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Optimal Operation for Green Supply Chain in Consideration of Collection Incentive and Quality for Recycling of Used Products

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ABSTRACT

In recent years, for the purpose of solving the problem regarding environment protection and resource saving, certain measures and policies have been promoted to establish a green supply chains (GSC) with material flows from collection of used products to reuse of recycled parts in production of products. In this study, we propose an optimal operation of the GSC while considering the collection incentive of the used products and quality for recycling of used products. Two types of decision-making approaches are used for product quantity, collection incentive of used products and lower limit of quality level of reusable parts in the used products for recycling in the GSC. One is the decision-making under an independent policy in decentralized supply chains where a retailer and a manufacturer make decisions so as to maximize profits individually. The other is the decision-making under a cooperative policy in centralized supply chains where a retailer and a manufacturer make decisions cooperatively so as to maximize the whole system's profit. Additionally, we also discuss supply chain coordination as a manufacturer-retailer partnership based on profit sharing. Furthermore, we show the effect of the quality of the reusable parts on the optimal decisions. The collection incentive of the used products was found to bring more profitability to the GSC activity.

Keywords: Green Supply Chain, Quality, Collection Incentive, Independent Policy, Cooperative Policy

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1. INTRODUCTION

In recent years, from the rise of social concern about the environment problem, the concept of a new supply chain management has been important in optimally controlling a supply chain including traditional forward chains/logistics and reverse chains/logistics. The traditional forward chains/logistics include the flows from procurement of new materials through production of new products to selling them. The reverse chains/logistics include the flows from collection of used products through recycling parts from the used products to reuse the recycled parts (Aras *et al*., 2004; Behret and Korugan, 2009; Ferguson *et al*., 2009; Fleischman *et al*., 1997; Guide and Van Wassenhove, 2001; Inderfurth, 2005; Konstantaras *et al*., 2010; Mukhopadhyay and Ma, 2009; Nenes *et al*., 2010; Pokharel and Liang, 2012; Teunter and Flapper, 2011; Wei *et al*., 2011; Wu, 2012).

Also, a supply chain including the forward chains and the reverse chains has been called a closed-supply chain, reverse supply chain or a green supply chain (GSC) (Bakal and Akcali, 2006; Fleischman *et al.,* 1997;

Guide and Van Wassenhove, 2001; Inderfurth, 2005; Kaya, 2010; Lee *et al*., 2010; Shi *et al.,* 2010, 2011; Tagaras and Zikopoulos, 2008; Thierry *et al*., 1995; Van Wassenhove and Zikopoulos, 2010; Wei *et al*., 2012; Yan and Sun, 2012; Zikopoulos and Tagaras, 2007; Zikopoulos and Tagaras, 2008). In this study, we refer a supply chain including the forward chains and the reverse chains to a GSC. The manufacturing to reuse recycled parts is called the remanufacturing. It is necessary to take some measures and policies in order to promote 3R activities (Reuse-Recycle-Reduce) in the GSC.

There are several previous papers regarding the optimal operations for GSC, and the uncertainty in remanufacturing has been attracting more attention in recent papers.

The incorporation of the uncertainty in demands of products/parts and collection quantity of used products into GSC have been discussed by Inderfurth (2005), Lee *et al*. (2011), Mukhopadhyay and Ma (2009), Shi *et al.* (2010, 2011), and Wei *et al*. (2011).

The incorporation of the price-sensitivity in collection quantity of used products and demands of products/parts into the optimal tactical production planning GSC have been discussed by Bakal and Akcali (2006), Pokharel and Liang (2012), Shi *et al*. (2010), Teunter and Flapper (2011), Wei *et al.* (2012), and Yan and Sun (2012).

Also, the effects of inspection and sorting of used products on the optimal tactical production planning in GSC have been discussed by Aras *et al.* (2004), Behret and Korugan (2009), Ferguson *et al.* (2009), Guide and Van Wassenhove (2001), Konstantaras *et al*. (2010), Nenes *et al*. (2010), Tagaras and Zikopoulos (2008), Van Wassenhove and Zikopoulos (2010), and Zikopoulos and Tagaras (2007, 2008).

When the GSC is dealt, it is necessary to consider a variety of quality of used products collected from a market. Some authors have discussed the optimal tactical production planning by incorporating uncertainty in the quality of used products into the GSC. Aras *et al.* (2004) investigate the issue of the stochastic nature of product returns and find conditions under which quality-based categorization is most cost effective. Zikopoulos and Tagaras (2007) investigated how the profitability of reuse activities is affected by uncertainty regarding the quality of returned products in two collection sites and determined the unique optimal solution (procurement and production quantities). In Guide and Van Wassenhove (2001) and Ferguson *et al.* (2009), returned products are assumed to have *N* quality categories, and the procurement prices and the remanufacturing costs are different based on the corresponding quality level. Behret and Korugan (2009) discussed a remanufacturing stage with uncertainties in the quality of remanufacturing products, return rates and return times of returned products. After returned products are classified by considering quality uncertainties, remanufacturing processing times, material recovery rates, the remanufacturing costs, and disposal costs are determined by using the ARENA simulation program. Mukhopadhyay and Ma (2009) discussed a GSC model consisting of a retailer who sells a single product and a manufacturer who collects used products from a market, remanufactures parts from the used products and then produces products. They assumed two situations for the remanufacturing ratio between reuse parts and used products: a constant situation and an uncertain situation. Under each situation, they proposed the optimal production strategy for the procurement quantity of used products, the remanufacturing quantity of parts from used products and the production quantity of new parts from new materials. Nenes *et al*. (2010) observed that both quality and quantity of returns (used products) are unfortunately high stochastic, and investigated the optimal policies for ordering of new products and remanufacturing of products so as to maximize the companies' performance such as minimizing their expected cost or maximizing their expected profit. Teunter and Flapper (2011) discussed how quality of cores (i.e., products supplied for remanufacturing) can vary significantly, affecting the cost of remanufacturing, and derived the optimal policies regarding acquisition and remanufacturing for both deterministic and uncertain demand.

Kaya (2010) discussed a GSC model consisting of a retailer who collects used products from customers and sells a single product and a manufacturer who remanufactures parts from the used products and produces the products. They proposed the optimal decisions for collection incentive of used products and production quantities of both remanufacturing parts and new parts.

Also, it is necessary to determine the optimal operations to establish a GSC to obtain its profitability. As one of the optimal decision-making approaches under a decentralized supply chain where all members in the GSC determine the optimal operations so as to maximize their profits, the Stackelberg game has been adopted in several previous papers. In the Stackelberg game, there is a single leader of the decision-making and a single/multiple followers of the decision-making of the leader. The leader of the decision-making determines the optimal strategy so as to maximize the leader's (expected) profit. The follower(s) of the decision-making determine(s) the optimal strategy so as to maximize the follower(s)'s (expected) profit under the optimal strategy determined by the leader of the decision-making (Aust and Buscher, 2012; Berr, 2011; Cachon and Netessine, 2004; Cai *et al*., 2009; Esmaeili and Zeephongsekul, 2010; Hu *et al*., 2011; Leng and Parlar, 2009; Liu *et al*., 2012; Mukhopadhyay *et al*., 2011; Xu *et al*., 2012; Yan and Sun, 2012).

Also, in a supply chain management, the optimal decisions under the cooperative policy which maximizes the whole system's expected profit can bring the more expected profit to the whole system than those for the independent policy which maximizes the individual members' expected profit. So, from the aspect of the total optimization in supply chain management, it is preferable for all members in supply chain to shift the optimal decisions for the cooperative policy. In this case, it is the absolute requirement for all members under the cooperative policy to obtain the more expected profits than those under the independent policy. In order to achieve the increases in profits of all members under cooperative policy in the supply chain, a variety of supply chain coordination approaches between all members have been discussed by Cachon and Netessine (2004), Du *et al.* (2011), Kaya (2010), Tsay *et al.* (1999), Wei *et al.* (2012), Wu (2012), Yan and Sun (2012), and Yano and Gilbert (2005).

The incorporation of the game theory into not only the optimal pricing strategies, but also the supply chain coordination in GSC have been discussed by Kaya (2010), Wei *et al.* (2012), Wu (2012), and Yan and Sun (2012).

From the previous papers regarding GSC, product recovery, recycling, remanufacturing and reverse logistics, the lower level of quality levels of used products were not considered for the optimal decision for the remanufacturing ratio. Also, in the previous papers above, the relation between a collection incentive of used products and the collection quantity of used products was not described clearly. In addition, the cost for recycling used products has not been considered as profits in GSC in the papers mentioned above.

Differing from the previous papers above, this paper proposes an optimal operation of a GSC while considering collection incentive of used products and quality of reusable parts in used products for recycling. Specifically, in the GSC, a retailer pays an incentive for collection of used products from customers and hands over the used products to a manufacturer. Further, the retailer specifies a production quantity of the product by considering product demand uncertainty. The manufacturer disassembles the used products, and then classifies the reusable parts into quality levels by the result of the inspection of the used products. After the classification, the manufacturer makes a decision for advisability of reuse based on quality level of the reusable parts and pays the compensation a part of the retailer's incentive for collection of used products based on the quantity of the recycled parts to the retailer.

This paper investigates two types of decision-making approaches for product quantity, collection incentive of used products and lower limit of quality level of reusable parts in the used products for recycling in the GSC. One is the decision-making under the independent policy in decentralized supply chains where a retailer and a manufacturer make decisions so as to maximize profits individually. We use the Stackelberg game when the independent policy is adopted in the GSC model. In the independent policy, the retailer is the leader of decision-making, and the manufacturer is the follower of decision-making of the retailer. The other is the decision-making under the cooperative policy in centralized supply chains where a retailer and a manufacturer make decisions cooperatively so as to maximize the whole system's profit. Additionally, we discuss supply chain coordination between a manufacturer-retailer partnership in order to guarantee more profits to the retailer and the manufacturer under the cooperative policy. We present a profit sharing approach in which the increment of the expected profit of the whole system obtained under the cooperative policy is shared between the retailer and the manufacturer under the this policy. Furthermore, we show the effect of the quality of the reusable parts in used parts on the optimal decisions and the expected profits. The collection incentive of the used products was found to bring more profitability to the GSC activity. Finally, we discuss how the optimal operations in the GSC in our model and the results in numerical analysis are interpreted in the real GSC practice.

The rest of our paper is organized as follows: in Section 2, notation used in our model is defined. In Section 3, operational flows of a GSC model and the model assumption are described. Section 4 proposes the optimal decision-making for the relative GSC model under the independent policy and the cooperative policy. Section 5 presents the results of numerical examples to illustrate managerial insights for the optimal operation of the GSC model proposed in our paper. In Section 6, conclusions for our paper are summarized.

2. NOTATIONS

The following notations are used to formulate a GSC model addressed in this paper.

General notations

- Q : production quantity of product, referred to production quantity
- t : collection incentive per used product (purchasing cost), referred to collection incentive
- u : lower limit of quality level to remanufacture reusable parts after disassembly of used products, referred to lower limit of quality level ($0 \le u \le 1$)
- $A(t)$: collection quantity of product for collection incentive t
- $R(t)$: compensation per used product paid to a retailer from a manufacturer for the amount of used products which are remanufactured
- c_a : disassembly and inspection cost per used product
- ℓ : quality level of reusable parts ($0 \le \ell \le 1$)
- $g(\ell)$: probability density function of quality level ℓ
- $c_r(\ell)$: remanufacturing cost per a reusable part in the case of quality level ℓ
- c_d : disposal cost per un-reused part
- c_n : procurement cost per new part
- c_m : production cost per product
- m_a : margin obtained from wholesale per product
- w : wholesale price of product, referred to unit wholesale price
- p : sales price per product, referred to unit sales price
- t_U : upper limit of collection incentive t

s : shortage penalty cost per product of which demand is unsatisfied
h_r : inventory holding cost per unsold products
x : demand of product in a market
$f(x)$: probability density function of demand x

Notations for independent policy
Q_D^* : optimal production quantity under independent policy
t_D^* : optimal collection incentive under independent policy
$u_D(t)$: provisional lower limit of quality level determined for a given collection incentive t under independent policy
u_D^* : optimal lower limit of quality level under independent policy

Notations for cooperative policy
Q_C^* : optimal production quantity under cooperative policy
t_C^* : optimal collection incentive under cooperative policy
u_C^* : optimal lower limit of quality level under independent policy

3. OPERATIONAL FLOWS OF GSC MODEL AND THE MODEL ASSUMPTIONS

3.1 Operational Flows of GSC Model

1. We consider a GSC model which consists of a manufacturer and a retailer. We also assume that a single product, such as mobile phone and personal computer, is produced and is sold in a market.
2. A retailer pays the collection incentives t to collect used products from a market. The retailer hands over all the used products to the manufacturer.
3. A manufacturer disassembles the used products and inspects all the reusable parts. In this study, we assume that the manufacturer reuses a single type of parts of used product to produce a single product. After the inspection, the manufacturer classifies the reusable parts for quality level ℓ. The manufacture determines optimally the lower limit of quality level u for quality level ℓ of the reusable parts. Here, we assume that the lower the value of a quality level ℓ $(0 \leq \ell \leq 1)$ of reusable parts is, the higher the remanufactured cost to remanufacture a reused part from a reusable part with quality level ℓ. The manufacturer remanufactures all the reusable parts with quality level more than the lower limit of quality level u. Here, we assume that the quality of reused parts remanufactured from reusable parts is as good as that of new parts produced from new materials. The manufacturer disposes all the reusable parts with the lower quality level than the lower limit of quality level u of reusable parts.
4. The manufacturer pays the compensation to the retailer for the cooperation to collection of the used products. Specifically, the manufacture pays the compensation $R(t)$ to the retailer who paid the collection incentive t to collect the quantity $A(t)$ of the used products that are used to reuse parts of the used products.
5. The retailer determines optimally the collection incentive t and the production quantity Q.
6. The manufacturer produces the production quantity Q ordered from the retailer, and sells the product to retailer at the unit wholesale price w.
7. The manufacturer produces the required quantity of new parts to compensate the shortage quantity of parts if reused parts are unsatisfied with the required quantity of parts for the production quantity Q.
8. The retailer sells a single product in a market with the unit sales price p during a single period. The retailer incurs the unit inventory holding h_r of unsold products and the unit shortage penalty cost s of products unsatisfied demand.

3.2 Assumption of GSC Model

We suppose the following situations:

i) A single type of reusable part is picked up from the used product. The single reusable parts are remanufactured as a single type of reused parts to produce a single product.
ii) Regarding collecting the used products, a retailer pays the collection incentive t to collect the used products from a market. Here, the collection quantity of the used products $A(t)$ varies according to the collection incentive t. In general, the higher the unit collection incentive t is, the more used products a retailer can collect from the market, where the collection incentive t has the upper limit t_U $(0 \leq t \leq t_U < p)$. The manufacturer pays the compensation to the retailer for cooperation in collecting the used products. Concretely, the manufacturer pays the compensation $R(t)$ to the retailer who paid the collection incentive t to collect the quantity $A(t)$ of the used products which are remanufactured.
iii) The collection quantity $A(t)$ of used products is not enough to satisfy the expected demand of product even if retailer pays the upper limit t_U of the collection incentive t.
iv) The unit wholesale price is calculated from the unit procurement cost of new parts, the unit production cost of product and the unit margin obtained from the unit wholesale of product.
v) Demand x of product in a market follows a probabilistic distribution with the probability density function $f(x)$.
vi) The distribution of quality level ℓ of reusable parts is modelled by using a probabilistic distribution with the probability density function $g(\ell)$.

vii) The remanufacturing cost $c_r(\ell)$ varies according to quality level ℓ of reusable parts. Here, $\ell = 0$ indicates the worst quality level of reusable products, in contrast, $\ell = 1$ indicates the best quality level of usable products. Therefore, $c_r(\ell)$ is a monotone decreasing function in terms of quality level ℓ $(0 \leq \ell \leq 1)$ of reusable parts.

4. OPTIMAL DECISION-MAKING FOR GSC MODEL

4.1 Expected Profits of GSC Model under Independent Policy and Optimal Decision-Making

We use the Stackelberg game when the independent policy is adopted in the GSC model. In the independent policy, the retailer is the leader of decision-making, and the manufacturer is the follower of decision-making of the retailer. The retailer determines the optimal production quantity Q_D^* and the optimal collection incentive t_D^* so as to maximize the expected profit. The manufacturer determines the optimal lower limit of quality level u_D^* to maximize the expected profit under the optimal order quantity Q_D^* and the optimal collection incentive t_D^*. Next, the manufacturer produces the same quality of the optimal order quantity Q_D^* and sells the product to the retailer at the unit wholesale price w. We explain the procedure for the optimal decision-making (Q_D^*, t_D^*, u_D^*) under the independent policy.

First, based on Sections 3.1 and 3.2, we formulate the expected profit of the retailer for production quantity Q and demand of product in a market. The expected profit of the retailer consists of the collection cost of used products from a market, the procurement cost of product, the compensation income, the product sales, the inventory holding cost of the unsold products and the shortage penalty cost of the market. Concretely, the expected profit of the retailer $E\left[\pi_R(Q,t,u)\right]$ for the production quantity Q, the collection incentive t and the lower limit of quality level u is formulated as

$$E\left[\pi_R(Q,t,u)\right] = -tA(t) - wQ + R(t)\int_u^1 g(\ell)A(t)d\ell$$
$$+\int_0^Q \left\{px - (Q-x)h_r\right\} f(x)dx$$
$$+\int_Q^\infty \left\{pQ - (x-Q)s\right\} f(x)dx. \quad (1)$$

Next, based on Sections 3.1 and 3.2, we formulated the expected profit of the manufacturer. The expected profit of the manufacturer consists of the product wholesales, the compensation cost, the disassembly and the inspection costs of used products, the remanufacturing cost of reusable parts, the disposal cost of un-recycled parts, the procurement cost of new parts and the production cost of product. Concretely, the expected profit $E\left[\pi_M(u,t,Q)\right]$ for the production quantity Q, the collection incentive t and the lower limit of quality level u of the manufacturer is formulated as

$$E\left[\pi_M(u,t,Q)\right] = wQ - R(t)\int_u^1 g(\ell)A(t)d\ell$$
$$-c_a A(t) - A(t)\int_u^1 c_r(\ell)g(\ell)d\ell - c_d A(t)\int_0^u g(\ell)d\ell$$
$$-c_n\left\{Q - A(t)\int_u^1 g(\ell)d\ell\right\} - c_m Q. \quad (2)$$

Here, no environmental impact cost function appears clearly in either the expected profit of retailer or that of manufacturer in Eqs. (1) and (2). This is the reason why we analyze the expected profit of each member in the GSC simply. However, it is possible to interpret that any environmental impact cost function is included in parts of the collection incentive per used product, the remanufacturing cost per reusable part and the disposal cost per reusable part in our model. It implies that it is possible to add any relevant environmental impact cost function into the expected profits of the retailer and the manufacturer by separating any relevant environmental impact cost from the collection incentive per used product, the remanufacturing cost per reusable part and the disposal cost per reusable part in our model. The concrete incorporation of the environmental cost into the relevant expected profit of each member will be discussed as one of the future topics in this study.

4.2 Optimal Decision-Making under Independent Policy

We can obtain the following first- and second-order differential equations between the production quantity Q and the expected profit $E\left[\pi_R(Q)\middle|t,u\right]$ of the retailer in Eq. (1) under the collection incentive t and the lower limit of quality level u:

$$\frac{dE\left[\pi_R(Q|t,u)\right]}{dQ} = -w + p + s$$
$$-p\int_Q^\infty f(x)dx - h_r\int_0^Q f(x)dx - s\int_Q^\infty f(x)dx. \quad (3)$$

$$\frac{d^2E\left[\pi_R(Q|t,u)\right]}{dQ^2} = -(p + h_r + s)f(Q) < 0. \quad (4)$$

From Eq. (4), we can see that the expected profit of the retailer in Eq. (1) is concave function in terms of the production quantity Q. Therefore, we can see that the optimal production quantity Q_D^* can be determined regardless of the collection incentive t and the lower limit of quality level u.

Therefore, the optimal production quantity Q_D^* can be determined as

$$Q_D^* = F^{-1}\left(\frac{-w+p+s}{p+h_r+s}\right), \tag{5}$$

satisfying $dE\left[\pi_R\left(Q\middle|t,u\right)\right]\Big/dQ = 0$ for Eq. (3).

Next, under the optimal production quantity Q_D^* in Eq. (5), the optimal collection incentive t_D^* and the optimal lower limit of quality level u_D^* under the independent policy is determined independently from standpoints where the retailer is the leader of decision-making and the manufacturer is the follower of decision-making.

We can obtain the following first-order differential equation between the lower limit of quality level u and the expected profit $E\left[\pi_M(u)\middle|Q_D^*, t\right]$ of the manufacturer in Eq. (2) under the optimal production quantity Q_D^* and the collection incentive t:

$$\frac{dE\left[\pi_M(u)\middle|Q_D^*, t\right]}{du} = A(t)\,d(u)\left\{c_r(u)+R(t)-c_d-c_n\right\}. \tag{6}$$

We can see that Eq. (6) is zero if and only if to satisfy the following condition:

$$c_r(u)+R(t)-c_d-c_n = 0. \tag{7}$$

Here, from vii) in Section 3.2, we have the following property regarding the remanufacturing cost of the reusable parts: the remanufacturing cost $c_r(\ell)$ is a monotonically decreasing function for the lower limit of quality level ℓ of reusable parts. Therefore, we can see that there is the unique lower limit of quality level u to satisfy Eq. (7) under the collection incentive t. We define the lower limit of quality level u to satisfy Eq. (7) as the provisional lower limit of quality level $u_D(t)$ determined under the collection incentive t. We can see that the provisional lower limit of quality level $u_D(t)$ maximizes the expected profit $E\left[\pi_M(u_D(t))\middle|Q_D^*, t\right]$ under the optimal production quantity Q_D^* and the collection incentive t.

Meanwhile, when the following condition:

$$c_r(u)+R(t)-c_d-c_n < 0. \tag{8}$$

is satisfied, the provisional lower limit of quality level $u_D(t)$ is determined as $u_D(t)=1$ from the property regarding the remanufacturing cost of the reusable parts. Similarly, when the following condition:

$$c_r(u)+R(t)-c_d-c_n > 0. \tag{9}$$

is satisfied, the provisional lower limit of quality level $u_D(t)$ is determined as $u_D(t)=0$. However, in the situation that the usable parts in used products are remanufactured as the reused parts, the situations of $u_D(t)=1$ or $u_D(t)=0$ are not common as the condition of $c_r(u)$, $R(t)$, c_d and c_n.

Therefore, note that it is common for the GSC model addressed in this paper to suppose a situation to satisfy the condition in Eq. (7) as the relation between the remanufacturing cost $c_r(u)$, the compensation $R(t)$, the disposal cost c_d and the procurement cost c_n. Eventually, from Eq. (7), the provisional lower limit of quality level $u_D(t)$ is determined as the lower limit of quality level u to satisfy generally the following condition:

$$c_r(u_D(t))+R(t) = c_d + c_n, \tag{10}$$

which means that the sum of the remanufacturing cost $c_r(u)$ and the compensation $R(t)$ is equal to the sum of the unit disposal cost c_d and the unit procurement cost c_n of new parts.

Furthermore, we substitute the collection incentive t and the provisional lower limit of quality level $u_D(t)$ into Eq. (1) under the optimal production quantity Q_D^*. We determine the optimal combination $\left(t_D^*, u_D^*\right)$ as a combination $\left(t, u_D(t)\right)$ to maximize the retailer's expected profit $E\left[\pi_R\left(t, u_D(t)\middle|Q_D^*\right)\right]$ by varying the collection incentive t within the range where $0 \le t \le t_U$.

Here, we assume that $u_D(t)$ is within the range where $0 \le u_D(t) \le 1$ and the compensation $R(t)$ is a monotonically increasing function in terms of the collection incentive t. Therefore, the upper limit t_U of the collection incentive t is set so as to satisfy the following condition which $u_D(t)=1$ is substituted into Eq. (7):

$$c_r(1)+R(t) = c_d + c_n. \tag{11}$$

Thus, the optimal collection incentive t_D^* and the optimal lower limit of quality level u_D^* are determined mutually between the retailer and the manufacturer. Substituting the optimal decision for the independent policy $\left(Q_D^*, t_D^*, u_D^*\right)$ into Eqs. (1) and (2), the expected profits of the retailer, the manufacturer are obtained. Also, the expected profit of the whole system under the independent policy is obtained as the sum of the expected profits of the retailer and the manufacturer under this policy.

4.3 Optimal Decision-Making under Cooperative Policy

In the cooperative policy, we determine the optimal production quantity Q_C^*, the optimal collection incentive t_C^* and the optimal lower limit of quality level u_C^* so as to maximize the expected profit of the whole system.

The expected profit of the whole system is obtained from the sum of the expected profits of the retailer and the manufacturer in Eqs. (1) and (2). The expected of the whole system $E\left[\pi_S\left(Q,t,u\right)\right]$ for the production quantity Q, the collection incentive t and the lower limit of quality level u is formulated as

$$E\left[\pi_S\left(Q,t,u\right)\right] = -c_m Q - tA(t) - c_a A(t)$$

$$
\begin{aligned}
& -tA(t)\int_u^1 c_r(u)g(\ell)d\ell \\
& -c_d A(t)\int_0^u g(\ell)d\ell - c_n\left\{Q - A(t)\int_u^1 g(\ell)\,d\ell\right\} \\
& +\int_0^Q \{px-(Q-x)h_r\} f(x)dx \\
& +\int_Q^\infty \{pQ-(x-Q)s\} f(x)dx. \qquad (12)
\end{aligned}
$$

In the cooperative policy, the relevant terms regarding the wholesale of product and the compensation for reused parts are canceled out between the retailer and the manufacturer.

In a way similar to the independent policy, we investigate if the expected profit of the whole system in Eq. (12) is concave function in terms of the production quantity Q under the collection incentive t and the lower limit of quality level u. We can obtain the following first-order and second-order differential equations between the production quantity Q and $\pi_S(Q|\,t,\,u)$ under the collection incentive t and the lower limit of quality level u:

$$
\begin{aligned}
& \frac{dE\left[\pi_S\left(Q\middle|\,t,\,u\right)\right]}{dQ} = -c_m - c_n + p + s \\
& -p\int_Q^\infty f(x)dx - s\int_Q^\infty f(x)dx - h_r\int_0^Q f(x)dx. \qquad (13)
\end{aligned}
$$

$$
\frac{d^2E\left[\pi_S\left(Q\middle|t,u\right)\right]}{dQ^2} = -\left(p+s+h_r\right)f(Q). \qquad (14)
$$

From Eq. (14), we can see that the expected profit of the whole system in Eq. (12) is concave function in terms of the production quantity Q in a way similar to the independent policy. Therefore, we can see that the optimal production quantity Q_C^* can be determined regardless of the collection incentive t and the lower limit of quality level u. Therefore, the optimal production quantity Q_C^* can be determined as

$$
Q_C^* = F^{-1}\left(\frac{-c_n - c_m + p + s}{p + h_r + s}\right), \qquad (15)
$$

satisfying $dE\left[\pi_S\left(Q\middle|t,u\right)\right]\big/dQ = 0$ for Eq. (13).

Next, under the optimal production quantity Q_C^* in Eq. (15), the optimal collection incentive t_C^* and the optimal lower limit of quality level u_C^* are determined under the cooperation policy. We can obtain the following first-order differential equation between the lower limit of quality level u and the expected profit $E\left[\pi_s\left(u\middle|\,Q_C^*,\,t\right)\right]$ of the whole system in Eq. (12) under the optimal production quantity Q_C^* and the collection incentive t:

$$
dE\left[\pi_S\left(u\middle|\,Q_C^*,\,t\right)\right] = A(t)g(u)\{c_r(u) - c_d - c_n\}. \qquad (16)
$$

Here, Eq. (16) is zero if and only if when the following condition is satisfied:

$$
c_r(u) - c_d - c_n = 0. \qquad (17)
$$

Here, from vii) in 3.2, the unit remanufacturing cost $c_r(u)$ is a monotonically decreasing function in terms of the lower limit of quality level u. So, we can see that there is the unique optimal lower limit of quality level u_C^* regardless of the production quantity Q and the collection incentive t. Therefore, we can obtain the optimal lower limit of quality level u_C^* so as to satisfy generally the following condition:

$$
c_r(u) = c_d + c_n, \qquad (18)
$$

which means that the remanufacturing cost $c_r(u)$ is equal to the sum of the unit disposal cost c_d and the unit procurement cost c_n of new parts.

The optimal collection incentive t_C^* is determined so as to maximize the expected profit of the whole system in the cooperative policy in Eq. (12) under the optimal production quantity Q_C^* in Eq. (15) and the optimal lower limit of quality level u_C^* in Eq. (18).

First, we substitute the optimal production quantity Q_C^* and the optimal lower limit of quality level u_C^* into the expected profit of the whole system in Eq. (12). We determine the optimal collection incentive t_C^* so as to maximize the expected profit of the whole system $E\left[\pi_S\left(t\middle|\,Q_C^*,\,u_C^*\right)\right]$ by varying the collection incentive t within the range where $0 \le t \le t_U$. Here, the unit collection incentive t is interpreted as the unit procurement cost of raw materials for remanufacturing. Therefore, in a way similar to Eq. (11), the upper limit t_U of the collection incentive t under the cooperative policy is set so as to satisfy the following condition:

$$
c_r(1) + t = c_n + c_d. \qquad (19)
$$

Substituting the optimal decision for the cooperative policy (Q_C^*, t_C^*, u_C^*) into Eqs. (12), (1), and (2), the expected profits of the whole system, the retailer and the manufacturer under the cooperative policy are obtained.

5. NUMERICAL ANALYSIS

In this section, we illustrate the properties of the independent policy and the cooperative policy through some numerical examples. Concretely, we compare the optimal production quantity, the optimal collection incentive, the optimal lower limit of quality level and the expect profits of a retailer, a manufacturer and the whole system under the independent policy with those under the cooperative policy.

5.1 Setting of System Parameters

We used the following system parameter values for numerical examples: $p=150$, $s=175$, $h_r=15$, $c_a=1$, $c_d=1$, $c_n=35$, $c_m=2$, $m_a=15$. Demand x of product in a market follows the normal distribution with the mean $\mu=1000$ and standard deviation $\sigma=300$. Also, we set $A(t)$, w and $c_r(\ell)$ as $A(t)=100+50t\ (0\le t\le t_U)$, $w=c_n+c_m+m_a$, $c_r(\ell)=40(1-0.9\ell)$, satisfying the conditions of ii), iv) and vii) in Section 3.2. Furthermore, $R(t)$ is defined as $R(t)=(1+\alpha)t$, where α denotes the parameter in the compensation per used product.

From ii) in Section 3.2, the retailer receives the compensation income from the manufacturer as cooperation of recycling of the used products. Then, for the retailer who pays collection incentive t for the used products, the compensation income per used reusable part should satisfy the following conditions:

$$tA(t) < R(t)\int_u^1 g(\ell)A(t)d\ell. \tag{20}$$

Meanwhile, it is possible for the manufacturer to pay the compensation to the retailer for cooperation of recycling of used products if the total cost regarding recycling of used products, corresponding to the sum of the compensation cost to the retailer, the disassembly and inspection cost of used products, the remanufacturing cost of reusable parts and the disposal cost of unreused parts, is lower than the procurement cost of new parts. That is, for the manufacturer to pay the compensation to the retailer, the relation between the total cost regarding recycling of used products and the procurement cost of new parts should satisfy the following condition:

$$R(t)\int_u^1 g(\ell)A(t)d\ell + c_aA(t) + A(t)\int_u^1 c_r(\ell)g(\ell)d\ell + c_dA(t)\int_0^u g(\ell)d\ell \le c_nA(t)\int_u^1 g(\ell)d\ell. \tag{21}$$

Therefore, we set $\alpha=0.5$ so as to satisfy Eqs. (20) and (21). Remark that, in the independent policy, the compensation income under t_D^* and u_D^* is calculated as follows:

$$R(t_D^*)\int_{u_D^*}^1 g(\ell)A(t_D^*)d\ell,$$

in the cooperative policy, the compensation income under t_C^* and u_C^* is calculated as follows:

$$R(t_C^*)\int_{u_C^*}^1 g(\ell)A(t_C^*)d\ell.$$

As shown in Figure 1, we assume some shapes of the distribution of quality level $\ell\ (0\le\ell\le1)$ of reusable parts in used products. We model each shape of the distribution of quality level $\ell\ (0\le\ell\le1)$ of reusable parts by using the beta distribution. This is the reason why the beta distribution is possible to express various shapes of distribution of reusable parts in used products, such as the uniform distribution-type shape, the normal distribution-type shape, the exponential distribution-type shape, the left-biased distribution shape, the right-biased distribution shape, by using the following probability density function with two shape parameters (a, b):

$$f(\ell|a,b)=\frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\ell^{m-1}(1-\ell)^{n-1}, \tag{22}$$

where $\Gamma(\cdot)$ denotes the gamma function. As shown in Figure 1, we provide four cases of the beta distribution:

Case 1. $B(\ell|1,1)$: the situation where each quality of reusable parts are uniformly distributed, corresponding to the uniform distribution-type shape for quality level $\ell\ (0\le\ell\le1)$,

Case 2. $B(\ell|2,2)$: the situation where there are the more reusable parts with the middle quality and each quality of reusable parts are symmetrically distributed, corresponding to the normal distribution-type shape for quality level $\ell\ (0\le\ell\le1)$,

Case 3. $B(\ell|3,2)$: the situation where there are the more reusable parts with the relatively high quality, corresponding to the right-biased distribution shape for quality level $\ell\ (0\le\ell\le1)$,

Case 4. $B(\ell|2,3)$: the situation where there are the more reusable parts with the relatively low quality, corresponding to the left-biased distribution shape for quality level $\ell\ (0\le\ell\le1)$. By changing two shape parameters (a, b) of the probability density function of the beta distribution, we can see how the results of the optimal operations in the GSC change.

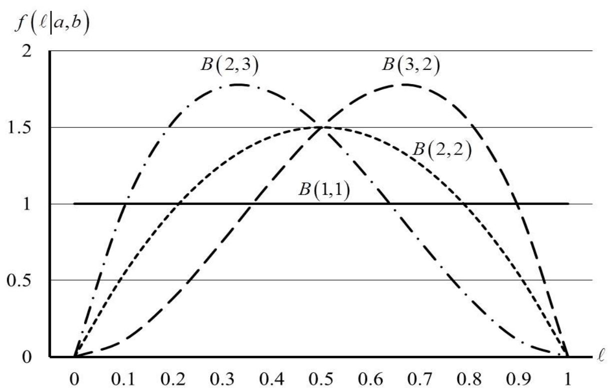

Figure 1. Four cases of distribution of quality level $\ell\ (0\le\ell\le1)$ of reusable parts in used products modeled as the beta distribution $B(\ell|a,b)$.

5.2 Results of Optimal Operations under the Independent Policy and under the Cooperative Policy

Tables 1 and 2 show the results of the optimal operations for (Q, t, u) under the independent policy and under the cooperative policy for each case of the probability distribution of quality level ℓ of reusable parts.

First, we compare the optimal production quantity Q_D^* under the independent policy with the optimal production quantity Q_C^* under the cooperative policy.

Q_D^* is determined from Eq. (5), meanwhile Q_C^* is determined from Eq. (15).

Comparing Eqs. (5) with (15), we can see that Q_D^* is affected by the whole price w, meanwhile Q_C^* is affected by the procurement cost c_n and the production cost of product c_m.

In general, it is natural to satisfy the condition where the whole price w is higher than the sum of the procurement cost c_n and the production cost of product c_m, that is, $w > c_n + c_m$.

From Eqs. (5) and (15), the optimal production quantities Q_D^* and Q_C^* can be determined as the value of inverse function for the cumulative distribution function of demand of product.

From the condition $w > c_n + c_m$, the value of the cumulative distribution function of demand of product under the cooperative policy in Eq. (5) is larger than that under the independent policy Eq. (15), that is

$$F\left(\frac{-c_n - c_m + p + s}{p + h_r + s}\right) > F\left(\frac{-w + p + s}{p + h_r + s}\right).$$

Therefore, Q_C^* under the cooperative policy is determined as a larger value than Q_D^* under the independent policy.

We can confirm that the comparison result of the optimal production quantity from the theoretical analysis regarding corresponds to that from the numerical results in Tables 1 and 2 verifying that Q_C^* is larger than Q_D^*.

It is possible to determine the more optimal order quantity under the cooperative policy than under the independent policy. This implies that the expected profits of the manufacturer and the whole system which is the sum of the retailer and the manufacturer are higher than those under the independent policy.

Next, we compare the optimal lower limit of quality level under the independent policy with that under the cooperative policy. In Tables 1 and 2, regarding the optimal lower limit of quality level, we also compare u_D^* with u_C^* under four cases of the distribution of quality level ℓ of reusable parts in used products. From the Eq. (7), it can be found that u_D^* is affected by t_D^* determined by the retailer. This is the reason why the manufacturer pays the compensation to the retailer. Meanwhile, from the Eq. (17), we can see that u_C^* is not affected by it. This is the reason why the term of compensation is canceled out between the manufacture and the retailer. Also, from Eqs. (7) and (17), u_C^* can be determined as lower values than u_D^*. This fact implies that the recycling of used products is encouraged under cooperative policy. We can confirm this feature from the results of numerical analysis, u_D^* and u_C^*, in Tables 1 and 2.

We also compare u_D^* with u_C^* for cases 1–4 of the distribution of quality level ℓ of reusable parts from Tables 1 and 2. It can be seen that u_C^* is not affected by

Table 1. Results of the optimal operation under the independent policy

Optimal operation	Case 1. $B(\ell\|1, 1)$	Case 2. $B(\ell\|2, 2)$	Case 3. $B(\ell\|3, 2)$	Case 4. $B(\ell\|2, 3)$
Optimal production quantity Q_D^*	1256	1256	1256	1256
Optimal collection incentive t_D^*	3.3	4.28	6.59	2.2
Optimal lower limit of quality level u_D^*	0.25	0.29	0.39	0.22
Expected profit				
Retailer	69741	69893	70352	69739
Manufacturer	20997	20821	21552	20006
Whole system	90738	90713	91904	89745

Table 2. Results of the optimal operation under the cooperative policy

Optimal operation	Case 1. $B(\ell\|1, 1)$	Case 2. $B(\ell\|2, 2)$	Case 3. $B(\ell\|3, 2)$	Case 4. $B(\ell\|2, 3)$
Optimal production quantity Q_C^*	1307	1307	1307	1307
Optimal collection incentive t_C^*	5.11	5.02	6.8	3.24
Optimal lower limit of quality level u_C^*	0.11	0.11	0.11	0.11
Expected profit				
Retailer	69816	70001	70684	69554
Manufacturer	21530	21283	22008	20693
Whole system	91347	91284	92692	90193

each case of the probability distribution of quality level ℓ of reusable parts. This is the reason why the compensation relevant to the distribution of quality level ℓ of reusable parts is canceled out between the retailer and the manufacturer under the cooperative policy. Meanwhile, u_D^* is affected by each case of the distribution of quality level ℓ of reusable parts.

In case 3, we can see that the more parts tend to be remanufactured, since there are the more reusable parts with the relatively high quality.

In case 4, it can be seen that the less parts tend to be remanufactured, since there are the more reusable parts with the relatively low quality. Next, the optimal collection incentive t_D^* under the independent policy is compared with the optimal collection incentive t_C^* under the cooperative policy. From Eq. (1), t_D^* is affected by the compensation income. Meanwhile, from Eq. (12), t_C^* is not affected by the compensation income, but t_C^* is affected by the compensation cost to the retailer, the disassembly and inspection cost of used products, the remanufacturing cost of reusable parts, the disposal cost of un-reused parts and the procurement cost of new parts. From Tables 1 and 2, we can see that t_C^* is determined as higher value than t_D^*. It is implied that the collection quantity of used products under the cooperation policy is more than the collection quantity of used products under the independent policy.

We also compare t_D^* with t_C^* for cases 1–4 of the distribution of quality level ℓ of reusable parts. From Tables 1 and 2, we can see that t_D^* and t_C^* are affected by the distribution of quality level ℓ of reusable parts. In case 3, because the quality of the reusable parts in the used products is relatively high quality, many used products tend to be collected under the higher collection incentive. On the other hand, in case 4, because the reusable parts which are high quality are not so many in the used products, the collection incentive is held low, relatively.

Generally, it is natural under the independent policy that the higher compensation income is, the more used products can be collected. So, we discuss the effect of the parameter α in the compensation $R(t)=(1+\alpha)t$ on t_D^* and t_C^*, shown in Table 3. From Table 3, we have the feature that the higher α is, the higher t_D^* can be obtained, meanwhile the lower α is, the lower t_D^* can be obtained. On the other hand, t_C^* is not affected by α. This reason is the compensation term is canceled out in Eq. (12). From the results, it is necessary that α is determined optimally under the independent policy.

Furthermore, we compare the expected profits under the independent policy with those under the cooperative policy. From Tables 1 and 2, the expected profits of the whole system and the manufacturer under the cooperative policy for cases 1–4 are higher than those under the independent policy. The results indicate that the profit difference between the total expected profits under the individual and cooperative policies is positive.

We can see the reason from analytical results by comparing the optimal production quantity Q_D^* under individual policy in Eq. (5) with the optimal production quantity Q_C^* under cooperative policy in Eq. (15). As mentioned above, we can see that Q_C^* is larger than Q_D^* from the general condition where $w > c_n + c_m$. The size of the whole system's profit which is the sum of the expected profits of the retailer and the manufacturer, corresponding to the size of the total expected profits, is affected by the size of the optimal production quantity. This always bring the larger expected profit to the total expected profits under cooperative policy than the individual policy, and always results in the result that the

Table 3. Effect of the compensation parameter on the optimal collection incentive

Compensation parameter	Case 1. $B(\ell\|1, 1)$		Case 2. $B(\ell\|2, 2)$		Case 3. $B(\ell\|3, 2)$		Case 4. $B(\ell\|2, 3)$	
	t_D^*	t_C^*	t_D^*	t_C^*	t_D^*	t_C^*	t_D^*	t_C^*
$\alpha=0.3$	1.99	5.11	3.56	5.02	6.26	6.8	2.05	3.24
$\alpha=0.5$	3.3	5.11	4.28	5.02	6.59	6.8	2.2	3.24
$\alpha=0.7$	3.98	5.11	4.5	5.02	6.49	6.8	2.96	3.24

Table 4. Effect of the profit sharing on the expected profits under the cooperative policy

Effect of profit sharing	Case 1. $B(\ell\|1, 1)$	Case 2. $B(\ell\|2, 2)$	Case 3. $B(\ell\|3, 2)$	Case 4. $B(\ell\|2, 3)$
Expected profits under independent policy				
Retailer	69741	69893	70352	69739
Manufacturer	20997	20821	21552	20006
Whole system	90738	90713	91904	89745
Expected profits under cooperative policy with profit sharing				
Retailer	70209	70333	70956	70087
Manufacturer	21138	20952	21736	20106
Whole system	91347	91284	92692	90193

profit difference between the total expected profits under the individual and cooperative policies is positive.

However, the retailer cannot always obtain as much benefit as the whole system and the manufacturer.

So, some profit sharing is needed between the retailer and the manufacturer under the cooperative policy so as to make the shift to the cooperative policy from the independent policy, guaranteeing more profits to the manufacturer and the retailer who is not only making most of the expected profit in the whole system, but also the leader of the decision making under independent policy.

5.3 Incorporation of Profit Sharing Approach into GSC Model

In order to guarantee more profits to the retailer and the manufacturer under the cooperative policy, we discuss a profit sharing approach that the increment of the expected profit of the whole system under the cooperative policy is shared between the retailer and the manufacturer under the this policy.

Specifically, we show a profit sharing approach adopted in this paper as follows: we calculate the difference ΔE_S between the expected profit of the whole system for the optimal decision under the cooperative policy and that under the independent policy as follows:

$$\Delta ES = E\left[\pi_S\left(Q_C^*, u_C^*, t_C^*\right)\right] - E\left[\pi_S\left(Q_D^*, u_D^*, t_D^*\right)\right]. \quad (23)$$

Since $\Delta ES > 0$ is generally satisfied, the increment of the expected profit of the whole system under the cooperative policy is shared between the retailer and the manufacturer under this policy, according to the ratio of the expected profit of each member and the whole system under this policy.

Here, the ratios of the expected profit of the retailer and the manufacturer under this policy, ρ_R and ρ_M, are respectively calculated as follows:

$$\rho_R = \frac{E\left[\pi_R\left(Q_C^*, u_C^*, t_C^*\right)\right]}{E\left[\pi_S\left(Q_C^*, u_C^*, t_C^*\right)\right]}, \quad (24)$$

$$\rho_M = 1 - p_R. \quad (25)$$

Based on these ratios ρ_R and ρ_M, the amounts of profit sharing of the retailer and the manufacturer, φ_R and φ_M, are respectively decided as follows:

$$\varphi_R = \Delta ES \times \rho_R, \quad (26)$$

$$\varphi_M = \Delta ES \times \rho_M. \quad (27)$$

Therefore, under the cooperative policy in the case of adopting the profit sharing approach, the expected profits of the retailer and the manufacturer can be obtained by adding the amount of profit sharing of each player, φ_R and φ_M, to the expected profit of each player for the optimal decisions under independent policy as follows:

$$\tilde{E}\left[\pi_R\left(Q_C^*, u_C^*, t_C^*\right)\right] = E\left[\pi_R\left(Q_D^*, u_D^*, t_D^*\right)\right] + \varphi_R, \quad (28)$$

$$\tilde{E}\left[\pi_M\left(Q_C^*, u_C^*, t_C^*\right)\right] = E\left[\pi_M\left(Q_D^*, u_D^*, t_D^*\right)\right] + \varphi_M, \quad (29)$$

Thus, from Eqs. (28) and (29), it can be clearly shown that the expected profit of each member under the cooperative policy with the profit sharing approach increases in comparison with the expected profit of each member under the independent policy.

Note that there are many other approaches for supply chain coordination (e.g., quantity discount contract, contract to coordinate parameters based on Nash bargaining solution, etc. (Cachon and Netessine, 2004; Du *et al*., 2011; Kaya, 2010; Tsay *et al*., 1999; Wei *et al.*, 2012; Wu, 2012; Yan and Sun, 2012; Yano and Gilbert, 2005), but we omit the analysis for different types of supply chain coordination here for the sake of brevity.

Table 4 shows the effect of the cooperative policy with the profit sharing approach on the expected profits. From Table 4, it can be found that the expected profits of the retailer and the manufacturer under cooperative policy with profit sharing are higher than those under the independent policy in all cases of the distribution of quality level ℓ of reusable parts. Thus, the effect of the profit sharing in the cooperative policy can be verified. Therefore, it is verified that profit sharing can play a valuable role in encouraging all players in the GSC to make the shift to the decision-making under the cooperative policy.

6. CONCLUSION

In this paper, we proposed an optimal operation for a GSC under the consideration of to promote the collection incentive of used products and the quality of reusable parts in the used products for recycling. Two types of decision-making approaches are used for product quantity, collection incentive of used products and lower limit of quality level of reusable parts in the used products for recycling in the GSC. One is the decision-making under the independent policy in decentralized supply chains where a retailer and a manufacturer make decisions so as to maximize profits individually. The other is the decision-making under the cooperative policy in centralized supply chains where a retailer and a manufacturer make decisions cooperatively so as to maximize the whole system's profit. Furthermore, we have illustrated the effect of the quality distribution of reusable parts in used products on the optimal decision-making and the expected profits. Consequently, it has been found that collection incentive of the used products brings more profitability to the GSC activity. Additionally, we also discussed supply chain coordination as a manufacturer-retailer partnership based on profit sharing.

Based on the results of numerical analysis, we suggest the following interpretations in the real GSC practice:

- It is profitable to determine optimally the lower level of quality of reusable parts after disassembly of the used products when the quality of reusable parts has is distributed several quality level.
- It is possible to guarantee to bring more profit to all the members, a retailer and a manufacturer, in a GSC by taking the more aggressive environmental activity where not only a retailer pays incentive to customers in order to collect the more used products from customers, but also a manufacturer compensate some parts of incentive the retailer paid.
- From the aspect of profit, it is possible to promote not only the more aggressive environmental activity among all the members in the GSC, but also shift to the decision-making under the cooperative policy from that under the independent policy by incorporating profit sharing approach into cooperative policy.

We have some future topics as the extendable consideration as follows:

- The incorporation of the environmental cost into the relevant expected profit of each member in the GSC in order to evaluate the impact of environmental impact on the objective function,
- the situation where the collection quantity of used products is larger than demand of product in a market,
- the situation of uncertainty in the collection quantity of used products,
- the situation where the higher quality level of reusable parts in the used products is, the higher the unit collection incentive is paid,
- the optimal decision for the compensation price for the parts remanufactured from the collected used product in consideration of supply chain coordination,
- the optimal decision for the unit wholesale price in consideration of supply chain coordination,
- the situation where the multiple types of the used products and the products are handled in the GSC.

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