Design for Global Sustainability

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Overview

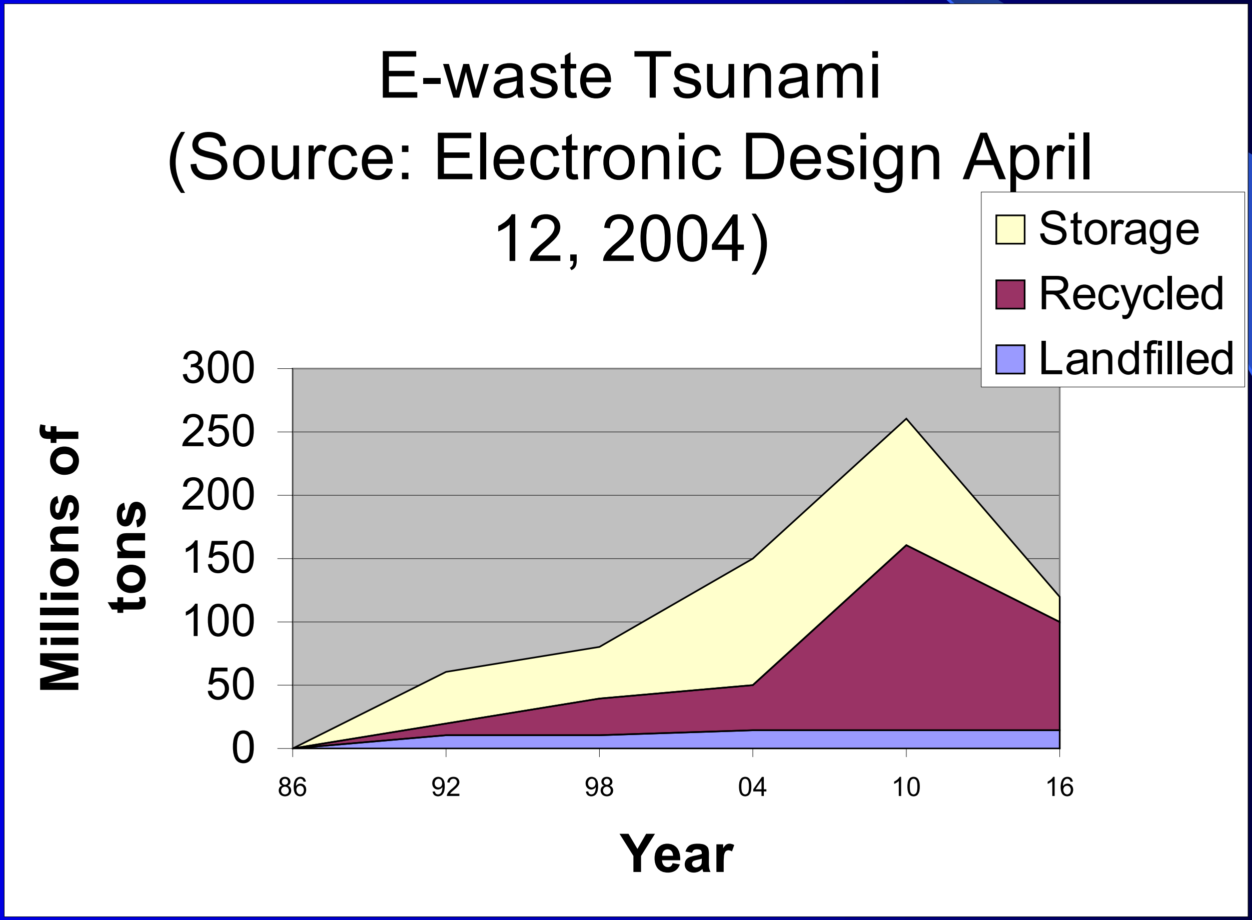
1. Background
2. Motivation
3. Previous Studies
4. E-cycling
5. Conclusion

Background

- 500 million PCs will be obsolete by 2007 in the U.S. (Appelbaum, 2002).
- About 9,000 tons of electric products are scrapped per year in Japan (Shimizu, 2002).
- In Europe, electronic waste is estimated to reach 12 million tons by 2010 (Shneiderman, 2004).

Background

The US will face a "tsunami" of e-waste (Silicon Valley Toxics Coalition, 2004)



Background

Characteristics of E-waste

- High product volumes and short product lives

- Depletion of landfill and incineration capacities

- Toxic materials and precious metals

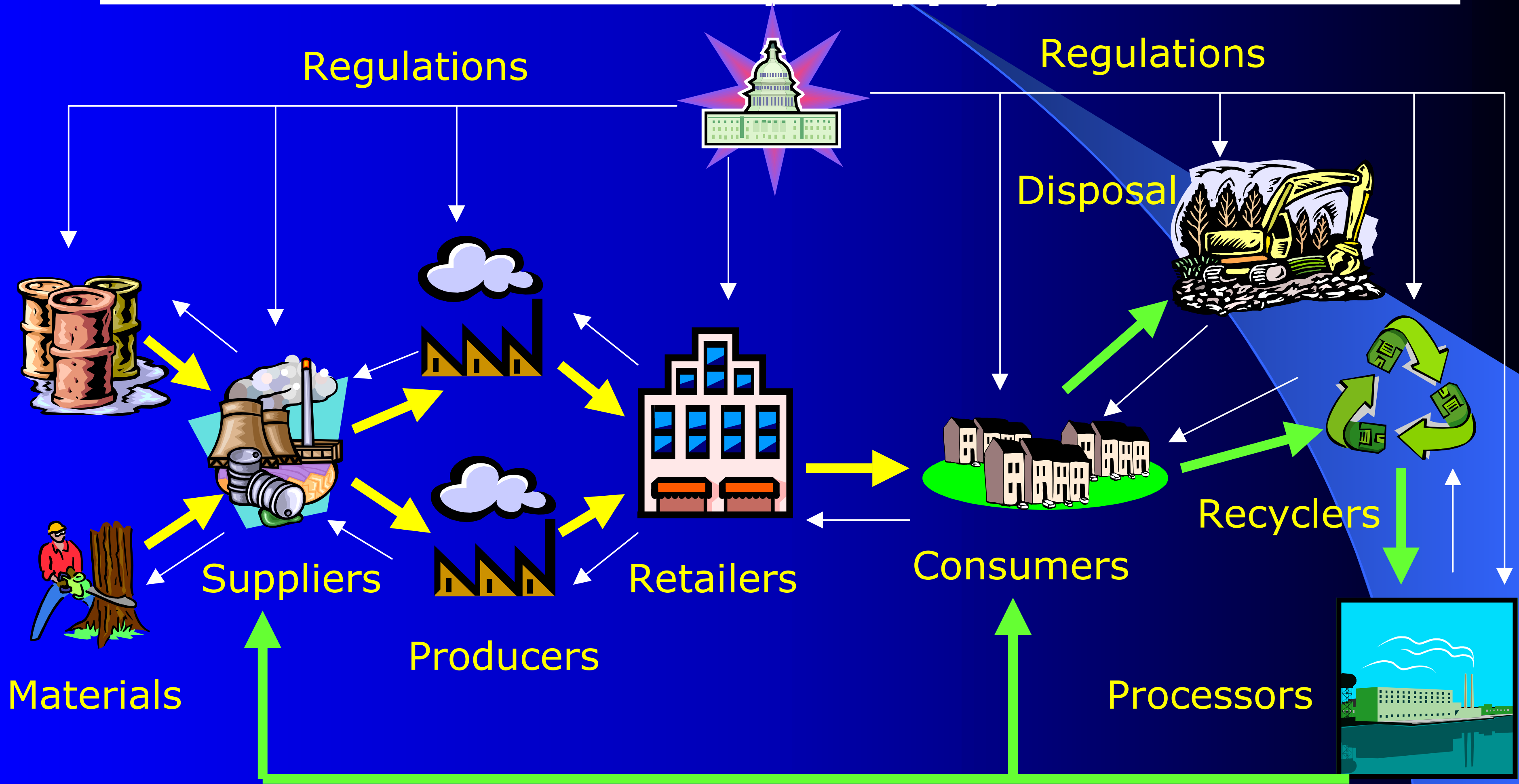
- Smelting precious metals and disposing hazardous materials
- Problem of exporting hazardous materials to developing countries

Motivation for Study of Reverse Supply Chains

- Depletion of landfill and incineration capacities
- Legislative Pressure (EU and Japan)
  - WEEE and RoHS (EU), Prevent Mercury Emissions (Maine, USA), Proposition 65 (California, USA), Computer and Electrical Appliances Recycling Law (Japan)
- Ecological Motivation
  - Power of green consumers
- Economic Motivation (US)
  - Remanufacturing machine parts
  - Smelting precious metals
  - US companies are losing $ 100 billion annually (Guide and Harrison, 2003).

Background

Framework Closed Loop Supply Chain Network



Source: Quality-based material selection for consumer electronics closed-loop supply chain networks under uncertainty, 2005

Uncertainties

- Material Choice Uncertainties
  - Supply and quality of recycled materials
  - Uncertainty about the amount, quality, and timing of returned e-waste
  - Material toxicity
- Regulatory Uncertainties
  - What specific environmental laws will be enacted in each country and how similar are they?
  - Are companies complying with applicable regulations?
- Consumer Demand Uncertainty
  - Uncertainty about consumers' willingness to pay for the recycled materials.

Previous Studies

	Separate Reverse Flow Model	Integration of Forward and Reverse Logistic Model	Forward Flow Model (Green Logistics)
Decentralized Supply Chain Network Modeling	Nagurney and Toyasaki (2005) and Stuart et al. (1999)		Nagurney and Toyasaki (2003)
Industrial Organization Models	Savaskan et al. (2004)	Debo, Toktay, and Van Wassenhove (2004)	
Environmental Risk Analysis			Qiu et al. (2001)
Regulatory Economics			Hill (1997)
Queuing Network		Toktay, Wein and Zenios (2000)	

Reverse Logistics Model : E-cycling

Nagurney A. and Toyasaki F. (2005)

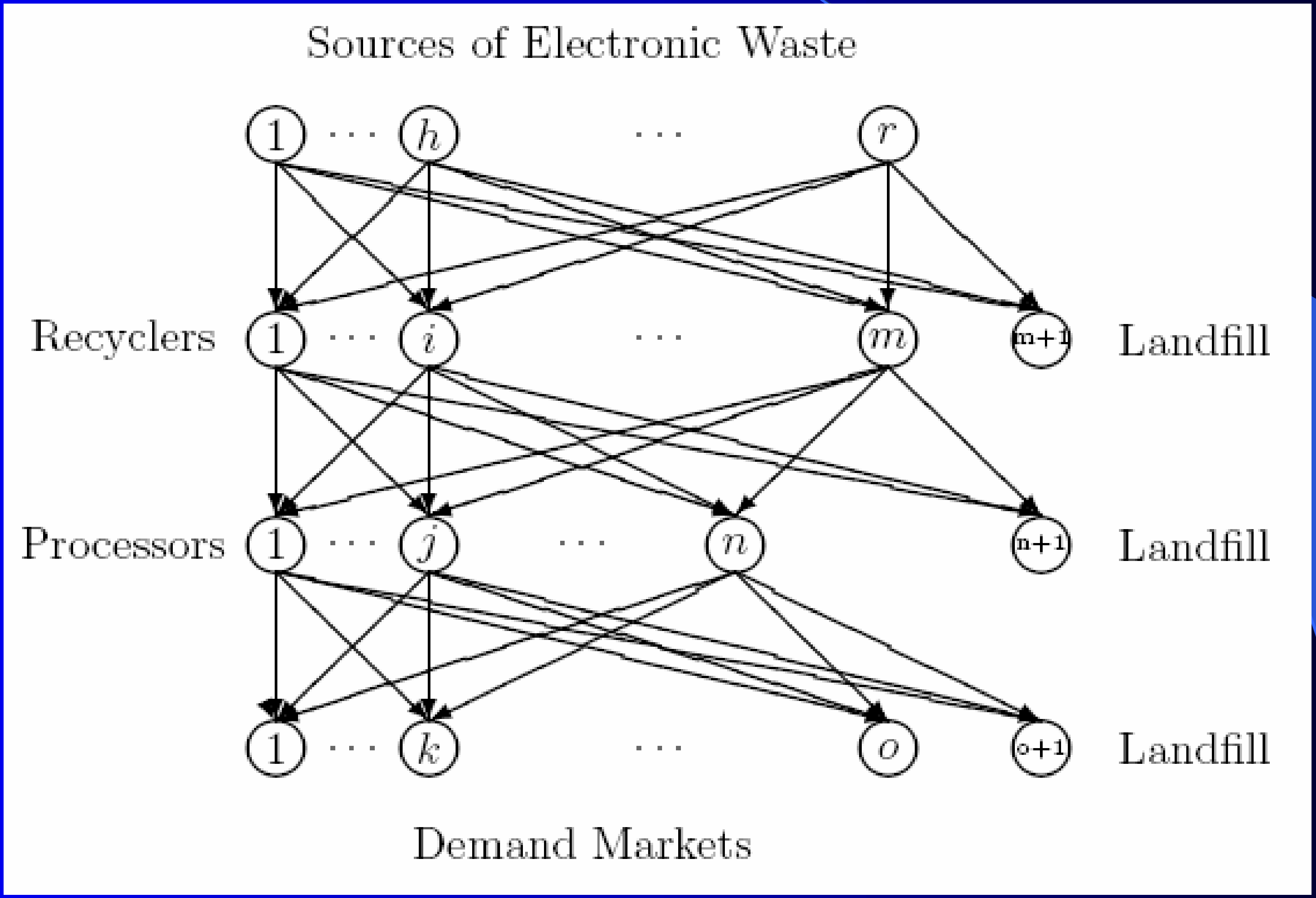
"Reverse Supply Chain Management and Electronic Waste Recycling: A Multitiered Network Equilibrium Framework for E-Cycling"

Transportation Research E **41**, 1-28.

Assumptions

- Decentralized reverse logistics model
- Oligopsony market (imperfect competition in input market)
- The prices and material flows are endogenously determined.
- The sources generate a fixed amount of electronic waste

The 4-Tiered E-Cycling Network



A Source's Behavior

Each source of e-waste:
Minimizes total cost associated with his management of e-waste

$$\text{Minimize} \sum_{i=1}^{m} \rho^*_{1hi} q_{hi} + \bar{\rho}_{1h(m+1)} q_{h(m+1)} + \sum_{i=1}^{m+1} c_{hi}(q_{hi}) \tag{2}$$

subject to:

$$\sum_{i=1}^{m+1} q_{hi} = S^h, \tag{3}$$

$$q_{hi} \geq 0, \quad i = 1, \ldots, m+1. \tag{4}$$

A Recycler's Behavior

Each recycler:
Maximizes his profit

$$\text{Maximize} \sum_{j=1}^{n} \rho^*_{2ij} q_{ij} + \sum_{h=1}^{r} \rho^*_{1hi} q_{hi} - \bar{\rho}_{2i(n+1)} q_{i(n+1)} - \sum_{j=1}^{n+1} c_{ij}(q_{ij}) - \sum_{h=1}^{r} \hat{c}_{hi}(q_{hi}) - c_i(Q^2)$$

subject to:

$$\sum_{j=1}^{n+1} \alpha_{ij} q_{ij} \leq \sum_{h=1}^{r} q_{hi}$$

$$q_{hi} \geq 0, \quad h = 1, \ldots, r; \quad q_{ij} \geq 0, \quad j = 1, \ldots, n+1.$$

A Processor's Behavior

Each processor:
Maximizes his profit

$$\text{Maximize} \sum_{k=1}^{o} \rho_{3jk}^{*} q_{jk} - c_j(Q^3) - \bar{\rho}_{3j(o+1)} q_{j(o+1)} - \sum_{i=1}^{m} \rho_{2ij}^{*} q_{ij} - \sum_{k=1}^{o+1} c_{jk}(q_{jk}) - \sum_{i=1}^{m} \hat{c}_{ij}(q_{ij})$$

subject to:

$$\sum_{k=1}^{o+1} \beta_{jk} q_{jk} \leq \sum_{i=1}^{m} q_{ij}$$

$$q_{ij} \geq 0, \quad i = 1, \ldots, m; \quad q_{jk} \geq 0, \quad k = 1, \ldots, o+1.$$

The Demand Markets

For all processors $j; \quad j = 1, \ldots, n$

$$\rho_{3jk}^* + \hat{c}_{jk}(q_{jk}^*) \begin{cases} = \rho_{4k}^*, & \text{if} \quad q_{jk}^* > 0 \\ \geq \rho_{4k}^*, & \text{if} \quad q_{jk}^* = 0, \end{cases}$$

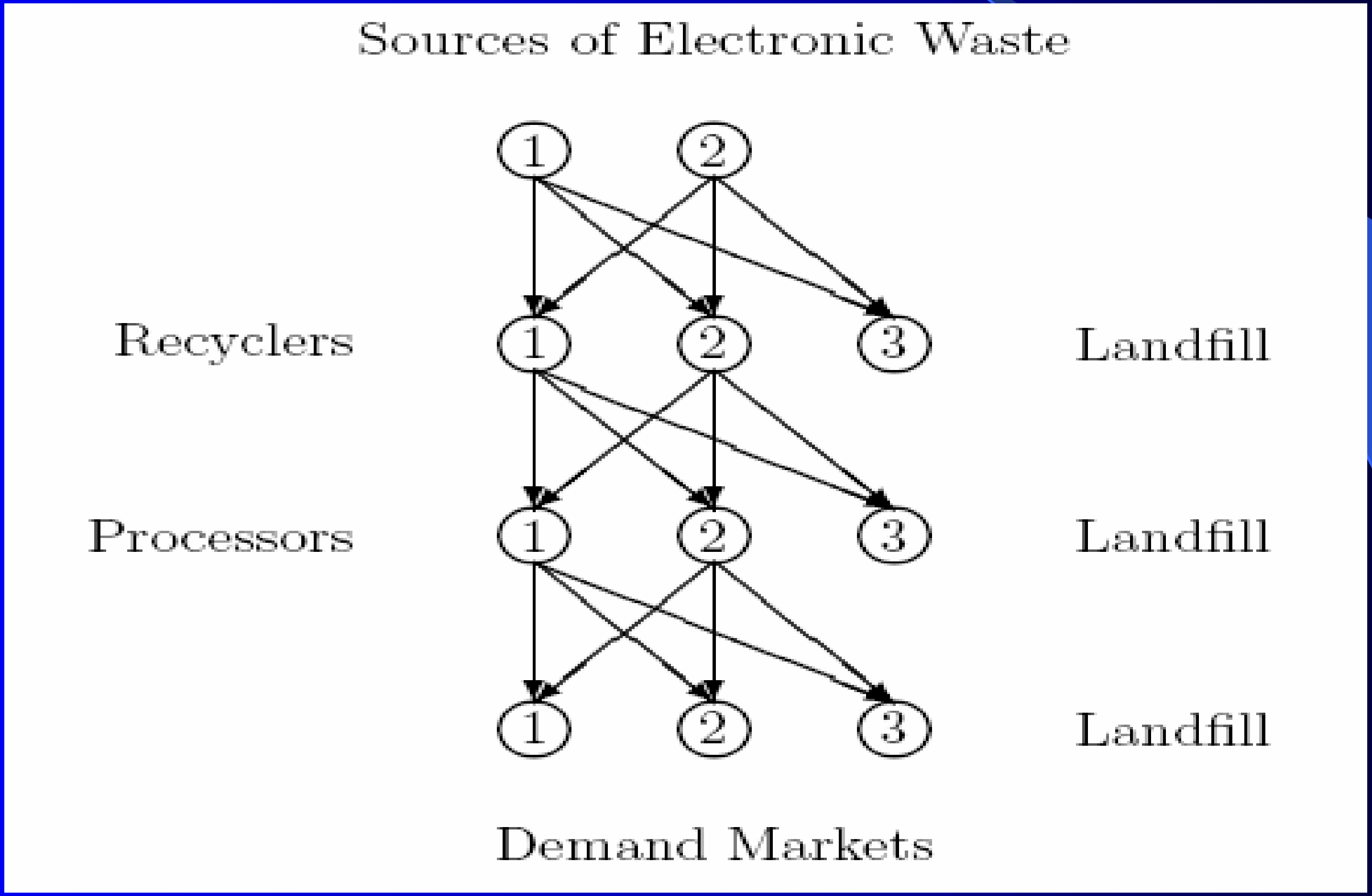
$$d_k(\rho_4^*) \begin{cases} = \sum_{j=1}^{n} q_{jk}^*, & \text{if} \quad \rho_{4k}^* > 0 \\ \leq \sum_{j=1}^{n} q_{jk}^*, & \text{if} \quad \rho_{4k}^* = 0. \end{cases}$$

Variational Inequality Formulation

$$
\begin{aligned}
&\sum_{h=1}^{r}\sum_{i=1}^{m}\left[\frac{\partial c_{hi}(q_{hi}^*)}{\partial q_{hi}}+\frac{\partial \hat{c}_{hi}(q_{hi}^*)}{\partial q_{hi}}-\gamma_i^*\right]\times\left[q_{hi}-q_{hi}^*\right]\\
&+\sum_{h=1}^{r}\left[\frac{\partial c_{h(m+1)}(q_{h(m+1)}^*)}{\partial q_{h(m+1)}}+\bar{\rho}_{1h(m+1)}\right]\times\left[q_{h(m+1)}-q_{h(m+1)}^*\right]\\
&+\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{\partial c_i(Q^{2*})}{\partial q_{ij}}+\frac{\partial c_{ij}(q_{ij}^*)}{\partial q_{ij}}+\frac{\partial \hat{c}_{ij}(q_{ij}^*)}{\partial q_{ij}}+\alpha_{ij}\gamma_i^*-\eta_j^*\right]\times\left[q_{ij}-q_{ij}^*\right]\\
&+\sum_{i=1}^{m}\left[\frac{\partial c_i(Q^{2*})}{\partial q_{i(n+1)}}+\frac{\partial c_{i(n+1)}(q_{i(n+1)}^*)}{\partial q_{i(n+1)}}+\bar{\rho}_{2i(n+1)}+\alpha_{i(n+1)}\gamma_i^*\right]\times\left[q_{i(n+1)}-q_{i(n+1)}^*\right]\\
&+\sum_{i=1}^{m}\left[\sum_{h=1}^{r}q_{hi}^*-\sum_{j=1}^{n+1}\alpha_{ij}q_{ij}^*\right]\times\left[\gamma_i-\gamma_i^*\right]\\
&+\sum_{j=1}^{n}\sum_{k=1}^{o}\left[\frac{\partial c_j(Q^{3*})}{\partial q_{jk}}+\frac{\partial c_{jk}(q_{jk}^*)}{\partial q_{jk}}+\hat{c}_{jk}(q_{jk}^*)+\beta_{jk}\eta_j^*-\rho_{4k}^*\right]\times\left[q_{jk}-q_{jk}^*\right]\\
&+\sum_{j=1}^{n}\left[\frac{\partial c_j(Q^{3*})}{\partial q_{j(o+1)}}+\frac{\partial c_{j(o+1)}(q_{j(o+1)}^*)}{\partial q_{j(o+1)}}+\beta_{j(o+1)}\eta_j^*+\bar{\rho}_{3j(o+1)}\right]\times\left[q_{j(o+1)}-q_{j(o+1)}^*\right]\\
&+\sum_{j=1}^{n}\left[\sum_{i=1}^{m}q_{ij}^*-\sum_{k=1}^{o+1}\beta_{jk}q_{jk}^*\right]\times\left[\eta_j-\eta_j^*\right]\\
&+\sum_{k=1}^{o}\left[\sum_{j=1}^{n}q_{jk}^*-d_k(\rho_4^*)\right]\times\left[\rho_{4k}-\rho_{4k}^*\right]\geq 0,\quad \forall(Q^{1*},Q^{2*},\gamma^*,Q^{3*},\eta^*,\rho_4^*)\in\mathcal{K},
\end{aligned}
$$

where $\mathcal{K}\equiv\{Q^1,Q^2,\gamma,Q^3,\eta,\rho_4)|(Q^1,Q^2,\gamma,Q^3,\eta,\rho_4)\geq 0,$ and Q^1 satisfies (3) for all $h\}$

E-Cycling Network for the Numerical Examples



Common Input Data
Low Demand for Recycled Materials

Volumes of electronic waste	$S^1 = S^2 = 20$
Transaction cost functions between sources and recyclers (cf. (1))	$c_{hi} = .5q_{hi}^2 + 3.5, h = 1, 2; i = 1, 2$
Transaction cost functions between sources and the landfill (cf. (1))	$c_{h3} = .5q_{h3}^2 + 2, h = 1, 2$
Second-tier landfill fixed prices	$\bar{\rho}_{1h3} = 1, h = 1, 2$
Transaction cost functions between recyclers and processors (cf. (6))	$c_{ij} = .5q_{ij}^2 + 5, i = 1, 2; j = 1, 2$
Transaction cost functions between recyclers and the landfill (cf. (6))	$c_{i3} = .5q_{i3}^2 + 3, i = 1, 2$
Third-tier landfill fixed prices	$\bar{\rho}_{2i3} = 1, i = 1, 2$
Transaction cost functions between recyclers and sources (cf. (7))	$\hat{c}_{hi} = 1.5q_{hi}^2 + 3, h = 1, 2; i = 1, 2$
Recycling cost functions (cf. (8))	$c_i = \sum_{j=1}^{3} q_{ij}, i = 1, 2$
Processing cost functions (cf. after (14))	$c_j = 2\sum_{k=1}^{3} q_{jk}, j = 1, 2$
Transaction cost functions between the processors and the demand markets (cf. (13))	$c_{jk} = .5q_{jk}^2 + 1, j = 1, 2; k = 1, 2$
Transaction cost functions between processors and demand market pair (from the perspective of the consumers at the demand markets) (cf. (19))	$\hat{c}_{jk} = q_{jk} + 1, j = 1, 2; k = 1, 2$
Fourth-tier landfill fixed prices	$\bar{\rho}_{3j3} = 1, j = 1, 2$
Demand functions (cf. after (19))	$d_1 = -2\rho_{41} - 1.5\rho_{42} + 100$ $d_2 = -2\rho_{42} - 1.5\rho_{41} + 100$

Results in Case of Low Demand for Recycled Products

Low Demand			
Equilibrium Solution	Example 1.1 $\alpha_{ij} = 1, \beta_{jk} = 1, \forall i, j, k$	Example 1.2 $\alpha_{ij} = .5, \beta_{jk} = 1, \forall i, j, k$	Example 1.3 $\alpha_{ij} = .5, \beta_{jk} = .25, \forall i, j, k$
Material Flows from Sources to Second Tier (Recyclers and Landfill)			
$q^*_{hi}, h = 1, 2; i = 1, 2$	3.50	2.75	2.75
$q^*_{h3}, h = 1, 2$	13.00	14.50	14.50
Material Flows from Recyclers to Third Tier (Processors and Landfill)			
$q^*_{ij}, i = 1, 2; j = 1, 2$	3.50	4.50	1.72
$q^*_{i3}, i = 1, 2$	0.00	0.00	0.00
Material Flows from Processors to Bottom Tier (Demand Markets and Landfill)			
$q^*_{jk}, j = 1, 2; k = 1, 2$	3.50	4.50	6.90
$q^*_{j3}, j = 1, 2$	0.00	0.00	0.00
Shadow Prices at the Recyclers			
$\gamma^*_i, i = 1, 2$	4.52	0.00	0.00
Shadow Prices at the Processors			
$\eta^*_j, j = 1, 2$	14.03	10.49	7.71
Demand Market Prices at the Demand Markets			
$\rho^*_{4k}, k = 1, 2$	26.56	26.00	24.63

Results in Case of Low Demand for Recycled Products (Cont.)

Low Demand			
Equilibrium Solution	Example 1.1 $\alpha_{ij} = 1, \beta_{jk} = 1,$ $\forall i, j, k$	Example 1.2 $\alpha_{ij} = .5, \beta_{jk} = 1,$ $\forall i, j, k$	Example 1.3 $\alpha_{ij} = .5, \beta_{jk} = .25,$ $\forall i, j, k$
E-waste Prices at the Sources			
$\rho^*_{1hi}, h = 1, 2, i = 1, 2$	5.98	8.25	8.25
E-waste Prices at the Recyclers			
$\rho^*_{2ij}, i = 1, 2, j = 1, 2$	9.02	5.5	2.72
E-waste Prices at the Processors			
$\rho^*_{3jk}, j = 1, 2, k = 1, 2$	22.06	20.5	16.73
Total Cost at the Sources			
$C^*_h, h = 1, 2$	160.61.4	181.56	181.56
Profit at the Recyclers			
$\Pi^*_i, i = 1, 2$	30	23.93	6.64
Profit at the Processors			
$\Pi^*_j, j = 1, 2$	63.03	94.75	144.31

Common Input Data (High Demand for Recycled Materials)

Volumes of electronic waste	$S^1 = S^2 = 20$
Transaction cost functions between sources and recyclers (cf. (1))	$c_{hi} = .5q_{hi}^2 + 3.5, h = 1, 2; i = 1, 2$
Transaction cost functions between sources and the landfill (cf. (1))	$c_{h3} = .5q_{h3}^2 + 2, h = 1, 2$
Second-tier landfill fixed prices	$\bar{\rho}_{1h3} = 1, h = 1, 2$
Transaction cost functions between recyclers and processors (cf. (6))	$c_{ij} = .5q_{ij}^2 + 5, i = 1, 2; j = 1, 2$
Transaction cost functions between recyclers and the landfill (cf. (6))	$c_{i3} = .5q_{i3}^2 + 3, i = 1, 2$
Third-tier landfill fixed prices	$\bar{\rho}_{2i3} = 1, i = 1, 2$
Transaction cost functions between recyclers and sources (cf. (7))	$\hat{c}_{hi} = 1.5q_{hi}^2 + 3, h = 1, 2; i = 1, 2$
Recycling cost functions (cf. (8))	$c_i = \sum_{j=1}^{3} q_{ij}, i = 1, 2$
Processing cost functions (cf. after (14))	$c_j = 2\sum_{k=1}^{3} q_{jk}, j = 1, 2$
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Transaction cost functions between processors and demand market pair (from the perspective of the consumers at the demand markets) (cf. (19))	$\hat{c}_{jk} = q_{jk} + 1, j = 1, 2; k = 1, 2$
Fourth-tier landfill fixed prices	$\bar{\rho}_{3j3} = 1, j = 1, 2$
Demand functions (cf. after (19))	$d_1 = -2\rho_{41} - 1.5\rho_{42} + 1000$ $d_2 = -2\rho_{42} - 1.5\rho_{41} + 1000$

Results in Case of High Demand for Recycled Products

High Demand			
Equilibrium Solution	**Example 2.1** $\alpha_{ij} = 1, \beta_{jk} = 1, \forall i, j, k$	**Example 2.2** $\alpha_{ij} = .5, \beta_{jk} = 1, \forall i, j, k$	**Example 2.3** $\alpha_{ij} = .5, \beta_{jk} = .25, \forall i, j, k$
Material Flows from Sources to Second Tier (Recyclers and Landfill)			
$q^*_{hi}, h = 1,2; i = 1,2$	10.00	10.00	9.53
$q^*_{h3}, h = 1,2$	0.00	0.00	.95
Material Flows from Recyclers to Third Tier (Processors and Landfill)			
$q^*_{ij}, i = 1,2; j = 1,2$	10.00	20.00	19.06
$q^*_{i3}, i = 1,2$	0.00	0.00	0.00
Material Flows from Processors to Bottom Tier (Demand Markets and Landfill)			
$q^*_{jk}, j = 1,2; k = 1,2$	10.00	20.00	76.26
$q^*_{j3}, j = 1,2$	0.00	0.00	0.00
Shadow Prices at the Recyclers			
$\gamma^*_i, i = 1,2$	231.97	372.47	40.67
Shadow Prices at the Processors			
$\eta^*_j, j = 1,2$	247.97	212.24	45.40
Demand Market Prices at the Demand Markets			
$\rho^*_{4k}, k = 1,2$	279.99	274.28	242.14

Results in Case of High Demand for Recycled Products (Cont.)

High Demand			
Equilibrium Solution	Example 2.1 $\alpha_{ij} = 1, \beta_{jk} = 1, \forall i, j, k$	Example 2.2 $\alpha_{ij} = .5, \beta_{jk} = 1, \forall i, j, k$	Example 2.3 $\alpha_{ij} = .5, \beta_{jk} = .25, \forall i, j, k$
E-waste Prices at the Sources			
$\rho^*_{1hi}, h = 1, 2, i = 1, 2$	-201.97	-342.47	-12.08
E-waste Prices at the Recyclers			
$\rho^*_{2ij}, i = 1, 2, j = 1, 2$	242.97	207.235	40.395
E-waste Prices at the Processors			
$\rho^*_{3jk}, j = 1, 2, k = 1, 2$	268.99	253.28	164.88
Total Cost at the Sources			
$C^*_h, h = 1, 2$	-3930.4	-6740.4	-129.0
Profit at the Recyclers			
$\Pi^*_i, i = 1, 2$	381	681	616.74
Profit at the Processors			
$\Pi^*_j, j = 1, 2$	378.4	1359.8	17485.02

Conclusions

- In the EU and Japan, pressure from legislation and other members in the system leads companies to integrate reverse logistics into their business model.
- In the US, companies have become interested in reverse logistics due to economic reasons.
- Reverse logistics has many uncertainties: material choice, legislation, and consumer demand uncertainties.
- A new type of supply chain, that is, a closed-loop supply chain, needs to be considered.

Thank you!

Questions, Comments ?

For more information on this paper and the Virtual Center for Supernetworks see: http://supernet.som.umass.edu

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Virtual Center for Supernetworks