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Economic and Environmental Benefits of Recovery Networks for WEEE in Europe

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Abstract

The EU directive on Waste Electrical and Electronic Equipment (WEEE) imposes the obligation to collect a large share of the end-of-life products on electronics manufacturers. Environmental aspects, however, are often considered only rudimentarily. Based on previous research and real-world data, a mixed-integer linear programming (MILP) model of a European reverse network for WEEE is developed, including collection, high-value recovery, or third-party collection and recycling. The results comprise optimal network decisions and corresponding opportunity costs for economic and 21 environmental categories (18 midpoints, 3 endpoints). The evaluation of the environmental impact is based on data from the ecoinvent database, characterized using the ReCiPe 2016 Life Cycle Impact Assessment (LCIA) method. The results unveil conflicts and congruencies between the objectives. Collection and high-value recovery are preferable in up to six countries for economically optimal networks and in up to 15 countries with optimal benefit for global warming and fossil resource depletion. Discrepancies in objective values are larger between economic and most of the environmental solutions than in between most of the environmental ones. The dimensions land use and freshwater eutrophication show the least conflicts with the economic rationale. Solutions for mineral resource depletion prefer third-party collection and recycling. Conflicts between solutions are resolved by the ε-constraint method. Sensitivity analyses show the robustness of key findings. This study emphasizes the importance of a broad assessment of environmental impacts as well as mutual economic and environmental opportunity costs in large-scale recovery networks for WEEE.

Keywords

Reverse network design, Life Cycle Impact Assessment, WEEE, Mixed-integer linear programming

1 Introduction

The implementation of reverse networks for Waste Electrical and Electronic Equipment (WEEE) is motivated by legislation, economic rationale, and environmental considerations. The EU directive on WEEE (Directive 2012/19/EU) obliges original equipment manufacturers (OEMs) to take back WEEE within the European Union with the goal of subsequent recycling or reuse. Presently, over nine million tons of electronic devices are put on the market in the EU every year, which equals more than 19 kg per capita. Only 39% of this was collected in 2015 (Eurostat, 2018a). In order to abide by the EU directive, however, the quota for recycling and/or re-use will need to increase to over 65%. Following the waste hierarchy of the European Waste Framework Directive (Directive 2008/98/EC), reuse and preparing for re-use take priority over recycling. Besides the legislative pressure, the nature of electrical and electronic equipment (EEE) offers a plethora of economic and environmental reasons to increase recovery operations. Economic reasons include the trade-in value of reusable products as well as the recycling potentials mainly due to a high fraction of precious metals. Apart from that, EEE is a major contributor to the environmental footprint (Quariguasi Frota Neto et al., 2010). The shortening of life cycles further intensifies these effects. With regard to legislative, economic, and environmental factors, recovery efforts gain importance.

Here, reverse logistics close the loop, resulting in a closed-loop supply chain (CLSC) (Guide and Van Wassenhove, 2009), which is often assumed to be environmentally advantageous in itself (Quariguasi Frota Neto et al., 2010). Research on sustainable supply chain management (SSCM), i.e. the incorporation of environmental and social aspects (Seuring and Müller, 2008), is ongoing, and Brandenburg et al. (2014) state the need for developing new models that incorporate a wider range of sustainable aspects. Ansari and Kant (2017) emphasize the qualitative character of the research field and call for further quantitative modeling approaches to account for the multi-disciplinarity of SSCM. Stindt (2017) presents a framework for decision-making in SSCM and in this context highlights the need for practicability in businesses. In particular, research on a more comprehensive set of sustainability issues in network design should be intensified (Singh and Trivedi, 2016).

While the economic dimension is frequently addressed by research (Rubio et al., 2008; Stindt and Sahamie, 2014), literature on reverse network design explicitly evaluating the environmental impact is not the norm. Only in recent years, the importance of integrating environmental assessment into CLSC optimization has been acknowledged. However, instead of a broad coverage of environmental impacts, single indicators are used in many cases, and carbon emissions are often the primary or sole indicator of the supply chain's environmental performance, followed by waste reduction and energy efficiency (Stindt, 2017).

Consideration of single environmental indicators only, however, does not do justice to the complexity of the problem of environmental impacts caused by reverse network activities. Beyond that, European environmental policy (Directive 2008/98/EC) calls for the consideration of a broader set of ecological objectives. For instance, unnecessary resource depletion should be minimized and the negative effects on ecosystems and human health need to be mitigated. Oliveira Neto et al. (2017) quantify economic and environmental performances of recycling and reuse for six existing manufacturers and recyclers, using material intensity factors as the main environmental indicator. For problems ranging from a 'cradle-to-grave' evaluation of single products (Yung et al., 2012) to the entire value chain including strategic location problems (Eskandarpour et al., 2015), Life Cycle Assessment (LCA) is one of the scientifically most accepted approaches for environmental evaluation (European Commission, 2010). Eskandarpour et al. (2015) find that a majority of studies in the field of sustainable supply chain network design uses the Life Cycle Impact Assessment (LCIA) method Eco-Indicator 99, followed by IMPACT 2002+, CML92 and ReCiPe 2008, to quantify the environmental impact.

Pertaining to these delimitations, a literature search identifies the most relevant articles. To be relevant for this study in a narrower sense, an article needs to meet the following criteria: 1) The article is published as a research article in a peer-reviewed scientific journal. 2) The article covers a quantitative strategic planning problem in a reverse supply chain context. 3) The article's decision-making (e.g. solved in an optimization model) problem covers the environmental dimension using Life Cycle Assessment. These criteria are taken into account by the following search string, which was applied to the databases *ScienceDirect*, *Web of Science*, and *EBSCOhost*: *("reverse supply chain" OR "closed-loop supply" OR clsc OR "reverse logistic*" OR "reverse network" OR "recovery network") AND (lca OR lcia OR "life cycle assessment" OR "life cycle impact assessment").*

After the examination of the search results with respect to the abovementioned criteria, as well as the exclusion of duplicates, 22 unique articles were identified, which are displayed in Appendix A. In current research, the dated, if not obsolete, LCIA methods Eco-Indicator 99 and ReCiPe 2008 remain the most common ones. Except for the optimization studies by Jin et al. (2019) and Duque (2010), and the simulation study by Gamberini et al. (2010), the sole result of most studies applying LCIA in this research field is a single score that represents the environmental impact of potential decisions. From a modeler's perspective, this yields the advantage of simplicity, as the damage categories *human health*, *ecosystem quality*, and *resource scarcity* are normalized, weighted and aggregated. Unfortunately, this aggregation leads to a loss of information about the actual inflicted environmental damage, let alone the different mechanisms on the midpoint level. Furthermore, in the specific context of environmental reverse network design, multi-criteria network models are developed for WEEE only seldom.

This overview testifies existing and increasing interest in the topic of balancing between economic and environmental aspects in a recovery network. Nevertheless, certain research gaps exist: First, current approaches for the design of reverse networks often lack a multi-dimensional environmental assessment explicitly considering the diverse goals of environmental policy, which are represented by LCIA midpoints and endpoints. Second, WEEE recovery is underrepresented in sustainable reverse network design despite its vast legal, economic and environmental implications, which corresponds to the findings of Islam and Huda (2018). Against this background and taking an OEM perspective, this study sets out to answer the following research questions:

- What is the benefit of optimal configurations of a WEEE recovery network from an OEM perspective compared to third-party recycling, considering economic and different environmental (LCIA endpoint and midpoint) aspects?

  RQ1. What are optimal configurations of a European WEEE recovery network?

  RQ2. What are economic and environmental benefits of network configurations in comparison to third-party recycling?

RQ3. How does the quantity of collectible WEEE affect the results?

In contrast to existing studies and in line with the goals of European environmental policy, this study considers a broad set of environmental objectives. The reverse network optimization is carried out for 21 environmental objective functions in addition to the economic one. This approach increases the tangibility of the results and thus helps to raise awareness for the manifold environmental consequences of decisions. In addition to the environmental dimensions, economic effects are quantified based on industry data. In this way, a decision support model is developed, representing the situation of a manufacturer obliged to collect WEEE.

Addressing these research questions, the following study is conducted: Section 2 outlines the methodological approach. Section 3 defines the problem, formulates a generic optimization model and describes necessary data acquisition. Section 4 presents the results and tests the robustness of the model concerning key parameters in a sensitivity analysis. Sections 5 and 6 sum up the results, insights, and learnings, and map out a path for future research on this topic.

2 Method

To address the stated research questions, a generic reverse network model for WEEE is developed which addresses WEEE collection and is developed as a Greenfield problem. To account for the research gap regarding the LCIA, the model is generic, and parameterizable with economic and environmental data for 22 different objectives, as displayed in Figure 1. Assumptions regarding the specific case of WEEE recovery in the EU (cf. section 3.7) are preliminarily based on Nuss et al. (2016). Economic and environmental assessments of recovery networks need to be carried out in the view of the fact that recycling, the low-ranking but mandatory recovery option in the EU waste hierarchy, is often carried out by third-party companies in lieu of OEMs. For a more microeconomics-oriented analysis of the effects of take-back legislation, the reader is referred to Esenduran et al. (2016) and Atasu et al. (2009).

Pivotal economic and other data, e.g. revenues, fixed and operating costs, as well as capacities, are retrieved in 2018 in a workshop with an industry expert from a large Bavarian refurbishment company, or based on literature. For the environmental data, environmental impacts associated with recovery are modeled in SimaPro 8.5 accessing the ecoinvent 3.4 Life Cycle Inventory database, and the new 2016 edition of the ReCiPe Life Cycle Impact Assessment method is applied. The impacts are specific for the case of recovery of private branch exchange (PBX) devices as a proxy for high-value WEEE. This is due to four reasons: First, there is a significant secondary market for PBXs, which proves the general viability of PBX refurbishment. Second, the industry expert was able to provide real-world data. Third, environmental modeling of a generic electronic device would be much vaguer than modeling a specific and existing device. Fourth, PBXs contain a high share of printed wiring board (PWB), which is one of the main contributors of environmental impacts of WEEE in general. For example, PWB makes up approximately between 75% and 79% of the respective endpoint damage values (aggregated according to the ReCiPe 2016 endpoint LCIA method, cf. section 3.6) of desktop computer production as modeled in ecoinvent 3.4 (Lehmann, n.d. a). These values are similar for other IT devices like computer keyboards (appx. 62%-86%, Lehmann, n.d. b) or other electronic devices like chargers for electric passenger cars (appx. 47%-49%, Del Duce, n.d.). In a further step, the optimization is carried out with regard to each of 22 objective criteria, i.e. one economic dimension and 21 environmental ones. Finally, a sensitivity analysis is conducted and interdependencies between the objective dimensions are discussed.

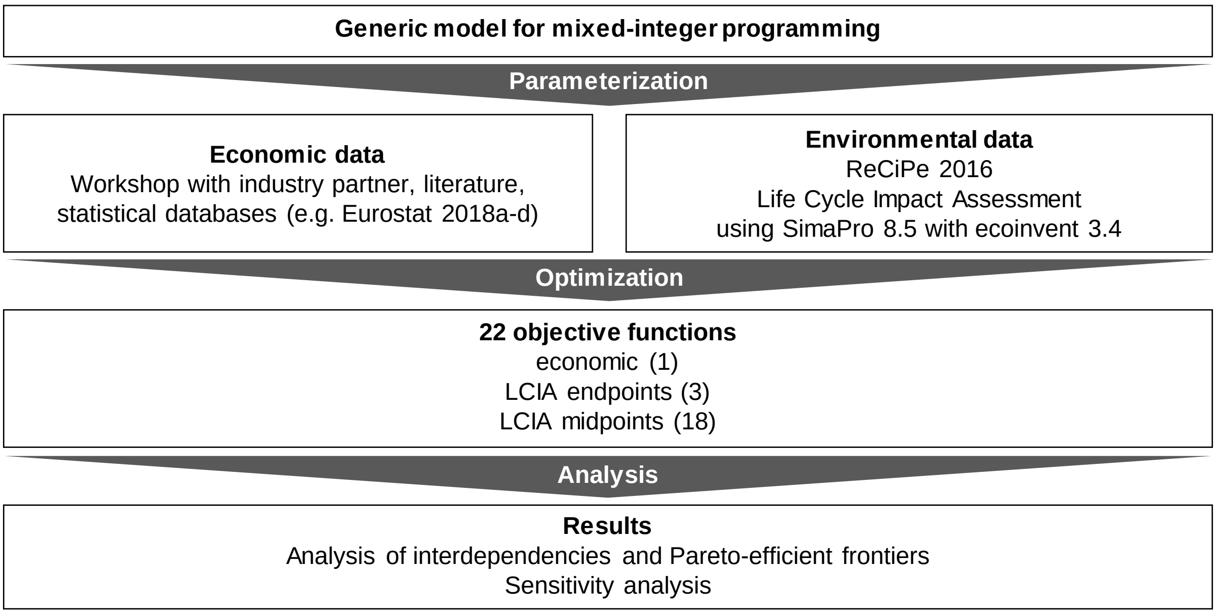

Figure 1. Multi-criteria methodological approach

3 Modeling approach

The reverse network model is static with parameters normalized towards one year. WEEE can be collected by the OEM or by third-party logistics on the regional level, and regions are the basis for location-based decision-making. Well-preserved devices are eligible for either recycling or high-value recovery. The latter comprises the preparation for reuse by means of retrieval, remanufacturing, or refurbishment. As industry observation shows, third-party collection mainly leads to recycling only, while in the presented case the OEM may also consider high-value recovery.

Figure 2 visualizes the generic problem description. The network consists of a set of collection and recovery centers (two-level network structure), as well as WEEE flows within this network. In countries where OEM collection is carried out, a set of decisions has to be made on the locations (regions), configuration levels, and capacities of collection centers (CCs) (first network level). The configuration level determines whether a CC is only suited to sort out the disposal fraction (parts of non-WEEE, packaging), or if it has the means to thoroughly inspect collected WEEE and store it in a value-preserving manner, in order to identify devices that are eligible for high-value recovery. Therefore, WEEE collected in CCs with configuration 1 can only be sold to third-party recyclers, while CCs with configuration 2 can ship WEEE to a recovery center (RC). Locations and capacities of RCs make up the final set of decisions (second network level). Here, well-preserved devices are prepared for reuse. Decisions are to be made so as to maximize profitability or environmental benefits concerning one of the 21 impact and damage categories.

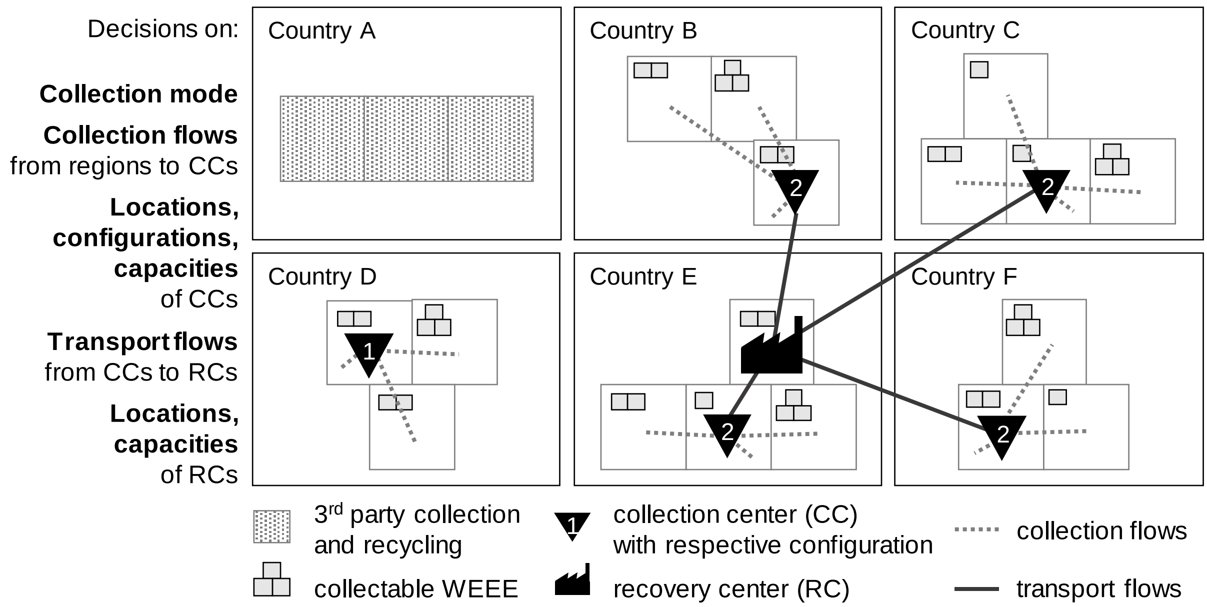

Figure 2. Problem structure and decisions

For the application to the case of the EU, the model covers 28 countries, which are further subdivided into 95 regions, based on the NUTS-1 classifications (*Nomenclature des unités territoriales statistiques*, Nomenclature of Territorial Units for Statistics). To abide by the EU directive on WEEE (Directive 2012/19/EU), the OEM can choose to contract third-party service providers to carry out the mandatory collection and recovery in a region, or it can decide to collect the arising WEEE at a CC. Taking into account the EU regulation on waste shipment (Regulation (EC) No 1013/2006), WEEE cannot be collected transnationally (Nuss et al., 2016), hence transnational shipping from WEEE is only allowed from a country with an established CC, thus third-party companies mostly cover regions without a CC within the same country.

3.1 Sets of indices

$C = \{1 \dots N_c\}$ countries, $|C| = 28$

$R = \{1 \dots N_r\}$ regions, $|R| = 95$

$A = \{1 \dots N_a\}$ configurations of CCs, $|A| = 2$

$K = \{1 \dots, N_k\}$ capacity levels, $|K| = 30$

3.2 General data

The general data contains information on the allocation of regions to countries, on transportation distances, on collectible WEEE amounts in each region, as well as on the fractions of WEEE with different quality. The distribution of amounts of arising WEEE between different countries is based on the annual amount of collected IT devices in Europe (Eurostat, 2018a), extrapolated to NUTS-1 regions using the GDP (Eurostat, 2018b) as explanatory variable. The distance matrix represents distances between NUTS-1 regions (Eurostat, 2018c), complemented by a diagonal that is calculated as the bisectrix of the surface area of respective regions. Values for general data are given in the supplementary material (M2).

$alloc_{rc}$	1 if region r ($r \in R$) is part of country c ($c \in C$) 0 otherwise
d_{rs}	distance (in kilometers of road) between regions r and s ($r, s \in R$)
$weee_r$	annual amount of arising WEEE (in kg) in region r ($r \in R$)
$frac^{disp}$	fraction (in %) of collected WEEE that is not suited for recovery and needs to be disposed of
$frac_a^{hv}$	fraction (in %) of collected WEEE that can be classified eligible for high-value recovery in CCs with configuration a ($a \in A$)
$cap_{ak}^{CC}, cap_k^{RC}$	annual capacities (in kilograms) of CCs with configuration a ($a \in A$) and RCs for each capacity level k ($k \in K$)

3.3 Decision variables

In accordance with the characteristics of the reverse network design problem described above, the model is set up to determine the following decision variables:

$\mathrm{T_{rs}} \in \{0,1\}$	collection of WEEE in region r ($r \in R$) and transport to region s ($s \in R$)
$\mathrm{S_r} \in \{0,1\}$	collection and recycling of WEEE in region r ($r \in R$) carried out by third-party contractors
$\mathrm{CC_{rak}} \in \{0,1\}$	construction of a CC in region r ($r \in R$) with configuration a ($a \in A$) and capacity level k ($k \in K$)
$\mathrm{RC_{rk}} \in \{0,1\}$	construction of an RC in region r ($r \in R$) with capacity level k ($k \in K$)
$\mathrm{X_{ra}} \in \mathbb{Q}_0^+$	amount of WEEE (in kg) which is handled in a CC in region r ($r \in R$) with configuration a ($a \in A$)
$\mathrm{Z_{rs}} \in \mathbb{Q}_0^+$	amount of WEEE (in kg) which is transported from a CC in region r ($r \in R$) to an RC in region s ($s \in R$)

3.4 Generic objective function

The mixed-integer optimization model is formulated as a maximization problem. Therefore, the objective function maximizes the profit or the environmental benefit realizable by product recovery. The generic structure of the objective function is described in Table 1. The mathematical formulation of the parameterized objective function is given in Appendices B and C. Economic benefits are generated as revenues from selling recycled materials and recovered devices. The environmental gains of product recovery are the result of a comparison between the environmental impact of the reverse network, and the environmental impact of the primary production of the recovered amount of devices and raw materials. Hence, the difference between satisfying a demand either by secondary raw materials and products or by primary ones is analogous to revenues and costs in the economic case. For instance, the reuse of a recovered PBX substitutes a new PBX, thus saving the environmental impacts of the primary production. Although this is an assumption, this kind of formulation enables the assessment of the ecological reasonability of recovery, and thus broadens the system boundaries. The environmental impacts of primary products contain those impacts of the primary raw material, and additionally impacts of processes required for assembly and transport. Both economic and environmental parameterization refer to one kilogram of WEEE for variable costs and impacts, while fixed costs and impacts are calculated as annual values based on an amortization period of 25 years, resulting in annual objective values.

Table 1 Generic structure of the objective function

Generic function	Economic interpretation	Environmental parameters
+ Benefits from the network	Annual revenues generated by sales of recyclable materials and reprocessed products	Annual environmental impact from primary production (raw materials, products) saved by the reverse network
- fixed costs from CCs and RCs *- variable costs at CCs and RCs* *- collection costs from regions to CCs* *- collection/recycling costs (3rd party)* *- transport costs from CCs to RCs* *- disposal costs in CCs*	Annual costs resulting from the network	Annual environmental impacts resulting from the network

3.5 Economic parameters

The majority of revenue and cost-related data is calculated within workshops with an industry expert in 2018. As the proposed model is static, fixed costs comprise annual depreciation and annual fixed operating costs. The background of the case is based on the case presented in studies by Stindt et al. (2014) and Nuss et al. (2016), both of which are based on an industry project with a major IT manufacturer. Other data, e.g. a country-specific investment cost factor (Eurostat 2018d), complement the set of economic parameters. Values for the presented parameters are given in the supplementary material (M2).

rev^{CC}	revenues for one kilogram of recyclable WEEE
rev^{RC}	revenues for one kilogram of recovered WEEE
fc_{ak}^{CC}	annual fixed costs for the construction of a CC with configuration a ($a \in A$) and capacity level k ($k \in K$)
fc_{k}^{RC}	annual fixed costs for the construction of an RC with capacity level k ($k \in K$)
vc_{a}^{CC}	variable costs for handling one kilogram of collected WEEE in a CC with configuration a ($a \in A$)
vc^{RC}	variable costs for recovering one kilogram of WEEE in an RC
vc^{3pl}	variable costs for third-party collection and recycling of one kilogram of WEEE
vc^{disp}	variable costs for the disposal of one kilogram of WEEE
vcc	variable costs for collecting one kilogram of WEEE and transporting it over a distance of one kilometer to a CC

vtc variable costs for transporting one kilogram of WEEE over a distance of one kilometer from a CC to an RC

icf_r investment cost factor for region r $(r \in R)$

3.6 Environmental parameters

The Life Cycle Impact Assessment (LCIA) method is applied to determine the environmental parameters. LCIA is part of the Life Cycle Assessment (LCA) methodology, which enables the evaluation of the environmental impacts of a product, a process, or a service in a comprehensive and quantitative manner throughout its entire life cycle, quantifying all relevant emissions and resources (European Commission, 2010). An LCA consists of four phases in a generic approach defined by the ISO 14040 and 14044 standards (ISO 14040; ISO 14044). It comprises the definition of goal and scope of the assessment (phase 1), the identification of inputs and outputs (Life Cycle Inventory (LCI), phase 2), the subsequent LCIA, which determines the specific impact of every input or output (phase 3), and an interpretation of results (phase 4). As shown in supplementary figure S1, environmental impacts can either be assessed on the level of their respective environmental mechanism (midpoints) or on the level of aggregated damages (endpoints). The number and kind of impact categories, as well as the aggregation rules, depend on the selected LCIA method.

This study uses the ReCiPe 2016 method (Huijbregts et al., 2017). ReCiPe was introduced by Goedkoop et al. (2009) and combines the strengths of the CML and Eco-Indicator 99 methods. By doing so, the generic objective function is parameterized in terms of one of 21 environmental aspects (18 midpoints, three endpoints), and thus determines optimal solutions for each of the 21 dimensions separately. The endpoint categories in particular can be seen as representations of the objectives of European environmental policy. The endpoints are not further normalized and weighted towards a dimensionless single score. This also circumvents the issue of double counting those midpoints that have more than one midpoint to endpoint path (*global warming* and *water consumption).* Supplementary figure S1 displays the relation between midpoint and endpoint categories in ReCiPe 2016.

LCI and LCIA are carried out using the SimaPro 8.5 software, accessing the ecoinvent 3.4 LCI database (Wernet et al., 2016). The midpoint parameters are given in their respective unit (e.g. kg CO_2 eq for *global warming*), representing the environmental mechanisms, while the endpoint parameters reflect the environmental damage. The damage on *human health* is measured in disability-adjusted life years (DALY), i.e. “the years that are lost or that a person is disabled due to a disease or accident”. Likewise, the damage on *ecosystem quality* represents “the local species loss integrated over time” and is measured in species years (Sp.yr). Finally, damage on *resource scarcity* refers to extra costs in Dollar equivalents (USD2013) for future resource extraction (Huijbregts et al., 2017). In this way, a vast array of environmental effects is considered, thus exceeding the common focus on emissions or another single criterion. Similar to the introduction of investment cost factors to the economic dimension, some environmental parameters are affected by regional specifics, such as the country’s energy mix. This results in an additional regional index for some of the environmental parameters. The LCI, as modeled in SimaPro 8.5 by allocating ecoinvent 3.4 processes, is given in the supplementary material (M1). The specific parameterization of the model takes place for each of the 21 environmental dimensions, with LCIA values given in the supplementary material (M2).

$eipr_r^{CC}$	impact of primary production of one kilogram raw material saved for region r $(r \in R)$
$eipr^{RC}$	impact of primary production of one kilogram EEE saved
fei_{ak}^{CC}	annual impact of constructing a CC with configuration a $(a \in A)$ and capacity level k $(k \in K)$
fei_k^{RC}	annual impact of constructing an RC with capacity level k $(k \in K)$
vei_{ra}^{CC}	impact of handling one kilogram of collected WEEE in a CC in region r $(r \in R)$ with configuration a $(a \in A)$
vei_r^{RC}	impact of recovering one kilogram of WEEE in an RC in region r $(r \in R)$
vei_r^{3pl}	impact of third-party collection and recycling of one kilogram of WEEE in region r $(r \in R)$
vei_r^{disp}	impact of disposing of one kilogram of WEEE in region r $(r \in R)$
$vei^{transport}$	impact of transporting one kilogram of WEEE over a distance of one kilometer

3.7 Constraints

The strategic choices for the design of the reverse network are delimited by legal, technological, and organizational constraints whose mathematical formulation is presented in Table 2. By European law, the OEM is responsible for the end-of-life management of its WEEE. In consequence, the OEM has to collect the arising in each region by himself or by contracted third-party companies (1). Collected WEEE of one region is sent to one receiving region (2). The latter requires a CC (3). The OEM always collects in regions with a CC (4). Since WEEE cannot be collected transnationally, a CC has to be built in every country in which the OEM desires to carry out the collection (5). Collected WEEE is pooled in CCs (6) and the CC's capacity level needs to be sufficient for the collected amount (7). The disposal fraction is sorted out (8) and only the high-value fraction is eligible for transportation to RCs (9). The RC's capacity level needs to be sufficient for the transported amount (10). Only one CC and only one RC are allowed per region (11, 12), but a region may possess both a CC and an RC.

Table 2 Constraints of the mathematical model

#	Mathematical constraint	
(1)	$S_r + \sum_{s \in R} T_{rs} = 1$	$\forall\, r \in R$
(2)	$\sum_{s \in R} T_{rs} \leq 1$	$\forall\, r \in R$
(3)	$T_{rs} \leq \sum_{a \in A} \sum_{k \in K} CC_{sak}$	$\forall\, r, s \in R$
(4)	$T_{rr} = \sum_{a \in A} \sum_{k \in K} CC_{rak}$	$\forall\, r \in R$
(5)	$T_{rs} \leq \sum_{c \in C} alloc_{rc} alloc_{sc}$	$\forall\, r, s \in R$
(6)	$\sum_{a \in A} X_{sa} = (1 - S_s) weee_s + \sum_{r \in R} T_{rs} weee_r - \sum_{t \in R} T_{st} weee_s$	$\forall\, s \in R$
(7)	$X_{ra} \leq \sum_{k \in K} CC_{rak}\, cap_{ak}^{CC}$	$\forall\, r \in R, \forall\, a \in A$
(8)	$Y_r + \sum_{s \in R} Z_{rs} = \sum_{a \in A} X_{ra}\, (1 - frac^{disp})$	$\forall\, r \in R$
(9)	$\sum_{s \in R} Z_{rs} \leq \sum_{a \in A} X_{ra}\, \left(1 - frac^{disp}\right) frac_a^{hv}$	$\forall\, r \in R$

(10)	$\sum_{r \in R} Z_{rs} \leq \sum_{k \in K} RC_{sk}\, cap_k^{RC}$	$\forall\, s \in R$
(11)	$\sum_{a \in A} \sum_{k \in K} CC_{rak} \leq 1$	$\forall\, r \in R$
(12)	$\sum_{k \in K} RC_{rk} \leq 1$	$\forall\, r \in R$

4 Computational results

The MILP model is implemented in IBM ILOG CPLEX Optimization Studio 12.7.0.0. The optimization is carried out on an Intel(R) Xeon(R) E5-2690 (64 Bit) 8x2.90 GHz and 64 GB of RAM. The average runtime is 4,190 seconds for all objective functions except for optimization of *ionizing radiation*, where the average runtime is 12,460 seconds. The model consists of 655,014 coefficients and 27,064 variables restricted by 19,179 constraints.

20 scenarios with differing amounts of arising WEEE are outlined, ranging from 0.075‰ (scenario 1) to 1.5 ‰ (scenario 20) in steps of 0.075‰ of the annually collected amount of IT devices in Europe (Eurostat, 2018a). This is done for four reasons: 1) The amount of annually collectible devices is one of the decisive criteria for the viability of the network. 2) The scenarios represent companies with different obligatory take-back volumes, which in practice depend on the company's size. Therefore, the scenarios could also be interpreted as differently sized OEMs. 3) As shown in section 4.1.2, the range of scenarios covers the break-even points (identified in pre-testing) for the creation of a reverse network versus third-party collection and recycling in most of the 22 objective dimensions. 4) The resolution of the set of scenarios is sufficient to allow for the identification of small changes and trends, while the number of 20 is still practicable for optimization and presentation. Consequently, the basic model is solved 440 times in total (20 scenarios times 22 objective functions).

4.1 Single-criteria optimization

This section presents the insights of the analysis focusing on the objective-dependent viability of the reverse network, commonalities between the different solutions, and the relation between the objectives. First, the network's structures for each criterion are analyzed. Second, the resulting objective values are interpreted. For this, each of the objective values needs to be compared to the base case of third-party collection and recycling only, the legal minimum requirement.

4.1.1 Recovery network structure

Figure 3 summarizes the results for each scenario in terms of the extent of the network, i.e. the number of CCs built. A detailed overview of the number and locations of facilities for each objective and scenario is given in the supplementary material (M3). For all solutions, it is economically and environmentally desirable to build at maximum one CC per country, therefore the number of countries that are part of the OEM recovery network equals the total number of CCs. The extent of the optimal network (and thus the amount collected in total) varies greatly for different midpoint objective functions. The number of CCs in scenario 20 ranges between 0 (no network) for *mineral resource scarcity* and 28 (all countries included) for *ionizing radiation*, showing the importance of a differentiated view on environmental impacts. Since the endpoint objective functions represent an aggregation of their respective midpoints, the differences between endpoint solutions are far less divergent. This can be illustrated with the endpoint *resource scarcity* and its midpoints *mineral resource scarcity* and *fossil resource scarcity*. The optimal network in terms of *fossil resource scarcity* consists of 15 CCs in scenario 20. For *mineral resource scarcity*, where the benefit of high-value recovery compared to third-party recycling is much smaller, no CCs are constructed. Since both midpoints contribute to their mutual endpoint *resource scarcity* within the same magnitude, the optimal network of the latter comprises eleven CCs. Besides the vast varieties between different environmental objectives, a significant difference between the economic and many environmental dimensions becomes evident. Depending on the scenario, only between two and five midpoints out of 21 environmental optimizations lead to smaller networks compared to the economically optimal network, while the majority favors considerably larger networks. In scenario 20, the six CCs in the economically optimal network collect 73.47% of the total collectable amount. In comparison, the eleven CCs from *resource scarcity* optimization collect 88.47%, and the 28 CCs for *ionizing radiation* cover the entire amount (100%).

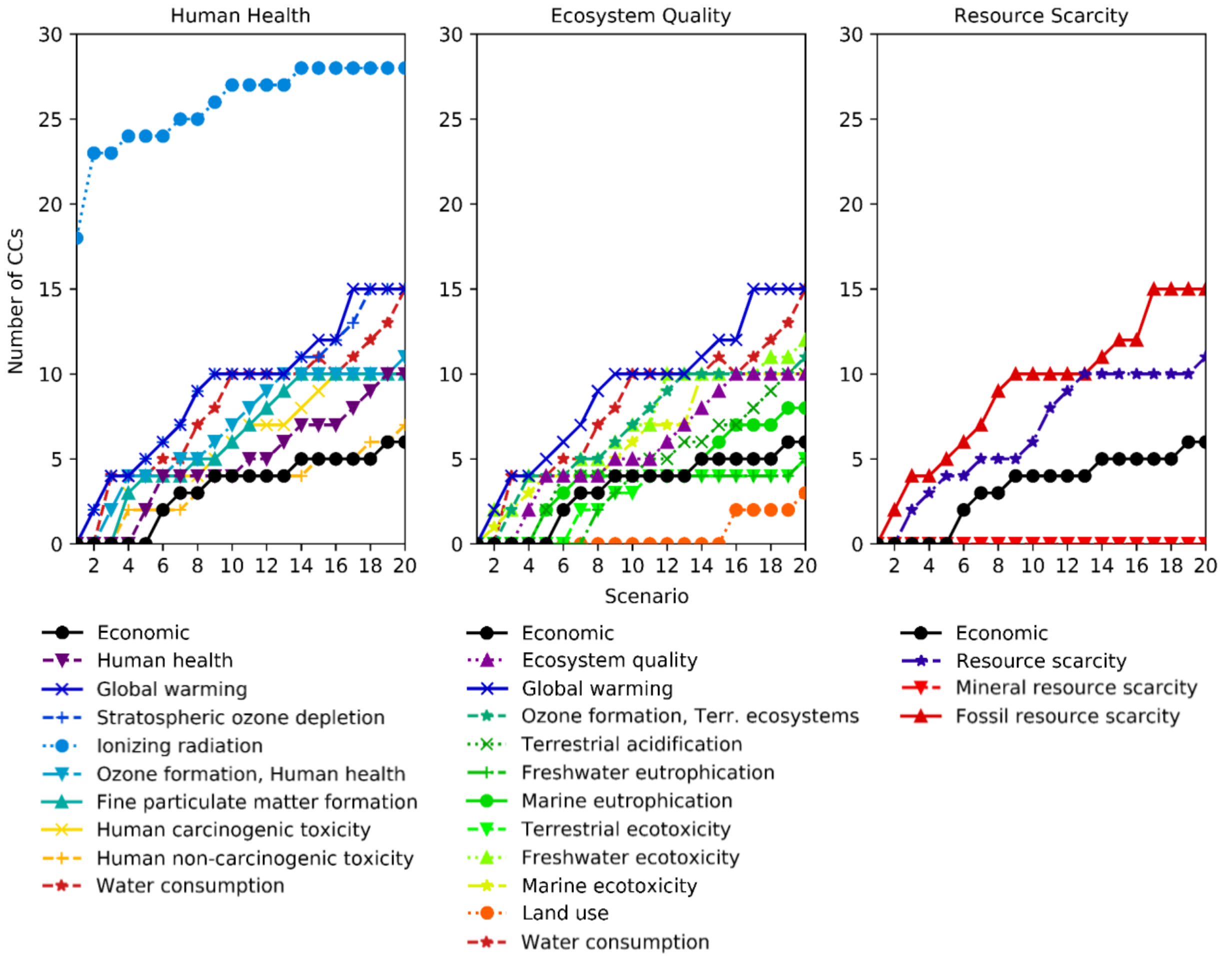

Figure 3. Number of CCs for the optimal solution of each objective dimension in each scenario

Focusing on the economic dimension over 20 scenarios, it shows that economies of scale are necessary to operate the network profitably. Small-sized companies should prefer to entirely contract third-party companies for reverse operations (scenarios 1 to 5), while active product recovery represents a viable business option for larger companies (scenarios 6 to 20). This insight is contradictory to current industry practice. Even large OEMs often do not build up own reverse capabilities in terms of an integrated European network, but rather fulfill their collection obligation by contracting third-party companies. Nuss et al. (2016) argue that this behavior could be due to legal uncertainties concerning the transnational shipment of waste products. In consequence, companies miss profit potentials, and all products are channeled to recycling. Pertaining to the environmental results, this is unfortunate as OEM-sided collection and high-value recovery would be desirable in many cases.

Despite the vast differences in the extent of the respective networks, a number of similarities between economic and environmental solutions can be detected. Economic, endpoint and the majority of midpoint solutions favor CCs with configuration 2 and thus OEM-sided high-value recovery in RCs, too. Only the solutions for freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity build CCs with configuration 1, from where WEEE is sold to recyclers. More importantly, the reverse network is centralized with one RC at maximum for every objective, except for solutions for *ionizing radiation*. The single RC in the environmental solutions is always located in Central Europe, such as Brussels (BE1), Flanders (BE2), Wallonia (BE3), Nord-Pas-de-Calais (FR3), or Southern Netherlands (NL4). These RC locations seem to represent the "center of gravity" of the collected amounts in the respective networks, and thus transportation distances and amounts appear to be the primary decision criterion. This observation, however, should not be misinterpreted in that transportation impacts are the main environmental driver. In fact, supplementary figure S2 shows that long transportation distances in a centralized network are preferable over the construction of additional facilities with shorter distances. Accordingly, the minimization of the number of facilities takes priority for economic and most environmental solutions, and the minimization of transportation distances acts as a secondary goal. This fact emphasizes the importance to consider multiple environmental effects when assessing supply networks. A sole focus on transport emissions or energy demand, which is frequently used as a proxy for environmental performance (see section 1), is not sufficient, thus making a broader set of indicators with inter alia resource consumption or land occupation compulsory. In contrast to the environmental networks but in line with the observations regarding transportation, economic optimization leads to one RC located in Romania's Macroregion Four (RO4), which can be attributed to the investment cost factor. Figure 4 depicts resulting networks for the objectives economic, *resource scarcity* and *global warming* in scenarios 6 and 18.

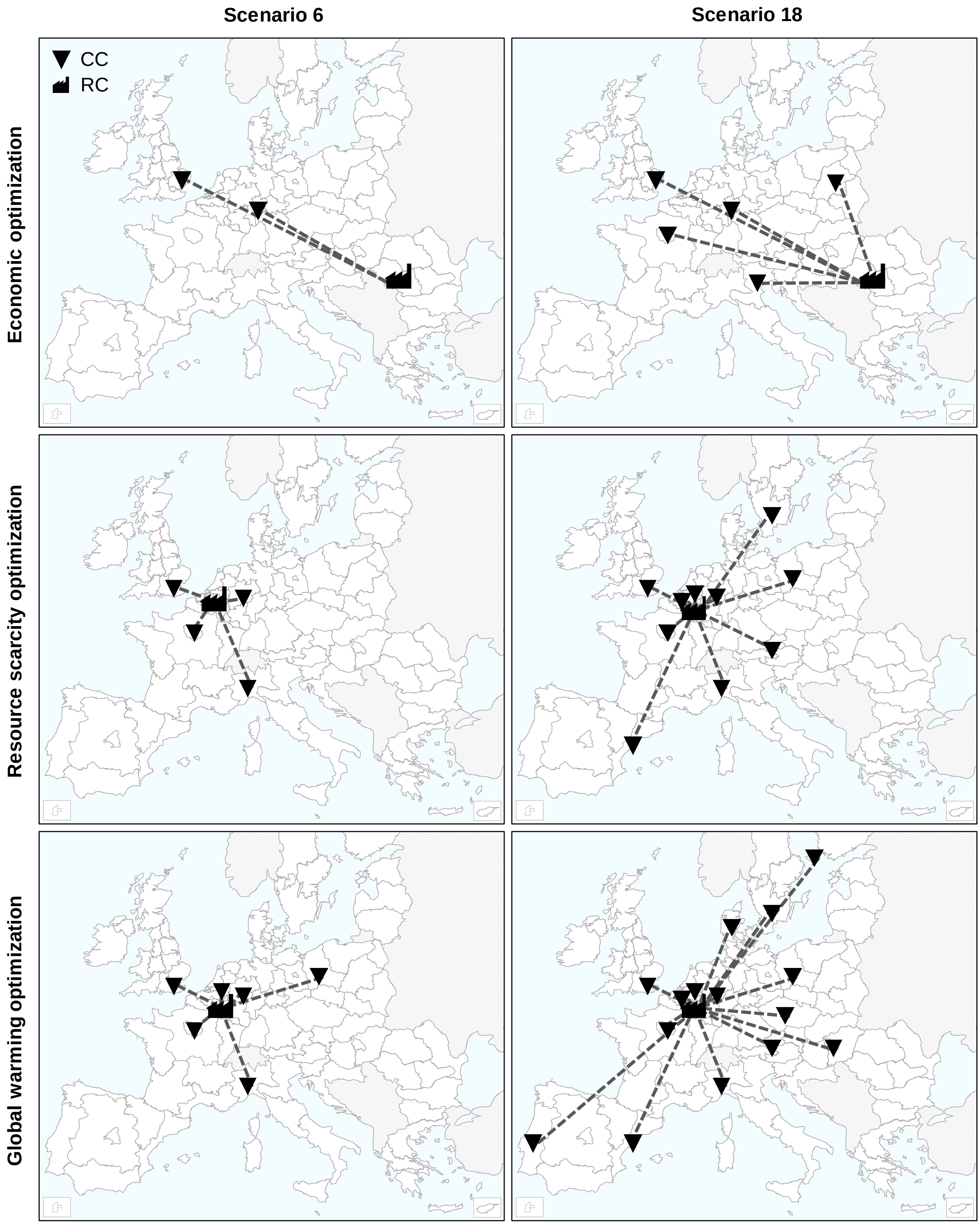

Figure 4. Optimal network design for economic, resource scarcity, and global warming optimization in scenarios 6 and 18

4.1.2 Objective values

It deserves mentioning that the objective values' contribution of each midpoint to its respective endpoint is also very diverse. The environmental impacts of *stratospheric ozone depletion*, *ionizing radiation*, *ozone formation human health*, and *water consumption* never equal more than 0.501% of the endpoint value for *human health*. *Marine eutrophication*, *terrestrial ecotoxicity*, *marine ecotoxicity*, and *water consumption* never contribute more than 8.310% to the endpoint value for *ecosystem quality*. *Human carcinogenic toxicity* and the ecosystems midpoints *freshwater ecotoxicity* and *land use* on average make up between 2.700% and 6.718% of their respective endpoints. In order to reduce the complexity and to increase the readability of the following Figure 5, the following paragraphs focus on the major contributors. They comprise *global warming*, *fine particulate matter formation*, and *human non-carcinogenic toxicity* for the endpoint *human health*; *global warming*, *terrestrial acidification*, and *freshwater eutrophication* for the endpoint *ecosystem quality*; as well as both *mineral resource scarcity* and *fossil resource scarcity* for the endpoint *resource scarcity*.

The objective values need to be compared to the alternative of third-party recycling. For example, the economically optimal network in scenario 6 leads to an economic result of -0.127 million €. Since collection and recycling is compulsory under the terms of the WEEE directive, the alternative to the network is recycling by third-party contractors, costs for which amount to 0.160 million €. Therefore, the net result of this optimized network is +0.033 million €. Likewise, high-value recovery in an optimal network for *human health* results in a benefit of 9.14 DALY, but since third-party recycling also yields environmental benefits of 8.79 DALY, the net benefit of the network amounts to +0.35 DALY. This helps to explain the differences between economic and environmental objectives. Values given in this section thus refer to the respective net results.

Designing an optimal network following one goal comes with opportunity costs in the other dimensions. These trade-offs are shown in Figure 5, depicting the economic opportunity costs of optimization towards different objectives. For example, solutions optimizing *freshwater eutrophication* deteriorate the economic result only slightly, i.e. by 0.033 million € in scenario 6, and by 0.304 million € in scenario 18. Optimal networks in terms of *human health*, *ecosystem quality* as well as for *ozone formation terrestrial ecosystems* are economically worse with -0.276 million € in scenario 6, and between -0.479 and -0.597 million € in scenario 18. *Resource scarcity* and *fine particulate matter formation* fare comparably in scenario 6 and 18, but much worse in scenario 12 (-0.694 and -0.572 million € respectively). For *mineral resource scarcity*, where collection and recycling are carried out by third-party companies entirely in every scenario, the deviation is minimal in scenario 6 (-0.033 million €) and severe in scenario 18 (-2.018 million €). The largest deviations are observable for *human non-carcinogenic toxicity* since the solutions dictate mostly CCs with configuration 1, which leads to economic costs but lacks the greater part of revenues from high-value recovery. When not accounting for solutions without OEM-based networks or without high-value recovery, and concerning only numerically relevant midpoints, *global warming,* and *fossil resource scarcity* lead to the worst solutions in economic terms, which is well observable in Figure 5. Here, the deviation is -0.526 million € for scenario 6 and -1.274 million € in scenario 18 for both objectives, because of identical optimal network structures. The supplementary figure S3 depicts the effects of optimization towards each objective function on every other dimension, with numerical results given for each dimension and each objective function in each scenario in the supplementary material (M4).

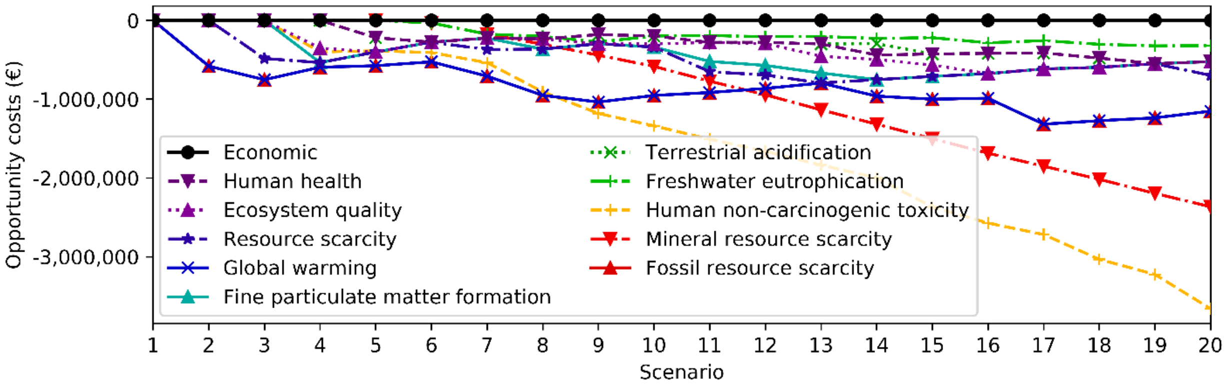

Figure 5. Economic effects of relevant optimization objectives

4.2 Multi-criteria optimization

One option to address the opportunity costs between economic optimization and many of the environmental optimizations is the ε-constraint method to identify the Pareto-optimal frontier between two dimensions. To account for different degrees of aggregation and for different levels of economic deviation, the Pareto-optimal frontier for economic vs. *global warming* optimization is identified (Figure 6). The supplementary figures include Pareto-curves for these two objective dimensions (supplementary figure S4) as well as for economic vs. *resource scarcity* (supplementary figure S5), *resource scarcity* vs. *global warming* (supplementary figure S6), and economic vs. *mineral resource scarcity* (supplementary figure S7) in every scenario. Depending on the environmental agenda of the OEM, compromises between economic and environmental dimensions can be achieved. For example, a detriment of 53,713 € (from 2.017 million € to 1.964 million € gained) could already help to increase the environmental benefit by 176,846 kg CO_2 eq (from 1.454 million kg CO_2 eq to 1.631 million kg CO_2 eq saved). For solutions closer to the environmental optimum, economic results are disproportionately worse and therefore decreasingly likely to be considered by companies in practice. Vice versa, an environmental benefit reduced by 26.404 kg CO_2 eq (from 1.870 million kg CO_2 eq to 1.844 million kg CO_2 eq saved) increases profitability by 677,043 € (from 0.744 million € to 1.421 million € gained). As part of the shift in goal attainment from the economic to the *global warming* result, the location of the RC changes from the economically optimal location in Romania (RO4) stepwise towards the environmentally optimal location in Belgium (BE1). Similar observations can be made for other Pareto curves of economic vs. environmental optimization (see supplementary figures S4-7 and supplementary material (M5)).

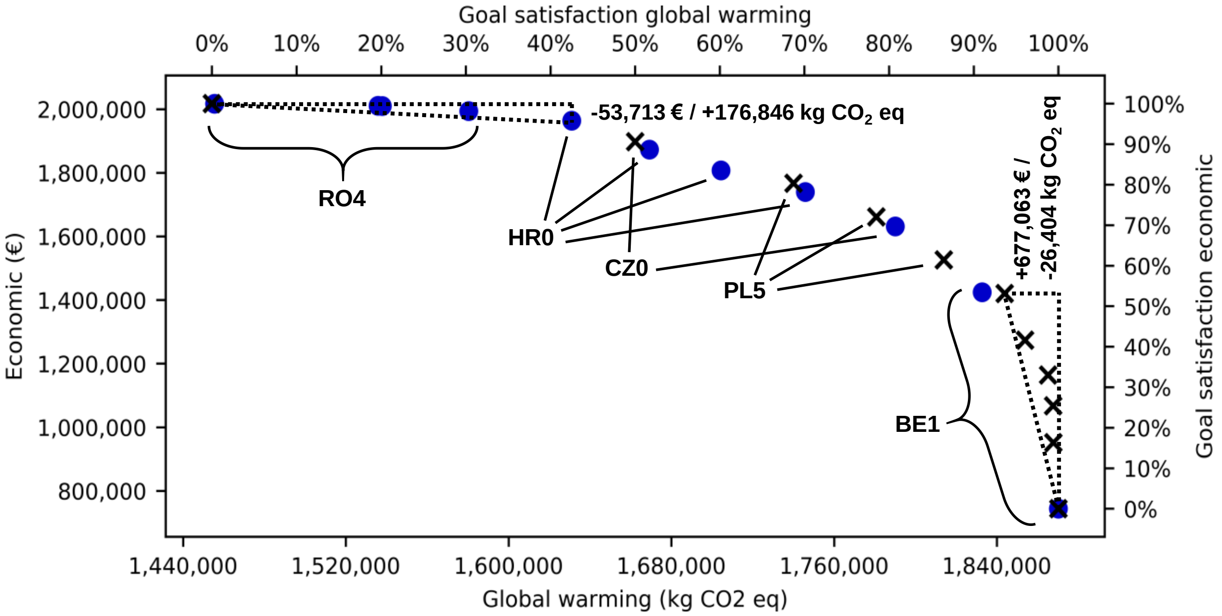

Figure 6. Pareto-optimal frontier for economic (crosses) and Global warming (circles) optimization with RC locations of respective solutions in scenario 18

4.3 Sensitivity analysis

In order to prove the robustness of the results, section 4.3 conducts a sensitivity analysis on key economic and environmental parameters for economic and three environmental (*resource scarcity*, *global warming*, *mineral resource scarcity*) objective functions. The sensitivity analysis tests the effects of changes by ±10% in revenues, variable costs in RCs, fixed costs of CCs and RCs, costs/benefits of third-party recycling, collection, and transportation costs, as well as their analogous environmental counterparts for three of the 20 scenarios (6, 12, and 18). In addition to parameter changes, the effects of a relaxation of the constraint that prohibits transnational collection, as suggested by Nuss et al. (2016), are analyzed.

4.3.1 Parameter alterations

The impact of increasing/decreasing key economic and environmental parameters is tested in three scenarios for four objective functions; economic, *resource scarcity*, *global warming*, and *mineral resource scarcity*. The objectives are selected in order to represent the economic dimension, as well as environmental dimensions with slightly larger, significantly larger, and smaller/non-existent networks. The results are compared with regard to the respective objective value, the number of CCs and RCs, and the collection quota, both before and after altering the parameters. An overview of the results is given in the supplementary material (M6).

As the analysis shows, changes in revenues and the environmental impacts of primary production of PBX devices lead to the most significant changes in the respective objective values compared to changes in other parameters. For example, revenues decreased by 10% lessen the overall economic result in scenario 18 (2.018 million €) by 0.354 million €. Changes in impacts from primary production are also the only cases where an RC becomes viable for *mineral resource scarcity.* Nevertheless, with some exceptions, the network design essentially remains the same. In most cases, the collection quota changes only marginally, and so does the number of CCs, and, except for the solution near the economic break-even points (scenario 6), the number of RCs. Most importantly, the differences in the number of CCs between different objective functions remain roughly the same.

Changes in fixed costs and impacts of CCs have a smaller effect on the respective objectives values compared to revenues, even though changes in the number of CCs and the collection quota are noticeable in this case as well. This can be explained by the marginal utility of CCs in the network. Excluding CCs from the network leads to lower revenues, but also to reduced fixed costs. When the marginal utility of the CCs is near or below 0, the exclusion of a CC does not alter the objective value by a lot but may have a more significant impact on the collection quota.

Altering the costs and impacts (or benefits) of third-party collection and recycling has different effects on the economic and the environmental dimension. Except for one case, changing the economic parameter has no effect on the network design. Decreasing the costs lessens the economic results while increasing the costs improves the result. What may sound counterintuitive at first glance makes sense within the scope of this study. When the costs of third-party collection and recycling decrease, a third-party recycling-only strategy becomes more viable compared to an OEM-based reverse network. Conversely, since third-party operations yield small environmental benefits on their own, decreasing the environmental parameter increases the viability of the network in comparison to a third-party recycling-only strategy. Here, more advanced methods for the evaluation and selection of third-party reverse logistics providers, as reviewed on by Govindan et al. (2018), could help practitioners to state these relations for different regions, countries, and service providers more precisely.

Lastly, fixed and variable costs and impacts of RCs have little effect on the respective objective values and do not alter the network design whatsoever. The same is true for collection and transportation costs and impacts, which is in accordance with the observations of section 4.1.

4.3.2 Transnational collection

In addition to parameter alterations, the possibility of a severe change in the underlying modeling assumptions is evaluated. To allow for transnational collection, the equation that restricts transnational collection (constraint (5), cf. section 3.7) is deactivated. Instead of collection by CCs, the OEM pays an additional lump sum to a local third-party logistics provider for collecting a device and sending it to the RC. Analogously, for the environmental cases, this corresponds to the calculatory contribution of the device to a logistics provider’s collection center. This assumption resembles a Brownfield problem, while the originally stated model was developed as a Greenfield problem.

The results of unrestricted international collection are listed in the supplementary material (M7). Unlike parameter changes, this severe change in modeling comes with major alterations in the network design and its subsequent objective values. While an RC is still economically infeasible in scenario 1, it becomes feasible for the entire recoverable amount in scenario 2 and upwards (instead of scenario 6). For *resource scarcity* and *global warming*, feasibility starts with scenario 1 (instead of scenarios 3 or 2 respectively), and scenario 10 even for *mineral resource scarcity*, which previously relied on third-party-based recycling entirely. All objective values benefit greatly from the reduced need for CCs. However, the principal locations of RCs remain the same, i.e. central Europe for the environmental dimensions and Romania (RO4) for economic optimization.

5 Discussion

The utilization of 21 midpoints and endpoints proves to have several advantages. Unlike often applied single score approaches, results come with an actual dimension, which eases conscious decision-making. Moreover, solutions for optimal configurations of recovery networks differ vastly between different objective functions, with up to 28 collection centers for *ionizing radiation* and no OEM-based network for *mineral resource scarcity*. The economic as well as some midpoint objective functions, e.g. *land use* or *freshwater eutrophication*, lead to smaller networks and OEMs rely more on third-party recycling contractors. This, however, is only valid as long as selected contractors in practice operate within the legal frame. Violations, such as the illegal shipment of wastes, are not considered in the generic network design decisions of this study and could invalidate the results in terms of third-party recycling. The majority of midpoint solutions and the endpoint solutions favor larger networks and thus larger collection amounts in comparison.

For OEMs able to collect larger amounts of high-value WEEE fractions, high-value recovery options (retrieval, remanufacturing, and refurbishment) could generate substantial revenues and lead to positive environmental objective values. Generally, both the financial as well as the environmental results are likely to improve significantly if the company uses existing facilities or teams up with peers driving down investments and environmental impacts associated with construction activities. In contrast to a number of recent approaches, transportation is a minor factor for both the economic and the environmental dimensions. This refutes the common notion that minimizing transport emissions inevitably equals minimizing the overall environmental impact of a logistics network, "despite [the] appealing win-win nature" (Quariguasi Frota Neto et al., 2010, p. 4478). The results of section 4.2 and Figure 6 in particular highlight that a deeper understanding of the multiplicity and complexity of environmental impacts is needed for OEM decision-making. This also includes a profound knowledge of the nature and the extent of conflicts and congruencies between economic and environmental objectives on the one hand, and in between environmental dimensions on the other hand.

The generic reverse network model can also be applied outside of the European Union or to other products. For an application outside of the EU, some of the economic and environmental parameters would need to be adapted. This entails, for example, the country-specific energy mixes, or the distance matrix, for which the data is retrieved from regional databases such as Eurostat in this case. Additionally, it is important to consider regulations that are in place on transnational shipment of WEEE, as well as priorities of environmental policy in specific regions. In regions where there is no take-back obligation, the reference frame for benefit and opportunity costs of high-value recovery may be landfilling instead of recycling, and thus lead to different results. Although the derived insights are particularly valid for PBX recovery, the model could be adapted for other electronic products by only adjusting parameters. Regarding trends as well as differences between objective functions, key results apply for electronic products with a similar composition, particularly regarding PWB (as argued in section 2). A generalization of these insights for other product groups (e.g. paper, vehicles, medical equipment) is not possible per se.

6 Conclusion

This study examines the optimal design of a WEEE reverse network from the perspective of an OEM and focuses on the influence of the size of the OEM and the impact of different economic and environmental objective functions. The analysis is based on a generic MILP model, parameterized with economic and 21-fold environmental data for the case study of a European recovery network. The economic dimension concerns revenues and industry cost data. Environmental parameters reflect the environmental impacts and benefits of private branch exchanges on an LCIA midpoint and endpoint basis. Model assumptions and constraints reflect the obligation of OEMs to collect WEEE within the European Union. The reverse network model is solved with regard to 22 objective dimensions (one economic, 18 midpoints, three endpoints), as well as 20 scenarios representing companies of different sizes.

The computational results show that economic profitability and environmental feasibility of the network mainly depend on the size of the OEM, i.e. the amount of collectible WEEE in each region. For smaller OEMs, the revenues of retrieval, remanufacturing or reuse do not compensate the fixed and variable costs necessary for operating company-owned CCs and RCs. With higher sales figures even in smaller EU countries, the break-even scenario is realized in more countries, leading to an increased number of CCs, higher profits and environmental benefits in most environmental categories. Concerning the number of RCs, the computational results show that the construction of only one RC, located in the center of Europe (most environmental solutions) or in an Eastern European country with low investment costs (economic solutions), seems preferable even for larger OEMs.

On principle, the conducted analysis provides valuable insights for different stakeholder groups. Corporate executives may utilize the proposed decision-support tool to evaluate the viability of product recovery strategies subsequent to case-specific adaptations of the underlying assumptions and parameters. The results show that current industry practice, which relies heavily on third-party contractors, could be improved significantly without contradicting economic goals of corporations. Business leaders miss profit potentials as well as the opportunity to improve the corporate environmental impact by hesitating to embark on product recovery, as corporations can realize significant improvements of their environmental balance with only minor opportunity costs. Politicians may use this as an indication for altering environmental governance. This research offers some ideas for regulatory measures. Quotas for high-value recovery should supplement recycling quotas that exist in current legislation. Moreover, subsidies may motivate OEMs to invest in a product recovery system. Lastly, Nuss et al. (2016) show that a relaxation of the EU regulation on waste shipment (Regulation (EC) No 1013/2006) eases the realization of economies of scale improving the business case of product recovery, which is in line with the findings in section 4.3.

For academia, the proposed approach opens new perspectives. First and foremost, the distinct midpoint and endpoint consideration of environmental impacts using ReCiPe increases transparency and enables the identification of more detailed cause-and-effect relationships. In future research, extensions of the model considering multiple products and remarketing as well as the integration of uncertainty would help to further improve the applicability of the presented case. Challenging the insights against various backgrounds with a similar methodology in the future is highly recommended. Furthermore, a comprehensive integration of social aspects into the presented problem is the next logical step in order to cover each pillar of sustainability.

Appendix

Appendix A. Summary of the relevant research articles

Author(s)	Year	Journal (abbr.)	Primary decision-making method	LCIA method	CO_2	Single sc.	Endpoint	Midpoint	Industry sector	Product	Country
Chaabane et al.	2012	Int. J. Prod. Econ.	MILP	EI 99	x				materials	aluminum	global
Dehghanian and Mansour	2009	Resour. Conserv. Recycl.	MOP	EI 99		x			automotive	tires	Iran
Duque et al.	2010	Ind. Eng. Chem. Res.	optimization	EI 99		x	x	x	materials	aluminum	Portugal
Fathollahi-Fard and Hajiaghaei-Keshteli	2018	Appl. Soft Comput.	metaheuristics	ReCiPe 2008		x					
Feitó-Cespón et al.	2017	J. Clean. Prod.	MINLP	EI 99		x			materials	plastic	Cuba
Gamberini et al.	2010	Resour. Conserv. Recycl.	simulation	EI 99			**x**	**x**	**WEEE**		Italy
Govindan et al.	2016	Ecol. Indic.	FMP	EI 99		x			medical	syringes	Iran
Günther et al.	2015	J. Clean. Prod.	MILP	not specified	x				automotive	electric vehicles	global
Jin et al.	2019	J. Clean. Prod.	MILP	TRACI				**x**	rare earths	NdFeB magnets	USA
Krikke	2011	Resour. Conserv. Recycl.	MILP	not specified	x				**WEEE**	copiers	global
Miao et al.	2017	Omega	optimization	not specified		x					
Mota et al.	2015	J. Clean. Prod.	MILP	ReCiPe 2008		x			batteries		Portugal
Mota et al.	2018	Omega	MILP	ReCiPe 2008		x			**WEEE**		
Pishvaee and Razmi	2012	Appl. Math. Model.	FMP	EI 99		x			medical	syringes	Iran
Pishvaee et al.	2014	Transp. Res. Part E	BDA	ReCiPe 2008		x			medical	syringes	Iran
Quariguasi Frota Neto et al.	2008	Int. J. Prod. Econ.	MOP	other		x			materials	pulp and paper	EU (11)
Quariguasi Frota Neto et al.	2009	Eur. J. Oper. Res.	MOP	CED		x			**WEEE**		Germany
Sahebjamnia et al.	2018	J. Clean. Prod.	metaheuristics	ReCiPe 2008		x			automotive	tires	
Shokouhyar and Aalirezai	2017	Int. J. Environ. Sustain. Dev.	metaheuristics	not specified		x			**WEEE**		Iran
Subulan et al.	2015	Appl. Math. Model.	MILP	EI 99		x			automotive	tires	Turkey
Taskhiri et al.	2016	J. Clean. Prod.	MILP	not specified	x				materials	wood residues	Germany
Tautenhain et al.	in press	Comput. Ind. Eng.	metaheuristics	ReCiPe 2008		x					
this study		*J. Clean. Prod.*	*MILP*	*ReCiPe **2016***			***x***	***x***	***WEEE***	*PBX*	*EU (28)*

Appendix B. Objective function for economic parameterization

$\max Profit$

$= \sum_{r \in R} Y_r \, rev^{CC}$	revenues in CCs
$+ \sum_{r \in R} \sum_{s \in R} Z_{rs} \, rev^{RC}$	revenues in RCs
$- \sum_{r \in R} \sum_{a \in A} \sum_{k \in K} CC_{rak} \, fc_{ak}^{CC} \, icf_r$	fixed costs from CCs
$- \sum_{r \in R} \sum_{k \in K} RC_{rk} \, fc_k^{RC} degr_k \, icf_r$	fixed costs from RCs
$- \sum_{r \in R} \sum_{a \in A} X_{ra} vc_a^{CC} lc_r$	variable costs in CCs
$- \sum_{r \in R} \sum_{s \in R} Z_{rs} \, vc^{RC} lc_r$	variable costs in RCs
$- \sum_{r \in R} \sum_{s \in R} T_{rs} weee_r d_{rs} \, vcc$	collection costs
$- \sum_{r \in R} S_r \, weee_r vc^{3pl}$	third-party collection/recycling costs
$- \sum_{r \in R} \sum_{s \in R} Z_{rs} d_{rs} \, vtc$	transportation costs
$- \sum_{r \in R} \sum_{a \in A} X_{ra} frac^{disp} \, vc^{disp}$	disposal costs

Appendix C. Objective function for environmental parameterization

$\max Environmental\ benefit$

$= \sum_{r \in R} Y_r \, eipr_r^{CC}$	saved impact from primary raw material
$+ \sum_{r \in R} \sum_{s \in R} Z_{rs} \, eipr^{RC}$	saved impact from new devices
$- \sum_{r \in R} \sum_{a \in A} \sum_{k \in K} CC_{rak} \, fei_{ak}^{CC}$	fixed impact from CCs
$- \sum_{r \in R} \sum_{k \in K} RC_{rk} \, fei_k^{RC}$	fixed impact from RCs
$- \sum_{r \in R} \sum_{a \in A} X_{ra} vei_{ra}^{CC}$	variable impact in CCs
$- \sum_{r \in R} \sum_{s \in R} Z_{rs} vei_r^{RC}$	variable impact in RCs
$- \sum_{r \in R} \sum_{s \in R} T_{rs} weee_r d_{rs} \, vei^{transport}$	impact from collection
$- \sum_{r \in R} S_r \, weee_r vei_r^{3pl}$	(saved) impact from third-party collection/recycling
$- \sum_{r \in R} \sum_{s \in R} Z_{rs} d_{rs} \, vei^{transport}$	impact from transportation
$- \sum_{r \in R} \sum_{a \in A} X_{ra} frac^{disp} \, vei_r^{disp}$	impact from disposal

Appendix D. List of abbreviations

Abbreviation	**Meaning**
BDA	Benders decomposition algorithm
EEE	Electrical and Electronic Equipment
EI 95 / 99	Eco-Indicator 95 / Eco-Indicator 99 *(LCIA method)*
EU / EU (28)	European Union / 28 member states of the European Union
FMP	Fuzzy mathematical programming
CC	Collection center
CED	Cumulative Energy Demand *(LCIA method)*
CLSC	Closed-loop supply chain
CML 92 / 2002	*(LCIA method)*
DALY	Disability-adjusted life years
IMPACT 2002+	*(LCIA method)*
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MILP, MINLP	Mixed-integer (linear, non-linear) programming
MOP	Multi-objective programming
NUTS	Nomenclature des unités territoriales statistiques
OEM	Original equipment manufacturer
PBX	Private branch exchange
PWB	Printed wiring board
RC	Recovery center
ReCiPe 2008 / 2016	*(LCIA method)*
Sp.yr	Species years
SSCM	Sustainable supply chain management
TRACI	Tool for the Reduction and Assessment of Chemical
WEEE	Waste Electrical and Electronic Equipment

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