The Closed-loop Supply Chain Network with Competition and Design for Remanufactureability

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Remanufacturing of used products at their end of life (EOL) reduces both the need for natural resources and the waste produced.

Remanufacturing photocopiers consumes 20-70% less materials, labor, and energy and generates 35-50% less waste than conventional manufacturing using virgin materials (Toffel (2004)). Production costs are further reduced since the cost for a remanufactured part is generally 30-50% less than a new part would be (Toffel (2004)).

Introduction - Legislation

Many government legislations have been put into effect to require firms to collect their products at their EOL.

- European end-of-life Vehicle (ELV) Directive
- The Waste Electrical and Electronic Equipment (WEEE) Directive within the European Union
- Electronics Recycling laws in the U.S.

The production of remanufactured goods increased from \$37.3 billion in 2009 to \$43.0 billion in 2011. Remanufactured goods are estimated to account for about 2% of total sales of all products (new and remanufactured) between 2009 and 2011 (United States International Trade Commission Investigation (2012)).

Remanufacturability

Kodak recently replaced some plastic parts in its high-speed copiers with more expensive, but reusable, stainless steel (Deutsch (1998)). Fuji Xerox was the first to achieve zero landfill of used products in Japan. Today, all the company's equipment is developed with remanufactureability components (cf. (Fuji Xerox Technical Report (2005)) and Benn and Dunphy (2004)).

The tire manufacturers can make the choice of material and production technology to influence the retreadability of tires (cf. BIPAVER (1998) and Bozarth (2000)).

Need for Analytical Tools

One product line of Bosch Tools is remanufactured only if the price or market share of this product line is above a certain threshold, otherwise it is not. The management of Bosch Tools admitted that more sophisticated tools are needed for making effective and differentiated remanufacturing decisions (Atasu et al. (2008a)).

Firms opt out of remanufacturing their products due to the fact that the fixed and variable costs of remanufacturing are high. Even if the remanufactured product itself is profitable, firms have concerns that the remanufactured product will cannibalize the new product (Ferguson and Toktay (2006)).

Remanufacturing decisions are made even more complicated when we start to analyze the consumers at the demand markets. It has been discussed in the literature that consumers value new and remanufactured product differently. Research has shown that consumers are heterogenous when it comes to their perception toward different remanufactured products (cf. Guide and Li (2007) and Subramanian and Subramanyam (2012)).

Contribution to the Literature I

Geyer et al. (2007) pointed out that most of the literature in this area deals with tactical and operational issues, such as resource planning, scheduling and shop floor management, inventory control, and network design and routing.

The above approach fails to recognize the CLSC as a business process and ignores the important strategic issues, such as the product design, supply chain coordination, and competition (Guide et al. (2003)).

The majority of the papers that deal with CLSC strategic issues only discuss monopolistic original equipment manufacturers (OEM) or competition between an OEM and a remanufacturer who are dealing with a single demand market ((Souza (2013) and Atasu et al. (2008b)). There is a lack of studies discussing the competition within the OEMs, which could be the main driver of the remanufacturing profitability and therefore, needs to be analyzed more in depth (Atasu et al. (2008b)).

Contribution to the Literature II

Nagurney and Toyasaki (2005) developed an integrated framework for the modeling of reverse supply chain management of electronic waste using the variational inequality approach.

Hammond and Beullens (2007) expanded the work of Nagurney and Toyasaki (2005) to present a closed-loop supply chain network consisting of manufacturers and consumer markets. However, the above papers did not consider such strategic issue as the design of the product remanufactureability.

We believe it is relevant and important to contribute to the CLSC research stream by analyzing a CLSC network with competition among OEMs and studying the impact of product remanufactureability on profitability. We propose a CLSC model followed by numerical examples to answer the following research questions:

- Will remanufacturing when facing OEMs competition be profitable?
- How does OEMs' competition and product design choice affect profit and market share?
- How does the consumers' perception discount towards the remanufactured product affect profit and market cannibalization?
- If the demand market is asymmetrical in terms of the consumers' discount towards the remanufactured product, how does it affect manufacturers' profit and market share?

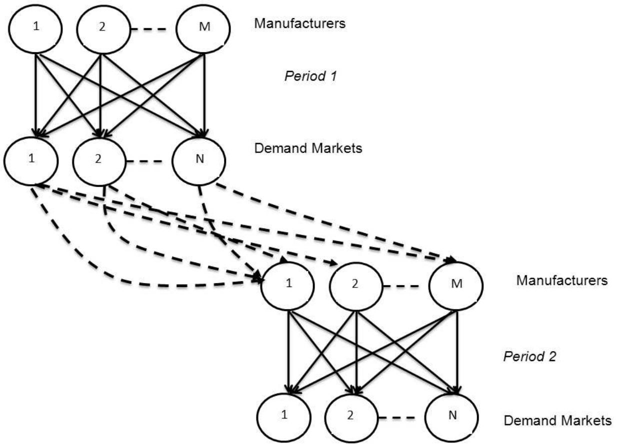

Figure : Two-period CLSC Network

In the first period, manufacturers determine the product remanufactureability level and production quantity.

In the second period, when the product sold in the first period is at its EOL, manufacturers will collect the used product from the consumers, which will be, in turn, remanufactured.

Manufacturer M's objective function:

$$\max_{q_{mi}^{1n}, q_{mi}^{2n}, q_{mi}^{2r}, s_m} Profit_m = \left[\sum_{i=1}^{N} \rho_i^{1n}(d^{1n}) * q_{mi}^{1n} - f_m^{1n}(Q^{1n}, s_m) - c_m^1(Q^{1n})\right]$$
$$+\delta * \left[\sum_{i=1}^{N} \rho_i^{2n}(d^{2n}, d^{2r}) * q_{mi}^{2n} + \rho_i^{2r}(d^{2n}, d^{2r}) * q_{mi}^{2r}\right.$$
$$\left. - f_m^{2n}(Q^{2n}, s_m) - c_m^2(Q^{2n}, Q^{2r}) - f_m^{2r}(Q^{2r}, s_m)\right] \quad (1)$$

At the demand markets, the following constraints need to be satisfied.

$$d_i^{1n} = \sum_{m=1}^{M} q_{mi}^{1n}, \quad i = 1, \ldots, N, \quad (2)$$

$$d_i^{2n} = \sum_{m=1}^{M} q_{mi}^{2n}, \quad i = 1, \ldots, N, \quad (3)$$

$$d_i^{2r} = \sum_{m=1}^{M} q_{mi}^{2r}, \quad i = 1, \ldots, N, \quad (4)$$

$$\sum_{i=1}^{N} q_{mi}^{2r} \leq \beta_m^r(\sum_{i=1}^{N} q_{mi}^{1n}). \quad (5)$$

Feasible set $\mathcal{K}$ is defined as $\mathcal{K} \equiv \{(Q^{1n}, Q^{2n}, Q^{2r}, s) | q_{mi}^{1n} \geq 0, q_{mi}^{2n} \geq 0, q_{mi}^{2r} \geq 0, s_m \in [0,1] \geq 0$ and (2)-(5) are satisfied $\forall m = 1, \ldots, M, i = 1, \ldots, N\}$. We then verify that the above feasible set is closed and convex.

Theorem 1: Variational Inequality Formulation of the CLSC with Competition and Design for Remanufactureability

The equilibrium conditions governing the CLSC with competition and design for remanufactureability coincide with the solution of the variational inequality given by determine $(Q^{1n}, Q^{2n}, Q^{2r}, s) \in \mathcal{K}$, such that

$$\sum_{m=1}^{M}\sum_{i=1}^{N}\left[\frac{\partial f_m^{1n}(Q^{1n^*}, s_m^*)}{\partial q_{mi}^{1n}} + \frac{\partial c_m^{1}(Q^{1n^*})}{\partial q_{mi}^{1n}} - \sum_{j=1}^{N}\rho_j^{1n}(d^{1n^*}) - \sum_{j=1}^{N}\frac{\partial \rho_j^{1n}(d^{1n^*})}{\partial q_{mi}^{1n}} q_{mi}^{1n^*}\right] \times (q_{mi}^{1n} - q_{mi}^{1n^*})$$
$$+\sum_{m=1}^{M}\sum_{i=1}^{N}\delta\left[\frac{\partial f_m^{2n}(Q^{2n^*}, s_m^*)}{\partial q_{mi}^{2n}} + \frac{\partial c_m^{2}(Q^{2n^*}, Q^{2r^*})}{\partial q_{mi}^{2n}} - \sum_{j=1}^{N}\rho_j^{2n}(d^{2n^*}, d^{2r^*}) - \sum_{j=1}^{N}\frac{\partial \rho_j^{2n}(d^{2n^*}, d^{2r^*})}{\partial q_{mi}^{2n}} q_{mi}^{2n^*}\right] \times (q_{mi}^{2n} - q_{mi}^{2n^*})$$
$$+\sum_{m=1}^{M}\left[\frac{\partial f_m^{1n}(Q^{1n^*}, s_m^*)}{\partial s_m} + \delta\frac{\partial f_m^{2n}(Q^{2n^*}, s_m^*)}{\partial s_m} + \delta\frac{\partial f_m^{2r}(Q^{2r^*}, s_m^*)}{\partial s_m}\right] \times (s_m - s_m^*)$$
$$+\sum_{m=1}^{M}\sum_{i=1}^{N}\delta\left[\frac{\partial f_m^{2r}(Q^{2r^*}, s_m^*)}{\partial q_{mi}^{2r}} + \frac{\partial c_m^{2}(Q^{2n^*}, Q^{2r^*})}{\partial q_{mi}^{2r}} - \frac{\partial \rho_i^{2n}(d^{2n^*}, d^{2r^*})}{\partial q_{mi}^{2r}} * q_{mi}^{2n^*} - \frac{\partial \rho_i^{2r}(d^{2n^*}, d^{2r^*})}{\partial q_{mi}^{2r}} * q_{mi}^{2r^*} - \rho_i^{2r}(d^{2n^*}, d^{2r^*})\right] \times (q_{mi}^{2r} - q_{mi}^{2r^*}) \geq 0,$$
$$\forall (Q^{1n}, Q^{2n}, Q^{2r}, s) \in \mathcal{K}. \quad (6)$$

Numerical Examples

Two manufacturers and two demand markets. The relevant cost and demand functions are listed below:

$$f_1^{1n} = \frac{0.01((q_{11}^{1n})^2+(q_{12}^{1n})^2)}{(1-s_1)}; \quad f_1^{2n} = \frac{0.01((q_{11}^{2n})^2+(q_{12}^{2n})^2)}{(1-s_1)};$$

$$f_2^{1n} = \frac{0.01((q_{21}^{1n})^2+(q_{22}^{1n})^2)}{(1-.5s_2)}; \quad f_2^{1n} = \frac{0.01((q_{21}^{2n})^2+(q_{22}^{2n})^2)}{(1-.5s_2)};$$

$$f_1^{2r} = 0.02((q_{11}^{2r})^2 + (q_{12}^{2r})^2) - 20(s_1+1); \quad f_2^{2r} = 0.08((q_{21}^{2r})^2 + (q_{22}^{22})^2) - (s_2+1);$$

$$c_1^1 = c_2^1 = c_1^2 = c_2^2 = 10;$$

$$\rho_1^{1n} = 1 - d_1^{1n} = 1 - (q_{11}^{1n} + q_{21}^{1n});$$

$$\rho_2^{1n} = 1 - d_2^{1n} = 1 - (q_{12}^{1n} + q_{22}^{1n});$$

$$\rho_1^{2n} = 1 - d_1^{2n} - \theta_1 d_1^{2r} = 1 - (q_{11}^{2n} + q_{21}^{2n}) - \theta_1(q_{11}^{2r} + q_{21}^{2r});$$

$$\rho_2^{2n} = 1 - d_2^{2n} - \theta_2 d_2^{2r} = 1 - (q_{12}^{2n} + q_{22}^{2n}) - \theta_2(q_{12}^{2r} + q_{22}^{2r});$$

$$\rho_1^{2r} = \theta_1(1 - d_1^{2n} - d_1^{2r}) = \theta_1(1 - (q_{11}^{2n} + q_{21}^{2n}) - (q_{11}^{2r} + q_{21}^{2r}));$$

$$\rho_2^{2r} = \theta_2(1 - d_2^{2n} - d_2^{2r}) = \theta_2(1 - (q_{12}^{2n} + q_{22}^{2n}) - (q_{12}^{2r} + q_{22}^{2r}))$$

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Scenario 1: Does Remanufacturing Make Sense?

We first compute the base case where both manufacturers do not opt for the remanufacturing business, where $s_1 = s_2 = 0$ and there is no refurbished demand market. In this base case, both manufacturers have the same cost functions and therefore, their profits are the same as well. To compare with the profit in the base case, we vary the impact of the remanufactureability level of the two manufacturers on their production cost to obtain the resulting profits.

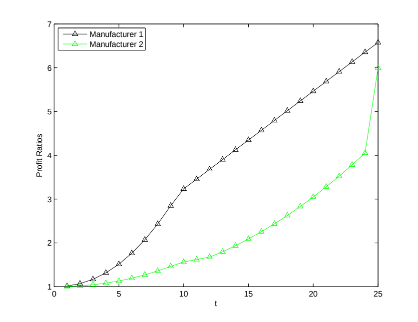

Figure : Ratio between Profits with and without Remanufacturing

The Impact of the Remanufactureability Level on Market Share

We vary the impact of the remanufactureability level on the production costs for both the new and refurbished products. Since the two manufacturers have different strategies on the remanufactureability design, we are interested in studying the impact of these different strategies on manufacturers' market share. Since the market size is fixed for both demand markets, the manufacturer with a higher market share will eventually gain a marketing advantage.

We calculate the ratios between the sales of Manufacture 1 and that of Manufacturer 2 in both periods and for both the new and the refurbished product. A ratio that is greater than 1 indicates a larger market share, and vise versa.

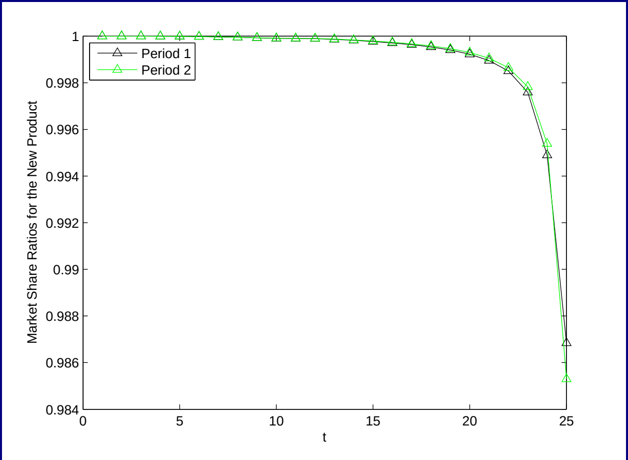

Figure : Market Share Ratios of the New Product for the Two Manufacturers

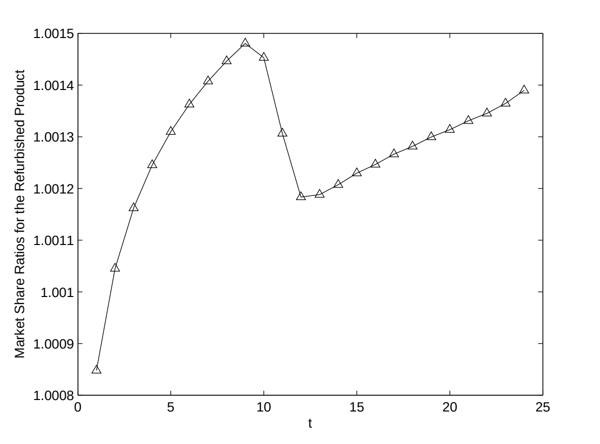

Figure : Market Share Ratio of the Refurbished Product for the Two Manufacturers

Impacts of Consumers' Valuation on the Refurbished Product

Consumers' willingness-to-pay on the remanufactured product will affect the remanufacturing decisions of manufacturers.

It is also the main drive for cannibalization. Therefore, to capture this effect, we vary θ_1 and θ_2 in both demand markets from 0.1 to 1 and study the following: 1. the profits of two manufacturers; and 2. the market share of the remanufactured product.

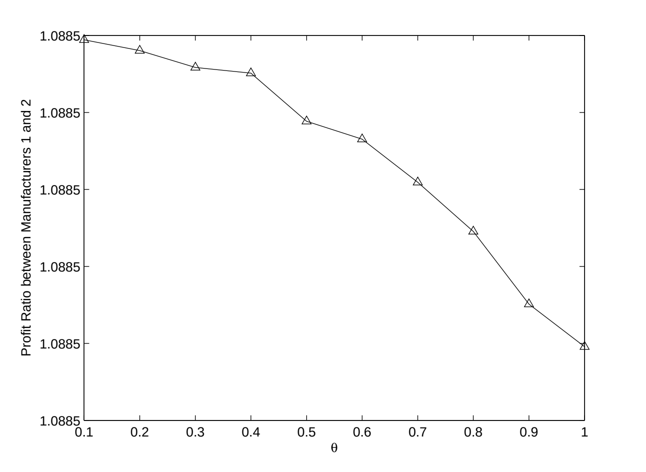

Figure : Ratio between the Profits of Manufacturers 1 and 2

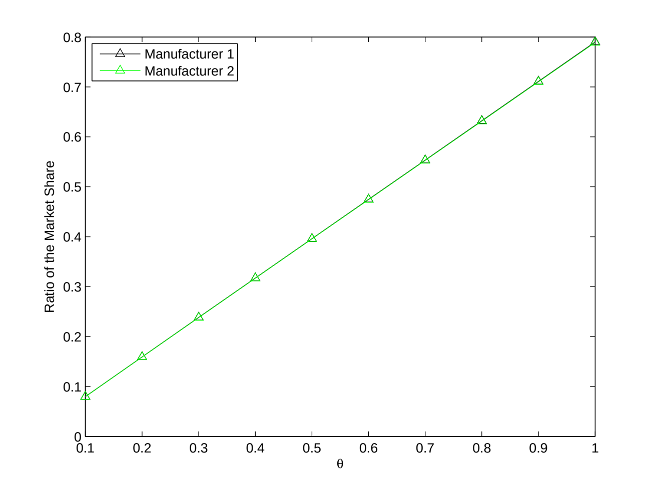

Figure : Ratio between the Market Shares for the Refurbished Product and the New Product in the Second Period

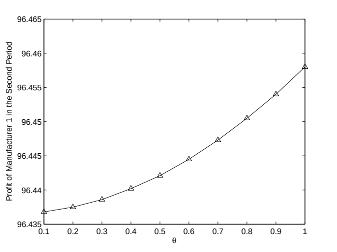

Figure : Profit of Manufacturer 1 with Different θ Values

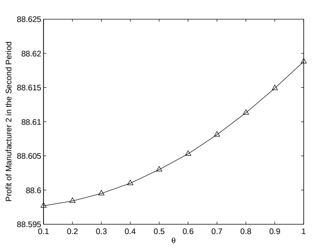

Figure : Profit of Manufacturer 2 with Different θ Values

Competition with Asymmetrical Demand Markets

In this scenario, we vary θ value in one demand market and study the resulting profits and market share. In particular, we let θ_1 vary from 0.1 to 1 in Demand Market 1 and fix θ_2 in Demand Market 2.

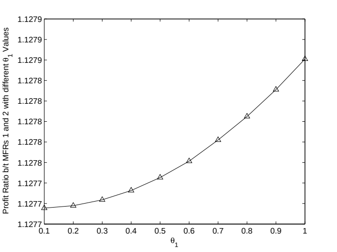

Figure : Profit Ratio between Manufacturers 1 and 2 with Different θ_1 Values

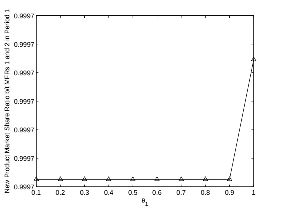

Figure : Market Share Ratio between Manufacturers 1 and 2 with Different θ_1 Values in Period 1

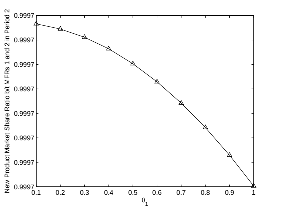

Figure : Market Share Ratio between Manufacturers 1 and 2 with Different θ_1 Values in Period 2

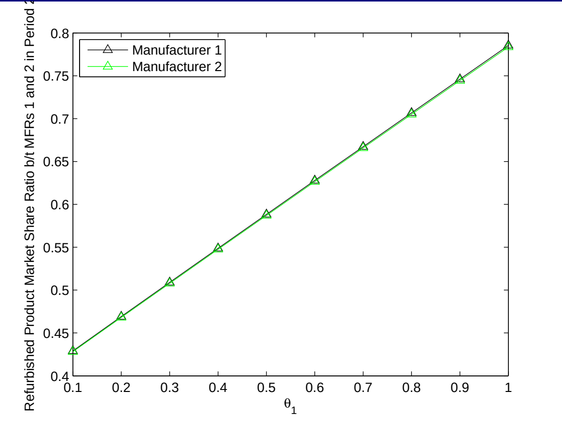

Figure : Market Share Ratio of the Refurbished Product between Manufacturers 1 and 2 with Different θ_1 Values in Period 2

Conclusion

- Proposed a two-period CLSC network model that considers the competition and product remanufactureability design.
- Studied theoretical properties of the network equilibrium solutions.
- Numerical examples provided managerial insights regarding the impacts of profit and market share from competition, remanufactureability design, and consumers' willingness-to-pay on the remanufactured product.

Thank You!