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Centralized versus Decentralized Decision-Making for Recycled Material Flows

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A reverse logistics system is a network of transportation logistics and processing functions that collect, consolidate, refurbish, and demanufacture end-of-life products. This paper examines centralized and decentralized models of decision-making for material flows and associated transaction prices in reverse logistics networks. We compare the application of a *centralized* model for planning reverse production systems, where a single planner is acquainted with all of the system information and has the authority to determine decision variables for the entire system, to a *decentralized* approach. In the decentralized approach, the entities coordinate between tiers of the system using a parametrized flow function and compete within tiers based on reaching a price equilibrium. We numerically demonstrate the increase in the total net profit of the centralized system relative to the decentralized one. This implies that one may overestimate the system material flows and profit if the system planner utilizes a centralized view to predict behaviors of independent entities in the system and that decentralized contract mechanisms will require careful design to avoid losses in the efficiency and scope of these systems.

Introduction

Reverse production systems (RPSs) include collection, sorting, demanufacturing, and refurbished processes networked by reverse logistics operations to recover discarded products (*1–3*). For many products, the infrastructure for RPS is still in its early stages of organization. Understanding the advantages and disadvantages of different approaches to structure RPS as well as the role government regulations, or subsidies, play in stimulating growth of the RPS infrastructure is important. For example, the Waste Electrical and Electronic Equipment Directive aims to minimize the impact of electrical and electronic goods on the environment by making producers responsible for financing the collection, treatment, and recovery of end-of-life electrical equipment and by obliging distributors to allow customers to return their scrap electronics without any charge (*4*). This legislative development is certain to have an impact on the behavior of each entity in a recycling network. Therefore, it is important to develop approaches for analyzing a RPS under different assumptions about its organization and the freedom of entities within it to pursue their own goals. The purpose of this paper is to examine two different organizational approaches, centralized and decentralized, and to demonstrate the potentially optimistic conclusions for system behavior if one analyzes a decentralized system from a centralized perspective.

In a centralized decision-making process, a single planner or organization is acquainted with all system information including transportation capacities, processing capabilities, and associated sales prices of end-of-life and refurbished products. The planner has the authority to determine decision variables of the system, for example, how recycled materials are flowing through the RPS network or how much the system can spend to acquire end-of-life products. One example of the decision maker in the centralized setup is a local government, which owns the municipal collection and processing sites in a recycling network. The government may be acting as a central planner to determine the RPS network behavior. In the past decade, many researchers have analyzed reverse logistics system planning for end-of-life products in a centralized framework (e.g., refs *3* and *5–7*). The major tasks of RPS planning consider collection, sortation, consolidation, disassembly, and demanufacturing processes within system limitations of the RPS network. Several studies have applied mathematical programming methods to find an optimal system plan and design for reverse supply chain systems (*1, 8–12*). Most of these studies propose mathematical programming models that solve the problem as a reverse network flow problem to obtain the optimal infrastructure design as well as associated material flow allocations or other decision variables within the network.

In a decentralized decision-making reverse supply chain system, a RPS consists of several independent entities operated by different private parties who are unwilling to reveal their own confidential information for processing capacities or cost structures to others or the public. In addition, the decision variables for each entity are often influenced by other entities' decisions, coupling prices between members of the same tier, and flows between supply chain tiers. For instance, the acquired price of an end-of-life product or a collected item is determined through the interactions between entities because the entities within one tier usually compete for materials from their preceding tier (*16*).

There are a growing number of research papers on forward or reverse supply chains that model the independent decision-making process of each entity in supply chains, specifically the interaction between pricing decisions and material flow volume transacted in the network (*13–17*). In addition, Savaskan et al. (*18*) model three options for collecting used products, subcontracting with retailers, outsourcing to a third-party firm, and collecting by themselves, as decentralized decision-making systems, with the manufacturer being the Stackelberg leader. Savaskan and Van Wassenhove (*19*) analyze different reverse channel designs of direct and indirect product collection systems where the manufacturer collects used products directly from the consumers or collects via retailers. Other studies analyze a manufacturer's recovery strategy: a choice of whether to recover the value in their end-of-life products or to refurbish

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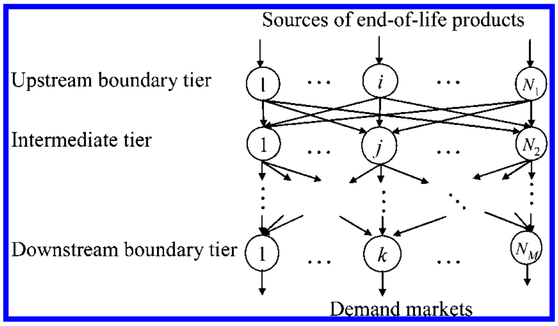

FIGURE 1. General multitiered RPS network structure (reprinted with permission of John Wiley & Sons, Inc. (*25*)).

some of the returned products through remanufacturing or refurbishing processes (*20, 21*).

There are also several studies on the comparison of the centralized and decentralized setups for the forward supply chain, especially for inventory problems (*22–24*). However, little research has addressed the comparison of centralized and decentralized problems for RPSs or reverse logistics networks. In this paper, we examine the behaviors of the individual entity and system for centralized versus decentralized RPS setups, demonstrate the potential bias if a policy maker predicts behavior using a centralized perspective for a decentralized system, and present several numerical implications and insights drawn from the centralized and decentralized models.

Multitiered RPS Problem

A RPS is a network of transportation logistics and processing functions that collect, recycle, refurbish, and demanufacture end-of-life products. In this paper, we model the RPS as a multitiered network, depicted in Figure 1, which consists of an upstream boundary tier, several intermediate tiers, and a downstream boundary tier. We consider N_1 entities in the upstream boundary tier as represented by the top tier of nodes in Figure 1, N_2, ..., $N_{M\text{-}1}$ entities in intermediate tiers 2, ..., $M-1$, respectively, and N_M downstream boundary tier entities associated with the bottom tier in the network. In addition, we let sources of recycled products and demand markets be the two end exogenous tiers of the network, which may be represented as several independent and possibly geographically distinct sources of end-of-life products and demand markets for secondary used products or raw materials.

Typical upstream boundary tier entities can be represented as municipal collection sites, nonprofit collection organizations, private collectors, etc. The entities in the upstream boundary tier collect end-of-life products from the source supply, which can include, for example, residential households, businesses, schools, or the government. There are a broad set of factors, such as consumers' willingness, product characteristics, transportation issues, etc., that determine the quantities of collected end-of-life products. We note that the sites in the upstream boundary tier, specifically collectors in the e-scrap recycling industry, may pay or charge for collecting or processing end-of-life products. In this paper, we assume that the collected amount is dependent on the collection fee paid or charged by the upstream boundary tier site. The intermediate tiers may contain several levels of entities: for example, the tier of consolidation sites, material brokers, and processing sites who bid for collected items from their preceding tier and conduct some value-added processes such as sorting or disassembling operations or simply act as an intermediary broker between tiers. Downstream boundary tier entities associated with nodes in the bottom tier in the network can be seen as the final stage of the entire RPS, where they purchase collected items from their preceding tier and conduct further dismantling/mechanical fragmentation of items or refurbish end-of-life products for consumption purposes. Hence, downstream boundary tier entities may convert the collected items into raw materials or refurbished products and sell them to specific demand markets. The amount of raw materials resulting from the decomposition of end-of-life products and used products is relatively small compared to the quantity in the virgin raw material and brand-new product markets. This observation leads to the assumption that the selling prices of raw materials or used products in final demand markets are fixed amounts, not affected by the sales quantities. In general, collected items flow from the upstream tier to the downstream tier of entities, but financial incentives are driven from the downstream tier back to the upstream tier of entities. For simplicity, we assume that materials must move through each tier sequentially and may not be transported directly across two or more tiers within the network.

We first consider a setup in which management is *centralized*. A single decision maker (e.g., the state or local government) has the requisite information about all of the participating entities and seeks the optimal solution for the entire system. The underlying assumption of the centralized problem setting is that the decision maker has the authority to manage associated operations or processes of all entities within the network. In a centralized setup, the decision maker determines the optimal level of the collection amount from the source, and the most efficient way of material flow allocation through the network, so that the system net profit is maximized. In addition, there are some internal transaction variables among entities in the network such as internal transaction prices; however, these are not relevant in the centralized setting.

Alternatively, a *decentralized* system is composed of several independent entities individually operated by self-interested parties. Each independent entity has its own profit function subject to its own processing or transportation constraints and is not willing to reveal its own information to other entities or the public. Often the decision variables for each entity in a decentralized system are also influenced by other entities' decisions. The foundations of the decentralized RPS models are derived from our recent work in a two-tiered RPS network (*17*). Using this decentralized RPS network framework, we obtain the equilibrium collection fee either paid or charged by the upstream boundary tier site and the resulting material flow allocation within the network. In this paper, we examine the comparison of behaviors for a centralized versus decentralized RPS approach and investigate implications and insights for public policy determination.

Centralized and Decentralized Models

In this section, first we illustrate a *centralized* model for a RPS consisting of an upstream boundary tier, intermediate tiers, and a downstream boundary tier, followed by an overview of the *decentralized* RPS model. In this paper, for model simplicity, we do not consider the issue of the material holding cost among multiple periods, resulting in the assumption of a flow conservation rule for each site within the network; in other words, each site is not allowed to have an imbalance in the input and output flow after all transactions. The centralized model finds the optimal collection fees and the material flow allocation so that the system profit function is maximized subject to the individual entity and system constraints. The decentralized model solves the equilibrium collection fee and resulting material flows, while each entity determines its own associated decision variables of acquisition prices and the price−flow contract mechanism.

Centralized Quadratic Programming Model. In the centralized RPS model, a single planner has the requisite information for all participating entities and seeks an optimal solution for the entire system. We characterize the collection amount for the upstream boundary tier site by using a linear relationship where the amount collected is a function of the collection fee. This captures the qualitative market behavior that the flow increases if the collection fee increases, where the positive (negative) collection fee indicates that the upstream boundary tier site pays (charges) for collected end-of-life products. The use of a linear function allows the analysis of the problem to be simplified and leads to a quadratic form for the centralized model. More complex, and possibly more realistic, models could be derived and used for the market behavior, but we do not have data to support their construction. The decision variables for the system are the optimal material flow allocation within the system and the collection fee in the upstream boundary tier. The mathematical form of the centralized RPS optimization model for the entire system is described in the Supporting Information, and the general form can be stated as

Maximize
(1) Net profit (Sales profits − Collection fees and Transportation costs)
Subject to
(2) Source supply function definition
(3) Flow balance between sites
(4) Processing and transportation capacity

The volume between the source and the upstream boundary tier site increases as the upstream boundary tier site increases the collection fee. Obviously, because the total amount collected is a linear function of the unit collection fee, the corresponding unit fee must be large when a large amount is collected. Consequently, end-of-life products flowing into the system are limited to either the system capacity itself or the optimal acquisition amount determined by the concave quadratic net profit objective function. In the latter case, the system limits its input because the marginal cost of acquiring more flow exceeds the marginal value derived from it.

Decentralized Model. In the decentralized decision-making framework, each entity within the RPS concentrates on optimizing its own profit subject to its own transportation and processing capacity constraints. The decentralized RPS model is also described in detail in the Supporting Information. The upstream entities in one tier provide the price−flow contract that connects the downstream price information to the flow they will provide. We refer to this price−flow contract as the *flow function*. Each upstream entity acts individually to determine the flow function used to contract with each member of the next tier. The flow function is determined using a robust optimization formulation that captures the idea that the upstream entity does not have exact price information from the downstream entities and wants to minimize the worst outcome it can have.

The downstream tier sites are assumed to reveal their bids for the items from the preceding tier until they have no incentive to change them. This allows a Nash equilibrium to be reached within the tier. An algorithm for finding this equilibrium is presented in (*17*) and the Supporting Information. The algorithm respects the structure of the system by only having the previous bids of each entity available for inspection when the next bid is being determined by each independent entity. Within this framework, entities in the system reach the equilibrium of the acquisition prices as well as the resulting material flow allocation in the network. The decentralized model contains this set of *internal* equilibrium acquisition prices, which are not present in the centralized problem setting.

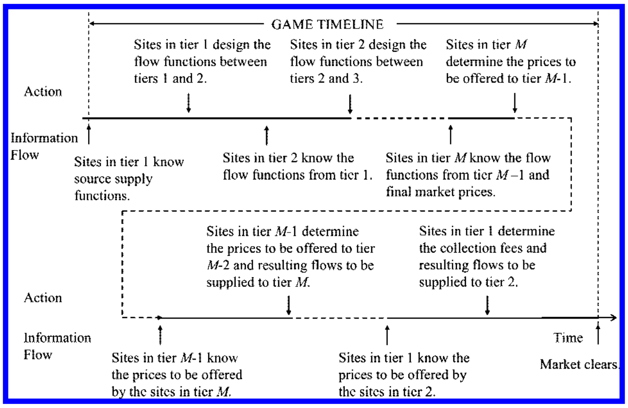

FIGURE 2. Decision timeline for a *M*-tiered problem (reprinted with permission of John Wiley & Sons, Inc. (*25*)).

The decision timeline for a *M*-tiered problem is shown in Figure 2 where the upper arrows indicate the entity tasks and the lower arrows show the information disclosure timeline. The flow functions are independently designed by the upstream tier sites and communicated to the subsequent downstream tier sites. The algorithm starts at the sites in tier 1 to determine the flow function between itself and the second tier sites, given the source supply functions, which describe the variation of the collected amount with the collection fee between the sites in tier 1 and the sources. The sites in tier 1 communicate flow functions to the sites in intermediate tier 2. Each intermediate tier site independently determines the associated flow functions and communicates them to its next tier sites. This proceeds sequentially until the last tier is reached. The sites in the downstream boundary tier determine the equilibrium acquisition price on the basis of the flow functions given by the sites in the preceding tier and the final market price. This completes the upper part of Figure 2. Then, the resulting flow into the downstream boundary tier site can be obtained by substituting the equilibrium price into the flow function.

Acquisition prices are set by the downstream tier and passed back to the upstream tier sequentially from the downstream to upstream boundary tier, as shown in the lower part of Figure 2. Because of our flow conservation assumption, the resulting flows can be determined as the acquisition prices are realized. Finally, the sites in the first tier decide the collection fees to acquire end-of-life products from sources. In the following sections, we investigate numerical results to compare the centralized and decentralized approaches.

Experimental Section

In this section, we provide a numerical example from ref *25* to demonstrate the mathematical behavior of the centralized and decentralized models and provide several insights from their comparison. We consider a three-tiered RPS, whose structure is depicted in Figure 1, with collection, consolidation, and processing sites. There are five collection sites, $i = 1-5$, in tier 1, three consolidation sites, $j = 1-3$, in tier 2, and four processing sites, $k = 1-4$, in tier 3. The transportation costs per unit flow between any two associated sites are given in Table 1.

The final market prices for processing sites, $k = 1-4$, are \$155, \$145, \$147, and \$150, respectively. The collection amount functions in collection sites, $i = 1-5$, are given by $S_1 = 400 + 5p_1^{(Co)}$, $S_2 = 420 + 6p_2^{(Co)}$, $S_3 = 440 + 6p_3^{(Co)}$, $S_4 = 430 + 6p_4^{(Co)}$, and $S_5 = 410 + 5p_5^{(Co)}$. We consider two cases of capacitated and uncapacitated settings for the arc-transportation and processing site capacities. In the capacitated case, we limit the arc-transportation capacity to 200 units, the collection site capacity to 600 units, the consolidation site capacity to 800 units, and the processing site capacity to 800 units.

TABLE 1. Unit Transportation Costs between Sites[a]

unit transportation cost		$j \in I_2$		
		1	2	3
$i \in I_1$	1	10.0	15.0	18.0
	2	10.0	13.0	16.0
	3	13.0	10.0	14.0
	4	15.0	13.0	11.0
	5	17.0	14.0	9.0

unit transportation cost		$k \in I_3$			
		1	2	3	4
$j \in I_2$	1	8.0	8.0	10.0	12.0
	2	10.0	8.0	7.0	11.0
	3	12.0	10.0	8.0	7.0

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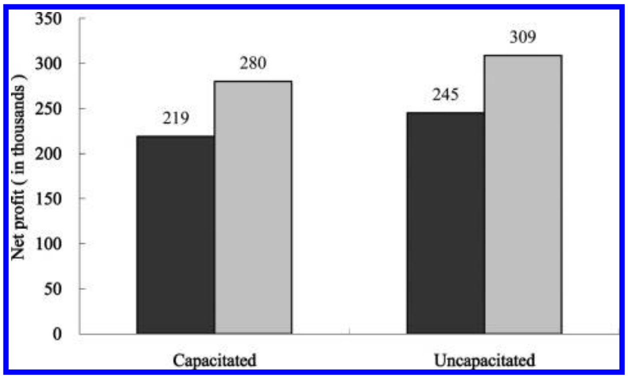

FIGURE 3. Net profits of centralized (gray □) and decentralized (■) models (reprinted with permission of John Wiley & Sons, Inc.).

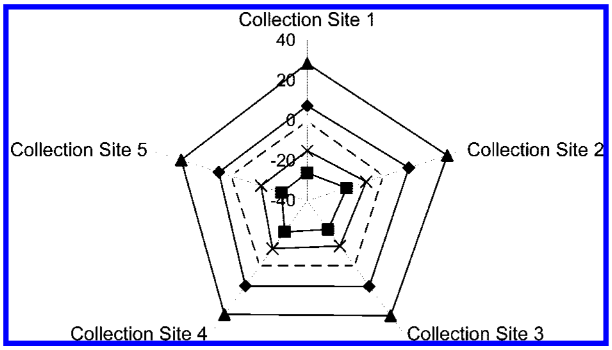

FIGURE 4. Collection fees of the decentralized-capacitated (■), decentralized-uncapacitated (×), centralized-capacitated (◆), and centralized-uncapacitated (▲) cases and the zero reference line (---). The negative collection fee indicates that the collection site charges the sources a positive fee for collecting items (reprinted with permission of John Wiley & Sons, Inc.).

The centralized model solution is derived from solving a quadratic programming problem, and the decentralized model solution is obtained using solution methodology described in the Supporting Information and (*17*). Our focus is on the comparison of the net profit, which is the sum of the sales profit from the final market, collection fees incurred between sources and collection sites, and transportation costs of all shipments through the system. We also examine the decision variables of the optimal collection fees paid or charged by collection sites, $i = 1-5$, in tier 1 and the material flow allocations within the network for the centralized and decentralized problems. Figures 3 and 4 and Table 2 summarize the numerical solutions of the net profits, collection fees, and material flow allocations for centralized and decentralized problems in capacitated and uncapacitated cases, followed by the sensitivity analysis for the net profit and several interpretations and insights drawn from these results.

There are several insights that can be drawn from the numerical results of this example. As expected, both of the capacitated and uncapacitated cases show that the net profit of the centralized model outperforms the net profit of the decentralized model. The net profit of the centralized model serves an upper bound on the net profit of the decentralized model for both of the capacitated and uncapacitated cases. For the centralized model, the flow is bounded by the arc-transportation capacity, especially in the arcs between tiers 2 and 3, as shown in the third row in Table 2. However, the flow in the uncapacitated case is constrained by the first-order condition so as to maximize its quadratic concave objective function. We conclude that the net profit of the system is bounded by the arc constraints in the capacitated case but is determined by the objective function's first-order condition in the uncapacitated case.

Figure 4 indicates that the collection sites in the centralized problem pay a positive collection fee to sources to acquire end-of-life products but charge for accepting end-of-life products in the decentralized problem. This implies that the centralized approach acquires more end-of-life products compared to the decentralized problem. Moreover, the net profit ratios of the decentralized to centralized problem settings are 78.2% and 79.4% in the capacitated and uncapacitated cases, respectively. In other words, especially in the capacitated case, one may overestimate the system profit and/or the volume of end-of-life products processed by the system if it is assumed that the decisions are made centrally in a system of independent entities. This result of the net profit difference between the centralized and decentralized problems, as shown in Figure 3, also captures the notion of *double marginalization* of the vertical supply chain where two independent firms, upstream and downstream, may end up with lower profits in the decentralized setting (*26*). Another factor resulting in the centralized and decentralized gap is *price uncertainty* because the price information is not revealed between two independent entities or to the public in the decentralized problem.

Given the problem set of the numerical example presented in this section, the net profits of centralized and decentralized models are 280 096 and 219 999, respectively, for the capacitated case and are 308 779 and 245 037, respectively, for the uncapacitated case shown in Figure 3. However, the given parameters such as price, transportation cost, and maximum amount of material that can be shipped and processed are subject to change by the types of products and timing. The centralized and decentralized models presented in the Supporting Information allow us to analyze the sensitivity of the parameters. We further investigate the net profits under different sets of given parameters, where the final market prices are increased by 50%, the transportation costs are decreased by 50%, or the transportation, collection, and processing capacities are increased by 50%. As expected, the net profits of centralized cases outperform those of decentralized cases in all parameter setups. Because the changes in the parameters are toward a profit-improving direction, we observe that the net profits of all cases in our sensitivity analysis are better than those in the original case. The detailed profits for the sensitivity analysis are summarized in the Supporting Information. The ratio of the profit difference between the centralized and decentralized cases to the profit of the centralized case is summarized in Figure 5. The ratio can be interpreted as the gap between the centralized and decentralized cases. We observe that the gap is relatively significant when the final market prices are increased by 50% in the uncapacitated case.

TABLE 2. Material Flow Allocation of Capacitated and Uncapacitated Cases[a]

Capacitated Case

$x_{ij}^{(\mathrm{Tr})}: i \in I_1,\ \ j \in I_2$

flows	$x_{11}^{(\mathrm{Tr})*}$	$x_{12}^{(\mathrm{Tr})*}$	$x_{13}^{(\mathrm{Tr})*}$	$x_{21}^{(\mathrm{Tr})*}$	$x_{22}^{(\mathrm{Tr})*}$	$x_{23}^{(\mathrm{Tr})*}$	$x_{31}^{(\mathrm{Tr})*}$	$x_{32}^{(\mathrm{Tr})*}$	$x_{33}^{(\mathrm{Tr})*}$	$x_{41}^{(\mathrm{Tr})*}$	$x_{42}^{(\mathrm{Tr})*}$	$x_{43}^{(\mathrm{Tr})*}$	$x_{51}^{(\mathrm{Tr})*}$	$x_{52}^{(\mathrm{Tr})*}$	$x_{53}^{(\mathrm{Tr})*}$
centralized	200.0	120.7	116.0	200.0	153.1	147.0	179.2	200.0	136.9	179.0	126.1	200.0	41.8	200.0	200.0
decentralized	79.7	99.7	90.7	106.4	107.3	90.7	101.7	110.3	94.3	90.4	107.3	107.6	90.3	106.0	80.6

$x_{jk}^{(\mathrm{Tr})}: j \in I_2,\ \ k \in I_3$

flows	$x_{11}^{(\mathrm{Tr})*}$	$x_{12}^{(\mathrm{Tr})*}$	$x_{13}^{(\mathrm{Tr})*}$	$x_{14}^{(\mathrm{Tr})*}$	$x_{21}^{(\mathrm{Tr})*}$	$x_{22}^{(\mathrm{Tr})*}$	$x_{23}^{(\mathrm{Tr})*}$	$x_{24}^{(\mathrm{Tr})*}$	$x_{31}^{(\mathrm{Tr})*}$	$x_{32}^{(\mathrm{Tr})*}$	$x_{33}^{(\mathrm{Tr})*}$	$x_{34}^{(\mathrm{Tr})*}$
centralized	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
decentralized	106.6	126.4	131.6	103.9	148.0	118.3	123.8	140.7	109.8	112.1	125.4	116.6

Uncapacitated Case

$x_{ij}^{(\mathrm{Tr})}: i \in I_1,\ \ j \in I_2$

flows	$x_{11}^{(\mathrm{Tr})*}$	$x_{12}^{(\mathrm{Tr})*}$	$x_{13}^{(\mathrm{Tr})*}$	$x_{21}^{(\mathrm{Tr})*}$	$x_{22}^{(\mathrm{Tr})*}$	$x_{23}^{(\mathrm{Tr})*}$	$x_{31}^{(\mathrm{Tr})*}$	$x_{32}^{(\mathrm{Tr})*}$	$x_{33}^{(\mathrm{Tr})*}$	$x_{41}^{(\mathrm{Tr})*}$	$x_{42}^{(\mathrm{Tr})*}$	$x_{43}^{(\mathrm{Tr})*}$	$x_{51}^{(\mathrm{Tr})*}$	$x_{52}^{(\mathrm{Tr})*}$	$x_{53}^{(\mathrm{Tr})*}$
centralized	542.5	0	0	621.0	0	0.0	0	625.0	0	191.2	185.3	234.5	0	0	540.0
decentralized	110.5	99.0	115.1	121.7	114.4	129.1	140.1	103.1	123.6	139.0	93.3	134.1	119.9	101.1	109.8

$x_{jk}^{(\mathrm{Tr})}: j \in I_2,\ \ k \in I_3$

flows	$x_{11}^{(\mathrm{Tr})*}$	$x_{12}^{(\mathrm{Tr})*}$	$x_{13}^{(\mathrm{Tr})*}$	$x_{14}^{(\mathrm{Tr})*}$	$x_{21}^{(\mathrm{Tr})*}$	$x_{22}^{(\mathrm{Tr})*}$	$x_{23}^{(\mathrm{Tr})*}$	$x_{24}^{(\mathrm{Tr})*}$	$x_{31}^{(\mathrm{Tr})*}$	$x_{32}^{(\mathrm{Tr})*}$	$x_{33}^{(\mathrm{Tr})*}$	$x_{34}^{(\mathrm{Tr})*}$
centralized	1354.7	0	0	0	810.3	0	0	0	386.5	0	0	388.1
decentralized	212.5	152.0	120.7	145.9	148.6	122.3	120.7	119.4	159.2	125.7	140.0	186.9

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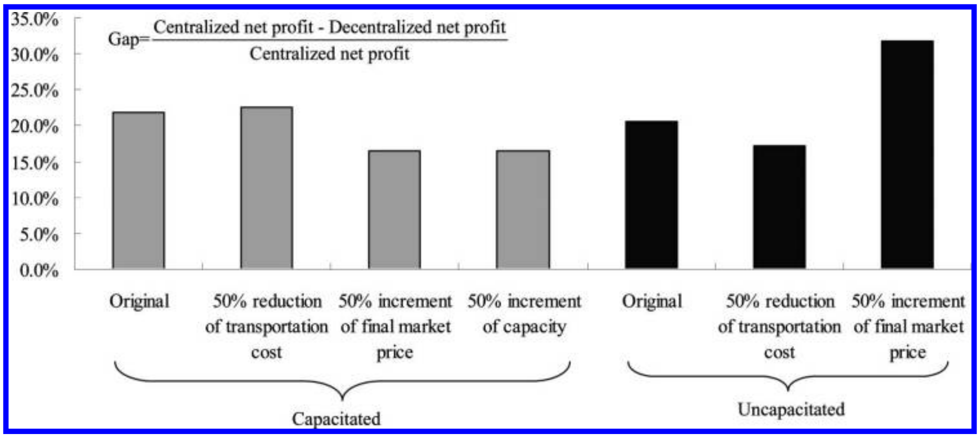

FIGURE 5. Sensitivity analysis results for net profits.

As a next step, we examine the most efficient material flow allocation under the centralized model given the equilibrium collection fees from the decentralized model. Here we are interested in the optimal material flow allocation within the network, from a centralized perspective, given the same source amount as that found in the decentralized problem. Given the same amount of source supply, this provides us with a comparison between the best case the system can achieve in a centralized setting and all independent entities can obtain in the decentralized problem setting. The equilibrium collection fees derived by the decentralized model are substituted into the centralized model to replace the price decision variables. Under this setting, the total flow amounts of end-of-life products are identical in the centralized and decentralized problems, and the centralized model is essentially a linear programming model. The material flow solutions under this framework are listed in the Supporting Information.

The net profits of the centralized model given the equilibrium collection fees under the capacitated and uncapacitated cases are 224 850 and 258 543, respectively, or 102.7% and 105.5% of the original decentralized net profits in capacitated and uncapacitated cases, respectively. The optimal net profit difference between the decentralized and centralized models given the equilibrium collection fees can be interpreted as the system gain due to the *efficiency* of material flow allocation in the centralized problem setting. This demonstrates that the loss of surplus in the decentralized model is due to a failure to both accept the economically optimal total amount and inefficiently allocate it among the network participants.

Summary and Discussion

There are considerable differences in the results of net profits and material flow allocations derived from the centralized and decentralized RPS models. This paper demonstrates the comparison of the individual and system behavior between the centralized and decentralized decision making for a RPS network. We develop a centralized framework for the recycling network system where a single decision maker is acquainted with all system information including transportation capacities, processing capabilities, and associated sales prices of recycled materials. In a centralized modeling manner, the planner also has the authority to determine system decision variables of the material flow allocation throughout the entire network and the collection fees paid by the upstream boundary tier sites to acquire end-of-life products from sources. The centralized RPS model presented in this paper can be used to generate results to compare the equilibrium solution obtained from the decentralized multitiered RPS model by analyzing and predicting the individual behavior of independent participants.

An important and intuitive managerial implication from our results is that the centralized solution is superior to the decentralized solution in terms of the net profit, especially in the capacitated case. However, many entities in recycling networks are self-interested parties instead of centrally controlled agents, particularly in countries and industries where recycling is not legislatively mandated. Our analysis demonstrates that one may overestimate the system flows and profits if the decision maker utilizes a centralized approach to model a truly decentralized RPS network. The difference in results for centralized and decentralized solutions is mainly attributed to price uncertainty and double marginalization, which are two common features of real-world decentralized systems. In addition, our results show that, for the centralized problem, the net profit of the system is bounded by the arc constraints in the capacitated case but is determined by the objective function's first-order condition in the uncapacitated case. Finally, we also demonstrate the system gain of the net profit due to the efficiency of material flow allocation in the centralized problem setting given the same level of the source supply in the decentralized problem.

A key extension of this work is to incorporate additional types of related end-of-life products or conduct a more complex network such that the materials may or may not move through all tiers sequentially. Another extension of the research is to examine the individual or the system behavior of the *semicentralized* or *semidecentralized* network, which may contain several independent recycling organizations or firms and several municipal collection sites or recyclers.

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Supporting Information Available

The detailed description of the centralized and decentralized models for a multitiered reverse supply chain network and the results of the example. This material is available free of charge via the Internet at http://pubs.acs.org.

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