When and for whom would e-waste be a treasure trove? Insights from a network equilibrium model of e-waste flows

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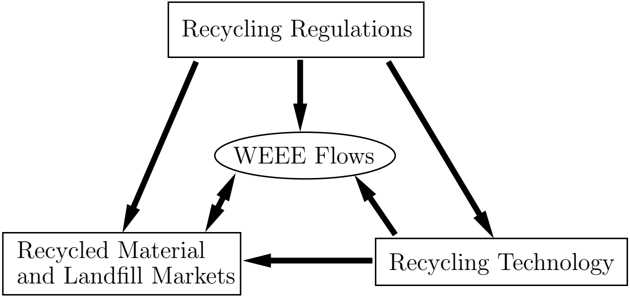
- Important that adequate amounts of WEEE flow into domestic recycling systems.
  - Adequate amounts encourage investment in advanced new recycling technologies.
  - Adequate amounts ensure that valuable resources included in WEEE are recovered.
  - WEEE flowing out of a country often causes environmental contamination and increases risks of environmental damages.

Factors that Influence E-Waste flows



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  - Legislative factors: Penalties for illegal dumping and import/export duties
  - Market factors: WEEE supply and demand
  - Technical factors: Sorting and recycling capabilities and the percentage of hazardous and precious materials included in and extracted from products
- The effects of the interaction among these factors are still largely unknown which makes it difficult to make policy recommendations.

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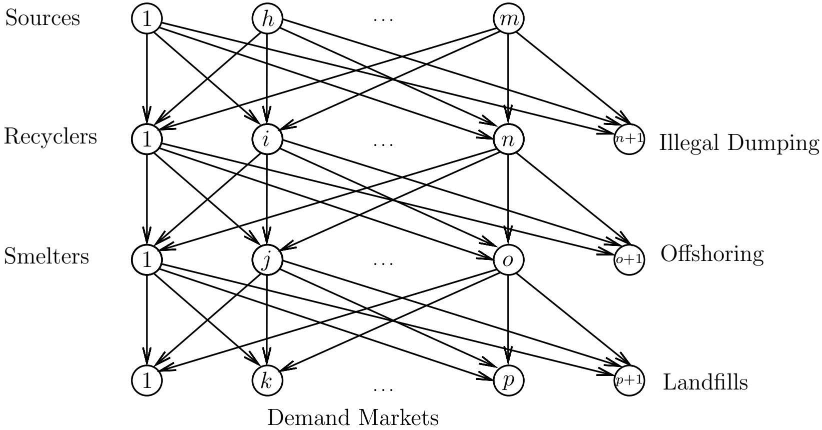
- How do legislative, market, and technical factors impact the profits of the stakeholders involved in the recycling process?
- How can policy-makers use this knowledge to design efficient and sustainable reverse logistics systems?

Multi-tiered E-Cycling Network Model



Sources' Behaviour

- Sources cannot give more e-waste to recyclers than they possess
- Incentive prices they get from recyclers reflect their transaction cost, disutility of holding e-waste and aversion to product returns

Sources' Behaviour

$$\bar{S}_h \begin{cases} = \sum_{i=1}^{n+1} q^*_{hi}, & \text{if} \quad \lambda^*_h > 0 \\ \geq \sum_{i=1}^{n+1} q^*_{hi}, & \text{if} \quad \lambda^*_h = 0; \end{cases} \tag{1}$$

$$a_h(Q^*_h) + c_{hi}(q^*_{hi}) - \varepsilon_h(\bar{S}_h, Q^*_h) + \lambda^*_h \begin{cases} = \rho^*_{1hi}, & \text{if} \quad q^*_{hi} > 0 \text{ for all } i = 1...n \\ \geq \rho^*_{1hi}, & \text{if} \quad q^*_{hi} = 0 \text{ for all } i = 1...n; \end{cases} \tag{2}$$

$$\begin{aligned} a_h(Q^*_h) + c_{h(n+1)}(q^*_{h(n+1)}) - \varepsilon_h(\bar{S}_h, Q^*_h) \\ + \lambda^*_h \begin{cases} = -\pi_{1h}\bar{\rho}_{1h}(q^*_{h(n+1)}), & \text{if} \quad q^*_{hi} > 0 \text{ for } i = n+1 \\ \geq -\pi_{1h}\bar{\rho}_{1h}(q^*_{h(n+1)}), & \text{if} \quad q^*_{hi} = 0 \text{ for } i = n+1. \end{cases} \end{aligned} \tag{3}$$

Recyclers' Behaviour

- Recyclers maximize their profit
- They need to transfer components that they extract to to the next tier (i.e., smelters and offshoring)
- They cannot give more components that they extract to the next tier than they get from the sources

Recyclers' Behaviour

$$\max_{Q^i,\, Q_i} \quad \sum_{j=1}^{o} \sum_{v=1}^{l+1} (\rho^*_{2ijv} \cdot q_{ijv}) + \sum_{v=1}^{l+1} \bar{\rho}_{2(o+1)} \cdot q_{i(o+1)v} - \sum_{h=1}^{m} (\rho^*_{1hi} \cdot q_{hi}) - f_i(Q_i) \tag{4}$$

subject to:

$$\sum_{j=1}^{o+1} q_{ijv} \geq \delta_i \sum_{h=1}^{m} (\alpha_{hv} \cdot q_{hi}), \quad \forall v \in \{1, \ldots, l\}, \tag{5}$$

$$\sum_{j=1}^{o+1} q_{ijv} \leq \delta_i \sum_{h=1}^{m} (\alpha_{hv} \cdot q_{hi}), \quad \forall v \in \{1, \ldots, l\}, \tag{6}$$

$$\sum_{j=1}^{o+1} q_{ij(l+1)} \geq \sum_{h=1}^{m} q_{hi} - \sum_{v=1}^{l} \sum_{j=1}^{o+1} q_{ijv}, \tag{7}$$

$$\sum_{h=1}^{m} q_{hi} \geq M_i, \tag{8}$$

$$q_{hi} \geq 0, q_{ijv} \geq 0, \quad h = 1, \ldots, m; \quad j = 1, \ldots, o+1; \quad v = 1, \ldots, l+1. \tag{9}$$

Smelters' Behaviour

- Smelters maximize their profit
- They cannot give more precious materials to demand markets than they can extract

Smelters' Behaviour

$$\max_{Q^j,\, Q_j} \quad \sum_{k=1}^{p}(\rho^*_{3jk} \cdot q_{jk}) - \sum_{i=1}^{n}\sum_{v=1}^{l+1}\rho^*_{2ijv} \cdot q_{ijv} - \rho_{j(p+1)}(Q^j, Q_j) - f_j(Q^j, Q_j) \qquad (10)$$

subject to:

$$\sum_{k=1}^{p} q_{jk} \leq \delta_j \sum_{v=1}^{l+1}(\beta_v^{prec.} \sum_{i=1}^{n} q_{ijv}), \qquad (11)$$

$$q_{ijv} \geq 0, q_{jk} \geq 0, \quad i = 1, \ldots, n; \quad k = 1, \ldots, p; \quad v = 1, \ldots, l+1. \qquad (12)$$

Demand Market Equilibrium

- Demand markets will not get more precious materials than they request
- Prices reflect their transaction cost associated to smelter j

Demand Market Equilibrium

$$d_k(\rho_{4k}^*) \begin{cases} = \sum_{j=1}^{o} q_{jk}^*, & \text{if} \quad \rho_{4k}^* > 0 \\ \leq \sum_{j=1}^{o} q_{jk}^*, & \text{if} \quad \rho_{4k}^* = 0; \end{cases} \tag{13}$$

$$\rho_{3jk}^* + c_{kj}(q_{jk}^*) \begin{cases} = \rho_{4k}^*, & \text{if} \quad q_{jk}^* > 0 \\ \geq \rho_{4k}^*, & \text{if} \quad q_{jk}^* = 0. \end{cases} \tag{14}$$

Methodology

- Network Equilibrium: In equilibrium, the equilibrium conditions for sources and demand markets as well the optimality conditions for recyclers and smelters must hold simultaneously and all the constraints must be satisfied (see e.g., Nagurney, 2006).
- We formulate the e-waste flow network as a variational inequality problem:

$$\left\langle \nabla f(x^*)^T, (x - x^*) \right\rangle \geq 0 \quad \forall x \in \mathbb{K}$$

Numerical Simulation

- The network for the numerical simulation consists of two sources of electronic waste, four recyclers, two smelters, and one demand markets.

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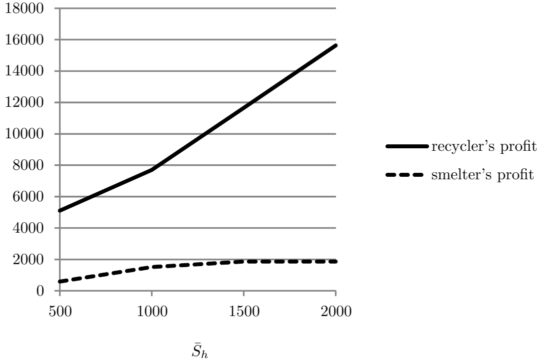
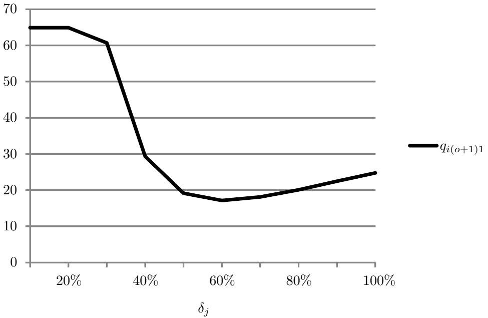
- Parameters and functions are based on existing research papers and white papers.
- The Euler method (Dupuis and Nagurney, 1993) was implemented in Matlab and applied to compute the solutions.

Variation of WEEE available at Sources



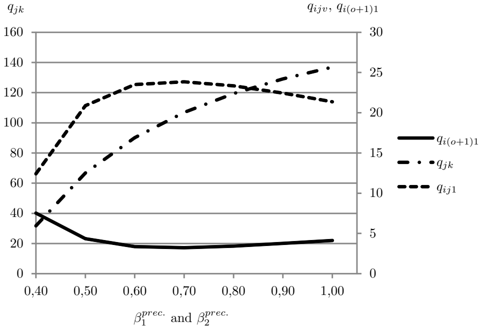
- Recyclers' and smelters' profits increase when the volume of e-waste possessed by sources increases.
- The increase in recyclers' profits is higher than the increase in smelters' profits

Variation of Smelters' Extraction Rate of Precious Materials



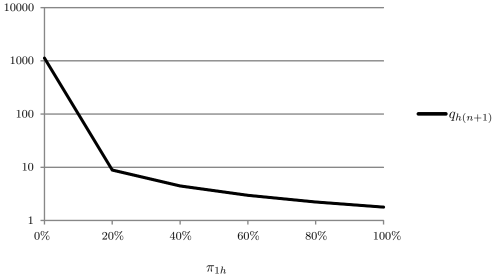
- When the extraction possibilities of a smelter increases, the quantities transshipped in the network increase.
- At first, this leads to lower offshoring quantities. However, at a certain point, the market gets saturated and offshoring quantities start to increase again.

Variation of Composition of WEEE



- An increase in the fraction of precious materials in components increases quantities transshipped to demand markets.
- For $\beta_1 > 0.7$ decreased prices will lower the incentive for materials to remain in the network.

Variation of the Probability that Sources' Illegal Dumping is Detected



- An increase of π_{1h} from 0% to 20% leads to a sharp decrease in quantities that are dumped illegally, while the decrease becomes smaller when π_{1h} is raised further.
- When transshipped quantities increase, prices at demand markets fall due to the bigger supply of waste.

Conclusions and Future Research

- Reverse logistics systems for end-of-life products are faced with many difficulties, including illegal dumping of waste, offshoring of waste and low waste collection rates.

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- Reverse logistics systems for end-of-life products are faced with many difficulties, including illegal dumping of waste, offshoring of waste and low waste collection rates.
- Improving the performance of reverse logistics systems requires a good understanding of the main factors and stakeholders and their interaction.
- The numerical examples show how this model can be used by policy makers to study the possible impacts of new laws on the stakeholders and e-waste flows.

Questions and Comments?

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