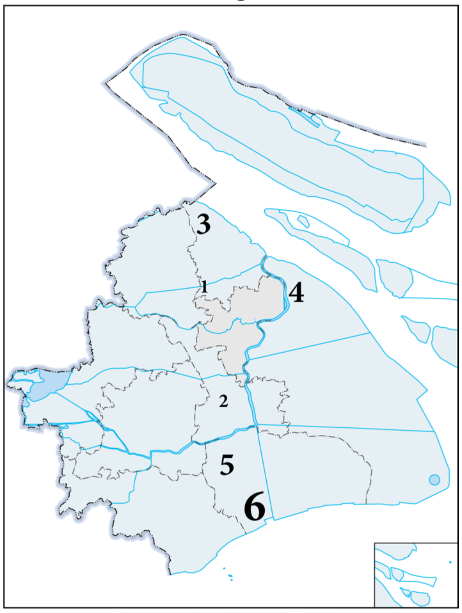


Table 2
Frequency distribution of optimal facility locations in location solutions by case scenario

Scenarios	Optimal facility locations in location solutions					
	1	2	3	4	5	6
A 1.1)	x	x				
A 1.2)			x	x	x	x
A 1.3)	x	x				
A 1.4)			x	x	x	x
A 2.1)						x
A 2.2)			x			x
A 2.3)						x
A 2.4)			x			x
B 1.1)				x		x
B 1.2)			x	x	x	x
B 1.3)				x		x
B 1.4)			x	x	x	x
B 2.1)						x
B 2.2)			x			x
B 2.3)						x
B 2.4)			x			x

Figure 11
Spatial distribution of optimal facility locations in Greater Shanghai



Note: Larger font sizes of location numbers indicate a higher frequency distribution of optimal locations across case scenarios.

In summary, it seems reasonable to argue that the foundational policy implementation challenge of WEEE reverse logistics network design in Greater Shanghai can be effectively addressed by "building bigger treatment facilities faster." From a cost-optimal network systems perspective, the two locational catchment areas in the far north and south of Shanghai appear best suited for initial facility installation, with potential additional installations in the north-eastern and upper southern areas if needed.

However, there are some limitations to be acknowledged in the practical interpretation of the case study results. These involve certain assumptions made to accommodate data, highlighting the infancy stage of formal WEEE recovery and disposal in China and Greater Shanghai, respectively. Although sensitivity analysis using diverse case scenarios can help in mitigating imprecisions and uncertainties, the current data still fall short of fully capturing actual real-world circumstances, potentially introducing bias. In particular, this is evident in the auxiliary solution of locating fictitious collection facilities at the collection stage using manually derived centroids of administrative divisions. In the preselection of candidate locations for primary processing facilities at the treatment stage, qualitative location factors, such as site suitability and traffic conditions, remain unconsidered. At the market option stage, although carefully conducted, the selection of major facilities for further recovery and disposal can hardly claim full representativeness. In this context, enhancing data quality in future studies is conducive to improving the analytical accuracy and applicability of computational results as well as the practical implications drawn therefrom. Not least, addressing data constraints in forthcoming MILP-based location model formulations through programming approaches such as robust and stochastic optimization techniques, together with qualitative location planning, could contribute to enhancing the reliability and actionability of location solutions.

5. Concluding Remarks

The sustainable management of WEEE has emerged as an important policy concern for eco-innovation in emerging market economies like China. However, the comprehensive introduction of formalized WEEE recovery and disposal poses significant challenges for practical policy implementation, requiring the development of foundational technical and organizational infrastructure. This study set out to develop and apply a locational decision-support system to address the infrastructural challenges of formalizing WEEE recovery and disposal in the Chinese context. Leveraging MILP modeling, the Shanghai case study illuminates the determination of cost-optimal facility locations, providing analytical insights into cost structures and the influencing factors underlying location solutions. It becomes clear that optimal locational network configurations can vary significantly across the 16 case scenarios considered, primarily depending on the factors of WEEE input and plant design. Overall, the computational optimization results suggest favoring larger processing capacities for initial facility installation in the far northern and southern areas of Greater Shanghai, in anticipation of increasing volumes of WEEE input and available downstream recovery options.

Although generally feasible in techno-organizational terms, it is crucial to emphasize that environmentally sustainable WEEE recovery and disposal, in compliance with Chinese legal requirements, are not solely a matter of advancing physical infrastructure development. Rather, it can be argued that successful policy implementation ultimately becomes apparent through legal enforcement and execution "on the ground." Formal WEEE businesses face intense competition from well-entrenched systems in the informal economy. This is notably true for WEEE supply, which is dominated by vast informal collection networks. The creation of a sustained collection system providing sufficient feed stream for effective formalized WEEE management operations is also, and in particular, contingent upon how and to what extent informal actors align with restrictive regulatory efforts. This calls close attention to the debatable aspect of the potential transformative influence of formalization on the Chinese informal-economy landscape. In fact, it stands to reason that people may conceivably hold on to existing informal business structures and patterns, at least for some time to come. In China, informal WEEE activities typically serve as the primary, or even sole, means of securing (family) livelihood. If alternative income opportunities are inaccessible for those excluded from China's economic progress, envisioning significant changes in near-term market conditions that would favor formal WEEE management operations becomes challenging. In addition, it remains highly contestable whether the eradication of informal WEEE recovery and disposal should be pursued by all means necessary. Considering the potentially disruptive social impact of a lawfully enforced "rectification" of informal employment, eco-innovation in industry extends beyond environmental and economic concerns, becoming a matter of socio-ethical responsibility. As such, the overarching policy challenge of formalization resides in harmonizing sectoral strengths and weaknesses through mutually beneficial ways and means. For instance, policy could refine the development of supportive infrastructure to facilitate the integrated collection, transportation, and treatment of WEEE within formal channels, allowing informal WEEE collectors and recyclers to participate as part of a broader formalized reverse logistics network. This not only includes promoting licensing and certification systems that incentivize informal agents to register and operate within the legal framework, offering benefits such as access to formal markets and added financial/economic value, but also involves the corresponding implementation of educational awareness and training programs to enhance knowledge and capacity building in environmental protection and safe recycling practices as well as business management. Such a strategic complementary concentration of formal and informal inputs and resources may pave the way for environmentally sound, economically viable, and socially acceptable WEEE recovery and disposal in China – as well as in other emerging market economies holistically striving for eco-innovation in industry. In this light, future practical approaches to reverse logistics network design can and should emphasize the formal-informal trichotomy of sustainability by synergizing theory with practice, capitalizing on in-depth stakeholder data to provide well-informed actionable guidance for enhancing real-world locational decision-making.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Steffen Wolfer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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Appendix

Table A1
Overview of facility locations across reverse logistics stages

Facility locations	Geocoordinates of the location [la / lo]	Capacity status [t/a]
Collection stage		
Existing collection facilities		
CS1 – Huangpu District	31.233105° / 121.480916°	Unrestricted
CS2 – Luwan District	31.206744° / 121.480683°	Unrestricted
CS3 – Xuhui District	31.181268° / 121.449083°	Unrestricted
CS4 – Changning District	31.200842° / 121.416742°	Unrestricted
CS5 – Jing'an District	31.227151° / 121.432056°	Unrestricted
CS6 – Putuo District	31.257217° / 121.425474°	Unrestricted
CS7 – Zhabei District	31.305817° / 121.446970°	Unrestricted
CS8 – Hongkou District	31.256202° / 121.507341°	Unrestricted
CS9 – Yangpu District	31.293488° / 121.539888°	Unrestricted
Fictitiously installed collection facilities		
CS10 – Pudong District	31.221614° / 121.631500°	Unrestricted
CS11 – Nanhui District	31.017038° / 121.770697°	Unrestricted
CS12 – Fengxian District	30.911318° / 121.546351°	Unrestricted
CS13 – Jinshan District	30.847254° / 121.227648°	Unrestricted
CS14 – Songjiang District	31.027580° / 121.230224°	Unrestricted
CS15 – Minhang District	31.106710° / 121.418122°	Unrestricted
CS16 – Qingpu District	31.119214° / 121.083292°	Unrestricted
CS17 – Jiading District	31.373163° / 121.240387°	Unrestricted
CS18 – Baoshan District	31.379020° / 121.421883°	Unrestricted
CS19 – Chongming County	31.638125° / 121.574362°	Unrestricted
Treatment stage		
Developed candidate locations with existing capacities		
TS1 – TES-AMM	31.353793° / 121.228432°	Restricted
TS2 – Shanghai Central WEEE Recycling	31.361474° / 121.434804°	Restricted
TS3 – Shanghai Mitsui Xin Rare Metal	30.794193° / 121.262686°	Restricted
TS4 – Shanghai New Jinqiao Industrial Waste	31.250728° / 121.632217°	Restricted
Undeveloped candidate locations for new capacity installation		
La1Lo6	31.795793° / 121.165071°	Scenario restricted
La1Lo7	31.795793° / 121.220829°	Scenario restricted
La1Lo8	31.795793° / 121.276587°	Scenario restricted
La1Lo9	31.795793° / 121.332345°	Scenario restricted
La1Lo10	31.795793° / 121.388103°	Scenario restricted
⋮	⋮	⋮
La24Lo9	30.739265° / 121.332345°	Scenario restricted
Market option stage		
Existing further recovery facilities		
MO1 – Shanghai First Copper Plant	31.365794° / 121.468803°	Restricted
MO2 – Shanghai Ketai Copper	31.366942° / 121.472529°	Restricted
MO3 – Shanghai Flywheel	31.071627° / 121.354938°	Restricted
MO4 – Xin Ye Copper Shanghai	30.802483° / 121.288558°	Restricted

Table A1
(*Continued*)

Facility locations	Geocoordinates of the location [la / lo]	Capacity status [t/a]
MO5 – Sigma Corporation	31.377072° / 121.406557°	Restricted
MO6 – Shanghai Xin Hua Iron & Steel	31.581689° / 121.524668°	Restricted
Existing disposal facilities		
MO7 – Jiang Qiao Waste Incineration	31.266107° / 121.355485°	Restricted
MO8 – Yu Qiao Waste Incineration	31.156079° / 121.561829°	Restricted
MO9 – Shanghai Chemical Industry Park	30.819235° / 121.539888°	Restricted

Note: Abbreviations/acronyms: CS = collection stage, TS = treatment stage, La = latitude, Lo = longitude, MO = market options stage. The listing of undeveloped candidate locations is incomplete and serves as an illustrative excerpt. Undeveloped candidate locations for new facility installations are named according to their position on the virtual grid; for instance, the location of the square in the upper left corner is designated as Lo1La1 (longitude 1, latitude 1), and so on.

Table A2
WEEE feed stream partitioned by administrative divisions for input scenario 1

District or county in Greater Shanghai	Appliance type [t]				
	TV set	Refrigerator	Washing machine	Air conditioner	Personal computer
Huangpu District	1104.07	235.84	250.45	108.53	388.20
Luwan District	588.71	125.75	133.54	57.87	206.99
Xuhui District	2139.36	456.99	485.30	210.30	752.21
Changning District	1457.78	311.40	330.69	143.30	512.56
Jing'an District	556.59	118.89	126.26	54.71	195.70
Putuo District	2399.97	512.66	544.42	235.91	843.85
Zhabei District	1645.05	351.40	373.17	161.71	578.41
Hongkou District	1698.21	362.76	385.23	166.93	597.10
Yangpu District	2610.89	557.71	592.26	256.65	918.01
Pudong District	6058.31	1294.12	1374.28	595.52	2130.14
Nanhui District	1921.93	410.54	435.98	188.92	675.76
Fengxian District	1593.62	340.41	361.50	156.65	560.33
Jinshan District	1284.83	274.45	291.46	126.30	451.76
Songjiang District	1922.15	410.59	436.03	188.94	675.84
Minhang District	3705.42	791.52	840.55	364.24	1302.85
Qingpu District	1600.34	341.85	363.03	157.31	562.69
Jiading District	2045.84	437.01	464.08	201.10	719.33
Baoshan District	2832.66	605.09	642.57	278.45	995.98
Chongming County	1425.23	304.44	323.30	140.10	501.12

Table A3
Scenario-based proration of WEEE material flows

Type of commodity	Flow scenario	Proportion of material fractions in process output [%]			
		Ferrous metal	Non-ferrous metal	Non-metal	Residues
Refrigerator					
	Flow scenario 1	54.48	3.62	39.85	2.05
	Flow scenario 2	43.50	2.69	36.57	1.21
Air conditioner					
	Flow scenario 1	54.40	25.92	15.88	3.80
	Flow scenario 2	25.36	0.78	14.08	1.22
TV set					
	Flow scenario 1	10.44	11.48	68.94	9.14
	Flow scenario 2	5.70	6.90	65.80	2.00
Personal computer					
	Flow scenario 1	20.47	21.10	42.20	16.23
	Flow scenario 2	3.10	17.70	37.20	7.90
Washing machine					
	Flow scenario 1	50.64	4.36	40.69	4.31
	Flow scenario 2	35.98	1.43	37.30	0.29

Table A4
Breakdown of investment-dependent installation costs for a primary processing facility with a treatment capacity of 15,000 t/a

Cost item	Total investment [€]	Depreciation period [a]	Specific investment [€/a]
Land and premises	2,802,064	15	186,804
Transport and conveying equipment	186,207	5	37,241
Tools and tooling equipment	263,004	5	52,601
Process plant and peripheral devices	2,270,323	15	151,355
Testing and control systems	73,641	5	14,728
Other investment	171,142	5	262,783
Sum investment	5,766,381		705,512