

Remanufacturing production planning considering quality cost and demand substitution

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Abstract: Aiming to minimize the total production costs in a single planning period, a nonlinear integer programming model for remanufacturing production plans is established considering the influence of different qualities of returns acting on production cost. Three different remanufacturing and discarding strategies are adopted to analyze the change rules of the total production costs. The results indicate that when the number of returns is greater than the demand, preferentially remanufacturing returns of high quality and discarding those of low quality can bring better economic benefits due to manufacturing cost reduction. However, when the number of returns is smaller than the demand, there is no need to consider grading of returns, whereas new parts are required to satisfy the demand of remanufacturing.

Key words: remanufacturing; production planning; quality cost; demand substitution

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Nowadays, more and more laws about remanufacturing have been enacted around the world, which require the original manufacturers to recycle and remanufacture worn-out or end-of-life products. The competition also forces the manufacturers to promote a warranty for a product's total life cycle^[1].

As we know that there are many uncertainties during the process of remanufacturing, such as quantity and quality of returned products, the demand for remanufactured products and the remanufacturing cost^[2]. Grading returned products according to their quality and considering the quality costs for remanufacturing are thought to be effective methods to solve the uncertain problems during the remanufacturing production.

Ref. [3] studied the random characteristics of recycling products and the cost-effectiveness problems based on quality grading. Galbreth and Blackburn^[4] studied the single cycle recycling and grading tactics when the condition of the demands is certain or uncertain. They concluded that when the recycling cost was linear, the recycling and grading tactics were independent of the yield. Li et al.^[5] considered multi-product production planning problem with demand substitution and proposed a dynamic programming approach under the assumption that the number of returned products was greater than the demand and the quantity of returned products along with the demand was certain. A multi-stage

inventory control simulation model was constructed using the software ARENA in Ref. [6], and the effects of uncertainties of return quality on the remanufacturing hybrid system were analyzed. Considering new manufacturing cost, remanufacturing cost and stock compensation cost, Gu et al.^[7] established a Markov decision model, and a stochastic optimal control strategy was obtained. Considering the remanufacturing of returned products and the demand substitution, Hu et al.^[8] studied the dynamic lot production planning problem for short-life products, and the impact of the product demand rate and the return rate on production planning and total profit was also analyzed.

The above studies mainly focused on the cost structure and the parameter optimization of production planning; however, most of them did not consider disposal and capacity constraints and assumed that the recycling quantity was greater than the demand. In actual production, the recoverable quantity is not always greater than the demand, and the impact of recycling quality on production planning and production cost is very important. In this paper, the single cycle production planning problem of remanufacturing is investigated, in which the production capacity is restricted and the quality cost is considered. A nonlinear integer programming model which considers grading and disposal of returned products is established in order to analyze the impact of the product demand rate and the return rate on the total cost and to optimize production planning.

1 Modeling of Remanufacturing Planning

1.1 Description of production planning for remanufacturing

The production planning of remanufacturing is an NP-hard problem^[9]. When the recycled quantity cannot meet the demand, new manufactured parts should be used to substitute for the remanufacturing, which will increase the complexity of remanufacturing. Most existing studies ignore the quality differences of returned products, although there is a big difference with the actual production. Fig. 1 illustrates the remanufacturing flow considering demand substitution.

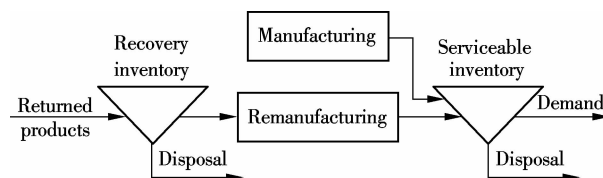


Fig. 1 Remanufacturing flow considering demand substitution

Statistics show that the quality level q obeys a continuous probability distribution, $q \in [0, 1]$ ^[10]. We do not know exactly the quality level of every returned product before inspection, but we can define the distribution function of the

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recycling quality based on historical data. Set $f(q)$ as the probability distribution function of the recycling quality and $F(q)$ as the cumulative distribution function of the recycling quality. According to the remanufacturing requirements, the quality level is divided into I intervals, they are $\{0, q_1\}$, $\{q_1, q_2\}$, ..., $\{q_{I-1}, q_I\}$, respectively. The formula used to divide the recycling quality is as follows:

$$i = \begin{cases} 1 & 1 < q \leq q_1 \\ 2 & q_1 < q \leq q_2 \\ \vdots & \\ I & q_{I-1} < q \leq q_I \end{cases}$$

Assume that there are several parallel processes in the remanufacturing system corresponding to returned products of different quality grades. Obviously, different quality grades lead to different processing times and costs. The higher the quality grade is, the lower the remanufacturing cost will be, and, at the same time, less remanufacturing equipment is demanded along with higher relevant inventory holding costs and disposal costs. The inventory holding costs of the serviceable products which are remanufactured from high quality returned products are high. The remanufacturing procedure which considers quality grade is shown in Fig. 2, in which MP is the material inventory; RP_i is the recovery inventory when the quality grade is i ; SP is the serviceable inventory; D is the demand within the planned period, and R is the recycling volume. The proportion of each quality grade in the recycling volume is relatively fixed in the planned period. The recycling volume of each quality grade after grading is $B_i = R(F(q_{i+1}) - F(q_i))$.

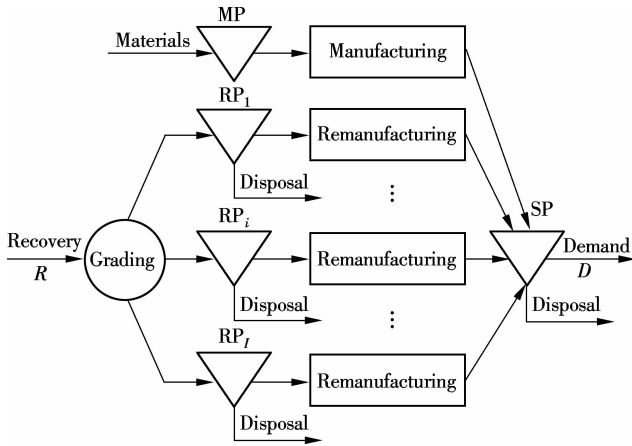


Fig. 2 Procedure of remanufacturing considering quality grade

The remanufacturing production planning problem of a single cycle meets the following assumptions^[10]:

- 1) The disassembly of returned products is finished before demand. The lead time is not considered.
- 2) The demand and recycling volume of each quality grade are determined in advance.
- 3) When the recycling volume is smaller than the demand and the remanufactured inventory cannot meet the demand, the manufactured products will be used as substitution. The set-up costs and the set-up time are not considered.
- 4) When the demand exceeds the available product capacity, new products will be bought to meet the production requirements.

The single-cycle remanufacturing planning considering quality grading is established based on the following assumptions:

- 1) The remanufacturing cost is negatively correlated with the recycling quality. The lower the recycling quality, the higher the remanufacturing cost.
- 2) The inventory holding cost is a non-decreasing function of the recycling quality. The higher the recycling quality, the higher the inventory holding cost.
- 3) The disposal cost is a non-decreasing function of the recycling quality. The higher the recycling quality, the higher the disposal cost.
- 4) The inventory holding cost of the remanufactured serviceable product is higher than that of the returned product, which reflects the value increment of the remanufacturing.
- 5) The utilization ratio of the remanufacturing capacity is a decreasing function of the recycling quality. The lower the recycling quality, the higher the utilization ratio of the remanufacturing capacity.

1.2 Model of remanufacturing production planning

1.2.1 Symbol definition

The recovery holding cost after grading of grade i is $h_i = \lambda p_r$, in which λ is opposite to the recycling quality grade, named the inventory cost coefficient. The recovery holding cost without grading is $\bar{h} = (\sum ih_i) / I$. The holding cost of the remanufactured product is $h_r = 2\bar{h}$. The per grading cost of a returned product is $c_g = \zeta \alpha_1$, in which ζ is the cost coefficient of grading. The new manufacturing cost is $c_m = 0.9p_r$. The ratio of the available capacity to the average demand is $\lambda = C/D$. The capacity occupancy of grade i is $a_i = 1 + A(i-1)/(I-1)$, in which A is the remanufacturing capacity occupied by the returned product with the poorest quality.

The remanufacturing cost $c_{r,i}$ is a function of recycling quality q_i , which can be formulated as $c_{r,i} = \alpha_0 + (\alpha_1 - \alpha_0)q_i^\beta$, $i \in \{1, 2, \dots, I\}$. α_0 is the remanufacturing cost of the lowest quality grade in the returned product; α_1 is the remanufacturing cost of the highest quality grade in the recovery; β is the coefficient of the quality cost. The disposal cost $c_{s,i}$ equals $\eta(p_r - c_{r,i})$; p_r is the price of the remanufactured product; η is the coefficient of the disposal cost.

1.2.2 Objective function

The objective function is as follows:

$$\min TC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \quad (1)$$

where TC is the total remanufacturing costs; C_1 is the total new manufacturing cost, which equals the new manufacturing cost c_m multiplied by new manufacturing quantity x in the planned period; C_2 is the cost of grading quality, which equals per grading cost c_g multiplied by the recycling volume R ; C_3 is the remanufacturing cost of the returned product, which equals the remanufacturing cost $c_{r,i}$ of grade i multiplied by the remanufacturing quantity z_i of grade i ; C_4 is the disposal cost of the returned product, which equals the per disposal cost $c_{s,i}$ of grade i multiplied by the disposal quantity v_i of grade i ; C_5 is the inventory holding cost of the returned product, which equals the recovery inventory hold-

ing cost h_i of grade i multiplied by the recovery inventory holding quantity u_{il} of grade i at the end of the period; C_6 is the serviceable inventory holding cost, which equals the per serviceable inventory holding cost h_r multiplied by the serviceable inventory holding quantity y_1 at the end of the period. So the formula of the total costs is obtained as follows:

$$\min TC = c_m x + c_g R + \sum_i (c_{r,i} z_i) + \sum_i (c_{s,i} v_i) + \sum_i h_i u_{il} + h_r y_1 \quad (2)$$

1.2.3 Constraints

The constraints of the logistics balance of the returned products and the logistics balance of the serviceable products are as follows:

$$u_{il} - u_{i0} + z_i + v_i = B_i \quad \forall i \quad (3)$$

$$y_0 - y_1 + x + \sum_i z_i = D \quad (4)$$

where u_{i0} is the recovery inventory of grade i at the beginning of the planned period; y_0 is the serviceable inventory at the beginning of the planned period.

The constraints of the inventory of the serviceable product and the new manufacturing and the disposal volume of the recycling products are as follows:

$$xy_1 = 0 \quad (5)$$

$$v_i \leq u_{i0} + B_i \quad \forall i \quad (6)$$

Eq. (5) means the inventory of the serviceable manufacturing and the new manufacturing cannot occur at the same time.

The inventory capacity constraints of the recycled products, the inventory capacity constraints of the serviceable products and the capacity constraints of remanufacturing are as follows:

$$u_{il} \leq K_R \quad (7)$$

$$y_1 \leq K_S \quad (8)$$

$$a_i z_i \leq C \quad \forall i \quad (9)$$

where K_R is the inventory capacity limit of the recycled products; K_S is the inventory limit of the serviceable products; C is the available capacity limit of remanufacturing.

The constraint of initial conditions is as follows:

$$u_{i0} = y_0 = 0 \quad (10)$$

The value constraints of the decision variable are as follows:

$$x, y_1 \geq 0; x, y_1 = 0, 1, 2, \dots \quad (11)$$

$$u_{il}, z_i, v_i \geq 0 \quad \forall i \quad (12)$$

2 Strategy Study for Production Planning

2.1 Strategy 1

In this strategy, the high quality recycling products are used and low quality recycling products are disposed of in

advance.

1) Decide the remanufacturing number of each grade according to quality from high to low and set the optimal remanufacturing number of each grade as follows:

$$z_i^* = \begin{cases} \min\{B_i + u_{i0}, \omega_i\} & \omega_i \geq 0 \\ 0 & \text{others} \end{cases}$$

$$\text{where } Z = \sum_i z_i, \omega_i = Z - \sum_{j=1}^{i-1} z_j.$$

2) When the remanufacturing number is satisfied, the disposal number of each grade needs to be decided on according to the quality from high to low, and the optimal disposal number is set as

$$v_i^* = \begin{cases} \min\{u_{i0} + B_i - z_i^*, \xi_i\} & \xi_i \geq 0 \\ 0 & \text{others} \end{cases}$$

$$\text{where } V = \sum_i v_i, \xi_i = V - \sum_{k=i+1}^I v_k.$$

3) The inventory residual volume of RP_i is $U_{il} = u_{i0} + B_i - z_i^* - v_i^*$. Considering the inventory capacity constraints, if U_{il} is greater than K_R , then $v_i = v_i^* + U_{il} - K_R$, $u_{il} = K_R$; otherwise, $v_i = v_i^*$, $u_{il} = U_{il}$.

2.2 Strategy 2

In this strategy, the low quality recycled products are used and the high quality recycled products are disposed of in advance.

1) Decide the remanufactured number of each grade according to quality from low to high, and set the optimal remanufactured number of each grade as follows:

$$z_i^* = \begin{cases} \min\{B_i + u_{i0}, \varphi_i\} & \varphi_i > 0 \\ 0 & \text{others} \end{cases}$$

$$\text{where } Z = \sum_i z_i, \varphi_i = Z - \sum_{l=i+1}^I z_l.$$

2) When the remanufactured number is satisfied, the disposal number of each grade needs to be decided on according to the quality from high to low and the optimal disposal number is set as

$$v_i^* = \begin{cases} \min\{u_{i0} + B_i - z_i^*, \phi_i\} & \phi_i > 0 \\ 0 & \text{others} \end{cases}$$

$$\text{where } V = \sum_i v_i, \phi_i = V - \sum_{h=1}^{i-1} v_h.$$

3) Similar to strategy 1, the inventory residual volume of RP_i is $U_{il} = u_{i0} + B_i - z_i^* - v_i^*$. Considering the inventory capacity constraints, if U_{il} is greater than K_R , then $v_i = v_i^* + U_{il} - K_R$, $u_{il} = K_R$; otherwise, $v_i = v_i^*$, $u_{il} = U_{il}$.

2.3 Strategy 3

In this strategy, the quality grading is not considered. Each cost coefficient obtains its mean value. The calculation process is as follows:

1) The remanufacturing cost of the recycled products is \bar{c}_r
 $= \sum_i (c_{r,i} (F(q_{i+1}) - F(q_i)))$;

2) The disposal cost of the recycled product is $\bar{c}_s =$

$$(c_{s,i}(F(q_{i+1}) - F(q_i)));$$

$$3) \text{ The inventory cost of recycling products is } \bar{h} = \sum_i (h_i(F(q_{i+1}) - F(q_i)));$$

$$4) \text{ The occupying cost of the remanufacturing capacity is } \bar{a} = \sum_i (a_i(F(q_{i+1}) - F(q_i))).$$

The objective function of the remanufacturing production planning model with no consideration of quality grading is

$$\min TC = c_m x + c_r \sum z_i + c_s \sum v_i + \bar{h} u_1 + h_r y_1 \quad (13)$$

where the items correspond to the new manufacturing cost, the remanufacturing cost, the disposal cost of the recycled product, the inventory holding cost of the recycling cost, the inventory holding cost of the serviceable cost, respectively. Omitting the subscript notation i in Eqs. (3) to (13), we can obtain the corresponding constraint conditions.

3 Case Study

3.1 Experimental parameter setting

Assume that the recycling quality obeys the Beta distribution with parameters a and b . Let $a = 5$ and $b = 5$. The returned products are divided into five quality grades, including excellent, good, middle, secondary and poor. The parameters in the experiment are set as follows: $p_r = 100$, $K_R = 10$, $K_s = 20$, $\mu_{i0} = 0$, $\gamma_0 = 0$, $\lambda = 1.6$, $A = 0.8$, $\lambda = \{0.025, 0.05, 0.075, 0.10, 0.125\}$. The cost constraints in the experiment are as follows: $\alpha_0 = 60$; $\alpha_1 = 25$; $\beta = 1.5, 1.0, 0.5$, respectively; $\eta = 0.2$; $\zeta = 0.01$.

3.2 Experimental results

The Matlab software is used to program and solve the above nonlinear integer programming model. The results of the experiment are as follows.

First, we compare the total cost of the three strategies when the demand is certain and the recycling volume changes. Fig. 3 illustrates the total cost comparison of the three strategies when the demand is certain and the recycling volume changes within a certain range. When the demand $D = 360$, R/D changes within the range of $[0.9, 1.2]$, and $\beta = 1.5$, the minimal total cost of strategy 1 is 15 164 yuan and the recycling volume $R = 1.020 0D$, while strategy 2 is 15 249 yuan and $R = 1.002 0D$; strategy 3 is 15 024 yuan and $R = 1.002 0D$.

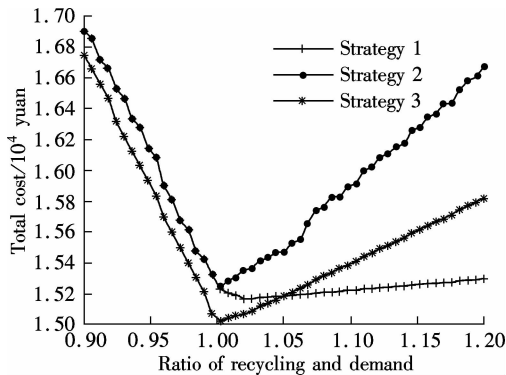


Fig. 3 Comparison of total production costs under different strategies

From the experiment, it can be concluded that the lowest cost of the three strategies occurs when $R = 1.002 0D$. As the ratio of the recycling volume to the demand changes, the differences in the total cost among the three strategies changes significantly. When the recycling volume is smaller than the demand, there is no notable difference among the three strategies, and strategy 3 is the best choice based on total costs.

The reason is that when the recycling volume is smaller than the demand, the returned products are all remanufactured. Grading cost occurs as quality grading is adopted. Additionally, when the recycling number is greater than the demand, the advantage of strategy 1 obviously grows as the recycling number increases, while the total cost of strategy 2 increases linearly with the recycling number.

Secondly, we set different quality cost coefficients to study the influence of the quality cost on the remanufacturing cost. The remanufacturing cost curves of different quality cost coefficients are shown in Fig. 4.

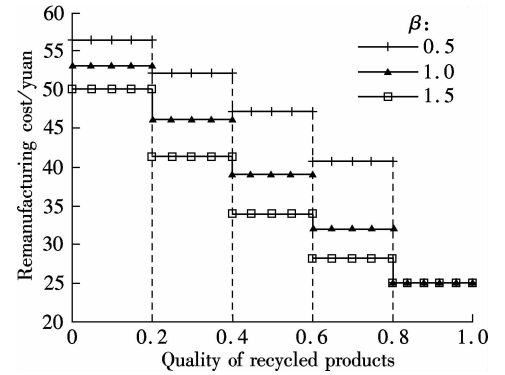


Fig. 4 The curves of remanufacturing cost

The total cost curves of different quality cost constraints in strategy 1 are shown in Fig. 5. When $\beta = \{0.5, 1.0, 1.5\}$, the minimal value respectively equals $\{18\ 882, 16\ 783, 15\ 164\}$ yuan, and respectively appears when the condition R equals $\{1.002, 1.02, 1.02\}D$. We intercept a certain ratio of the return products to the demand, and the total cost is compared when β takes on different values. It can be concluded that the total cost reaches the highest when $\beta = 1.5$, while it reaches the lowest value when $\beta = 0.5$. The calculation results show that the quality cost constraint has a great influence on the total cost.

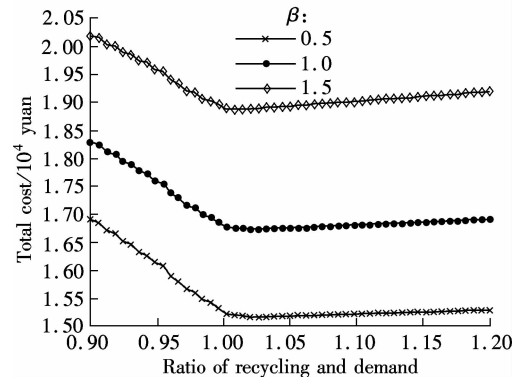


Fig. 5 Total cost under different quality cost coefficients

4 Conclusion

The quality of returned products has a great influence on the remanufacturing cost. The single cycle remanufacturing production planning with the nonlinear programming model is studied, the remanufacturing costs in different production planning strategies are compared considering quality cost and capacity as constraints.

In this paper, we only consider the single cycle remanufacturing production planning. In fact, the production planning for multi-cycle remanufacturing is more practical, which is needed to be done in the future.

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考虑质量成本和需求替代的再制造生产计划

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摘要:以单计划周期内总生产成本最小为目标,考虑回收件质量差异对生产成本的影响,建立了面向再制造生产计划的非线性整数规划模型.采用3种不同的再制造和废弃策略,比较总生产成本的变化规律.研究结果表明:当回收量小于需求量时,无需考虑分级,但需使用新零部件以满足再制造需求;当回收量大于需求量时,优先采用高质量回收件和优先废弃低质量的回收件,有利于降低制造成本,获得最佳的经济效益.

关键词:再制造;生产计划;质量成本;需求替代

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