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Optimal Acquisition and Remanufacturing Policies for Multi-product Remanufacturing Systems

Abstract: This paper studies an acquisition and remanufacturing problem in a market-driven multi-product remanufacturing system, where the remanufacturer acquires multiple used products (cores) of highly variable quality under independently uncertain demand and carbon emissions regulation. In order to balance between the environmental and economic benefit, the problem is formulated as a nonlinear programming model in presence of the quality variability of cores and carbon tax scheme, subject to budget and risk constraints. Since the average cost of the remanufactured products is independent of the remanufacturing quantity, the model is then decomposed into two separated sub-problems, namely the remanufacturing problem and the acquisition problem. In the remanufacturing problem, the optimal remanufacturing policies, including the optimal remanufacturing cost thresholds and the optimal remanufacturing rate, are derived. In the acquisition problem the optimal policies of core portfolio, acquisition quantities, and remanufacturing quantities can be derived. The acquisition problem, viewed as an extended Multi-Product Newsvendor Problem (MPNP), is a convex optimization problem. Furthermore, a two-tier bisection method with polynomial computational complexity can be developed to obtain the optimal policies based on the Karush-Kuhn-Tucker (KKT) conditions. Finally, numerical experiments are provided to show the application of the model and the effect of the quality variability.

Keywords: Remanufacturing; Core acquisition; Multi-Product Newsvendor Problem (MPNP); Quality variability; Carbon emission.

1. Introduction

Remanufacturing, as the key link of the sustainability development strategy, is becoming more and more important today due to limited resources and environmental conservation. Remanufacturing can extends the product life cycle, and reduces resource consumption and waste generation over entire life cycle, which offers social, economic, and environmental benefits (Guide and Van Wassenhove, 2009). Smith and Keoleian (2004) pointed out the remanufactured automotive engine in the United States can be produced with "68% to 83% less energy and 73% to 87% fewer carbon dioxide emissions", and be purchased with 30%-50% price difference. Firms are motivated to incorporate remanufacturing operations into the business process. For instance, IBM opened the first server remanufacturing center in Shenzhen, China. The new facility expands its' global remanufacturing and refurbishment operations in Australia, Singapore, Japan, Brazil, Canada, France, Germany and the United States. It estimated that this facility can handle (remanufacture) over 100,000 PCs and low-end and mid-range IBM and non-IBM servers per year [1]. In addition, HP also established a "renew and remanufacturing process" to enhance its sustainability development. Specially, renew products offer the same peace of mind provided with new product with a discount that is at least 15% off the equivalent new product price [2]. Thus, the aforementioned cases highlight the significance of the remanufacturing, and the business phenomenon is the motivation of our research.

In reality, acquirable cores have not only high volumes but also various types, series and versions. According to the survey conducted by Guide and Jayaraman (2000), a remanufacturer in the United States acquired on average more than 1400 types of cores and 50000 types of parts. A rational remanufacturer cannot acquire all types of cores in the market. The real problem the remanufacturer faces is how to acquire multiple types of cores from one or more third third-party brokers. In other words, the remanufacturer should establish acquisition and remanufacturing policies: which types of cores should be acquired, which cores should be remanufactured and which cores should be scrapped? Take mobile phones as an example. From June 2010 to September 2013, ZTE (a mobile phone manufacturer in China) issued 43 different types of mobile phones in the United States, but ReCellular (a leading remanufacturer of cellular phones) remanufactured and sold only 6 types of these 43 in September 2013. Similarly, from September 2010

[1] https://www-03.ibm.com/press/us/en/pressrelease/36976.wss
[2] http://www.shapesystems.com/HP-Renew.aspx

to September 2013, Kyocera (a mobile phone manufacturer in Japan) issued 22 different types of mobile phones, but ReCellular remanufactured and sold only 8 types of them in September 2013.

In remanufacturing, the quality of acquirable cores is the primary consideration factor, which has made production planning and control of remanufacturing systems difficult. Remanufacturing cost largely depends on the highly variable quality of acquirable cores. In addition, the remanufacturer will also consider other conditions of acquirable cores, such as budget, acquisition capacity, remanufacturing resources, and processing time. However, in traditional acquisition and remanufacturing decisions, the remanufacturer mainly focuses on potential profitability option of a market-driven remanufacturing system. The environmental burdens associated with energy consumption, material consumption, air emissions, and solid waste generation usually are ignored. These burdens have significant influence on the acquisition and remanufacturing decisions. Specially, the effect of these burdens depends on core size, remanufacturing technology, and component material composition. For example, "The production of the minimum, total dependent, and maximum part replacement engines results in 110, 160, and 230 kg of CO_2 emissions, respectively." (Smith and Keoleian, 2004). Hence, when the remanufacturer selects the appropriate types of cores to be remanufactured, he should consider the environmental burdens, and balance between the environmental and economic benefit.

The rest of this paper is organized as follows. In Section 2, related research is briefly reviewed. In Section 3, the problem statement is detailed, and a nonlinear programming model is formulated. Section 4 mainly analyzes the properties of the model, and an approach is developed for solving the model. Section 5 quantifies the effect of the quality variability. Numerical examples are given in Section 6 to illustrate the model and the approach with managerial insights. Finally, Section 7 concludes the paper with future research directions.

2. Literature review

As one of critical concerns in sustainable development, core acquisition and remanufacturing have received considerable attention from researchers. Guide and

Jayaraman (2000) described the complex managerial activities and impact factors in core acquisition, and provided a framework of *Product Acquisition Management* (PAM) to coordinate activities between reverse logistics and production planning and control. Guide (2000) also analyzed the influence of the complicated characteristics of remanufacturing, and emphasized that significant efforts should be made to change remanufacturing production planning and control. Guide and Van Wassenhov (2001) compared the difference of product returns between a waste stream system and a market-driven system, and proposed a general framework to assess the potential profitability option based on the *Economic Value Added* (EVA) concept. From the aforementioned papers, it can be seen that high variability of acquired cores (quantity, quality and time) has brought negative effect to production planning and control of remanufacturing systems.

Accordingly, many researchers pointed out that positive incentives should be considered to influence or control the quality and quantity of acquirable cores (Guide et al., 2003; Vadde et al., 2007; Ovchinnikov, 2011; Zhou and Yu, 2011; Minner and Kiesmuller, 2012; Jena and Sarmah, 2014; Cai et al., 2014). These papers highlighted that it is important to categorize acquirable cores during remanufacturing processes. Quality-based categorization has prominently operational benefits and can avoid the managerial difficulties. In the existing papers, core quality is discussed from two aspects of both condition uncertainty and quality variability.

Condition uncertainty is usually measured by proportional yield, which represents “the fraction of remanufacturables in acquired cores” (Yang et al., 2015). When the proportional yield is stochastic, “the number of the cores to be remanufactured is stochastic for a certain acquisition quantity” (i.e., condition uncertainty) (Panagiotidou et al., 2013). Aras et al. (2004), Zikopoulos and Tagaras (2007), Van Wassenhove and Zikopoulos (2010), Galbreth and Blackburn (2010b), Li et al. (2013), and Panagiotidou et al. (2013) discussed the effect of condition uncertainty in various acquisition and remanufacturing operations. However, it is assumed that acquirable cores had been sorted into some grades before acquisition, and the all remanufacturable cores in each grade were assumed to be homogenous with identical unit remanufacturing cost. (Aras et al., 2004; Zikopoulos and Tagaras, 2008; Ferguson et al., 2009; Loomba and Nakashima, 2012). That is, the quality variability in each grade was ignored.

In practice, the quality of each acquirable core may be different and unknown before acquisition (Teunter and Flapper, 2011). That is, the quality of each core was assumed to be heterogeneous, and the quality variability was considered before core acquisition (Robotis et al., 2005; Ferguson et al., 2009; Galbreth and Blackburn, 2006; Lu, 2009). In addition, some researchers also analyzed the joint effects of both quality variability and condition uncertainty (Galbreth and Blackburn, 2010a; Teunter and Flapper, 2011; Yang et al., 2015). The aforementioned papers investigated models in a single-product setting.

The acquisition and remanufacturing problem in multi-product remanufacturing systems is more practical. Souza et al. (2002), Tagaras and Zikopoulos (2008), and Nikolaidis (2009) proposed different models to analyze the core acquisition problem in a multi-site or multi-supplier setting. Li et al. (2006) developed a multi-period and multi-product production planning model in a hybrid manufacturing/remanufacturing system without capacity constraint. Shi et al. (2011) studied a multi-product hybrid manufacturing and remanufacturing problem with a linear constraint, and the optimal solution was derived by a Lagrangian relaxation based approach. In the above papers, it was also assumed that all remanufacturable cores in each grade were assumed to be homogenous, and the quality variability was not considered.

In addition, the aforementioned papers only consider economic benefit. The models were profit-maximization or cost-minimization models by an overwhelming majority. Due to huge environmental benefit, remanufacturing is a crucial environmental preferable choice (Wang and Chen, 2011). Some researchers proposed that environmental factors should be incorporated into remanufacturers' decisions (Bovea and Perez-Belis, 2012; Nikolopoulou and lerapetritou, 2012). For example, Smith and Keoleian (2004) presented a life-cycle assessment (LCA) model to assess the value of remanufactured automotive engines in the Unite Stated from environmental and economic perspectives (i.e., energy consumption, air emissions, solid waste generation, material consumption, and economic benefits). Krikke (2011) developed a closed-loop network configurations model with carbon footprints, which was applied to CopyDoc (a global company in document management for professionals). The results showed that the carbon footprints strongly depended on the substitution effect and the network design. Likewise, Kannan et al. (2012) developed a mixed integer linear model for reverser logistics network design with carbon footprint. Liu et al. (2015) presented a distribution-free newsvendor models to study remanufacturing decisions on the basis of the three carbon emissions regulations. Ghazilla et al. (2015) investigated Design for Environment and Design for Disassembly in Malaysia for a practitioner's perspective. However, as shown in Sundin and Lee (2012), "in the area of remanufacturing, there has been a lack of environmental assessment studies."

Compared with the aforementioned papers, we incorporate quality variability into an acquisition and remanufacturing problem in a multi-product setting. The problem is formulated as a nonlinear programming model in presence of the quality variability. In the model, not only linear budget but also nonlinear risk constraints in the model are considered from the trade-off between cost and risk. In addition, carbon footprints involved in remanufacturing process are considered, and the effect of carbon emissions is incorporated into the model based on carbon tax scheme. In order to obtain the optimal policies of core portfolio, acquisition and remanufacturing quantities simultaneously, the properties of the model are analyzed. Accordingly, the model is decomposed into two separated sub-problems, namely remanufacturing problem and acquisition problem. A simple and effective approach is developed to obtain the optimal solution. Our approach can be applicable to large scale instances with any continuous demand distribution and quality distribution, and various environmental burdens. Furthermore, the effect of the quality variability is analyzed in the multi-product remanufacturing system.

3. The model

3.1 The problem descriptions and assumptions

In a remanufacturing system, there are *n* different types of acquirable cores from one or more third-party brokers. Since that acquirable cores are not unsorted, and the quality of each core is different and unknown before acquisition (i.e., quality variability), the remanufacturer should estimate the quality of the acquirable cores according to historical data before acquisition. Here, the suitable indices are selected to represent the core quality, such as total running time and error conditions in the entire machine lifetime (Simon et al., 2001), remanufacturing cost (Galbreth and Blackburn, 2006; Lu, 2009), and remanufacturing process time (i.e., time required for remanufacturing) (Guide et al., 2008). In this paper, we measure the core quality by the remanufacturing cost (t), which includes the costs of disassembly, cleaning, testing, remanufacturing, and repacking. In general, the remanufacturing cost t depends on the core quality. Furthermore, t is increasing as quality worsens. That is, the worse the quality is, the higher the remanufacturing cost t (Galbreth and Blackburn, 2006). t is a random variable with the cumulative distribution function of $G(\cdot)$ and the probability density function of $g(\cdot)$. The relation between the remanufacturing cost and the core quality, and the estimate of the cumulative distribution function of $G(\cdot)$ were detailed by Guide et al. (2008).

After estimating the core quality, the remanufacturer should calculate remanufacturing quantities. In other words, the remanufacturer should estimate which should be remanufactured or scrapped in given acquirable cores. In general, a remanufacturing cost threshold (t_0) is provided, and acquirable cores can be divided into two categories: high quality and poor quality. The cores are in high quality if their remanufacturing costs are below the threshold. The rest of the cores, with their remanufacturing costs above the threshold, are scrapped due to their poor quality. Note that the remanufacturing cost threshold (t_0) is only an estimate for the quality variability of the acquirable cores, and the actual classification operation is not conducted before acquisition.

In addition, the demands of remanufactured products should be estimated before acquisition. The demands are independent from each other, and they are randomly distributed and their distribution functions are known.

Similar to manufacturing of new products, the remanufacturing brings environmental burdens, such as air emissions and solid waste. Carbon emissions, as classical environmental burdens, are incorporated into the model. Furthermore, carbon tax scheme is a frequent-used cost-effective means for reducing carbon emissions. This paper considers the effect of carbon emissions under carbon tax scheme. The other environmental burdens can be incorporated into the model in the similar way.

After estimating the core quality and the demands of remanufactured products, the remanufacturer determines the optimal acquisition and remanufacturing policies, including core portfolio, acquisition quantities, and remanufacturing quantities. The above analysis is applied to a single-period setting. The notation used in this paper is defined as follows:

Parameters

n	number of core types
i	index of cores, i =1, 2, …, n
j	index of constraints, j =1, 2
p_i	unit selling price of remanufactured products of core type i
v_i	unit salvage value of remanufactured products of core type i
s_i	unit shortage cost of remanufactured products of core type i
c_{si}	unit scrapping cost of scraped products of core type i
u_i	unit acquisition and inspection costs of core type i
t_i	unit remanufacturing cost of core type i
$r_i(\cdot)$	average remanufacturing cost of core type i
D_i	random demand of remanufactured products of core type i
$f_i(\cdot)$	probability density function of the demand of core type i
$F_i(\cdot)$	cumulative distribution function of the demand of core type i
$g_i(\cdot)$	probability density function of the quality of core type i
$G_i(\cdot)$	cumulative distribution function of the quality of core type i
B_G	available budget

L_s	maximum acceptable loss
e_i	carbon emissions of unit remanufactured product of core type i
e_{si}	carbon emissions of unit scraped product of core type i
c_e	carbon tax of unit carbon emission

Decision Variables

x_i	acquisition quantity of core type i; $X = (x_1, x_2, \ldots, x_n)$.
y_i	quantity of remanufactured products of core type i; $Y = (y_1, y_2, \ldots, y_n)$.
t_{0i}	remanufacturing cost threshold of core type i; $T_0 = (t_{01}, t_{02}, \ldots, t_{0n})$.

3.2 Model formulation

With the quality of the acquirable cores estimated, for core type i, the cores in high quality (i.e., $t_i \le t_{0i}$) are remanufactured. The expected remanufacturing rate is $\Pr\{t_i \le t_{0i}\} = G_i(t_{0i})$. Accordingly, the expected number of the remanufactured products is $y_i = x_i G_i(t_{0i})$ for a given acquisition quantity x_i. The remaining $x_i(1-G_i(t_{0i}))$ cores, due to poor quality, are scrapped. Here, the average remanufacturing cost is $r_i(t_{0i}) = \int_0^{t_{0i}} t g_i(t)dt \,/ \int_0^{t_{0i}} g_i(t)dt$.

Then, the expected profit of core type i is given by:

$$\begin{aligned}\pi_i(x_i, t_{0i}) = {} & p_i E\min(y_i, D_i) + v_i E(y_i - D_i)^+ - s_i E(D_i - y_i)^+ - [u_i x_i + r_i(t_{0i}) y_i + c_{si}(x_i - y_i)] \\ & - c_e[e_i y_i + e_{si}(x_i - y_i)]\end{aligned} \tag{1}$$

where $y_i = x_i G_i(t_{0i})$, $(\cdot)^+ = \max\{\cdot, 0\}$.

In Eq. (1), the first term $p_i E\min(y_i, D_i)$ is the sales revenue from the remanufactured products, the second term $v_i E(y_i - D_i)^+$ is the salvage value, the third term $s_i E(D_i - y_i)^+$ is the shortage loss, the fourth term $u_i x_i + r_i(t_{0i}) y_i + c_{si}(x_i - y_i)$ is the total cost of core type i, including the total acquisition and inspection costs $u_i x_i$, the total remanufacturing cost $r_i(t_{0i}) y_i$, and the total scrapping cost $c_{si}(x_i - y_i)$, and the last term $c_e[e_i y_i + e_{si}(x_i - y_i)]$ is the carbon emissions cost of remanufactured products and scrapped products.

Here, $B_i(x_i, t_{0i})$ is used to represent the total cost of core type *i*, that is,

$$B_i(x_i, t_{0i}) = u_i x_i + r_i(t_{0i}) y_i + c_{si}(x_i - y_i) + c_e[e_i y_i + e_{si}(x_i - y_i)] \tag{2}$$

When the optimal policies are derived in multi-product remanufacturing systems, the remanufacturer usually faces a limited budget. That is, the total cost of all acquired cores should be less than the available budget.

In practice, customers prefer to buy new products rather than remanufactured products. Furthermore, if the remanufacturer ends up with a high number of unsold products at the end of the period, the financial losses can be devastating (Ozler et al., 2009). Here, the remanufacturer may be conservative, and the risk should be considered in the model. Referred to Zhou et al. (2008), the risk constraint is defined as the sum of expected loss of unsold remanufactured products to be less than the maximum acceptable loss, where the expected loss of core type *i* is written as follows:

$$L_i(x_i, t_{0i}) = u_i \frac{I_i(y_i)}{G_i(t_{0i})} + r_i(t_{0i}) I_i(y_i) + c_{si}\left(\frac{I_i(y_i)}{G_i(t_{0i})} - I_i(y_i)\right) - v_i I_i(y_i) + c_e\left[e_i I_i(y_i) + e_{si}\left(\frac{I_i(y_i)}{G_i(t_{0i})} - I_i(y_i)\right)\right] \tag{3}$$

where, $I_i(y_i) = E(y_i - D_i)^+$.

Hence, the profit-maximization model with the carbon tax scheme is given as follows:

$$\text{(Model P1)} \quad \max \Pi(X, T_0) = \sum_{i=1}^{n} \pi_i(x_i, t_{0i}) \tag{4}$$

Subject to:

$$B(X, T_0) = \sum_{i=1}^{n} B_i(x_i, t_{0i}) \le B_G \tag{5}$$

$$L(X, T_0) = \sum_{i=1}^{n} L_i(x_i, t_{0i}) \le L_s \tag{6}$$

$$y_i = x_i G_i(t_{0i}),\ i = 1, 2, \ldots, n \tag{7}$$

$$X \geq 0, T_0 \geq 0 \tag{8}$$

In Model P1, the decision variables are acquisition quantities $X = (x_1, x_2, \ldots, x_n)$ and remanufacturing cost thresholds $T_0 = (t_{01}, t_{02}, \ldots, t_{0n})$. Given X and T_0, the quantities of remanufactured products $Y = (y_1, y_2, \ldots, y_n)$ can be derived by Eq. (7).

4. Properties and solution of the model

4.1 Properties of the model

Due to $y_i = x_i G_i(t_{0i})$, $B_i(x_i, t_{0i})$ can be transformed as:

$$B_i(y_i, t_{0i}) = u_i x_i + r_i(t_{0i}) y_i + c_{si}(x_i - y_i) + c_e[e_i y_i + e_{si}(x_i - y_i)]$$

$$= u_i \frac{y_i}{G_i(t_{0i})} + y_i r_i(t_{0i}) + c_{si}\left(\frac{y_i}{G_i(t_{0i})} - y_i\right) + c_e e_i y_i + c_e e_{si}\left(\frac{y_i}{G_i(t_{0i})} - y_i\right)$$

$$= \frac{u_i + \Lambda_i(t_{0i}) + c_{si} + c_e e_{si} - (c_{si} + c_e e_{si} - c_e e_i) G_i(t_{0i})}{G_i(t_{0i})} y_i$$

$$= A_i(t_{0i}) y_i \tag{9}$$

where, $A_i(t_{0i}) = \dfrac{u_i + \Lambda_i(t_{0i}) + c_{si} + c_e e_{si} - (c_{si} + c_e e_{si} - c_e e_i) G_i(t_{0i})}{G_i(t_{0i})}$, $\Lambda_i(t_{0i}) = \int_0^{t_{0i}} t g_i(t) dt$.

As shown in the above expressions, $A_i(t_{0i})$ can be viewed as the average cost of remanufactured products of core type i, and has the following property.

Proposition 4.1. $A_i(t_{0i})$ is independent of y_i.

This property without carbon emissions was pointed out first by Galbreth and Blackburn (2006) for the single-product setting. Obviously, this property is also valid in this multi-product setting.

Similarly, $\pi_i(x_i, t_{0i})$ can be transformed as:

$$\pi_i(y_i, t_{0i}) = p_i E \min(y_i, D_i) + v_i E(y_i - D_i)^+ - s_i E(D_i - y_i)^+ - A_i(t_{0i}) y_i \tag{10}$$

$L_i(x_i, t_{0i})$ can be transformed as:

$$L_i(y_i, t_{0i}) = (A_i(t_{0i}) - v_i) I_i(y_i) \tag{11}$$

Consequently, Model P1 can be converted into the following model:

(Model P2) $$\max \Pi(Y, T_0) = \sum_{i=1}^{n} \pi_i(y_i, t_{0i}) \tag{12}$$

Subject to:

$$B(Y,T_0)=\sum_{i=1}^{n} B_i(y_i,t_{0i}) \le B_G \tag{13}$$

$$L(Y,T_0)=\sum_{i=1}^{n} L_i(y_i,t_{0i}) \le L_s \tag{14}$$

$$Y \ge 0, T_0 \ge 0 \tag{15}$$

In Model P2, the decision variables are Y and T_0. Once Y and T_0 are known, then X can be obtained from $x_i = y_i / G_i(t_{0i})$, i =1, 2, …, n.

According to the above analysis, the quality variability of acquirable cores and the uncertain demand of remanufactured products independently affect the remanufacturer's decision. Here, Model P2 can be divided into two separated sub-problems, namely remanufacturing problem and acquisition problem. In the remanufacturing problem, the minimal value of $A_i(t_{0i})$ is calculated, and the optimal remanufacturing policies (i.e., the remanufacturing cost thresholds t_{0i}^* and the optimal expected remanufacturing rate $G_i(t_{0i}^*)$) are determined. In the acquisition problem, the optimal acquisition quantities are derived after substituting t_{0i}^* into Eqs. (12-15). That is, the remanufacturer firstly estimates the remanufacturing rate and the average cost of remanufactured products according to the quality condition of the acquirable cores. Then, the remanufacturer can derive the optimal acquisition quantities under the stochastic demand of remanufactured products, and the budget and loss constraints. The whole process is consistent with the decision-making process in reality.

4.2 The remanufacturing problem

The remanufacturing problem is a single variable optimization problem. Obviously, according to the first order condition of $A_i(t_{0i})$, we have:

$$\left.\frac{dA_i(t_{0i})}{dt_{0i}}\right|_{t_{0i}=t_{0i}^*} = \frac{g_i(t_{0i})}{G_i^2(t_{0i})}\left(t_{0i}G_i(t_{0i})-\Lambda_i(t_{0i})-u_i-c_{si}-c_e e_{si}\right)\Big|_{t_{0i}=t_{0i}^*}=0 \tag{16}$$

In general, $t_{0i}^* \ne 0$. For example, if t_i follows the uniform distribution, the exponential distribution, the Weibull distribution, and the Gamma distribution (Guide et al., 2008; Yang et al., 2015), $g_i(t_{0i}^*) \ne 0$. Here, we only discuss $t_{0i}G_i(t_{0i})-\Lambda_i(t_{0i})-u_i-c_{si}-c_e e_{si}=0$.

When $t_{0i}G_i(t_{0i})-\Lambda_i(t_{0i})-u_i-c_{si}-c_e e_{si}=0$, $t_{0i}^* \in (0,\infty]$ satisfies:

$$\int_0^{t_{0i}^*}(t_{0i}^*-t)g_i(t)dt=u_i+c_{si}+c_e e_{si} \tag{17}$$

The left side of Eq. (17) represents the expected cost saving of unit remanufactured product, and the right side represents total disposal cost of unit scrapped core. Hence, Eq. (17) indicates that the optimal remanufacturing cost threshold is the tradeoff between the expected cost saving of unit remanufactured product and total disposal cost of unit scrapped core.

Substitute t_{0i}^* into $A_i(t_{0i})$, and consequently,

$$A_i(t_{0i}^*)=t_{0i}^*+c_e e_i-c_{si}-c_e e_{si} \tag{18}$$

Note that, if $A_i(t_{0i}^*)\geq p_i$, the remanufacturer cannot get profit from core type i. Here, core type i will be removed from the list of the acquirable cores. Without loss of generality, we assume $A_i(t_{0i}^*)<p_i$, i =1, 2, …, n.

From Eq. (17), it is obvious that the optimal remanufacturing policies depend on total disposal cost of unit scrapped core, including unit scrapping cost u_i, unit acquisition and inspection costs c_{si}, and carbon emission cost of unit scraped product $c_e e_{si}$, while the optimal remanufacturing policies are independent on the carbon emission cost of unit remanufactured product $c_e e_i$. Specially, the remanufacturing cost thresholds and the remanufacturing rate is increasing functions of u_i, c_{si}, and $c_e e_{si}$. In other words, if total disposal cost of unit scrapped core is high, the remanufacturer prefers to remanufacture more acquired cores rather than scrapping after acquisition. Hence, the remanufacturing cost threshold and the remanufacturing rate are high, so is the average cost of the remanufactured products.

In addition, according to Eq. (17), the quality of acquirable cores has crucial influence on the remanufacturing policies. Generally, the higher the quality of the acquirable cores, the lower the expected scrapping rate (i.e., $1-G(t_0)$). That is, for any given t_0, if core type i has higher quality than core type j, $1-G_i(t_0)\leq 1-G_j(t_0)$. Here,

$$\int_0^{t_0}(t_0-t)g_i(t)dt\geq\int_0^{t_0}(t_0-t)g_j(t)dt \tag{19}$$

Given the same parameters (i.e., $u_i=u_j=u$, $c_{si}=c_{sj}=c_s$, and $e_{si}=e_{sj}=e_s$), we have:

$$\int_0^{t_{0i}^*}(t_{0i}^*-t)g_i(t)dt=\int_0^{t_{0j}^*}(t_{0j}^*-t)g_j(t)dt \tag{20}$$

According to Eqs. (19) and (20), $t_{0i}^* < t_{0j}^*$. That is, the higher the quality, the smaller the optimal remanufacturing cost threshold. Furthermore, the higher the quality of the acquirable cores, the lower the average cost of remanufactured products (i.e., $A_i(t_{0i}^*) = t_{0i}^* + c_e e_i - c_{si} - c_e e_{si} < t_{0j}^* + c_e e_j - c_{sj} - c_e e_{sj} = A_j(t_{0j}^*)$).

Next, the optimal remanufacturing policies under some frequently-used quality distributions can be derived by the explicit expression.

When t_i follows the uniform distribution (i.e., $g_i(t_i) = \frac{1}{\beta_i - \alpha_i}$, $\alpha_i \le t_i \le \beta_i$), Eq. (17) can be rewritten as follows:

$$t_{0i}^* = \alpha_i + \sqrt{2(\beta_i - \alpha_i)(u_i + c_{si} + c_e e_{si})} \quad (21)$$

When t_i follows the exponential distribution (i.e., $g_i(t_i) = \lambda_i e^{-\lambda_i t_i}$, $t_i \ge 0$), Eq. (17) can be rewritten as follows:

$$\lambda_i t_{0i}^* + e^{-\lambda_i t_{0i}^*} = \lambda_i (u_i + c_{si} + c_e e_{si}) + 1 \quad (22)$$

For most of quality distributions, the expressions of the remanufacturing policies cannot be derived. Since the left hand side of Eq. (17), $\int_0^{t_{0i}} (t_{0i} - t) g_i(t) dt$, is a monotonically increasing function of t_{0i}, t_{0i}^* can be derived by a single bisection method over the interval $[o, p_i]$ (Burden and Faires, 1985).

4.3 The acquisition problem

After substituting t_{0i}^* into Eqs. (12-15), the acquisition problem is an extended Multi-Product Newsvendor Problem (MPNP) with a linear constraint and a nonlinear constraint. MPNP is a classical model in operations research, and has been widely applied to "aid decision making at manufacturing and retail level" (Khouja, 1999). For detailed discussions and reviews of MPNP, we refer the reader to Khouja (1999), and Turken et al. (2012).

In Model P2, the objective function $\Pi(Y, T_0^*)$ is concave, $B(Y, T_0^*)$ is linear, and $L(Y, T_0^*)$ is convex. Hence, the acquisition problem is still a convex optimization problem, and the KKT conditions are necessary and sufficient for optimality.

Let $c_i = A_i(t_{0i}^*)$, λ_1 and λ_2 be the shadow price of the budget constraint and the risk constraint, respectively. Then, the KKT conditions of the acquisition problem are rewritten as follows:

$$(p_i + s_i - c_i) - (p_i + s_i - v_i)F_i(y_i) - \lambda_1 c_i - \lambda_2 (c_i - v_i)F_i(y_i) = 0 \,,\ i = 1, 2, \ldots, n, \tag{23}$$

$$\lambda_1 (\sum_{i=1}^{n} c_i y_i - B_G) = 0 \,, \tag{24}$$

$$\lambda_2 (\sum_{i=1}^{n} (c_i - v_i) I_i(y_i) - L_s) = 0 \,, \tag{25}$$

$$\lambda_1 \ge 0 \,, \lambda_2 \ge 0 \,. \tag{26}$$

According to Eq. (23), $y_i = F_i^{-1}(\dfrac{p_i + s_i - c_i - \lambda_1 c_i}{p_i + s_i - v_i + \lambda_2 (c_i - v_i)})$, i =1, 2, …, n. Since $y_i < 0$ is meaningless, let:

$$Y_i(\lambda_1, \lambda_2) = \max\{\frac{p_i - c_i + s_i - \lambda_1 c_i}{p_i - v_i + s_i + \lambda_2 (c_i - v_i)}, F_i(0)\} \text{, and } y_i = F_i^{-1}(Y_i(\lambda_1, \lambda_2)) \,.$$

Let $R_1(\lambda_1, \lambda_2) = \sum_{i=1}^{n} c_i y_i$, $R_2(r_1, r_2) = \sum_{i=1}^{n} (c_i - v_i) I_i(y_i)$, y_i^{**} (i =1, 2, …, n) be the optimal solution, and λ_j^{**} ($j = 1,2$) be the corresponding shadow price. When only the j-th constraint is binding, the optimal solution is defined as $y_{j,i}^*$ ($j = 1,2$, i =1, 2, …, n), and λ_j^* ($j = 1,2$) is the corresponding shadow price. In addition, the optimal solution of unconstrained Model P2 is represented as:

$$y_i^* = F_i^{-1}(\frac{p_i + s_i - c_i}{p_i + s_i - v_i}) \,,\ i = 1, 2, \ldots, n \tag{27}$$

In the following analysis, properties of the acquisition problem are presented in Proposition 4.2.

Proposition 4.2. The optimal solution y_i^{**}, i =1, 2, …, n, has the following properties:

(a) If $\sum_{i=1}^{n} c_i y_i^* \le B_G$, $\sum_{i=1}^{n} (c_i - v_i) I_i(y_i^*) \le L_s$, then $y_i^{**} = y_i^*$, and $\lambda_1^{**} = \lambda_2^{**} = 0$.

(b) If $\sum_{i=1}^{n} (c_i - v_i) I_i(y_{1,i}^*) \le L_s$, and $\sum_{i=1}^{n} c_i y_{1,i}^* = B_G$, then $y_i^{**} = y_{1,i}^*$, $\lambda_1^{**} = \lambda_1^* > 0$, and

$\lambda_2^{**} = 0$. If $\sum_{i=1}^{n} c_i y_{2,i}^* \leq B_G$, and $\sum_{i=1}^{n} (c_i - v_i) I_i (y_{2,i}^*) = L_s$, then $y_i^{**} = y_{2,i}^*$, $\lambda_1^{**} = 0$, and $\lambda_2^{**} = \lambda_2^* > 0$.

(c) If $\sum_{i=1}^{n} (c_i - v_i) I_i (y_{1,i}^*) > L_s$ and $\sum_{i=1}^{n} c_i y_{2,i}^* > B_G$, then $\sum_{i=1}^{n} (c_i - v_i) I_i (y_i^{**}) = L_s$, $\sum_{i=1}^{n} c_i y_i^{**} = B_G$, $0 < \lambda_1^{**} < \lambda_1^*$, and $0 < \lambda_2^{**} < \lambda_2^*$.

Based on complementary slackness in the KKT conditions, Proposition 4.2 is obvious, and explains the characteristics of the optimal solution whether the corresponding constraints are binding or not.

According to Proposition 4.2, the acquisition problem has unique maximum solution, which can be derived through solving Eqs. (23-26). The according solving method is a two-tier bisection method, which has the polynomial computational complexity in the number of core types (n). The details can be referred to the exist papers of MPNP (Lau and Lau, 1995; Lau and Lau, 1996; Abdel-Malek et al., 2004; Abdel-Malek and Montanari, 2005a; Abdel-Malek and Montanari, 2005b; Gotoh and Takano, 2007; Abdel-Malek and Areeratchakul, 2007; Niederhoff, 2007; Zhang and Hua, 2008; Zhang et al., 2009; Zhang and Du, 2010; Zhang and Hua, 2010; Zhang 2012; Zhang and Xu, 2013).

Since the quality distribution and the demand distribution are not hypothesized, the above solving method can be applied to any continuous quality distribution and demand distributions. Furthermore, the general environmental burdens, such as air emissions, solid waste, are represented in the form of linear function or linear piecewise function (Kannan et al., 2012). The environmental burdens and the according regulations can be easily incorporated into the object function and constraint conditions of the aforementioned model. The solving method still is applied in the extended model with promising computational efficiency.

5. The value of quality information

The estimate of core quality and carbon footprint depends on abundant historical data available. However, in remanufacturing, “Often there is a need to acquire life cycle data from the different part of the supply chain and this can be too much of a hassle to collect. Furthermore, to assess the life cycle environmental benefits is an emerging area and there are many companies who are not ready to keep and/or share data yet" (Sundin and Lee, 2011). Lack of perfect historical data is a hassle to make decisions. In this section, taking core quality as the example, we analyze the remanufactuer's decision if little historical data is available. Due to little historical data, the remanufacturer does not obtain the full knowledge of quality distribution, only gain the mean of the quality. In other words, the cores in each type are assumed to be homogenous, and will be all remanufactured with the same unit remanufactured cost (i.e., $\mu_{gi} = E(t_i)$, i =1, 2, …, n). Here, the quality variability of acquirable cores is neglected (i.e., the non-variability case). Next, we quantify the effect of the quality variability by comparing the optimal policies proposed by our model (i.e., the variability case) with the non-variability case.

In the non-variability case, the average cost of the remanufactured products of core type i is $c_{i,N} = u_i + \mu_{gi} + c_e e_i$. Furthermore,

$$\lim_{t_{0i}\to\infty} A_i(t_{0i}) = \lim_{t_{0i}\to\infty} \frac{u_i + \Lambda_i(t_{0i}) + c_{si} + c_e e_{si} - (c_{si} + c_e e_{si} - c_e e_i) G_i(t_{0i})}{G_i(t_{0i})} = u_i + \mu_{gi} + c_e e_i = c_{i,N} \ .$$

Hence, $A_i(t_{0i}^*) < c_{i,N}$ (i.e., $c_i < c_{i,N}$). That is, the average cost of the remanufactured products in the variability case is smaller than that in the non-variability case. Due to quality variability, the cores would not be all remanufactured. Some acquired cores are "likely to be costly to remanufacture, and scrapping may be the appropriate disposition decision" (Galbreth and Blackburn, 2006), which accounts for the lower remanufacturing cost. It implies that the remanufacturer will overestimate the average cost of remanufactured products without considering the quality variability.

Let $x_{i,N}$ be the acquisition quantity in the non-variability case. Then, the expected profit of core type i in the non-variability case is given by:

$$\pi_{i,N}(x_{i,N}) = p_i E \min(x_{i,N}, D_i) + v_i E(x_{i,N} - D_i)^+ - s_i E(D_i - x_{i,N})^+ - c_{i,N} x_{i,N} \qquad (28)$$

The corresponding optimal solution is derived as follows:

$$x_{i,N}^{**} = \max\{F_i^{-1}(\frac{p_i + s_i - c_{i,N} - \lambda_1 c_{i,N}}{p_i + s_i - v_i + \lambda_2 (c_{i,N} - v_i)}), F_i^{-1}(0)\} \qquad (29)$$

Due to $c_i < c_{i,N}$, the following inequality is derived for given λ_1 and λ_2:

$$F_i^{-1}\left(\frac{p_i + s_i - c_{i,N} - \lambda_1 c_{i,N}}{p_i + s_i - v_i + \lambda_2 (c_{i,N} - v_i)}\right) < F_i^{-1}\left(\frac{p_i + s_i - c_i - \lambda_1 c_i}{p_i + s_i - v_i + \lambda_2 (c_i - v_i)}\right) \tag{30}$$

That is, given λ_1 and λ_2, the acquisition quantity in the non-variability case is smaller than that in the variability case. Here, $\pi_{i,N}(x_{i,N}) < \pi_i(x_{i,N}, t_{0i}^*) < \pi_i(y_i, t_{0i}^*)$. The expected profit in the non-variability case is also smaller than that in the variability case. In order to measure the effect of the quality variability, the difference of the expected profit in the two cases is defined by:

$$\Delta = \sum_{i=1}^{n} (\pi_i(y_i^{**}, t_{0i}^*) - \pi_{i,N}(x_{i,N}^{**})) \tag{31}$$

Δ is viewed as the upper bound of the price the remanufacturer is willing to pay for exploiting the quality information and identifying the quality variability before acquisition. The value of Δ is shown in numerical examples in the next section.

Similarly, the relative difference of the expected profit in the two cases is also defined as follows:

$$z = \sum_{i=1}^{n} (\pi_i(y_i^{**}, t_{0i}^*) - \pi_{i,N}(x_{i,N}^{**})) / \sum_{i=1}^{n} \pi_i(y_i^{**}, t_{0i}^*) \tag{32}$$

Note that, the value of the information about carbon footprint can be calculated by similar approach. However, the data of carbon footprint comes from various parts of supply chain, and is more difficult to collect.

6. Numerical study

In this section, numerical examples are presented to show the application of the model. In addition, the effect of quality variability is discussed. All computational experiments are conducted on Lenovo laptop (Dual processor 2.40GHz and Memory 4.00G) with Matlab 7.04, and $\varepsilon = 10^{-5}$.

6.1 Numerical examples

There are four different types of acquirable cores. As shown in Guide et al. (2008), a gamma distribution is chosen to represent highly variable remanufacturing processing times, "because it is a very flexible continuous probability distribution that can be used to model different levels of variability." In numerical examples, it is assumed that the quality of core type i follows the Gamma distribution $\Gamma_i(\alpha_i, \beta_i)$ (i.e., $\mu_{gi} = \alpha_i \beta_i$). The demand of remanufactured products of core type i follows the normal distribution $N_i(\mu_i, \sigma_i)$ (Zhang and Hua, 2008; Zhang et al., 2009; Zhang and Du, 2010; Zhang and Hua, 2010). The parameters are shown in Table 1.

Table 1: Parameters of the examples

core type	p_i	s_i	v_i	μ_i	σ_i	u_i	c_{si}	α_i	β_i	e_i	e_{si}	c_e
1	3.6	0.1	0.4	1500	245	1.1	0.3	1	1.25	0.1	0.5	1
2	7.9	0.1	0.8	2000	360	3.1	1.2	1	1.25	0.1	0.5	1
3	15	0.2	1.6	1000	161	3.2	1.5	2.7	3.3	0.2	0.5	1
4	25	0.2	2.4	600	108	4	2.1	2.7	3.3	0.3	0.5	1

Firstly, the remanufacturing problem is solved. t_{0i}^*, $A_i(t_{0i}^*)$, and $G_i(t_{0i}^*)$ are derived as shown in Table 2.

Table 2: The results of the remanufacturing problem

core type	t_{0i}^*	$A_i(t_{0i}^*)$	$G_i(t_{0i}^*)$
1	3.0402	2.3402	91.22%
2	6.0400	4.4400	99.20%
3	13.2744	11.4744	81.57%
4	14.9333	12.6333	86.94%

Substituting the value of t_{0i}^* and $A_i(t_{0i}^*)$ into Eqs. (12-15), the acquisition problem is solved. Three groups of available budgets and maximum acceptable losses are set. The results are summarized in Table 3.

Table 3: The optimal solutions under various scenarios

parameters		optimal solution	core type				Π	λ_1^{**}	λ_2^{**}
B_G	L_s		1	2	3	4			
9000	100	y_i^{**}	0	702	0	466	7555	0.8015	0
		x_i^{**}	0	707	0	536			
18000	200	y_i^{**}	1142	1590	173	498	13023	0.3247	2.5923

		x_i^{**}	1252	1603	212	573			
33000	1500	y_i^{**}	1446	1995	903	614	16703	0	0
		x_i^{**}	1585	2011	1107	706			

From Table 3, the optimal policies are derived. For example, if $B_G = 9000$ and $L_s = 100$, the remanufacturer determines to acquire core type 2 and core type 4, that is, $Y = [0, 702, 0, 466]$ and $X = [0, 707, 0, 536]$. In addition, the quantities of the acquired cores and the remanufactured products, and the expected profit are increasing with the available budget and maximum acceptable loss. Furthermore, when $\lambda_1^{**} = 0$ and $\lambda_2^{**} = 0$ (the last setting in the table), that is, the two constraints are not binding, we can find that the real budget and loss are 30360 and 1439, respectively. Hence, Model P2 is unconstrained when the available budget and maximum acceptable loss are not less than 30360 and 1439, respectively.

6.2 The effect of quality variability

In this section, the effects of the quality variability are discussed by comparing the optimal policies under the variability case with that under the non-variability case. The performance criteria are the difference of the remanufacturing cost (i.e., $\rho_i = (c_{i,N} - c_i) / c_i$) and the expected profit (i.e., Δ and z), respectively.

Firstly, the effect of quality variability on the remanufacturing problem is analyzed. The results are shown in Table 4.

Table 4: The comparison of the average costs of the remanufactured products

core type	the variability case		the non-variability case	ρ_i (%)
	$G_i(t_{0i}^*)$ (%)	c_i	$c_{i,N}$	
1	91.22%	2.3402	2.4500	4.69
2	99.20%	4.4400	4.4500	0.23
3	81.57%	11.4744	12.3100	7.28
4	86.94%	12.6333	13.2100	4.56

According to Table 4, if the remanufacturer exploits the quality information and identifies the quality variability before acquisition, the remanufacturer may acquire more cores and select the best cores to be remanufactured. Accordingly, the remanufacturing cost will reduce. Furthermore, with the remanufacturing cost decreasing, the average cost of the remanufactured products is smaller than that in the non-variability case.

Then, the effect of quality variability on the acquisition problem is analyzed. The results are shown in Table 5.

Table 5: The comparison of the optimal acquisition policies

parameters		optimal solution	core type				expected profit	Δ	*z* (%)
B_G	L_s		1	2	3	4			
9000	100	x_i^{**}	0	707	0	536	7555	482	6.38
		$x_{i,N}^{**}$	0	730	0	436	7073		
18000	200	x_i^{**}	1252	1603	212	573	13023	725	5.57
		$x_{i,N}^{**}$	1137	1602	130	491	12298		
33000	1500	x_i^{**}	1585	2011	1107	706	16703	1271	7.61
		$x_{i,N}^{**}$	1424	1994	872	607	15432		

Take B_G = 9000 and L_s = 100 as the example. The acquired cores in the variability case are X = [0, 707, 0, 536], while the acquired cores in the non-variability case are X_N = [0, 730, 0, 436]. Compared with the non-variability case, the remanufactuer's expected profit increases 482 (7555-7073), and the improvement of the expected profit is 6.38% (482/7555). Here, the price the remanufacturer is willing to pay for exploiting the information of the quality variability is 482. In other words, if historical data is not available, the remanufacturer can not obtain the quality information and estimate the quality variability before acquisition. Hence, the remanufacturer remanufactures all acquired cores, and incurs a loss of 482.

By comparison, we can conclude that the optimal acquisition and remanufacturing polices in the variability case outperform that in the non-variability case. Of course, the remanufacturer should determine whether to adopt the optimal policies with quality variability by comparing the value of quality information with the additional cost of exploiting the information of the quality variability.

7. Conclusions

In this paper, a multi-product acquisition and remanufacturing problem has been studied under variable core quality and carbon tax scheme. In order to maximize the remanufacturer's expected profit, a nonlinear programming model with the budget and risk constraints was established. The model has favorable structural properties as follows.

(i) Since the average cost of the remanufactured products is independent of the remanufacturing quantity, the model can be decomposed into two separated and simple sub-problems (i.e., the remanufacturing problem and the acquisition problem). In the remanufacturing problem, the remanufacturer estimates the remanufacturing rate and the remanufacturing cost according to the quality condition of the acquirable cores. In the acquisition problem, the remanufacturer determines the optimal core portfolio, acquisition quantities based on the trade-off of between environmental and economic benefit. The solving process conforms to the decision-making process of the remanufacturer.

(ii) The remanufacturing problem is a single variable optimization problem, which can be solved by a single bisection method. Furthermore, the acquisition problem is an extended MPNP. This problem is a convex optimization problem and has unique maximum solution, which can be solved by a two-tier bisection method with polynomial computational complexity.

(iii) The model has a positive expansibility. The model can be applied in the case with any continuous quality distribution and demand distributions. In addition, the model can be applied in the case with general environmental burdens and relevant regulations.

In addition, the effect of carbon emissions is discussed under the carbon tax scheme. Carbon emissions generated from remanufactured products and scraped products have different influences on the optimal policies. The optimal remanufacturing rate is dependent on carbon emission cost of unit scraped product, but is independent on carbon emission cost of unit remanufactured product. Furthermore, the optimal remanufacturing polices and the average cost of remanufactured products is increasing functions of carbon emission cost of unit remanufactured product and unit scraped product.

Furthermore, the effect of quality variability is analyzed. When quality variability is neglect, the average cost of remanufactured products is overestimated, which leads to the decrease of the remanufacturer's expected profit.

For future work, it is natural to consider both quantity and quality of acquirable cores with the relationship of acquisition price in a multi-product remanufacturing system from the practical point of view. In addition, the multi-product acquisition and remanufacturing problem under various material and parts production is worthy of study.

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