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ORIGINAL PAPER

INVENTORY MANAGEMENT IN A MANUFACTURING-REMANUFACTURING SYSTEM WITH CANNIBALIZATION AND STOCHASTIC RETURNS

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ABSTRACT. **Background:** The design of a remanufacturing system that recovers sold products for reprocessing is needed to meet Japan's environmental objectives. However, to establish closed-loop supply chains for sustainability, it is necessary to consider not only environmental factors but also economic efficiency. Selling remanufactured products at prices lower than new products, may expand market sizes and allow a firm to accrue higher profits. However, a cannibalization effect will occur in which consumers who would have purchased new products, instead purchase remanufactured products at lower prices. The purpose of this study is to design a manufacturing-remanufacturing system in consideration of the cannibalization effect. Furthermore, we evaluate the system including cycle of a product by using the use period of products.

Methods: Based on a previous study, we develop a demand model with cannibalization effect using the Bass model. We deal with the demand affected by the different prices of products by introducing a demand function that increases as the price of products decreases. Moreover, by giving the use period of each product, we consider the case that the recovery period of each product is different.

Results: In numerical examples, a manufacturing-remanufacturing system using the proposed model is evaluated. The numerical results clarify the influence of the price of remanufactured products, cannibalization rate, and introduction timing of remanufactured products on total profit and remanufacturing rate of our system.

Conclusions: This manufacturing-remanufacturing system revealed the influence of cannibalization effect on total profit and the importance of price and the timing of introduction of remanufactured products. In addition, by using the use period of each product, fluctuation in the quantity of reusable products can also be taken into consideration. It is shown that it is necessary to sell remanufactured products according to product recovery.

Key words: supply chain management, economic efficiency, product recovery, market size, cannibalization effect.

INTRODUCTION

Remanufacturing systems that recover sold products and use resources more effectively are increasingly needed because of contemporary environmental problems and public awareness and concern about these problems [Ilgin and Gupta 2010, Matsumoto 2010, Gupta 2013]. Designing a remanufacturing system can facilitate the sustainable business of companies [Golińska 2014]. For example, one Japanese electronics company recovers used printers for a fee and reduces the quantity of new resources used in production by reusing and recycling parts from the recovered printers [Ricoh]. When considering recovery costs and processing costs, it is necessary to consider not only the environmental impacts but also economic efficiency to build a closed-loop system that reuses parts and recycles resources [Yamada 2012].

When remanufacturing printers, there are two methods: a new printer is produced by

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reusing and recycling parts, or a remanufactured printer is produced by replacing degraded or outdated parts. Even though the former involves reusing parts, the printer is sold as a newly manufactured product; in contrast, the latter is sold as a remanufactured printer at a lower price than a newly manufactured printer. When the prices of remanufactured products differ from those of newly manufactured products, a cannibalization effect occurs in which the demand for newly manufactured products decreases because consumers who would have originally purchased the newly manufactured products instead purchase remanufactured products at lower prices. Souza [2013] argued that pricing of newly manufactured products and remanufactured products is critical because of the cannibalization effect and a market expansion effect. Therefore, in a manufacturing-remanufacturing system that sells recovered products as remanufactured products, it is necessary to consider the prices of remanufactured products and the cannibalization effect. Nanasawa and Kainuma [2017] showed that a hybrid manufacturing-remanufacturing system is more profitable. They controlled the remanufactured product demand via the remanufactured critical ratio. Zhou et al. [2017] developed a model that addresses the issue of pricing the latest generation remanufactured products and oldest generation new products. They consider a new product with a short lifecycle that leads to a limited availability of used products. In those studies, although the cannibalization effect depending on the price of remanufactured products is introduced in their model, the fluctuation in the quantity of reusable products due to the sales quantity fluctuating over time is not taken into consideration. However, since the quantity of returned products is affected by the past sales quantity, it is necessary to consider that recovery products correspond to the sales quantity when the demand varies over period.

The purpose of this study is to design a manufacturing-remanufacturing system to propose a production planning and inventory control policy in consideration of the quantity of reusable products affected by past demand and the cannibalization effect. First, demands for newly manufactured products and remanufactured products depending on the prices of remanufactured products are formulated. Next, the economic efficiency and environmental impact of the system are evaluated by simulation experiments.

LITERATURE REVIEW

Nanasawa and Kainuma [2017] investigated the cannibalization effect in a manufacturing-remanufacturing system. They illuminated the profitability of the system by considering a two-stage scenario in which only new products are sold in the first stage and both new and remanufactured products are sold in the second stage. Moreover, the Bass model is used to express a product life cycle curve, and the influence of the introduction timing of remanufactured products, and the prices of remanufactured products in the life cycle of new products are investigated. Atasu et al. [2008] investigated the impact of competition among OEMs, the existence of green consumers, and the change in market size on the profitability of remanufacturing. Ovchinnikov [2011] analyzed the pricing strategy for a firm considering putting remanufactured products on the market together with new products. He estimated the number of consumers who would switch from purchasing a new product to purchasing a remanufactured product at a lower price and showed that it is an inverted U-shape. He noted that this implies that by charging lower prices for remanufactured products, a firm may decrease consumer switching and hence minimize cannibalization of new products while simultaneously attracting more low-end, price-sensitive consumers. However, uncertainties vis-a-vis the quantity of demand, returned products, and reusable products are not considered in this model.

In many studies focused on the uncertainty of quantity of returned products in a closed-loop supply chain, the quantity of returned products is assumed to be dependent on demand [Kurugan and Gupta 1998, Mahadevan et al. 2003, Mitra 2009, Mitra 2012, Takahashi et al. 2012]. Kurugan and Gupta [1998] assumed that the demand and the quantity of returned products are stationary and follow a Poisson distribution with a known arrival rate and return rate. Mahadevan et al. [2003] developed heuristics to determine produce-up-to levels, and they also assumed the quantity of demand and returned products follows a Poisson distribution. Zhou et al. [2017] investigated the impact on dynamic performance of uncertainties in a three-echelon manufacturing and remanufacturing closed-loop supply chain. They assumed that all remanufactured products are as-good-as-new and controlled product returns by return rate. Mitra [2012] suggested a decision model for economic order quantity using the assumption that the quantity of demand and returned products follows a normal distribution. It is also assumed that the recovery period of all products sold at the same period is equal. However, when use periods of each product are considered, the recovery period of "same period" products differ by each use period. Moreover, since the quantity of returned products is influenced by past demand, it is imperative to consider use period and past demand fluctuations in case the quantity of returned products varies with a period. Some returned products may be discarded as end-of-life products because of quality degradation. Therefore, the quantity of returned products is different from that of reusable products.

Umeda et al. [2007] proposed a "marginal reuse rate" that represents the rate of reusable products among sold products and analyzed the reusability for some products. They calculated the distribution of recovered products using the distribution of demand and use period. Their study revealed that the reusability depends on the relationship between the sales period and the use period of the products. Rai and Singh [2006] posited that the relationship between automobiles' mileage and their downtimes adheres well to a logarithmic normal distribution. Therefore, the mileage data for each product is user-dependent. Assuming that use period varies between products, we assume that use period of products follows a logarithmic normal distribution.

MANUFACTURING-REMANUFACTURING SYSTEM

The following notation is used to formulate the manufacturing-remanufacturing system.

Notations

Π: Total profit
$D(p_0)$: Potential market scale at price p_0
$D'(p_0)$: Potential market scale at price p_0 when cannibalization occurs
$f(t)$: Probability density function of newly manufactured products at period t
$R(t)$: Quantity of reusable product at period t
$M(t)$: Quantity of newly manufactured products at period t
$W(t)$: Quantity of disposals at period t
$D_n(t)$: Demand for newly manufactured products at period t
$D_r(t)$: Demand for remanufactured products at period t
$I_n(t)$: Inventory of newly manufactured products at period t
$I_r(t)$: Inventory of remanufactured products at period t
$S_n(t)$: Sales quantity of newly manufactured products at period t
$S_r(t)$: Sales quantity of remanufactured products at period t
$L_n(t)$: Lost sales of newly manufactured products at period t
$L_r(t)$: Lost sales of remanufactured products at period t
$U(i, j)$: Use period of product i recovered j-th time
$T(i, j)$: Recovery period of product i recovered j-th time
r: Return rate
p: Coefficient of innovation
q: Coefficient of imitation
p_1: Price of newly manufactured products
p_2: Price of remanufactured products
M: Potential market scale
b: Price sensitivity
γ: cannibalization rate
Δt: Introduction timing of remanufacturing products
μ: Average of use period
σ: Standard deviation of use period
l: Manufacturing lead time
l': Remanufacturing lead time

n: Maximum number of remanufacturing cycles
H: Planning horizon
Ch: Inventory holding cost per unit per period
Cs: Shortage cost per unit per period

Figure 1 shows the manufacturing-remanufacturing system used in this study. We consider a supply chain consisting of a manufacturer and its market. A manufacturer sells and recovers directly. The demands for newly manufactured products $D_n(t)$ and remanufactured products $D_r(t)$ occur at period *t* from the market, and a manufacturer meets each unit demanded from its inventory of newly manufactured products $I_n(t)$ and its inventory of remanufactured products $I_r(t)$ at period *t*, respectively. When the demand exceeds the on-hand inventory, this insufficiency of supply becomes lost sales. It is assumed that the sold products are recovered at a rate of *r* after the use period for each product $U(i, j)$. $U(i, j)$ expresses the use period until product *i* is recovered the *j*-th time. The recovered product is inspected for its recovery time. If the recovery time is less than the maximum number of remanufacturing cycles ($j < n$), the recovered product is remanufactured and kept as remanufactured product inventory. When the recovery time equals the maximum number of remanufacturing cycles ($j = n$), the recovered product is discarded. The quantity of reusable products at period *t*, the sum of the quantity of recovered products whose recovery time is less than *n*, is denoted by $R(t)$, and the quantity of disposals is denoted by $W(t)$. Manufacturing and remanufacturing lead times are denoted by *l* and *l'*, respectively. It is assumed that the demand for remanufactured products occurs after Δ*t*.

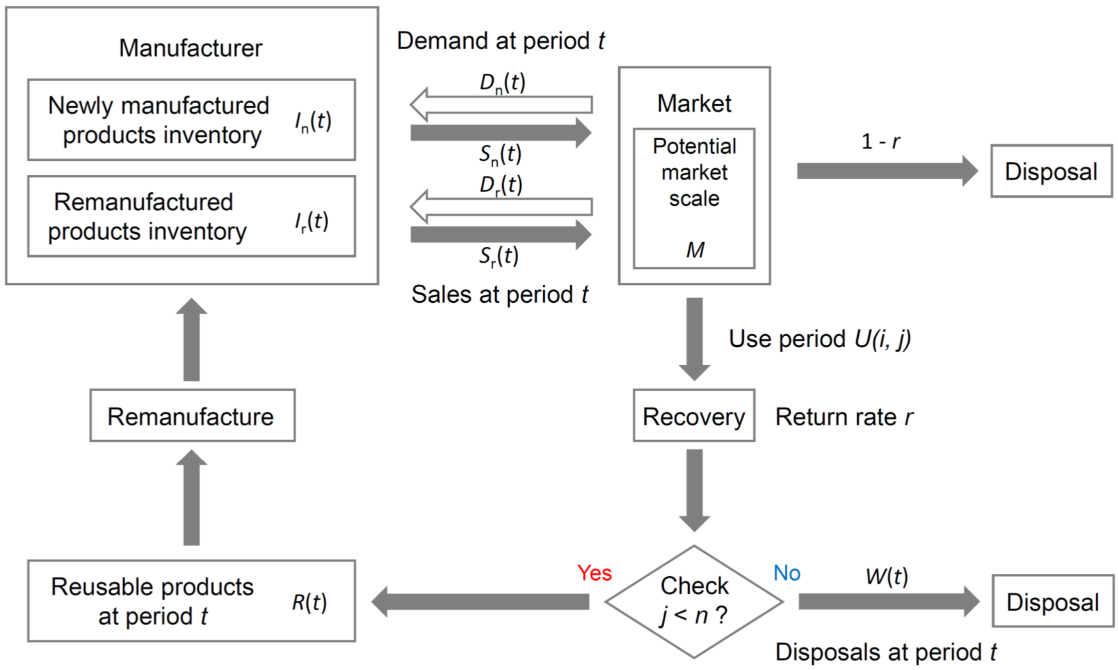

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Fig. 1. Manufacturing-remanufacturing system

DEMAND MODEL

In this section, the demand for newly manufactured products and remanufactured products affected by the prices of these products is formulated. A probability density function of newly manufactured products at period *t* using the Bass model can be expressed as follows [Bass 1969]:

$$f(t)=\frac{p(p+q)^2 e^{-(p+q)t}}{(p+qe^{-(p+q)t})^2} \qquad (1)$$

Since demand tends to decrease as the price of the product increases, the demand model shown in equation (2) is used in many studies.

$$D(p_1)=M-bp_1 \qquad (2)$$

Using equation (2), we derive the cannibalization rate γ when the prices of newly manufactured products and remanufactured products are p_1 and p_2, respectively. It is clear that $D(p_1) < D(p_2)$, since we assume that $p_1 > p_2$. The increase in demand $D(p_2)$ - $D(p_1)$, due to the price falling from p_1 to p_2, can be considered as purchasing remanufactured products. If cannibalization occurs, demand for newly manufactured products becomes smaller than $D(p_1)$, and demand for remanufactured products becomes larger than $D(p_2)$ - $D(p_1)$. Letting $D'(p_1)$ and $D'(p_2)$ be actual demand for newly manufactured products and remanufactured products at p_1 and p_2, respectively, the formula $D'(p_1) < D(p_1)$ is established when cannibalization occurs. Assuming that the cannibalization rate γ is defined as the degree of reduction by cannibalization, γ can be expressed via the following equation:

$$\gamma=\frac{D(p_1)-D'(p_1)}{D(p_1)} \qquad (3)$$

Since demand for newly manufactured products can be taken from 0 to $D(p_1)$, the formula $0 \leq \gamma \leq 1$ is established. This shows that cannibalization does not occur when $\gamma = 0$ and maximum cannibalization occurs when $\gamma = 1$, that is, there is only demand for remanufactured products in the market. By solving (2) and (3), the potential market scale of newly manufactured products is derived.

$$D'(p_1)=(1-\gamma)D(p_1) \qquad (4)$$

Since the potential market scale of remanufactured products is obtained by subtracting the demand for newly manufactured products from the demand for remanufactured products at price p_2, it is calculated by the following equation:

$$D'(p_2)=D(p_2)-D(p_1)+\gamma D(p_1) \qquad (5)$$

Using equations (1), (4), and (5), the demand for newly manufactured products and remanufactured products at period t can be expressed as follows.

$$D_n(t)=D'(p_1)f(t) \qquad (6)$$

$$D_r(t)=D'(p_2)f(t-\Delta t) \qquad (7)$$

This allows us to calculate the demand affected by cannibalization caused by the prices of newly manufactured products and remanufactured products. Figure 2 shows an example of the demand for newly manufactured products and remanufactured products when market size and price sensitivity are 5000 and 0.02, respectively.

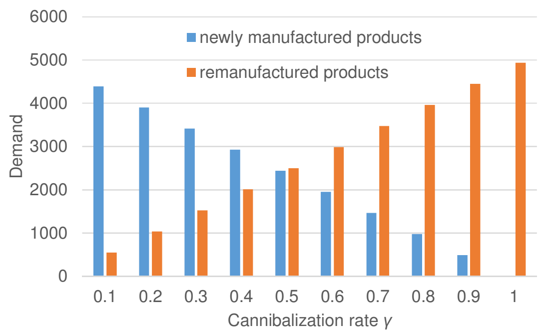

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Fig. 2. Demand for newly manufactured products and remanufactured products when p_1 = 6000 and p_2 = 3000.

FORMULATION

In a manufacturing-remanufacturing system, reusable products in returned products impinge on economic efficiency and environmental objectives. To calculate the quantity of reusable products and disposals, we introduce an indicator function, which takes the value of 1 when products are recovered from period t - 1 to t and 0 otherwise.

$$\chi_t\{T(i,j)\} = \begin{cases} 1, & t-1 \le T(i,j) < t \\ 0, & otherwise \end{cases} \quad (8)$$

The recovery period of product i recovered j-th time, $T(i, j)$ is calculated by adding the use period of each product to the period when the product was sold.

$$T(i,j) = t + U(i,j) \quad (9)$$

The quantity of reusable products at period t can be defined as the quantity of products with a recovery time less than n - 1 among the products recovered at a rate of r in period t. $R(t)$ reusable products at period t can be sold at period t + 1.

$$R(t) = r \sum_{i=1}^{S_n(t)+S_r(t)} \sum_{j=1}^{n-1} \chi_t\{T(i,j)\} \quad (10)$$

Since the quantity of disposals at period t is the quantity of products recovered for the n-th time, the quantity of disposals at period t can be expressed in the following equation, which also defines the quantity of reusable products:

$$W(t) = r \sum_{i=1}^{S_n(t)+S_r(t)} \chi_t\{T(i,n)\} \quad (11)$$

The inventory of newly manufactured products at period t $I_n(t)$ is the sum of the inventory of newly manufactured products at period t - 1 and the quantity of newly manufactured products $M(t - l)$ at period $t - l$ minus the demand for newly manufactured products at period t. The inventory of remanufactured products at period t is the sum of the inventory of remanufactured products at period t - 1 and the quantity of reusable products at period $t - l'$ less the demand for remanufactured products at period t. Therefore, the inventory of newly manufactured products $I_n(t)$ and remanufactured products $I_r(t)$ at period t can be expressed as follows. For the sake of exposition, it is assumed that the quantity of newly manufactured products at period t is equal to the demand for newly manufactured products at period $t - l$.

$$I_n(t) = I_n(t-1) + M(t-l) - D_n(t) \quad (12)$$

$$I_r(t) = I_r(t-1) + R(t-l') - D_r(t) \quad (13)$$

The sales quantity of newly manufactured products and remanufactured products is determined according to their demands and inventories.

$$S_n(t) = \begin{cases} D_n(t), & D_n(t) \le I_n(t) \\ I_n(t), & D_n(t) > I_n(t) \end{cases} \quad (14)$$

$$S_r(t) = \begin{cases} D_r(t), & D_r(t) \le I_r(t) \\ I_r(t), & D_r(t) > I_r(t) \end{cases} \quad (15)$$

Using the sales quantity of newly manufactured products and remanufactured products at period t, lost sales of newly manufactured products $L_n(t)$ and of remanufactured products $L_r(t)$ can be calculated by the following equation:

$$L_n(t) = D_n(t) - S_n(t) \quad (16)$$

$$L_r(t) = D_r(t) - S_r(t) \quad (17)$$

The total profit of this system can be derived by the following equation using storage cost per unit Ch and shortage cost per unit Cs:

$$\Pi = \sum_{i=1}^{H} (S_n(i)p_1 + S_r(i)p_2)$$

$$- \sum_{i=1}^{H} \{(I_n(i) + I_r(i))Ch + (L_n(i) + L_r(i))Cs\} \quad (18)$$

NUMERICAL EXAMPLES

Some numerical examples are explored using the model explained in the preceding section to evaluate the performance of the proposed system. We investigate the influence of the cannibalization rate, the price of remanufactured products, and introduction timing of remanufactured products. The parameters used in this section are as follows:

$r = 0.1, 0.2, \ldots, 0.9$, $p = 0.005$, $q = 0.1$, $p_1 = 6000$, $p_2 = 1000, 2000, \ldots, 5000$, $Ch = 50$, $Cs = 500$, $M = 5000$, $\gamma = 0.1, 0.2, \ldots, 0.9$, $\Delta t = 45$, $H = 150$, $l = l' = 1$, $b = 0.02$, $n = 2$.

The values of introduction timing of remanufactured products, coefficient of innovation, and coefficient of imitation are quoted from Nanasawa and Kainuma [2017]. Other parameters are uniquely set to investigate the influence of the return rate, price of remanufactured products, and the cannibalization rate. In this study, the use period of each product is generated as a random number according to a logarithmic normal distribution. The average μ and standard deviation σ of this logarithmic normal distribution are set to 5 and 1, respectively. First, we set the price of remanufactured products and the return rate to 3000 yen and 0.7, respectively, and investigate the influence of the cannibalization rate γ on the total profit of this system and the remanufacturing rate.

Figure 3 shows the total profit and the remanufacturing rate when changing γ, and Figure 4 shows the transition of quantity of reusable products when changing γ. Table 1 shows the holding cost, the shortage cost, the total cost, the sales amount of newly manufactured products, the sales amount of remanufactured products, the total profit, and the remanufacturing rate when the price of remanufactured products is 3000 yen. As the cannibalization rate γ increases, the demand for remanufactured products increases. Therefore, the remanufacturing rate grows when γ is large. Figure 3 shows that the boundary when the remanufacturing rate is 100% is $\gamma = 0.6$ for a return rate of 0.7. The total profit first increases and then decreases as γ increases. The total profit is maximized when γ is 0.6, which is consistent with a remanufacturing rate of 100%, because, as seen in Table 1, the quantity of reusable products that are not sold leads to an increase in holding costs since demand for remanufactured products is small when γ is small. On the other hand, if the quantity of reusable products is insufficient due to the large demand for remanufactured products, shortage costs increase when γ is large. Figure 4 shows that the quantity of reusable products also varies with changes in γ. If γ is small (large), the maximum reusable products occur before (after) $t = 50$ because the potential market scale of newly manufactured products is large when γ is small. That is, the quantity of reusable products increases according to the demand for newly manufactured products. Because the potential market scale of newly manufactured products is small when γ is large, the quantity of reusable products is small at the beginning of the planning horizon. However, because the demand for remanufactured products is larger than the demand for newly manufactured products occurring after Δt, the quantity of reusable products increases when $t > 50$.

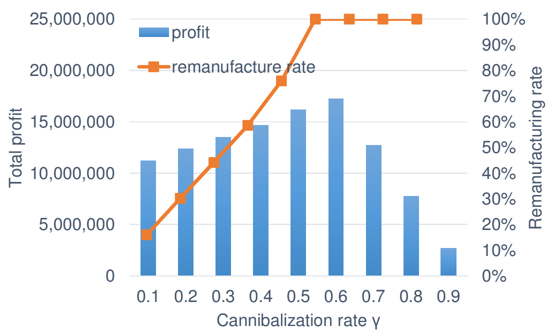

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Fig. 3. Total profit and remanufacturing rate as a function of γ

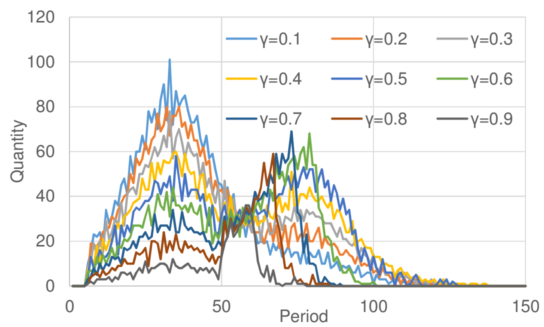

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Fig. 4. Reusable product quantities as a function of period and γ

Although the shape of the total demand function differs depending on γ, total demand is almost the same value regardless of γ in the transition period when demand for remanufactured products becomes larger than the demand for newly manufactured products. Therefore, the same value of total demand for all γ occurs at about the 50th period, and the same quantities of reusable products are recovered correspondingly. In addition, since demand for newly manufactured products is small when γ is 0.6 or more, the total quantity of reusable products decreases and some remanufactured products become out of stock. Therefore, firms need to consider the cannibalization rate and introduction timing of remanufactured products.

Table 1. Costs, sales amount, profit, and remanufacturing rate when p_2 is 3000 yen

γ	Holding cost	Shortage cost	Total cost	Sales amount of new products	Sales amount of remanufactured products	Total sales amount	Total profit	Remanufacturing rate
0.1	16,654,900	0	16,654,900	26,244,000	1,641,000	27,885,000	11,230,100	15.9%
0.2	14,104,550	0	14,104,550	23,352,000	3,123,000	26,475,000	12,370,450	30.2%
0.3	11,509,100	0	11,509,100	20,460,000	4,569,000	25,029,000	13,519,900	44.2%
0.4	8,819,450	0	8,819,450	17,460,000	6,039,000	23,499,000	14,679,550	58.6%
0.5	5,930,200	0	5,930,200	14,568,000	7,518,000	22,086,000	16,155,800	76.0%
0.6	2,310,400	153,000	2,463,400	11,658,000	8,064,000	19,722,000	17,258,600	100.0%
0.7	1,301,150	739,500	2,040,650	8,760,000	6,009,000	14,769,000	12,728,350	100.0%
0.8	675,650	1,326,000	2,001,650	5,802,000	3,954,000	9,756,000	7,754,350	100.0%
0.9	244,200	1,910,000	2,154,200	2,892,000	1,920,000	4,812,000	2,657,800	100.0%

Next, we investigate the influence of the price of remanufactured products on sales amount of remanufactured products, total profit, and remanufacturing rate as p_2 varies from 1000, 2000, 3000, 4000, and 5000 yen. Table 2 and Figures 5 show total profit and remanufacturing rate, respectively, when changing p_2 and γ. Figures 5 shows that total profit increases until γ is 0.6 and decreases thereafter because, as explained above, shortages of remanufactured products occur when γ is 0.6 or more. Although we propose a model in which demand for remanufactured products increases as the price of remanufactured products decreases, total profit increase as p_2 becomes larger due to the influence of price sensitivity in the numerical examples. Total profit takes the maximum value when γ is 0.6 regardless of p_2. Therefore, it can be said that the cannibalization rate that maximizes the total profit is 0.6 when the return rate is 0.7. Figure 6 shows the total profit when changing γ and the return rate r. The price of remanufactured products is set to 3000 yen. From Figure 6, it can be seen that the cannibalization rate γ that maximizes the total profit increases as the return rate increases. As the return rate increases, demand for remanufactured products balances with the quantity of reusable products by increasing γ. As a result, it is possible to suppress extra holding costs and shortage costs. When the return rate is 0.7 or more, the cannibalization rate that maximizes total profit is 0.6, regardless of the return rate. Even if the return rate increases, demand for newly manufactured products is small and the quantity of reusable products is not significantly affected by the return rate when γ is large. Therefore, γ that balances the quantity of reusable products and the demand for remanufactured products does not increase from 0.6, even if the return rate increases. Since the optimal value of γ depends on the introduction timing of remanufactured products and the price of each product, it is necessary to investigate the influence of γ when changing the introduction timing of remanufactured products and the price of each product. The remanufacturing rate increases as p_2 decreases when γ is less than 0.6. However, when γ is 0.6 or more, the remanufacturing rate remains at 100%, regardless of p_2.

Table 2. Total profit when changing γ and p_2

γ	p_2=1000	p_2=2000	p_2=3000	p_2=4000	p_2=5000
0.1	10,176,950	10,722,100	11,187,650	11,611,650	12,038,550
0.2	10,365,700	11,383,400	12,379,250	13,294,650	14,166,600
0.3	10,580,050	12,053,400	13,514,450	14,948,850	16,339,950
0.4	10,723,850	12,714,250	14,629,300	16,561,450	18,441,750
0.5	11,316,100	13,752,400	16,167,750	18,528,350	20,852,650
0.6	11,901,450	14,574,500	17,264,650	19,945,500	22,613,800
0.7	8,707,300	10,710,700	12,724,750	14,726,200	16,743,200
0.8	5,100,850	6,425,200	7,759,550	9,081,150	10,416,250
0.9	1,360,100	2,014,250	2,671,250	3,319,500	3,958,900

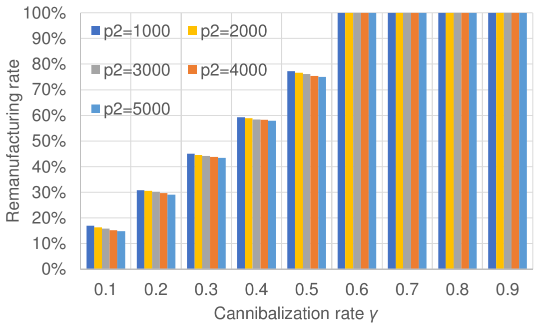

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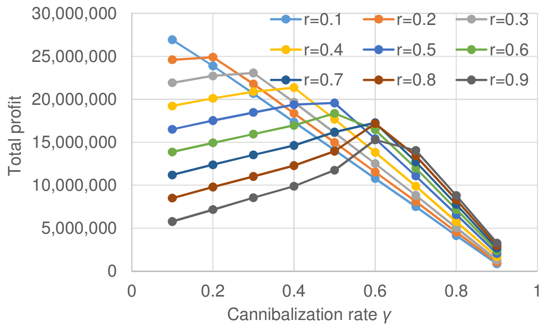
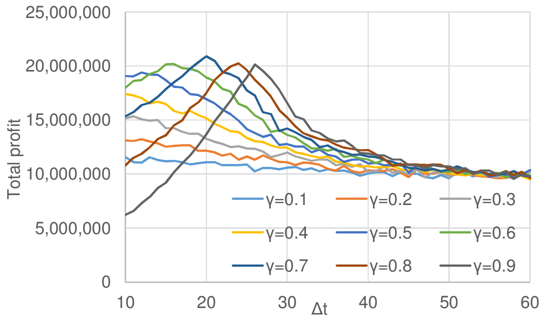
Fig. 5. Remanufacturing rate as a function of γ and p_2



Source: own work

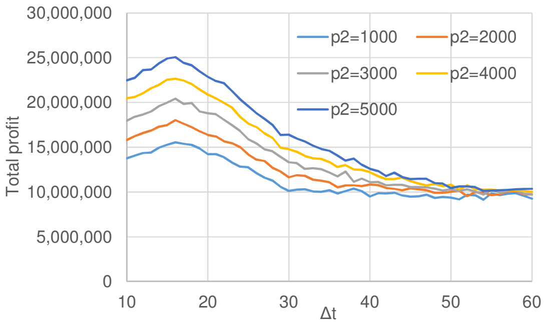
Fig. 6. Total profit as a function of γ and return rate r

Finally, we investigate the influence of the introduction timing of remanufactured products on total profit as Δt varies from 10 to 60 periods. Figure 7 shows the relationship between introduction timing of remanufactured products Δt and total profit when changing γ. The price of remanufactured products is set to 3000 yen. From this figure, it can be seen that when the introduction timing of remanufactured products is late, total profit becomes higher as the cannibalization rate is higher, and the cannibalization rate maximizing total profit becomes lower as the introduction timing of remanufactured products becomes earlier. Moreover, when the return rate is 0.7 and the price of remanufactured products is 3000 yen, it is seen that total profit becomes the maximum when the cannibalization rate is 0.7 and the introduction timing of remanufactured products is 20 periods. When the introduction timing of remanufactured products is early, the reusable products must be secured at an early period. Therefore, in this case, total profit when the cannibalization rate is high, that is, the demand for newly manufactured products decreases, is low due to an increase in shortage costs. As the introduction timing of remanufactured products is delayed, the quantity of reusable products that can be recovered by introduction timing of remanufactured products increases. As a result, it is possible to avoid shortage even if the demand for remanufactured products increases, and total profit becomes higher when the cannibalization rate is high. In the case where the cannibalization rate is low, the shortage cost increases because of the increase in the demand for newly manufactured products and the quantity of reusable products. This is the reason why total profit is low regardless of the introduction timing of the remanufactured products. These results suggest that firms need to decide on the introduction timing of remanufactured products, taking into consideration the impact of cannibalization.



Source: own work

Fig. 7. Total profit as a function of γ and Δt



Source: own work

Fig. 8. Total profit as a function of p_2 and Δt

Figure 8 shows the relationship between the introduction timing of remanufactured products and total profit when changing p_2. The cannibalization rate is set to 0.6. This figure shows that the price of remanufactured products maximizing total profit is 5000 yen, regardless of the introduction timing of remanufactured products. We use the function such that the demand increases as the price of products decreases in our demand model. However, there is no advantage of lowering the price of the remanufactured products. This may be due to the low value of price sensitivity used in the numerical examples. Therefore, to clarify the influence of the price of newly manufactured products and remanufactured products on the profit of the system, it is necessary to consider the influence of price sensitivity.

CONCLUSIONS

In this study, we design a manufacturing-remanufacturing system in consideration of remanufactured products whose prices are lower than those of newly manufactured products to propose an optimal production planning and inventory control policy. First, we posit a demand model that considers the cannibalization effect as affected by the prices of newly manufactured products and remanufactured products. Furthermore, by introducing the use period of each product, we design a manufacturing-remanufacturing system in which the quantity of reusable products is influenced by past demand and evaluate the performance of this system using the proposed demand model. Numerical examples suggest that the total profit of the system increases as the cannibalization rate γ increases and decreases when γ is 0.6 or more. This means that while a certain amount of demand for remanufactured products is required to sell remanufactured products, an appropriate adjustment of demand for remanufactured products is needed because the total profit decreases when the demand for remanufactured products becomes large. In this study, the cannibalization rate is given independently of the price of remanufactured products. However, cannibalization originally occurs because the price of remanufactured products is lower than the price of newly manufactured products. Therefore, it is preferable to use the cannibalization rate that is affected by the price of newly manufactured products and remanufactured products. Future research should consider the cannibalization rate depending on the price of newly manufactured products and remanufactured products. Furthermore, it is necessary to investigate the influence of parameters that are assumed to be fixed values in the numerical examples, such as price sensitivity and the price of newly manufactured products on total profit and remanufacturing rate.

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ZARZĄDZANIE ZAPASEM W SYSTEMIE PRODUKCYJNYM PRZY WYSTĘPOWANIU KANIBALIZACJI I ZWROTÓW STOCHASTYCZNYCH

STRESZCZENIE. **Wstęp:** System produkcyjny odzyskiwania zużytego sprzętu jest bardzo pożądany z punktu widzenia ochrony środowiska. Aby jednak stworzyć ten system w pełni zrównoważony, należy wziąć pod uwagę nie tylko aspekty ekologiczne ale także ekonomiczne. Przy sprzedaży używanych produktów w cenach niższych aniżeli wyroby nowe, wielkość rynku zbytu może ulec zwiększeniu a firmy są w stanie osiągnąć wyższe zyski. Jednak istnieje niebezpieczeństwo pojawienia się efektu kanibalizacji, czyli zjawiska nabywania przez klientów produktów używanych zamiast nowych.
Celem pracy było opracowanie modelu produkcyjnego uwzględniającego tej efekty jak również cykl życia produktu.
Metody: W oparciu o wcześniejsze został opracowany model popytu uwzględniający efekt kanibalizacji przy użyciu modela Bassa. Określenie popytu w zależności od ceny produktu następowało poprzez zastosowanie funkcji popytu rosnącej przy malejącej cenie produktu. Równolegle, przypisując odpowiedni okres każdemu produktowi, uwzględniono różny czas odtworzenia, specyficzny dla każdego z produktów.
Wyniki: Zaproponowany model został przedstawiony w przykładach numerycznych. Ich wyniki wskazują na wpływ ceny odzyskanych produktów, wskaźnik kanibalizacja oraz okresu odtworzeniowego na całkowity zysk uzyskany w opracowanym modelu.
Wnioski: Zaproponowano produkcyjny model odzysku zużytego sprzętu uwzględniający efekt kanibalizacji przy użyciu modelu popytu ze zmienną niezależną w postaci ceny produktu. Wykryto efekt kanibalizacji na całkowity zysk oraz istotność ceny i okresu odtworzenia zużytych produktów. Dodatkowo, poprzez zróżnicowanie okresu odtworzenia dla różnych produktów wykazano potrzebę sprzedaży odzyskiwanych produktów.

Słowa kluczowe: zarządzanie łańcuchem dostaw, efektywność ekonomiczna, odzyskiwanie produktu, wielkość rynku, efekt kanibalizacji

BESTANDSFÜHRUNG INNERHALB EINES PRODUKTIONSSYSTEMS ANGESICHTS DES AUFTRETENS VON KANNIBALISATION UND STOCHASTISCHEN RÜCKLIEFERUNGEN

ZUSAMMENFASSUNG. Einleitung: Produktionssysteme für die Rückgewinnung von Gebrauchtwaren sind aus dem Gesichtspunkt des Umweltschutzes sehr erwünscht. Um ein völlig nachhaltiges System dieser Art zu schaffen, müssen nicht nur ökologische, sondern auch wirtschaftliche Aspekte beachtet werden. Bei Verkauf von Gebrauchtprodukten zu niedrigeren Preisen als die Neuprodukte selbst kann das Ausmaß des Absatzmarktes vergrößert werden und die Firmen sind imstande, höhere Gewinne zu erzielen. Es besteht jedoch die Gefahr des Auftretens eines Kannibalisationseffektes, das heißt des Erstehens seitens der Kunden von Gebraucht- anstatt Neuprodukten. Das Ziel der vorliegenden Arbeit war es, ein Produktionsmodell, das die Kannibalisationseffekte und auch den Produkt-Lebenszyklus berücksichtigt, auszuarbeiten.

Methoden: In Anlehnung an die früheren Forschungen wurde ein Nachfrage-Modell, das den Effekt der Kannibalisation unter Anwendung des Bass-Modells mit berücksichtigt, konzipiert. Die Festlegung der Nachfrage in Abhängigkeit von dem Produktpreis erfolgte durch die Anwendung der Nachfragefunktion, die bei dem niedriger werdenden Produktpreis wächst. Indem man jedem Produkt eine bestimmte Zeitperiode zugemessen hatte, ermittelte man parallel dazu unterschiedliche Wiederherstellungszeit, die für jedes Produkt spezifisch ist.
Ergebniss: Das empfohlene Modell wurde anhand von nummerischen Beispielen dargestellt. Deren Ergebnisse weisen auf den Einfluss des Preises der rückgewonnenen Produkte, der Kennziffer der Kannibalisation und der Wiederherstellungszeit des jeweiligen Produktes auf den im Rahmen des ausgearbeiteten Modells erzielten Gesamtgewinn hin.
Fazit: Es wurde ein Produktionsmodell für die Rückgewinnung von Gebrauchtprodukten, das den Effekt der Kannibalisation unter Anwendung des Nachfrage-Modells mit einer unabhängigen Variable in Form des Produktpreises berücksichtigt, vorgeschlagen. Es wurden der Einfluss der Kannibalisation auf den Gesamtgewinn, sowie die Relevanz des Produktpreises und der Wiederherstellungszeit der Gebrauchtprodukte festgestellt. Durch die Differenzierung der Wiederherstellungszeit für unterschiedliche Produkte zeigte man zusätzlich die Notwendigkeit des Absatzes der rückgewonnenen Produkte auf.

Codewörter: Lieferketten-Management, wirtschaftliche Effektivität, Rückgewinnung von Produkten, Marktgröße, Kannibalisationseffekt

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