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Production planning in a multi-product manufacturing system considering the carbon cap and trade mechanism and product recycling mechanism

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Abstract: With the deterioration of ecological environment and the shortage of natural resources, firms are forced to change and adjust their production planning along an environmentally friendly road to reduce the negative effects on the environment. This paper investigate the optimal production planning in a multi-product manufacturing system considering the product recycling mechanism and carbon cap and trade mechanism, in which a firm uses limited machine capacity, working time and carbon quotas to manufacture multiple products for fulfilling stochastic market demands. Based on the cost-volume-profit analysis, a profit maximization model is proposed to characterize the optimization problem. In this model, the cost structure consists of production cost, holding or shortage cost, recycling cost and carbon cost. The revenue structure consists of sales revenue and recycling benefits. According to the profit maximization model and the numerical example, the optimal production and recycling decisions are analyzed. Meanwhile, the effects of cap and trade mechanism and product recycling mechanism on production quantity, total carbon emissions and total profits are also investigated. The results indicate that under the carbon cap and trade mechanism and the product recycling mechanism, a higher carbon permit price can motivate manufacturers to produce green product, and that product recycling mechanism is beneficial to lower carbon emissions and increase the firm profit. Managerial insights and suggestions for future research are given.

Keywords: production planning; carbon cap and trade mechanism; recycling mechanism; carbon permit price; profit maximization

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1 Introduction

There is consensus that the worsening environmental problems are largely caused by firms' activities and they have become a major threat to the development of the economy and the society[1-4]. In recent years, to alleviate the negative effects of their design, production and after-life on the environment, a series of command-and-control policies and motivational policies and programs, such as imposing carbon tax on energy intensive firms, shutting down the energy intensive firms, improving the energy consumption efficiency, developing renewable energy and promoting cleaner production, have been implemented by many countries and regions[5-8]. In comparison with these policies and programs, carbon cap and trade mechanism, which is a market-based emission control mechanism, has attracted widespread attention and been regarded as a more effective way to protect the environment and reduce carbon emissions[6,9-11].

According to the carbon cap and trade mechanism, a firm initially obtains certain amount of carbon emission quotas (carbon cap) which is allocated based on the firm production capacity by an external regulatory body[11,12]. The total carbon emissions generated from firms' production manufacturing activities should be less than those of the carbon quotas. If the total carbon emissions are less than the carbon quotas, the surplus quotas can be traded for profits through the carbon trading market. However, if the total carbon emissions are more than the carbon quotas, the shortage can be solved by buying carbon quotas from the carbon trading

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market[13]. It is evident that under the carbon cap and trade mechanism, carbon emissions constraint will put pressures on firms and make them spend extra expenditure to emit carbon dioxide, which will force or encourage them to adopt green production technologies and make changes in their production planning decisions[6,14,15]. Meanwhile, many consumers are more environmentally conscious than in the past and willing to pay more for environmentally friendly products[9]. To respond to these concerns, firms should adopt sustainable practices in their product designs and production process and adjust their business strategies and production planning[15,16].

Furthermore, product recycling mechanism has also drawn much attention in recent years[17-19]. Product recycling mechanism is a critical part of green supply chain management and refers to the series of activities that are required to retrieve a used product from the market and either dispose of it or recover value from it[17,18]. Recycling mechanism could significantly reduce energy consumption and carbon emissions due to fewer raw materials consumed and fewer production procedures arranged[1,6,20,21]. Hence, it is often seen as an effective way to save energy and resources and minimize the environmental impact during the product life cycle[10,22]. Some well-known companies, such as IBM and Huawei, have paid a great deal of attention on recycling activities[23]. Currently, some firms are still hesitant to implement product recycling mechanism and perceive product recycling activities as the additional expenditure to their normal overhead costs[1,6]. However, the shortage of natural resources and energy, strict environmental regulations and the rising price of materials have forced them to implement product recycling mechanism, perform sustainable and intensive production practices, and change manufacturing planning and procedures[19,22].

It is known that for firms which engage in carbon cap and trade mechanism and product recycling mechanism, resource and environment constraint will lead them to adapt the manufacturing systems and remake decisions on production planning to satisfy market demands with the consideration of profits, costs and carbon emissions[24]. This leads to several meaningful and interesting research questions: how to make the optimal production planning and recycling decisions for firms to maximize the profit under the constraint of carbon emissions? Whether conducting recycling activities are much better for firms under the constraint of carbon emissions? Can the recycling activities lead to carbon emission reduction and profit increase? How does the carbon permit price affect the production decisions, total carbon emissions and total profits?

In fact, some works have been done for exploring the effects of carbon emission regulations on firms' operations decisions and production planning. Letmathe and Balakrishnan[25] explored the firm's optimal product mix and production quantity considering the environmental constraints and production constraints. They found that the product mix and production quantity are affected by emission taxes and emission threshold values. Tsai et al. [26] developed a mathematical model for a green product mix decision that incorporates capacity expansion features and considered the constraints of carbon emissions. Zhang and Xu[9] investigated the multi-item production planning problem under the constraint of carbon emissions and compared the effects of carbon trading policy and taxation policy on production planning. Chang et al. [6] studied a monopolist firm who makes new products in the first period and makes the new and remanufactured products in the second period and investigated the optimal production quantities for each period under the carbon cap and trade mechanism. He et al. [12] examined the optimal production planning and production lot-sizing issues of a firm considering the cap-and-trade mechanism and carbon tax regulations and investigated the impacts of regulation parameters on the optimal production quantities and emissions.

There are also some works have been done to explore the effects of recycling activities on firms' operations decisions and production planning. Debo et al. [27] analyzed the problem of pricing and production technology selection for recyclable products. Kaya[28] studied the optimal price and production quantities of new and remanufactured products in a stochastic demand market. Zanoni et al. [29] investigated the multi-product economic lot scheduling and production planning problem with recycling. Liu et al. [10] presented three optimization models to determine the recycling quantity under three common carbon emission regulation policies: mandatory carbon emissions capacity, carbon tax and cap and trade. Mahmoudzadeh et al. [30] and Xiong et al. [31] also explored the problems of recycled products and pricing decisions.

The researches mentioned above explored the effects of carbon cap and trade mechanism and product recycling mechanism on firm's production planning separately. Up to now, less research has been done to incorporate these two mechanisms together to explore their combined effects on production planning. Considering this issue may lead to novel optimization model and interesting findings. Meanwhile, most research merely considers the carbon emission constraint, other constraints such as machine capacities and working time constraints are not considered. Such a void leaves a significant research gap. In the current research, we try to address this shortfall. In addition, as the market competition intensifies, firms need more flexibility to arrange their production process and make production planning decisions in a multi-product manufacturing system to maximize the expected profit[9]. Thus, in this research, a profit maximization model is presented to understand the production planning in a multi-product manufacturing system considering the carbon cap and trade mechanism and product recycling mechanism.

The rest of this paper is organized as follows. Section 2 describes the problem and presents the optimization model. Section 3 employs a numerical example to illustrate the results. Finally, the conclusions and suggestions for future research are presented in Section 4.

2 Problem statement and the optimization model

Most firms make production planning decisions based on the profit maximization principle[2,6,21,32]. Cost-volume-profit analysis is a traditional method to show the relationships between cost, revenue and profit among the firms[33,34]. In this section, based on cost-volume-profit analysis, an optimization model is presented to illustrate the production planning problem in a multi-product manufacturing system considering the carbon cap and trade mechanism and product recycling mechanism. Following, we will discuss the revenue and the cost of the firm separately. In addition, in order to develop the model clearly, several assumptions are made as follows:

①A product is made of several parts and materials and they can be recycled. All the recycled parts and materials can be reused totally, namely, without disposal cost.

②The product market demand is stochastic and it is not always equal to the production quantity[35,36].

③The carbon quotas allocated to the firms are lower than their carbon emissions.

④The cost and energy need to recycle products are less than the cost and energy required to produce originally.

⑤The firm manufactures various products, and the production cost, selling price and carbon emission for each product are different but constant.

2.1 Cost analysis

Without loss of generality, under the cap and trade and product recycling mechanism, the cost structure of a firm consists of production cost, holding or shortage cost, recycling cost and carbon cost[37].

2.1.1 Recycling cost

For every product $i(i=1,\cdots,n)$, it is made of $j(j=1,\cdots,s)$ materials. The production quantity, market demand and selling price of product i are x_{it}, D_{it}, P_i in period $t(t=1,\cdots,T)$, respectively. After implementing the product recycling mechanism, some of the products can be recycled and disassembled into several materials, and these recycled materials can be sent back to production process. In generally, the recycling process can be divided into four stages: disassembly, shredding, recovery and disposition[38,39]. Accordingly, recycling of a product has a given cost for the firm in each stage. For simplicity, we don't consider the disposal cost. The costs related to recycling activities include disassembly and shredding cost and recovery cost.

In the disassembly and shredding process, the recycled products will be disassembled and shredded by machine or labor. The disassembly and shredding process has a given cost. In this research, the unit disassembly and shredding cost of product i can be denoted as Cd_i, and the quantity of the recycled product i in period t is denoted as r_{it}. Thus, the total disassembly and shredding cost is represented as $\sum_{t=1}^{T}\sum_{i=1}^{n}Cd_i r_{it}$. After disassembling and shredding, the recycled materials will be sent for a recovery process and then to the production process. The unit recovery cost for the recycled material y_{ijt} is represented as d_{ij}, and the total recovery cost is denoted as $\sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{j=1}^{s}d_{ij}y_{ijt}$. Hence, the recycling cost (RC) can be denoted as

$$\mathrm{RC}=\sum_{t=1}^{T}\sum_{i=1}^{n}Cd_i r_{it}+\sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{j=1}^{s}d_{ij}y_{ijt} \qquad (1)$$

In addition, it is worth noting that the disassembly, shredding and recovery process is a time consuming process and they will be restricted by machine capacity and working time[40]. As a result, the machine capacity and working time constraints can be expressed as

$$\sum_{i=1}^{n}\sum_{j=1}^{s}\varphi_{ij}y_{ijt}\leqslant\Gamma \text{ and } \sum_{i=1}^{n}\sum_{j=1}^{s}k_{ij}y_{ijt}\leqslant\vartheta.$$

The meanings of the notations are summarized in Table 1.

2.1.2 Carbon cost

Firm's production activities are restricted by carbon emissions[41]. Under the cap and trade mechanism and product recycling mechanism, there are two sources of carbon emissions. One is generated from the manufacturing process and the other is from the recycling process. The total carbon emissions generated by the firm can be denoted as $\sum_{t=1}^{T}\sum_{i=1}^{n}\left[(e_i+ea_i)x_{it}+\sum_{j=1}^{s}(ed_{ij}-e_{ij})y_{ijt}\right]$ $\left(e_i=\sum_{j=1}^{s}e_{ij}\right)$. Since the initial carbon quotas are lower than the carbon emissions, the shortage carbon quotas which need to buy from market is

Table 1. The meaning of the notations.

Notation	Description
x_{it}, D_{it}, P_i	Production quantity, market demand and selling price of product i in period t
c_{ij}	The price of material j of product i
C_i	Unit production cost of product i
r_{it}	The quantity of the recycled product i in period t
y_{ijt}	The quantity of the recycled material j from product i in period t
Cd_i	Unit disassembly and shredding cost of product i
d_{ij}	Unit recovery cost of the recycled material y_{ijt}
S_i and O_i	Unit holding cost and shortage cost of product i
P_C	Carbon permit price
ψ	The shortage carbon quotas which need to buy from the market
e_{ij}	Carbon emission for consuming one unit of material j to produce product i
e_i	Carbon emission for producing one unit of product i
ed_{ij}	Carbon emission for disassembly, shredding and recovery material j from product i ($ed_{ij} < e_{ij}$)
w_t	Carbon quotas in period t
ea_i	Carbon emission for assembling x_{it} in the manufacturing process
k_{ij}	The machine working time for the recycled material y_{ijt}
φ_{ij}	The machine capacity for the recycled material y_{ijt}
ϑ	Total available machine working time in the recycling process
Γ	Total machine capacity in the recycling process
τ_i	The machine working time for producing x_{it}
TT	Total machine working time for producing all products
φ_i	The machine capacity for producing x_{it}
Φ	Total machine capacity for producing all products
β_i	Assembled time for x_{it}
B	Total assemble time for all products
Sto_i	The maximum inventory level of product i

$$\psi = \sum_{t=1}^{T}\sum_{i=1}^{n}\left[(e_i + ea_i)x_{it} + \sum_{j=1}^{s}(ed_{ij} - e_{ij})y_{ijt}\right] - \sum_{t=1}^{T} w_t.$$

Therefore, the carbon cost (CC) can be estimated by the following equation:

$$\mathrm{CC} = P_C\psi = P_C\left\{\sum_{t=1}^{T}\sum_{i=1}^{n}\left[(e_i + ea_i)x_{it} + \sum_{j=1}^{s}(ed_{ij} - e_{ij})y_{ijt}\right] - \sum_{t=1}^{T} w_t\right\} \quad (2)$$

2.1.3 Production cost and holding or shortage cost

Production cost is the fundamental cost of a firm and it is decided by production quantity and the unit production cost. In this research, the production cost can be represented as $\sum_{t=1}^{T}\sum_{i=1}^{n} C_i x_{it}\,(C_i = \sum_{j=1}^{s} c_{ij})$. In the manufacturing process, machines will be used to process and assemble or form the materials into products[42]. Hence, the manufacturing process can be restricted by machine working time, machine capacity and assembled time. The constraints are expressed as $\sum_{i=1}^{n}\tau_i x_{it} \leqslant \mathrm{TT}$, $\sum_{i=1}^{n}\varphi_i x_{it} \leqslant \Phi$ and $\sum_{i=1}^{n}\beta_i x_{it} \leqslant B$.

Considering production quantity may not equal to market demand, there may exist holding or shortage cost. The holding or shortage cost can be denoted as $\sum_{t=1}^{T}\sum_{i=1}^{n}[\lambda_1 S_i(x_{ip} - D_{ip}) + \lambda_2 O_i(D_{ip} - x_{ip})]$. If

$$\sum_{p=1}^{t}(x_{ip} - D_{ip}) > 0,$$

then $\lambda_1 = 1$ and $\lambda_2 = 0$. Otherwise $\lambda_1 = 0$ and $\lambda_2 = 1$. In addition, the inventory level is often restricted by warehousing capacity[43]. The constraint is expressed as $(x_{it} - D_{it}) \leqslant Sto_i$. The production cost and holding or shortage cost (PC) can be expressed as

$$\mathrm{PC} = \sum_{t=1}^{T}\sum_{i=1}^{n}\left[C_i x_{it} + \lambda_1 S_i(x_{ip} - D_{ip}) + \lambda_2 O_i(D_{ip} - x_{ip})\right] \quad (3)$$

Therefore, the total cost (TC) can be estimated by the following equation:

$$\mathrm{TC} = \mathrm{RC} + \mathrm{CC} + \mathrm{PC} = \sum_{t=1}^{T}\sum_{i=1}^{n}\left[C_i x_{it} + \lambda_1 S_i(x_{ip} - D_{ip}) + \lambda_2 O_i(D_{ip} - x_{ip}) + Cd_i r_{it} + \sum_{j=1}^{s} d_{ij} y_{ijt}\right] + P_C\psi \quad (4)$$

2.2 Revenue analysis

The revenue structure consists of product sales revenue and the recycling benefits. Sales revenue is decided by selling price and selling quantity. It can be expressed as $\sum_{t=1}^{T}\sum_{i=1}^{n} P_i \min(x_{it}, D_{it})$. In addition, as mentioned above, with the product recycling mechanism, all the usable materials will be recovered and returned to the production process with other raw materials. These recycled materials are valuable for the firm. The value of recycled materials can be denoted as $\sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{j=1}^{s} c_{ij} y_{ijt}$. Hence, the total revenue (TR) can be estimated through the following equation:

$$\mathrm{TR} = \sum_{t=1}^{T}\sum_{i=1}^{n} P_i \min(x_{it}, D_{it}) + \sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{j=1}^{s} c_{ij} y_{ijt} \quad (5)$$

2.3 The profit maximization model

Based on the cost and revenue analysis, it is ready to present the optimization model for illustrating the production planning problem in a multi-product manufacturing system under the carbon cap and trade mechanism and product recycling mechanism. The mathematical model for maximizing the total profit (π) is expressed as follows:

$$\text{Max } \pi = \text{TR} - \text{TC} = \sum_{t=1}^{T}\sum_{i=1}^{n} P_i \min(x_{it}, D_{it}) + \sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{j=1}^{s} c_{ij} y_{ijt} - \{ \sum_{i=1}^{T}\sum_{i=1}^{n} [C_i x_{it} + \lambda_1 S_i (x_{ip} - D_{ip}) + \lambda_2 O_i (D_{ip} - x_{ip}) + Cd_i r_{it} + \sum_{j=1}^{s} d_{ij} y_{ijt}] + P_C \psi \} \tag{6}$$

where $C_i = \sum_{j=1}^{s} c_{ij}$, $e_i = \sum_{j=1}^{s} e_{ij}$ and

$$\psi = \sum_{t=1}^{T}\sum_{i=1}^{n} [(e_i + ea_i) x_{it} + \sum_{j=1}^{s} (ed_{ij} - e_{ij}) y_{ijt}] - \sum_{t=1}^{T} w_t,$$

subject to

$$\lambda_1 + \lambda_2 = 1, \lambda_1, \lambda_2 = 0, 1 \tag{7}$$

$$\sum_{p=1}^{t} (x_{ip} - D_{ip}) > 0, \lambda_1 = 1 \tag{8}$$

$$\sum_{p=1}^{t} (x_{ip} - D_{ip}) < 0, \lambda_2 = 1 \tag{9}$$

$$\sum_{i=1}^{n} \tau_i x_{it} \leqslant \text{TT} \tag{10}$$

$$\sum_{i=1}^{n} \varphi_i x_{it} \leqslant \Phi \tag{11}$$

$$\sum_{i=1}^{n} \beta_i x_{it} \leqslant B \tag{12}$$

$$(x_{it} - D_{it}) \leqslant Sto_i \tag{13}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{s} k_{ij} y_{ijt} \leqslant \vartheta \tag{14}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{s} \varphi_{ij} y_{ijt} \leqslant \Gamma \tag{15}$$

3 Numerical example

In this section, we take a manufacturing firm Y as an example to conduct the numerical analysis to illustrate the proposed model. For simplicity, we assume Y produces three kinds of products and each product consists of five materials. The time period $T = 4$, the carbon quotas $\omega = 500$ tonnes and carbon permit price $P_C = 50$ RMB per tonne. Several constraint parameters are assumed as follows: TT = 12400 h, $\Phi = 11000$ pieces, $B = 1640$ h, $\Gamma = 2500$ pieces and $\vartheta = 5000$ h. The values of other parameters are presented in Tables 2 and 3. In addition, MATLAB 2016a software packages are used to conduct the data analysis in this research[44,45].

Based on the data analysis, we obtain the optimal production quantity, recycled product quantity, recycled material quantity, revenue, cost, profit and carbon emission for each product. The results are presented in Table 4. As depicted in Table 4, the optimal production quantity mix is (440, 641, 610) and the optimal recycled product quantity mix is (120, 165, 220). Compared with Product 1 and Product 2, Product 3 is much "greener". The carbon emission of Product 3 is lower than that of Product 1 and Product 2, while the profit and recycled material quantity of Product 3 is larger than that of Product 1 and Product 2. The results support the conclusion that the more green products produced, the more profits can be obtained.

Table 2. The values of product parameters for the numerical example.

Parameters	Product (i)		
	$i = 1$	$i = 2$	$i = 3$
P_i	1500	2250	2700
C_i	750	1000	1250
D_{i1}	219	164	131
D_{i2}	241	181	145
D_{i3}	266	199	159
D_{i4}	292	219	175
Cd_i	150	200	250
S_i	45	60	75
O_i	300	400	500
e_i	2	1.50	1
ea_i	0.20	0.15	0.10
τ_i	20	30	35
φ_i	17	26	31
β_i	2	4	5
Sto_i	40	30	20

Table 3. The values of material parameters for the numerical example ($j = 1, \cdots, 5$).

Parameters	Product (i)		
	$i = 1$	$i = 2$	$i = 3$
c_{i1}	150	210	237.5
c_{i2}	75	110	125
c_{i3}	225	290	400
c_{i4}	165	230	275
c_{i5}	135	160	212.5
d_{i1}	42	∞	∞
d_{i2}	∞	82	∞
d_{i3}	∞	156	192
d_{i4}	65	∞	∞
d_{i5}	∞	∞	129
e_{i1}	0.40	0.315	0.19
e_{i2}	0.20	0.165	0.10
e_{i3}	0.60	0.435	0.32
e_{i4}	0.44	0.345	0.22
e_{i5}	0.36	0.24	0.17
ed_{i1}	0.20	0.1575	0.095
ed_{i2}	0.10	0.0825	0.05
ed_{i3}	0.30	0.2175	0.16
ed_{i4}	0.22	0.1725	0.11
ed_{i5}	0.18	0.12	0.085
k_{i1}	4	6.30	7.60
k_{i2}	2	3.30	4
k_{i3}	6	8.70	12.80
k_{i4}	4.40	6.90	8.80
k_{i5}	3.60	4.80	6.80
φ_{i1}	0.60	1.68	1.90
φ_{i2}	0.30	0.88	1
φ_{i3}	0.90	2.32	3.20
φ_{i4}	0.66	1.84	2.20
φ_{i5}	0.54	1.28	1.70

[Note] ∞ means non-disassembly.

Table 4. Data analysis results.

Parameters	Product (i)		
	$i = 1$	$i = 2$	$i = 3$
Production quantity	440	641	610
Recycled product quantity	120	165	220
Revenue	798600	1628140	1979400
Cost	590240	898707.625	1047686
Profit	208360	729432.375	931714
Carbon emission	748	918.2325	538.04
The recycled material 1	440	0	0
The recycled material 2	0	0	0
The recycled material 3	0	641	610
The recycled material 4	440	0	0
The recycled material 5	0	0	416

Furthermore, to further illustrate the effects of cap and trade mechanism and product recycling mechanism on production planning, we explore the effect of carbon permit price on production quantity, carbon emission and profit, and compare the effects of recycling and non-recycling activities on the carbon emission and profit. The results are presented in Figures 1 − 3. According to Figure 1, it is shown that the optimal production quantity of Product 1 and Product 2 decreases as the carbon permit price increases, while the optimal production quantity of Product 3 increases as the carbon permit price increases. According to Table 2, it is known that Product 3 is much greener than Product 1 and Product 2. Thus, it can be concluded that under the cap and trade mechanism and product recycling mechanism, a higher carbon permit price can motivate manufacturers to produce more green product.

As shown in Figure 2, the total carbon emissions decrease as the carbon permit price increases, which means that cap and trade mechanism can encourage the firm to reduce carbon emissions. It is also shown that the total carbon emissions in the recycling context

$$\left(\sum_{t=1}^{T}\sum_{i=1}^{n}\left[(e_i+ea_i)x_{it}+\sum_{j=1}^{s}(ed_{ij}-e_{ij})y_{ijt}\right]\right)$$

is lower than the total carbon emissions in the non-recycling context ($e_i x_{it}$), which means that the implementing product recycling mechanism is benefit to lower carbon emissions.

Figure 3 indicates that the profit decreases as the carbon permit price increases, which means that the cap and trade mechanism reduces the firm's profit since the firm needs to buy shortage carbon quotas from the market. It is also depicted that the profit in the recycling context (Equation (6)) is always higher than the profit in the non-recycling context

$$\Big(\sum_{t=1}^{T}\sum_{i=1}^{n}P_i\min(x_{it},D_{it})-$$

$$\Big\{\sum_{i=1}^{T}\sum_{i=1}^{n}\left[C_i x_{it}+\lambda_1 S_i(x_{ip}-D_{ip})+\lambda_2 O_i(D_{ip}-x_{ip})\right]+$$

$$P_C\Big(\sum_{t=1}^{T}\sum_{i=1}^{n}e_i x_{it}-\sum_{t=1}^{T}w_t\Big)\Big\}\Big),$$

which means that implementing product recycling mechanism is useful to increase the firm profit.

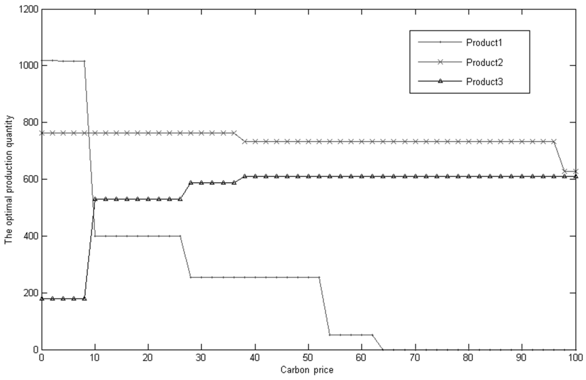

Figure 1. The relationship between carbon permit price and the optimal production quantity.

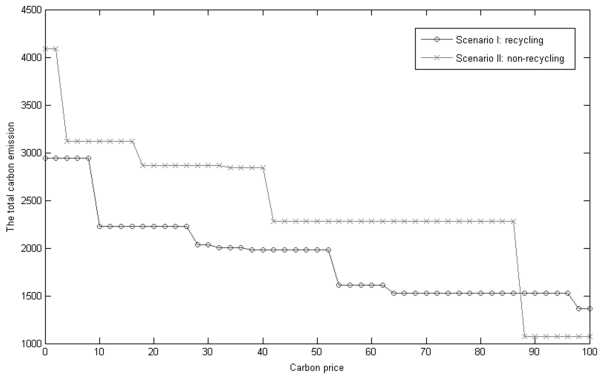

Figure 2. The relationship between carbon permit price and carbon emission.

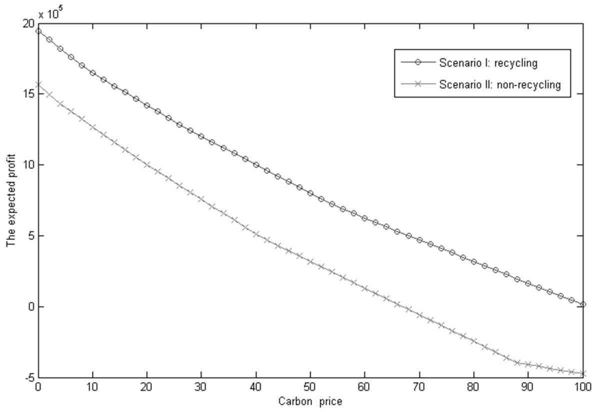

Figure 3. The relationship between carbon permit price and the total profit.

4 Conclusions

With the shortage of natural resources and the strict regulation on carbon emissions, it is necessary for firms to incorporate green concept and environmental concern into their decision-makings. In this paper, based on the cost-volume-profit analysis, a profit maximization model is established to investigate the production planning in a multi-product manufacturing system with the consideration of cap and trade mechanism and product recycling mechanism. By analyzing the cost and revenue structure and conducting the numerical example, we obtain the optimal production quantity, recycled product quantity and recycled material quantity and the maximum profit for each product. Furthermore, we also explore the effects of cap and trade mechanism and product recycling mechanism on production quantities, profits and carbon emissions.

By analyzing the impacts of cap and trade mechanism and product recycling mechanism on production quantities, carbon emissions and total profits, some interesting managerial insights can be obtained: ①Carbon permit price is positively associated with the production quantity of green products. The firm tends to produce green products under the cap and trade mechanism. ② Carbon permit price is negatively associated with the firm's profit. The higher the carbon permit price is, the less profit the firm obtains. ③A higher carbon permit price will induce the firm to reduce carbon emissions. Cap and trade mechanism is useful to lower the carbon emissions. ④ The profit in the recycling context is always larger than the profit in the non-recycling context, and the carbon emissions in the recycling context is lower than the carbon emission in the non-recycling context. In terms of firms, it is better to implement product recycling activities. These findings provide a good reference for policy makers to design the cap and trade mechanism and product recycling mechanism.

Although this research has some interesting findings, we are mindful of the fact that the research can be expanded in some directions. For instance, the market competition factors are not considered in this research. In the following research, market competition factors can be considered in the carbon trading market and product market. Another extension of this research is that we can compare the effects of cap and trade mechanism and carbon tax policy on production planning in a multi-product manufacturing system considering product recycling mechanism.

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Conflict of interest

The authors declare no conflict of interest.

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碳交易和产品回收机制下多产品制造系统中产品生产计划研究

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摘要：生态环境恶化、自然资源短缺问题日益严峻，为减少企业对生态环境的负面影响，企业需改变和调整相关生产计划. 本研究在考虑碳排放权交易机制、产品回收机制以及企业面临有限生产容量、工作时间和碳排放权配额的情形下，对多产品制造系统中产品生产计划问题进行了研究. 在量-本-利分析的基础上，本研究提出了一个利润最大化模型来刻画生产优化问题. 在该模型中，成本结构包括产品生产成本、产品持有或短缺成本、产品回收成本和碳成本；收入结构包括产品销售收入和产品回收收益. 根据利润最大化模型和数值算例，本研究分析了企业最优生产和回收决策. 同时，进一步探究了碳排放权交易机制和产品回收机制对产品产量、碳排放总量和利润总额的影响. 结果表明，在碳排放权交易机制和产品回收机制下，较高的碳排放权价格可以激励企业生产绿色产品；产品回收机制有利于降低企业总碳排放量，增加企业利润. 根据研究结论，本研究进一步提出了管理建议与未来研究方向.

关键词：生产计划；碳排放权交易机制；产品回收机制；碳排放权价格；利润最大化