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Steffen Wolfer
Harald Sander
Frank Gogoll

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by

Steffen Wolfer*
Research Associate, Faculty of Economics and
Business Administration, Cologne University of Applied Sciences, Claudiusstr.1,
50678 Cologne, Germany.

Prof. Dr. Harald Sander
Professor of Economics and International Economics, Faculty of Economics and
Business Administration, Cologne University of Applied Sciences, Claudiusstr.1,
50678 Köln, Germany.

Prof. Dr. Frank Gogoll
Professor of Economics and International Economics, Faculty of Economics and
Business Administration, Cologne University of Applied Sciences, Claudiusstr.1,
50678 Köln, Germany.

Abstract:
On January 01, 2011, the legal basis paving the way towards environmentally sustainable WEEE recovery and disposal in China has entered into force. Against this background, we propose a mixed-integer linear programming formulation for determining the physical configuration of a reverse logistics system for WEEE in Chinese contexts. The resulting optimization-based warehouse location model is applied to a case study on the development of a formal WEEE recycling infrastructure in Greater Shanghai Area. Based on the computational results, we identify several crucial factors determining the cost-efficient configuration of the reverse logistics system and derive recommendations for integrated network design.

Keywords: WEEE, China, Reverse logistics network design, Eco-innovation, Sustainability, Regional policy implementation

* Author contact: Tel.: +49-221-8275-3422, Fax: +49-221-8275-73422, E-mail: steffen.wolfer@fh-koeln.de (Steffen Wolfer)

1. Introduction

Pressing global challenges such as climate change, resources depletion, or the loss of biodiversity demonstrate the imperative for structural change of our economic and societal systems towards sustainable development. In this vein, the sustainable management of waste electrical and electronic equipment (WEEE) has increasingly come to the fore for various reasons. WEEE is the fastest-growing waste stream worldwide. Use of electrical and electronic equipment (EEE) has proliferated in recent years, the volume of discarded appliances is "globally soaring" (Robinson 2009; Widmer et al. 2005; Puckett et al. 2002). In addition, WEEE is comprised of an increasingly diversified and steadily growing range of appliances whose hazardous substances inherent may have adverse effects on the terrestrial, aquatic, and aerial environments as well as on humans and animals if not treated in technically appropriate manners (Sepúlveda et al. 2010; Robinson 2009; Brigden et al. 2005). WEEE recovery and disposal presents a formidable challenge to environmentally acceptable waste management – notably in developing countries and emerging nations contexts. Here, informally organized waste systems frequently reign supreme in 'daisy chains' of legal and illegal activities. Organized in small companies, groups, or even individuals, WEEE is collected, traded, processed, and finally disposed of under the primacy of economic viability only (Chi et al. 2011; Streicher-Porte/Geering 2008; Osibanjo/Nnorom 2007).

In China, the basically profit-driven WEEE recovery and disposal in the informal economy has not only been causing serious damage to the environment and human health. Crude treatment practices are indeed major reason for considerable loss of valuable secondary raw materials (Sepúlveda et al. 2010; Brigden et al. 2005). Both domestic use and obsolescence of EEE have increased rapidly in recent years. China's accession of wealth is not only expected to facilitate consumption but also to further shorten the utilization phase of EEE and, in turn, to gradually increase the per-capita generation of WEEE over time (Yang et al. 2008; Li et al. 2006; Tian et al. 2006). In addition, China remains a major destination for a large proportion of shipments of illegal WEEE exports from industrialized nations (Robinson 2009; Liu et al. 2006a; Puckett et al. 2002). Against this backdrop, integrated waste management strategies at province, county, and township levels have evolved to a major policy issue. On January 01, 2011, the legal basis paving the way towards environmentally sustainable WEEE treatment in China has entered into force. However, the implementation of the eco-innovation policy imposes substantial requirements on infrastructure and infrastructure development in both technological and organizational terms.

Based on a decision-support system for reverse logistics network design for WEEE recycling, we intend to shed more light on the issue of efficient regional eco-innovation policy implementation in China. We first investigate the framework conditions for WEEE recovery and disposal in China with special focus on the end-of-life value chain and derive implications for locational decision-making. We then propose a mixed-integer linear programming formulation for determining the physical configuration of the reverse logistics system at minimal costs in due consideration of recent legal developments. The resulting optimization-based warehouse location model is applied to a case study on the development of a formal WEEE recycling infrastructure in Greater Shanghai Area. Based on the computational results, we identify several crucial factors determining the cost-efficient configuration of the reverse logistics system and derive recommendations for integrated network design. We conclude with a discussion of practical problems of eco-innovation policy enforcement in the societal contexts of circular economy development in China.

2. Framework conditions for WEEE recovery and disposal in China

2.1 Technical framework for WEEE recovery and disposal

In the literature, a common terminological basis for WEEE[1] does not exist (Terazono et al. 2006; Widmer 2005). Following the EU directive on WEEE, the present paper refers to the term as "… electrical or electronic equipment which is waste within the meaning of Article 1(a) of Directive 75/442/EEC, including all components, subassemblies, and consumables which are part of the product at the time of discarding". In this vein, EEE is accordingly understood as equipment depending on "… electric currents or electro-magnetic fields in order to work properly and equipment for the generation, transfer, and measurement of such cur-rents and fields (…) designed for use with a voltage rating not exceeding 1000 Volt for alternating current and 1 500 Volt for direct current" (EU 2003).

The physical transition from the consumer to the end-of-life manager sphere finally turns EEE into WEEE. After having the waste appliances (re-)collected, WEEE can basically be steered into umpteen end-of-life recovery alternatives; namely: reuse (further use of commodities or components thereof in the original state), servicing (extension of a commodity's utilization phase trough repair or maintenance), remanufacturing (selected components are prepared for reuse), recycling (recovery of secondary raw ma-

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[1] WEEE is often mentioned as e-waste or e-scrap as well.

terials), and the final disposal of residues in landfills or incinerators as well as certain combinations of the latter recovery options. Reuse and servicing as well as remanufacturing activities[2] can at the best solely extent the utilization phase of EEE however. Naturally, such appliances ultimately occur as non-reusable waste which can only be recovered through respective recycling activities as last remaining option (Bohr 2007; Li et al. 2006). The recycling stage includes manual dismantling (separation of hazardous as well as valuable materials), upgrading of valuable material fractions (mechanical/physical and/or metallurgical treatment) as well as refining (recovered materials return to their life cycle) (Cui/Forssberg 2003). Recycling enterprises thus depend on both upstream supply and downstream sales market and disposal options.

Accordingly, WEEE is collected and transferred to recycling units. Processed commodities and/or residues are subjected to further treatment in respective recovery and disposal facilities thereafter. In technical terms, a reverse logistics infrastructure has to provide for all said 'reverse activities' involved in the accumulation of commodities to be recovered, the respective recovery processes, and the redistribution of recovered commodities as well as residues to various demand points (Kajendirakumar et al. 2007).

2.2 Regulatory and economic framework for WEEE recovery and disposal in China

China's economic trajectory has not only been inducing increasing demand for energy and raw materials. Rapid economic growth as well as progressing industrialization and urbanization have certainly contributed to environmental degradation and health hazards eventually even limiting further economic expansion. China's national emphasis on the environment thus aims at a forth going economic, social, and cultural progress and enhancement of the quality of life of its people through sustainable development (OECD 2009). Future organization of economic activity shall hence be increasingly subject to compliance with social and ecological concerns. In vigorously driving forward circular economy promotion laws and regulations, the Chinese government has been pressing claim on striving towards a resource-conserving and environment-friendly society (Mo et al. 2009). In recent years, the authorities have been gradually establishing a regulatory framework for environmentally sustainable WEEE recovery and disposal. WEEE management-related laws and regulations are thereby embedded into the policy framework for resource recovery and conservation in China (see Table 1).

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[2] It should be noted that the terms 'reuse', 'servicing', and 'remanufacturing' are henceforth used synonymously and understood as any recovery activity within a WEEE appliance's life cycle prior to recycling targeting at the recirculation of appliances and components thereof in the original state.

Table 1. Regulatory framework for WEEE management in China

Law / regulation	Key content	Effective date
Environmental Protection Law of the People's Republic of China	Establishment of pollution control; definition of authorities responsible for enforcement	26 December 1989
Regulations on Prohibited Imports of Waste Electrical and Electronic Equipment	Restrictions on WEEE imports	15 August 2002
Cleaner Production Promotion Law	Promotion of cleaner production and "eco-design as well as the principles of life-cycle oriented resource use and waste management	01 March 2003
Law on the Prevention and Control of Environmental Pollution from Solid Waste	Specification of responsibilities of producers, retailers, importers, and consumers as well as the principles of reduction, reuse, and recycling (3R)	01 April 2005
Technical Policy of Prevention and Control of Environmental Pollution from Waste Electrical and Electronic Equipment	Requirements on WEEE collection, transport, storage, reuse, and treatment; promotion of "eco-design"	27 April 2006
Management Measures for the Prevention and Control of Environmental Pollution by Electronic Information Equipment	Restrictions on the use of hazardous substances; provisions on product design and product labeling	01 March 2007
Administrative Measures for the Prevention and Control of Environmental Pollution from Waste Electrical and Electronic Equipment	Establishment of institutional pollution prevention and control; provisions on environmental impact assessment for WEEE dismantling, utilization, and disposal	01 February 2008
Circular Economy Promotion Law	Provisions on the principles of reduction, reuse, and recycling (3R) in WEEE management contexts	01 January 2009
Regulations for the Administration of the Recovery and Disposal of Waste Electrical and Electronic Equipment	Obligation to recycling of WEEE; implementation of "extended producer responsibility"; establishment of a fund for WEEE management; certification of second-hand EEE; certification of WEEE management enterprises; requirements on environmental performance, monitoring institution, and data management systems in WEEE treatment facilities	01 January 2011

Source: following (Chi et al. 2011; Steicher-Porte et al. 2010; Yu et al. 2010, Yang et al. 2008)

The regulatory infrastructure presently in place indeed provides guidance and constraints in due consideration of the entire product life cycle – 'from the cradle to the grave'. Key legal elements intended to leverage more ecological betterment from EEE manufacturing and WEEE management include the restricted use of certain toxic and hazardous materials in EEE, import regulations for WEEE, the institutional prevention and control of pollution from WEEE treatment, licensing obligations for WEEE collection and treatment as well as the delegation of financial and organizational responsibility for WEEE management to EEE manufacturers and importers. The effectiveness of the Chinese government's recent reform efforts for eco-innovation in industry will finally become apparent upon practical policy implementation and its enforcement 'on the ground' however. Certainly, such laws and regulations may provide a fundamental step in moving towards environmentally acceptable WEEE management in China. However, vague definition of legal terms hence restricting its legal power or fairly immature provisions on policy implementation leaving ample margin for interpretation may eventually impair the introduced reform

process. Most importantly, rather modest –legal and thus strategical– note has been taken of the informal economy prevailing in China thus far (Chi et al. 2011; Steicher-Porte et al. 2010; Yu et al. 2010).

China's myriad of informal workforce is well-adapted to local conditions and has been establishing largely diversified and interconnected systems for many years. Beyond a veritable flood of illegal imports, informal collection also yield sufficient WEEE supplies from domestic sources (Chi et al. 2011; Streicher-Porte/Geering 2008). Domestic WEEE is almost exclusively collected by informal itinerant buyers that accumulate appliances from households through orderly door-to-door collection for onselling purposes (Streicher-Porte/Geering 2008; Liu et al. 2006; Ye at al. 2009). Such masses of domestic WEEE may be differentiated into appliances intended for direct reuse or respective recovery as well as into appliances that are stored and passed along temporally delayed for one of the two former purposes. The WEEE pool intended for recovery can be further differentiated into appliances that are destined for reconditioning and hence reutilization on the one side and for manual dismantling on the other side. At the dismantling stage, appliances are broken down into components in variable ways and depths as a first step. Components in good working order and condition may be further destined for reconditioning, whereas the balance is either recycled or disposed of. Resultant WEEE material fractions such as copper, silver, or aluminum are applied as secondary raw materials in various industry sectors, whereas reuse of second-hand appliances is regarded to directly increase the domestic WEEE pool of adjacent periods (Yang et al. 2008; Streicher-Porte/Geering 2008; Ye et al. 2007; Liu et al. 2006) (see Figure 1).

In technological terms, the manner under which WEEE recycling is carried out largely depends upon whether or not the recovery process forms a part of the formal or informal supply chain (Eugster et al. 2008). In China, the recently certified WEEE recycling plants are deemed to apply advanced recovery technologies and appropriate environmental and labor protection installations (Li et al. 2006). By contrast, in the informal economy WEEE is primarily treated manually. Commodities and components thereof eligible for reuse are preferably sold on as second-hand EEE. Remains are frequently either disposed of airily in fields or river banks or are subjected to crude recycling methods such as open burning and acid stripping for material recovery (Yang et al. 2008; Li et al. 2006).[3]

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[3] See e.g. Puckett et al. (2002), Brigden et al. (2005), Wong et al. (2007), or Leung et al. (2006) for a review of the crude recycling methods prevailing in China's informal economy as well as e.g. Sepúlveda et al. (2010), Robinson (2009), or Brigden et al. (2005) for an analysis of associated impacts on the environment and human health.
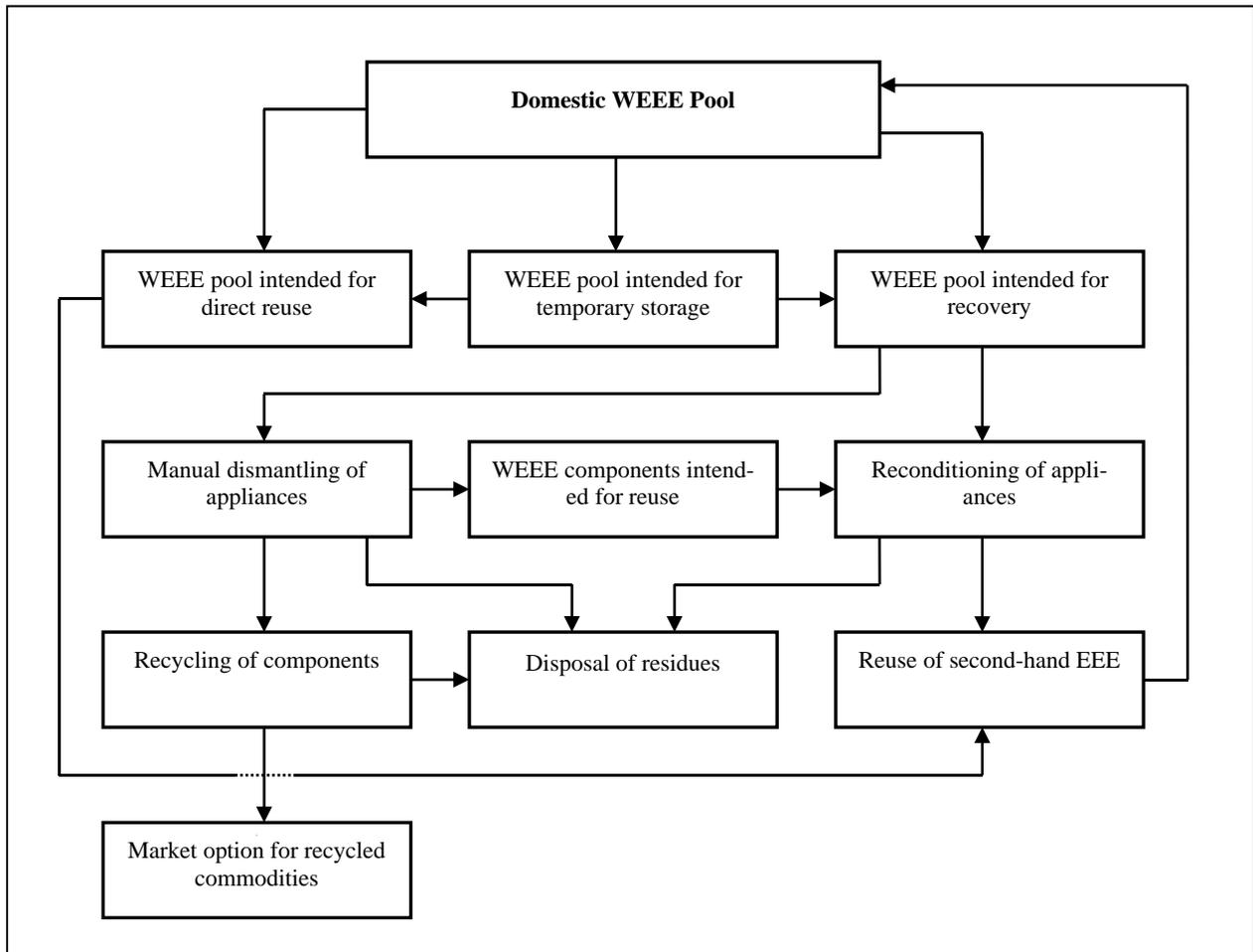
Figure 1. Domestic WEEE value chain in China

Source: following (Yang et al. 2008; Streicher-Porte / Geering 2008; Ye et al. 2007; Liu et al. 2006)

In China, WEEE is considered an economically valuable resource in particular for deprived strata of the population. Competition between the formal and informal sectors is accordingly fierce (Yang et al. 2008; Li et al. 2006). The informal sector's involvement in WEEE management thus plays a decisive role on two counts: informal sector activities are not only associated with environmental and health risks giving cause for serious concern, but also pose a major obstacle to market success of accredited WEEE management enterprises. In this respect, profitability of certified ventures has been notably affected by severe shortages of recyclables feed stream and by disproportionately higher investment and operational costs for environment-friendly plants and equipment (Yang et al. 2008). Basically, WEEE recovery and disposal is happening in the shade of the informal economy, with the number of small-scale recycling sheds still remaining on the increase (Ye et al. 2009).

3. Reverse logistics network design for WEEE recycling in China

3.1 Location decision making in reverse logistics contexts

Location planning in network contexts has to deliver an integrative approach to considering both the recycling network's influence on a single location's eligibility and the single location's influence on the network structure as for cost minimality. Consequently, each recycling location should rather provide for an 'appropriate' ratio of its associated outgo and income flows with each location yielding the maximal contribution to fulfillment of total cost optimality. Reverse logistics network design is accordingly not confronted with the problem of determining locations in isolation, but must rather configure the structure of an entire system. In this vein, the locational objective of the present paper refers to the cost-minimal configuration of the physical structure of an environmentally acceptable reverse logistics system through determination of the number and locations of WEEE recycling facilities in due consideration of facility interactions and the efficient use of existing processing resources.

The application of location models to reverse logistics network design is a comparatively new research field with rather few models and case studies being presented thus far. It appears that only few approaches in the literature refer to a continuous decision space. Most of the models rely on finite solutions and hence on mixed-integer linear programming which allows for discrete mathematical optimization. In the following a brief survey of key contributions to location planning in reverse logistics contexts is presented.

Louwers et al. (1999) developed a reverse logistics infrastructure for the collection, reprocessing, and redistribution of carpet waste by means of a non-linear continuous location model. Here, both locations and capacities for recovery facilities were determined. Barros et al. (1998) propose a two-tier location model for the recycling of sand. Number, capacities, and locations of recovery facilities are determined through mixed-integer linear programming. Realff et al. (1999) address the design of a reverse production system for carpet waste involving recycling and transport activities. A mixed-integer linear programming model delivers case solutions in terms of number and locations of collection as well as reprocessing facilities. Spengler et al. (1997) apply a multilevel mixed-integer location model to a large scale recycling planning problem for industrial by-products in the German iron and steel industry. In addition to the determination of locations for recycling facilities, the approach not only considers processing capacities and technologies, but also facilitates integrated location-allocation decisions for said by-products. Lu and

Bostel (2007) present a two-tier location problem with three different types of facilities to be located. They proposed an uncapacitated mixed-integer programming model in which they simultaneously consider forward and reverse material flows as well as interactions between production, remanufacturing, and intermediate facilities. Jayaraman et al. (1999) present a multi-level mixed-integer programming model that solves for locations of remanufacturing and distribution facilities. The formulation furthermore supports decisions on interlocational transshipment, production, and optimal warehousing for second-hand electronic equipment. Kricke et al. (1999) design a reverse logistics network for copiers recycling. They apply a mixed-integer linear programming model to determine optimal locations for processing facilities and optimal commodity flows in a single-product environment. Queiruga (2006) formulated a mixed-integer linear programming model for the strategic planning of a return system for large household appliances in Spain. The model allows for several capacity classes as well as for integrated location-allocation decisions on both appliances and material fractions. Walther (2005) applied a mixed-integer location planning model to a case study on the physical design of a material flow network for sustainable WEEE recovery in Lower Saxony, Germany.

Although material flows are reversed, the practical solutions to network design solely appear to marginally differ from those models being applied to traditional production-distribution problems (Kajendirakumar et al. 2007; Melo et al. 2007; Fleischmann (2001).[4] In methodological terms, a well suitable and hence frequently applied quantitative approach to mixed-integer linear programming for distribution system design refers to the warehouse location problem (WLP). Typically, WLP models include a given number of demand points (customers) with given demand at given locations, a finite number of –predetermined– candidate locations for facilities (warehouses) with fixed location and –often– variable operating costs as well as variable transport costs between customer and warehouse locations. The basic function of classical WLP formulations can then be described as to identify the number and locations of warehouses for which the total sum of fixed location and variable transport costs is minimal (Feige/Klaus 2008; Wollenweber 2008).[5] Such optimization-based approaches likewise allow for combined quantitative location and route as well as material flow planning based on a given traffic system. Existing resources may also be included in a finite set of location alternatives being basically eligible for settlement.

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[4] See e.g. the work of Kajendirakumar et al. (2007), Melo et al. (2007), or Fleischmann (2001) for a review of production-distribution and reverse logistics networks.
[5] See e.g. Dasci and Verter (2001) or Domschke and Drexl (1996) for an overview of WLP formulations.

Accordingly, linear programming delivers a methodically suitable approach to integrated location-allocation decision making in the present case. WLP modeling is thus applied in order to achieve an optimum distribution of technological resources in space. However, the programming methodology must first be methodically adapted to the contexts of WEEE recovery and disposal in China. The WLP basic model is hence to be transformed into a quantifiable reverse logistics system that allows for large-scale mathematical optimization.

3.2 Linear programming formulation for reverse logistics network design in China

Basically, WEEE is collected and transferred to recycling units. Processed commodities and/or residues are subjected to further treatment in respective recovery and disposal facilities thereafter. In operational practice, the recycling process may occasionally stretch out over more than one processing stage through integration of downstream processors. Not least in view of the early developmental stage of the Chinese recycling sector, the location model shall therefore consider the market entrance and diffusion of rather non-capital-intensive business models henceforth exemplified as alternative recovery options at primary processing facilities. The Chinese demand for both second-hand appliances and components thereof constitutes another essential planning element. The spatial distribution of reuse locations must be given due consideration as consequence. For these very reasons, the geographical position of collection, processing, further recovery, disposal, and reuse facilities, the masses of WEEE feed stream at the collection stage as well as certain recovery preferences and levels at different stages of the reverse logistics network shall be likewise considered in the linear programming model.

The system boundary of the mathematical model considers three different recovery levels. The product level of the WLP formulation is limited to the five main types of large WEEE that is properly documented in China at the outset; namely, waste refrigerators, air conditioners, TV sets, washing machines, and personal computers including respective peripheries. At the component level, parts of dismantled appliances are referred to as masses of intermediate commodities. At the material level, the main fractions ferrous metal (WEEE material fraction I), non-ferrous metal (WEEE material fraction II), non-metal (WEEE material fraction III), and residues (WEEE material fraction IV) are finally distinguished.

For basic programming purposes, various material flows are considered. The model covers a treatment stage, a collection stage as source and downstream sales market and disposal options as sinks as well as

umpteen recovery alternatives. At the initial <u>collection stage</u>, the decision maker is conceded to have two basic recovery options: (a) appliances eligible for appliance reuse may be sent to reuse facilities and/or (b) appliances may be transported to primary processing facilities for recycling purposes. Primary processing facilities are those certified for the qualified treatment of large WEEE. Any processing is hence carried out provided that the applicable environmental and occupational safety and health regulations are maintained. At the <u>primary processing stage</u>, the appliances are dismantled and broken down into components as a first step. At the component level, the decision maker is presumed to exercise three basic options thereafter: (a) components in good working order and condition may be transferred to reuse facilities; (b) components may undergo in-house final treatment processes where appropriate, whereas consequent material fractions are shipped to further recovery/disposal facilities; and/or (c) components are conveyed to secondary processing facilities. In the model, secondary processing facilities are not –yet– certified for the stand-alone treatment of large WEEE and thus solely remain downstream recovery options for certain components. All technical assumptions on work safety and environmental protection apply accordingly however. At the <u>secondary processing stage</u>, components are further processed with the resulting material fractions being transported to further recovery/disposal facilities thereafter. Finally, the <u>market options stage</u> includes facilities for further recovery, disposal as well as certain reuse options: (a) further recovery facilities treat material fractions I, II, and III for the purpose of material conditioning; (b) disposal facilities dispose of/incinerate residues (fraction IV) and incinerate non-metal material fractions (fraction III) for energy recovery; while (c) reuse facilities are recipient of both appliance and component commodities. In order to determine 'optimal' recycling locations, all these masses and material flows need to be taken into account (see Figure 2).
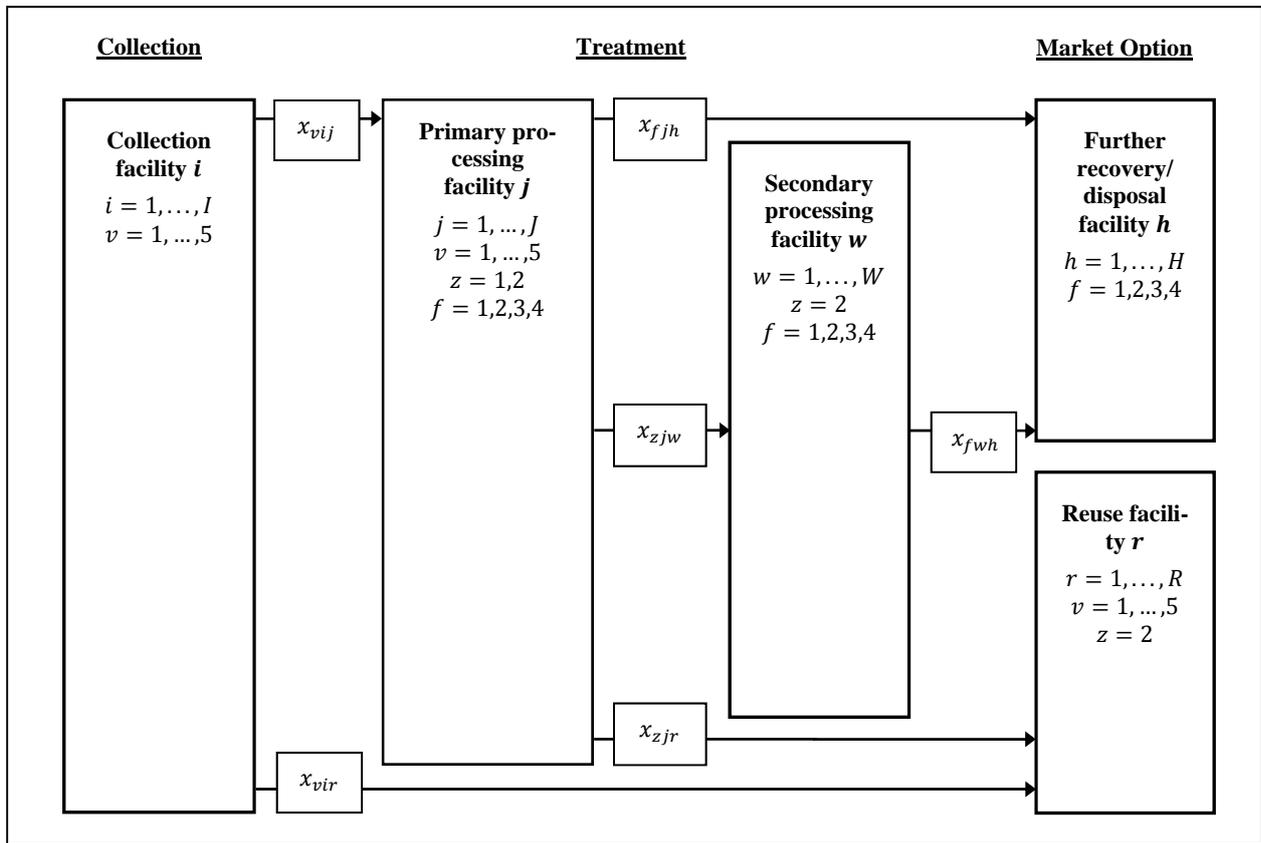
Figure 2. Material flows of the mathematical WLP formulation

Source: (authors' contribution)

The illustration shows the material flows and transshipment facilities considered in the model. For the mathematical formulation of the optimization problem, the following indices, parameters, and variables are introduced:

Indices

i Collection facilities $i = 1, \ldots, I$

h Further recovery/disposal facilities $h = 1, \ldots, H$

r Reuse facilities $r = 1, \ldots, R$

j Candidate locations of primary processing facilities $j = 1, \ldots, J$

w Candidate locations of secondary processing facilities $w = 1, \ldots, W$

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 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 mathematical optimization model can be described as follows:

Minimize $F(x, y) =$

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

$$\sum_{z=1}^{Z}\sum_{j=1}^{J}\sum_{r=1}^{R} c_{zjr}x_{zjr} + \sum_{f=1}^{F}\sum_{w=1}^{W}\sum_{h=1}^{H} c_{fwh}x_{fwh} + \sum_{j=1}^{J} d_j y_j + \sum_{w=1}^{W} d_w y_w$$

<div align="right">(1)</div>

subject to

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

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

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

$$\sum_{v=1}^{V} \sum_{i=1}^{I} x_{vij} \leq Cap_j y_j \qquad for\ j = 1, \dots, J \qquad (5)$$

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

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

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

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

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

$$\sum_{j=1}^{J} x_{zjw} \leq Cap_w y_w \qquad for\ n = 1,2;\ w = 1, \dots, W;\ z = 2 \qquad (11)$$

$$y_j + y_w \leq 1 \qquad for\ J \cap W \qquad (12)$$

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

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

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

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

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

$$y_j \in \{0,1\} \qquad\qquad for\ j = 1, \dots, J \qquad\qquad (18)$$

$$y_w \in \{0,1\} \qquad\qquad for\ w = 1, \dots, W \qquad\qquad (19)$$

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

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

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

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

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

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

In the linear program, equation (1) represents the objective function that is intended to minimize the sum of crucial costs, namely: (a) transport costs from collection facilities to primary processing facilities; (b) transport costs from collection facilities to reuse facilities; (c) transport costs from primary processing facilities to further recovery/disposal facilities; (d) transport costs from primary processing facilities to secondary processing facilities; (e) transport costs from primary processing facilities to reuse facilities; (f) transport costs from secondary processing facilities to further recovery/disposal facilities as well as (g) investment dependent costs of primary processing facilities and (h) investment dependent costs of secondary processing facilities.

Constraints (2) express the decision makers' recovery options and balance the incoming and outgoing flow of WEEE at the collection facilities. For that matter, constraints (3) and (4) determine the masses of appliances to be shipped to reuse and/or primary processing facilities for respective treatment. In primary processing facilities the appliances delivered with are dismantled into components in a pre-treatment process, in a final treatment process these components are further broken down into material fractions. Equations (5) obviate the maximum processing capacity of primary processing facilities at each location j to be exceeded. Constraints (6)-(10) impose full delivery of all appliances and components processed at the primary processing stage to further recovery/disposal, secondary processing, and/or reuse facilities in the form of material fractions and components. Resulting masses of material fractions and components are calculated based on the respective proportion of component types within appliance types as well as material fractions within component types. Equation (8) defines the masses of components fed into the final treatment process of certified facilities for primary processing. In secondary processing facilities the components exclusively accumulated from primary facilities receive final treatment. Equations (11) thereby prevent the secondary processing facilities being supplied with feed stream above capacity. Since any candidate location exhibits characteristics potentially meeting the location requirements of both recycling process stages, a location may be likewise adaptable for the installation of both primary and secondary processing facilities. Equation (12) thus prevents locational interference of 'shared' candidate locations. Equations (13)-(15) indicate the recovery options at the secondary processing facilities and provide for a balanced incoming and outgoing material flow. They regulate the transport volumes for reuse and further recovery/disposal facilities by determining the respective mass portion of processed components eligible for reuse and material recovery, respectively. Masses of material fractions are again estimated based on the respective proportion of a material fraction within each component type. Equations (16) and (17) present processing capacity constraints hence limiting the maximum allowable feed stream of further recovery/disposal facilities for material fractions as well as of reuse facilities for both appliances and components. Equations (18)-(25) impose integrality and non-negativity constraints. Constraints (18) and (19) declare the decision variables as binary, while constraints (20)-(25) prevent the variables of all masses considered from taking negative values.

4. Case study on the physical design of a WEEE recycling infrastructure in Shanghai

4.1 Case study specification

The system boundary of the case study includes certain limitations. The case study hence aims at locating primary processing facilities only; determination of number and locations of secondary processing facilities is hence renounced. Integration of down-stream recovery options is modeled as a decrease of tradable and non-tradable process output of primary processing facilities. Thus, shipments to undefined reuse and secondary processing locations are not quantified explicitly but prorated according to an in-house processing ratio. Interactions between primary processing facilities are also excluded. Calculations are based on costs for transport and plant installation only without consideration of variable and fixed cost items. WEEE treatment is reduced to a 'black box' exclusively balancing input and output streams without consideration of efficiency losses. The case study is also proceeded on the assumption that an area-wide collection system able to handle all WEEE masses is set in place. At this stage solely nine collection points have been established located in the urban center of Shanghai however. Accordingly, a provisional collection infrastructure fictitiously assigning additional collection capacities to the adjacent areas of Shanghai conurbation is installed for case study purposes.[6] At the treatment stage, the set of candidate locations includes locations for both already existing as well as newly to be established facilities. For the determination of the latter, Shanghai territory and its adjacent areas are overlain with a virtual grid dividing the coverage into 480 quadrates with an edge length of 5.25 km each. Thus, 248 candidate locations can be considered and taken for mathematical optimization. At the market option stage, reuse activities are allusively incorporated by a proportionate decrease of masses of commodities available for processing. Locations of reuse facilities thus remain undefined. Furthermore, waste incineration is regarded the only applicable destination for residues for environmental reasons. The case study takes thus note of three modern treatment sites for disposal and energy recovery of hazardous and non-hazardous commodities. As for the market options for secondary raw-material, ferrous and non-ferrous metal fractions are taken together into one consolidated metal cluster.

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[6] It should be noted that the estimation of center of gravities as locations for collection facilities represents an auxiliary solution only. Assumptions do neither take the spatial distribution of WEEE masses nor the optimal supply of collection facilities into account.

4.2 Data basis

This section refers to model input data. Sensitivity analysis is a major instrument for gaining both confidence into the location model and practical insights into the planning problem (Francis et al. 1983). Different case scenarios are accordingly developed and applied below in order to be enabled to estimate the robustness of results and to identify crucial factors determining the configuration of the reverse logistics system. In the following, assumptions on the spatial distribution of WEEE masses and flows as well as on cost parameters that are streamlined into the decision support system are presented.

Assumptions on spatial distribution and quantities of WEEE feed stream

Valid data on both WEEE generation and composition of Shanghai has not been made public. The average generation rate henceforth assumed therefore refers to a sample study of Beijing urban households. Assumptions on WEEE masses are based on the average generation rate of appliances per resident. It is estimated that total domestic generation will be 56,500 t (5.86 kg/capita) in 2010, 74,500 t (6.93 kg/capita) in 2015, and will have reached 92,000 t (7.78 kg/capita) by the year 2020 (Liu et al. 2006). Accordingly, a global WEEE generation of Shanghai of 5.86 kg/capita or 105,000 t in total is anticipated from which about 70 % or 73,000 t is available for recycling (input scenario 1). The quantity survey of input scenario 1 is partitioned by appliance type for each administrative division of Shanghai (see Annex 1). Estimations are based on global WEEE generation in consideration of the average allotment amongst the appliance types. Allotment of appliances is thereby conducted based on calculations of the proportion of each appliance within total masses generated. In order to estimate the robustness of a location solution to certain variations of WEEE input, anticipated masses of input scenario 1 are globally extended by an uncertainty factor of 1.5 (input scenario 2). Accordingly, arisings of about 110.000 t are proportionately allocated.

Assumptions on masses and distribution of commodity flows

Reuse of appliances initiated at the collection stage is –indirectly– factored in through variation of the WEEE input stream available for processing. At the processing stage, feed stream may be entirely processed into tradable and non-tradable material fractions (flow scenario 1) or partly redirected to downstream processing and reuse facilities in the form of components (flow scenario 2). Integration of downstream recovery options is modeled as respective decrease of process output of material fractions at the

primary processing stage. Any balance is fictitiously transferred to the undefined secondary processing and/or reuse facilities. The flow scenarios are calculated based on the proportions of tradable and non-tradable material fractions partitioned by appliance type (see Annex 2). Flow scenario 2 is based on average proportions of components that are not processed in-house, but redirected for downstream recovery options. Since there is no corresponding data on Chinese operations provided, assumptions refer to a survey on Japanese WEEE recycling enterprises (see Annex 2).

Assumptions on cost parameters

The first cost item relates to transportation. Based on local experience, transport costs for WEEE in China are assumed to amount to 0.15 € per ton and km. In the case study, two transport scenarios are again included for sensitivity analysis. Transport scenario 1 assumes that the distribution of commodities is mandatorily operated at full load assignment. For transport scenario 2 however, double carrying charges of 0.30 € are preconditioned for empty runs in freight traffic. Secondly, specific investment dependent costs are based on an unpublished feasibility study on the installation of a pilot plant of facility type 1 for WEEE recycling in Beijing (see Annex 3). Thus, specific investment costs of 705,512 €/a for a facility with a processing capacity of 15,000 t/a are referred to as plant design scenario 1. Calculations on the installation costs for plant design scenario 2 are based on the same investment costs in due consideration of effects of economies of scale. Based on a coefficient of economies of scale of 0.6, this scenario pertains to a capacity of 30,000 t/a and associated assumed investment dependent costs of 1,069,356 €/a.

4.3 Computational results and discussion

In total, 19 locations of collection centers (nine are already existing / 10 are fictitiously installed), 248 candidate locations for primary processing facilities (four are already installed / 244 can be newly installed), and 9 locations of demand points for tradable and non-tradable material fractions as well as nearly 7,000 transport routes are considered across 16 scenarios. The two basis scenarios of the case study consist in A) complete in-house processing (flow scenario 1) and B) partial in-house processing (flow scenario 2) as well as in sub-scenarios related to input quantities (input scenario 1 and 2), transport costs (transport scenario 1 and 2), and processing capacities (plant design scenario 1 and 2). For the purpose of computation, the commercial optimization software Lingo 8.0 has been applied. The results of the computer-aided decision support system are presented in the following.

A) Complete in-house processing

For plant design scenario 1 results confirm that transport costs from collection centers to primary processing facilities (transport costs 1) and the costs incurring through shipment of commodities from primary processing facilities to market options (transport costs 2) contribute to a considerable extent to total costs (see Annex 4). Increases in total costs are allegeable through increasing transport rates on the one side and WEEE masses on the other side. Concerning the latter, additional investment costs for the installation of treatment facilities incur. It appears that transport costs double across the transport scenarios. Remarkably, transport costs 2 thereby exceed transport costs 1 in line with an increasing WEEE input. Across all sub-scenarios, the already installed capacities for WEEE treatment are part of the solution. Notably, the physical structure of the recycling system remains robust to modifications of transport rates across all sub-scenarios (see Figure 3).
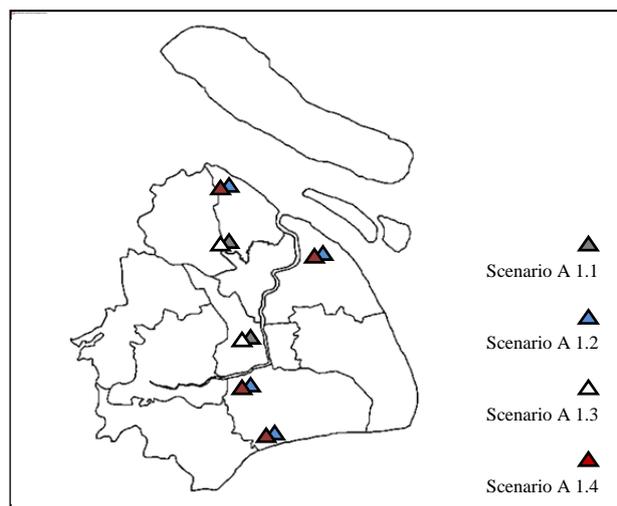

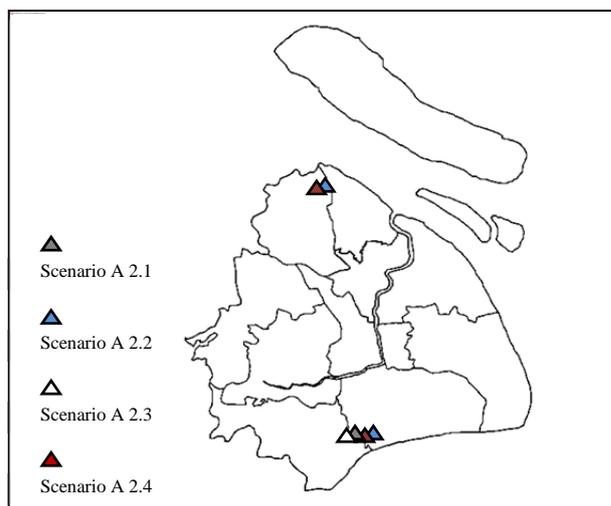**Figure 3.** Scenario A.1) Plant design: 15,000 t/a

Figure 4. Scenario B.2) Plant design: 30,000 t/a

Source: (authors' contribution)

Within input scenario 1, two additional recycling facilities are installed at corresponding locations for both transport rates. The same applies to input scenario 2, where four additional facilities are installed at the same geocoordinates. By contrast, it becomes evident that masses of WEEE input bear significant influence on the configuration of the recycling infrastructure. Not only that there are additional treatment capacities to be installed, the spatial distribution of input scenario 2 does not include any location solution of input scenario 1. Results of plant design scenario 2 lead to similar conclusions. Although a decline of total costs is globally induced through realization of economies of scale, the processing capacity of 30,000 t/a has minor influence on the cost structure. Again, all four existing recycling facilities are part of

the location solution. However, increasing capacities make the optimal locations move towards the southern division for input scenario 1. Increasing material flows thus induce the installation of additional capacities in northern territory. By contrary, the locations of input scenario 2 show certain robustness (see Figure 4).

B) Partial in-house processing

This basis scenario refers to the integration of downstream recovery options. Since it is modeled as output decrease at the primary processing stage, certain downstream flows to the market option stage remain unconsidered. Comparison of costs is thus not significant (see Annex 4). Similar to the basis scenarios A.1) and A.2), variation of transport rates does not result in structural changes. Solutions in fact remain robust to the effect that facilities are consistently allocated in both transport scenarios. Noteworthy, analogue to the basis scenarios A.1) and A.2), sensitivity of optimal locations is closely related to variations of input flows and plant design. The influence of downstream recovery on network configuration is thus twofold, primarily subjected to capacity constraints. Integration of downstream recovery results in settlings of facilities in the northeastern and southern part of Shanghai within input scenario 1. On the contrary, locations of input scenario 2 appear to remain robust when it comes to output volumes. Variations solely result in additional installations in northern and upper southern regions (see Figure 5).
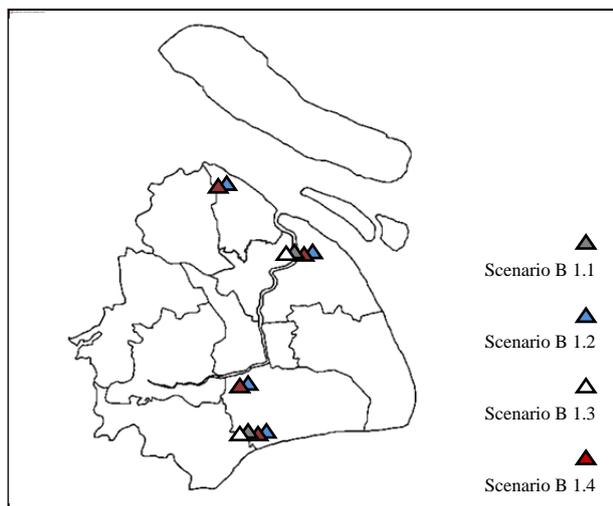

Figure 5. Scenario B.1) Plant design: 15,000 t/a   **Figure 6.** Scenario B.2) Plant design: 30,000 t/a
Source: (authors' contribution)
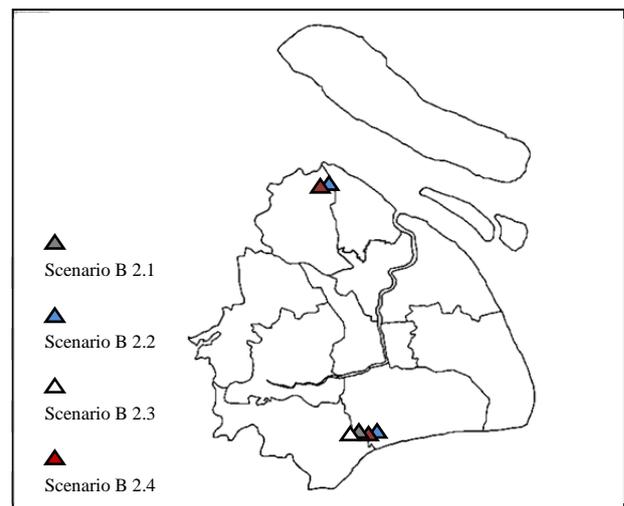
Plant design scenario B.2) and A.2) show identical results. Optimality of locations is therefore deemed to be virtually independent from process output for larger capacities. Results remain also robust towards

input variations within the respective basis scenario; notwithstanding the number of facilities to be located (see Figure 6).

In the case study, a total of 16 cases have been considered. Naturally, due to non-occurring installation costs, the four processing capacities that have already been installed are part of any location solution. Of the catalogue of 244 additional candidate locations that has been applied to the case scenarios, six locational catchment areas have been appointed optimality only (see Figure 3-6). In principle, it hence appears recommendable to take these and the surrounding areas into closer consideration for future installation purposes. However, the spatial arrangement of optimal locations is subject to reconfiguration as the case arises. Computational results on optimal locations indeed vary widely across the scenarios. Findings reveal that variations of input parameters frequently result in different numbers and a modified spatial allocation of facilities. As a result, total cost differentials of the considered case scenarios may vary significantly. It becomes evident that the masses of WEEE input have major influence on the robustness of a location solution. On the contrary, variation of transport costs bears no structural effect. Results further clearly show minor sensitivity towards the quantities of tradable and non-tradable process output available at the primary processing stage. The influence of downstream recovery primarily depends on the parameters WEEE input and plant design. Concerning the latter, increasing capacities of course reduce the number of facilities to be located; which affects the network structure in turn. However, through realization of effects of economies of scale total network costs can be reduced, since the sum of reduced installation costs constantly outvalues resultant changes in transport costs incurring across all scenarios. Consequently, evidence suggests that the two catchment areas located in far northern and in far southern regions of Greater Shanghai Area appear to be most reasonable for installation.

5. Conclusions

WEEE management has evolved to a major policy issue for eco-innovation in China. However, environmentally acceptable WEEE recovery and disposal within the rule of law indeed poses a major challenge to China's current waste management system – notably in terms of technical and organizational infrastructure. The present case study on reverse logistics network design provides insights into cost structures as well as into the sensitivity and influencing factors of location solutions. As such, it appears that the optimal network configuration may vary widely across the 16 case scenarios considered. While

any variation of transport costs shows no structural effect, the two parameters WEEE input and plant design are bearing major influence on system design, and thus, total network costs. In this vein, computational evidence clearly suggests to considering larger processing capacities to accommodate the increasing masses of future WEEE flows potentially arising in China.

However, environmentally sustainable WEEE recovery and disposal in China is not a matter of technological or organizational infrastructure development only, but will rather become ultimately apparent upon practical policy implementation and its enforcement 'on the ground'. Basically, formal ventures are situated in fierce competition with well-established systems in the informal economy. Especially the market for WEEE collection remains to be dominated by informal collections networks. Under the prevailing circumstances, accredited recycling enterprises would thus have to rely on informal resources for WEEE feed stream. Accordingly, development of a sustained collection system ensuring the certified recovery and disposal channel to be sufficiently supplied with WEEE evolves to a major determinant. Solely moderate progress has been accomplished on that account though. The regulatory framework recently enforced may help to find a remedy in future. However, it remains to be seen in which way and to what extent the informal economy will be responsive to such state interventionism. Actually, it is a debatable point whether informal recovery will disappear from the market at all in the foreseeable future. In fact, it is rather assumable that people would continue to hold up to existing business structures and patterns. Most importantly, informal WEEE recycling in China is primarily undertaken for a living. In case inappropriate income alternatives are available for those unable to participate in China's economic progress, it is hard to imagine that the market conditions will change significantly in favor of formal processors in the short to medium term. Beyond that it is even arguable whether abolition of informal employment should be pursued at any cost. In the light of considerable social impact potentially arising from a legally enforced 'rectification' of this sector, eco-innovation in industry is not a matter of economic and environmental issues only, but evolves to a question of social and ethical responsibility. The challenge that lies ahead is thus to bring the sectoral strengths in a mutually beneficial manner together. In doing so, concentration of informal and formal resources may pave the way for the benefit of an environmentally sound and economically viable as well as socially acceptable WEEE recycling industry in China.

Acknowledgments

Annex

Annex 1. WEEE feed stream of input scenario 1 partitioned by administrative divisions

District or county in Shanghai	Type of appliance [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

Source: (authors' contribution)

Annex 2. Scenario-based proration of commodity flows of material fractions

Type of appliance / scenario	Proportion of material fractions within 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

Source: (Liu et al. 2009; Matsuto et al. 2004; own calculations)
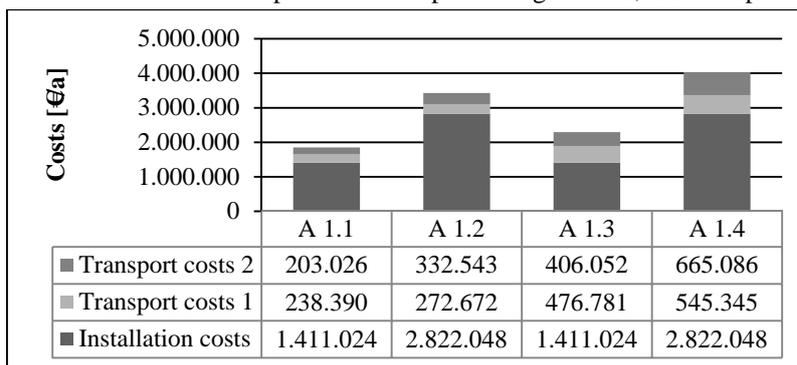
Annex 3. Specific investment of a reference plant with a treatment capacity of 15,000 t/a

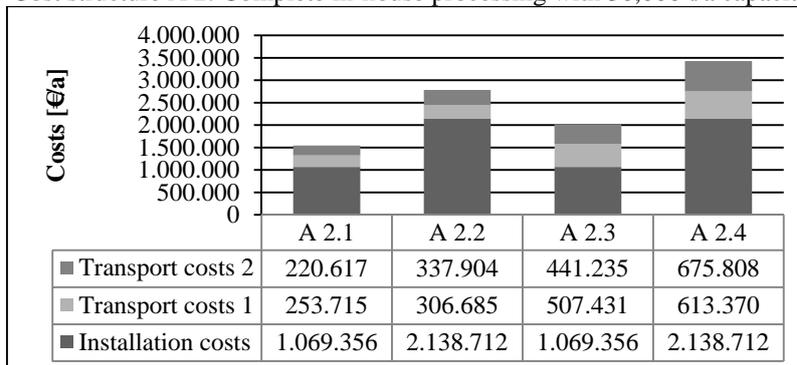| Cost item	Total investment [€]	Depreciation period [a]	Specific investment [€/a]
Land and premises	2,802,064	15	186,804
Transport and conveying equipment	186,207	5	37,241
Tools and tooling equipment	263,004	5	52,601
Process plant and peripheral devices	2,270,323	15	151,355
Testing and control systems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

Source: (CRAUC 2003; Queiruga 2006; own calculations)

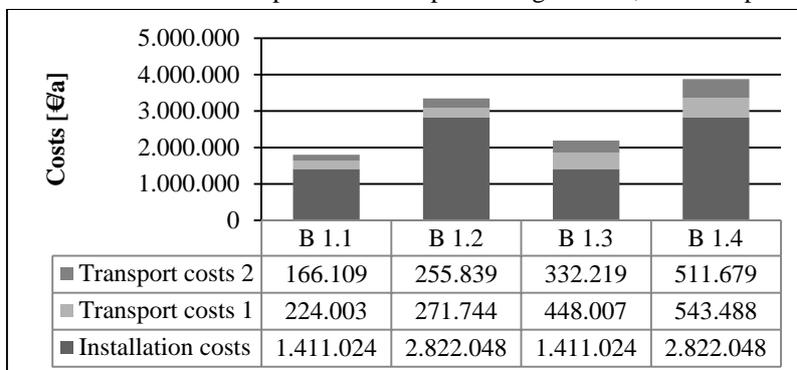**Annex 4.** Cost structures of basis scenarios A) and B)

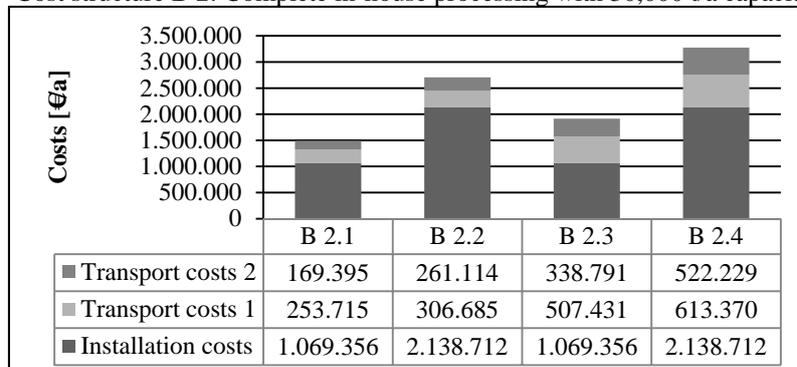Cost structure A 1: Complete in-house processing with 15,000 t/a capacity

	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

Cost structure A 2: Complete in-house processing with 30,000 t/a capacity

	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

Cost structure B 1: Complete in-house processing with 15,000 t/a capacity

	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

Cost structure B 2: Complete in-house processing with 30,000 t/a capacity

	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	253.715	306.685	507.431	613.370
■ Installation costs	1.069.356	2.138.712	1.069.356	2.138.712

Source: (authors' contribution)

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