Ann Oper Res (2020) 290:567–590
https://doi.org/10.1007/s10479-017-2696-8

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Weight reduction technology and supply chain network design under carbon emission restriction

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Published online: 30 October 2017

Abstract As policies and regulations related to environmental protection and resource constraints are becoming increasingly tougher, corporations may face the difficulty of determining the optimal trade-offs between economic performance and environmental concerns when selecting product technology and designing supply chain networks. This paper considers weight reduction technology selection and network design problem in a real-world corporation in China which produces, sells and recycles polyethylene terephthalate (PET) bottles used for soft drinks. The problem is addressed while taking consideration of future regulations of carbon emissions restrictions. First, a deterministic mixed-integer linear programming model is developed to analyze the influence of economic cost and carbon emissions for different selections in terms of the weight of PET bottle, raw material purchasing, vehicle routing, facility location, manufacturing and recycling plans, etc. Then, the robust counterpart of the proposed mixed-integer linear programming model is used to deal with the uncertainty in supply chain network resulting from the weight reduction. Finally, results show that though weight reduction is both cost-effective and environmentally beneficial, the increased cost due to the switching of the filling procedure from hot-filling to aseptic cold-filling and the incumbent uncertainties have impacts on the location of the Pareto frontier. Besides, we observe that the feasible range between economic cost and carbon emission shrinks with weightreduction; and the threshold of restricted volume of carbon emission decreases with the increase of uncertainty in the supply chain network.

Han, Jiang, Zhao, Leung and Luo have contributed equally to the manuscript.

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Keywords Supply chain networks · Weight-reduction technology · Product development · Carbon emission · Sustainability

List of symbols

t	The index of operational periods $t = 1, \ldots, T$
i	The index of potential new PET chips suppliers $i = 1, \ldots, I$
j	The index of potential manufacturing centers $j = 1, \ldots, J$
k	The index of potential distribution center locations $k = 1, \ldots, K$
m	The index of potential recycling center locations $m = 1, \ldots, M$
n	The index of markets $n = 1, \ldots, N$

Decision variables

PN_{ijt}	The quantity of new PET chips in manufacturing center j provided by supplier i in period t
MD_{jkt}	The quantity of PET bottles shipped from manufacturing center j to distribution center k in period t
DX_{knt}	The quantity of PET bottles shipped from distribution center k to market n in period t
RX_{mnt}	The quantity of returned PET bottles recycled from market n to recycling center m in period t
MR_{jmt}	The quantity of recovered PET chip from recycling center m to manufacturing center j in period t

$$S_i = \begin{cases} 1 & \text{If a new PET chips supplier } i \text{ is opened,} \\ 0 & \text{Otherwise,} \end{cases}$$

$$MC_j = \begin{cases} 1 & \text{If a manufacturing center } j \text{ is opened,} \\ 0 & \text{Otherwise,} \end{cases}$$

$$DC_k = \begin{cases} 1 & \text{If a distribution center } k \text{ is opened,} \\ 0 & \text{Otherwise,} \end{cases}$$

$$RC_m = \begin{cases} 1 & \text{If a recycling center } m \text{ is opened,} \\ 0 & \text{Otherwise,} \end{cases}$$

Key parameters

θ_t	Average recovery rate in period t
σ_{mt}	Discard rate of unusable recycling PET chips at recycling center m in period t
γ	Conversion coefficient from chips to a bottle
ω	Ratio of recovered chips contained in a bottle
Δ	Net weight of water contained in a bottle
d_{nt}	Demand of market n in period t

1 Introduction

The soft drink industry has gradually expanded its market scale in the global market since the beginning of the twenty-first century. According to data on the global soft drink industry released by Euromonitor International, global production of soft drinks expanded over 4% in 2013 and sales value grew by more than 5%. Polyethylene terephthalate (PET) is one of the versatile polymers widely used in various applications such as soft drink bottles, packaging, fibers, films and textile applications (Jamdar et al. 2017). Different soft drinks companies are seeking various ways of packaging to draw customers' attention. Aluminum cans, glass bottles and polyethylene terephthalate (PET) bottles are the three most commonly used forms of packaging. Compared with the other two forms of packaging, PET bottle has the advantage of possessing barrier and mechanical properties, chemical resistance, transparency and the possibility of repeated recycling. In addition, it consumes less energy and emit less carbon dioxide during material purchasing, processing and transportation. Figure 1 shows the energy consumption and carbon emissions of these three commonly used modes of packaging as reported by Euronmonitor International. Currently half of the global soft drinks are packaged in PET bottles owing to the aforementioned advantages, and the number is growing around 1.15% annually.

In China, there are many corporations that produce and sell soft drinks packaged PET bottles in different sizes. In order to curb the high level of carbon emissions of these corporations, new regulations have been proposed to control their total carbon emissions (Stranlund 2007). Fierce market competition and a growing concern for enviromental sustainability are prompting the corporations to consider new technology for product development that may lead to reduced energy consumption, cost savings and carbon emission reduction (Chiang and Che 2015).

Weightreduction technology is a potential way to achieve these goals because it can not only save the purchased quantity of new PET chips (raw materials) but also reduce the variable manufacturing costs and carbon emissions. The weight of soft drinks loaded on each vehicle will also be reduced if lighter PET bottles are used. However, the high fixed cost incurred from switching to a new product line and process may scare off the corporations. Moreover, uncertainty that arise as a result of adopting the weight reduction technology is also worth noting. Customers may prefer the feeling of a heavier bottle in their hand and thus not support the energy saving efforts with their buying patterns. Moreover, the rate of

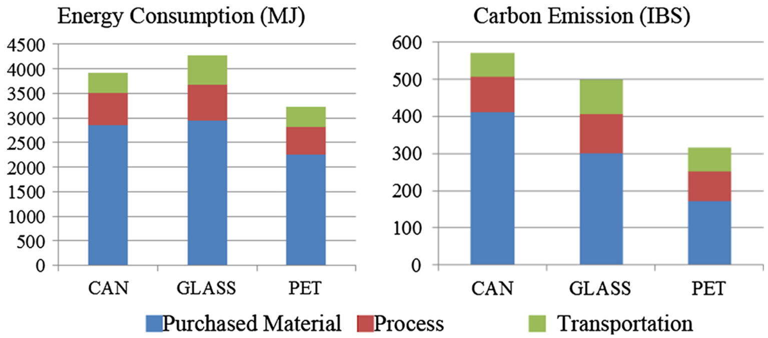

Fig. 1 Energy consumption and carbon emission for aluminum can, glass bottle and PET bottle (per 1000 units). *Source: Euronmonitor International*

recovery, discarding and recycling chips may lead to larger fluctuating results with increasing degree of weight reduction.

Therefore, three major problems of the weight-reduction technology are put forward: (1) how to determine the level of weight-reduction and how to design the network? (2) what is the trade-off between economic performance and environmental sustainability? and (3) what is the impact of uncertainty resulting from weight-reduction on the costs and carbon emission of the supply chain network? The remainder of this paper is organized as follows. In Sect. 2, relevant literature is reviewed and summarized. In Sect. 3, a real case in China is introduced, and the functions of costs and carbon emissions on manufacturing are formulated based on statistical data. Deterministic and robust mathematical models are developed in Sect. 4. Computational analysis is conducted, and the results obtained are discussed in Sect. 5. Finally, Sect. 6 gives the conclusion and directions for future research.

2 Literature review

2.1 Production technology selection

Production technology selection problem concerns the selection of technology used for a product's appearance, functionality and structure in the product development process. Steele (1989) called production technology selection "*knowledge of how to do things*". It is considered to be a classic but complex problem in supply chain management. On the one hand, production technology selection determines the ability of a corporation to satisfy customer demand with the right products at minimal total production and operational costs (Evans et al. 2013; Li and Zhu 2011). On the other hand, the selecting of a sustainable production technology that considers environmental issues such as global warming and pollution is also concerned about using minimum energy and materials and producing minimum hazardous waste (Chiu and Chu 2012). However, eco-friendly production technology selection can incur additional cost and hence the concerned corporation might lose cost competitiveness. Besides, production technology selection has significant impact on the structure of supply chain network.

Much research on the models of production technology selection concludes that significant trade-off exists between economic profit and environmental quality (FrotaNeto et al. 2008; Govindan and Sivakumar 2016; Ramudhin et al. 2010). Chen (2001) developed a quality-based model by jointly considering the interactions among customers' preferences, product development strategies and the environmental standards imposed by governments and concluded that the success of green product development and its benefits to the environment depend heavily on corporations and policy makers. Ravi et al. (2009) examined the influence of extended producer responsibility (EPR) policies on the making of strategic decisions in product development for recycling, pricing and supply chain coordination in monopolistic markets.

Almost all of the relevant research on green product development has assumed that extra resources should be put into the production systems to address environmental issues when developing new products (Kuo et al. 2014), a strategy that will increase the variable production costs. However, the green technologies for product development considered in this paper may lead to both lowering of variable production costs and adding environmental attributes, though there are trade-offs between economic profit and environmental quality as a result of uncertainty and the high cost incurred from the switching of production lines and process.

2.2 Supply chain network design

Supply chain network design problems include strategic supply chain planning decisions such as facility locations (Fattahi et al. 2016) that run through the whole supply chain process on purchasing, manufacturing, distribution and recycling. Traditionally, the objective of designing a network is to minimize production and operational costs and maximize its long-term economic benefits (Taki et al. 2016; Petridis 2015). But now, environmental indicators such as carbon emissions, fuel consumption and potential threats to humans and the environment are also defined to assess the environmental sustainability in supply chain network design (Dong et al. 2016).

A large number of literatures have discussed how carbon emission impact on the design of a supply chain network. Cholette and Venkat (2009) calculated the energy and carbon emissions associated with transportation links and warehousing activities in the food and beverage supply chains, particularly in the wine industry. They showed that depending on the supply chain design, energy consumption and carbon emissions can vary substantially. Based on this, Pan et al. (2013) found that supply chain network pooling is an efficient approach to reduce carbon emissions. Ramudhin et al. (2010) proposed an MILP model for the design of sustainable supply chain network sensitive to the carbon market. The results showed that the considering of external control variables is very important for decision makers of sustainable supply chains. Fahimnia et al. (2013) considered carbon emissions in a closed-loop supply chain and developed a unified optimization model. It is one of the first models to evaluate the influences of forward and reverse supply chain on carbon emissions. Kuo et al. (2014) applied multi-objection planning in a low-carbon product design to minimize carbon emissions and cost simultaneously. Lately, cap-and-trade regulation has been extensively discussed by scholars in the field of supply chain management due to its huge impact on supply chain performance (Bojarski et al. 2009; Chiu and Choi 2016). Nouira et al. (2016) and Abdallah et al. (2012) also designed a sustainable supply chain network that takes carbon footprint into consideration.

However, most of the research on sustainable supply chain network design has not addressed the selection of product technology as a key parameter or decision variable in their models. Chaabane et al. (2012) studied the optimal design strategy for sustainable supply chains under different environmental policies, and his strategy contains the production technology selection problem. However, the economic and environmental impact of such technology is limited compared with that of the weight reduction technology. Unlike previous research, this paper contributes to research in this area by: (1) integrating the policy on carbon emission restrictions into the problem of weight reduction technology selection and network design based on a real-world supply chain network of PET-bottled soft drinks. Relevant decisions involve raw material purchasing, vehicle routing and facility location; manufacturing and recycling plans are highly integrated in the proposed model; (2) overcoming the uncertainty resulting from weight reduction through proposing a robust optimization model that considers the worst case scenario to analyze the impact of uncertainty on technology selection and network design; and (3) The tradeoffs between economic and environmental objectives under various cost and operating strategies in a real-world application can be applied to a wide range of weight reduction technology selection problems in the soft drink industry.

3 Problem statement

A corporation in China, which produces and sells PET-bottled soft drinks with a well-known brand name, is studied in this paper. This corporation also recycles its PET bottles. In general,

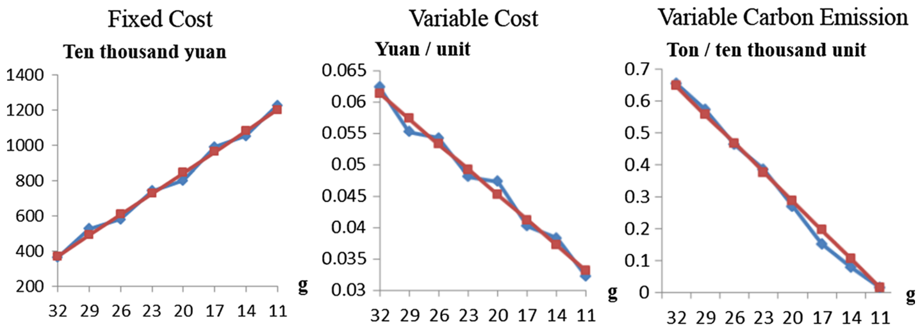

Fig. 2 Correlation between weight of PET bottle and fixed cost, variable cost and variable carbon emissions

the corporation purchases ingredients and new PET chips from suppliers. PET bottles are produced and beverage is filled and packaged in its manufacturing centers. Then, the PET-bottled soft drinks are delivered to the markets via its transit distribution centers. Returned empty PET bottles collected from the markets are decomposed, tested and discarded in the recycling centers, and the remaining recoverable PET chips are used for making new PET bottles. However, the proportion of reused PET chips contained in a bottle is limited.

The PET bottled soft drink containing 500 ml of beverage is the corporation's core product and the current weight of each PET bottle is 32 grams (g). Due to the weight reduction technological feasibility constraint, the lowest possible weight of PET bottle is 11 g. There are two kinds of filling technology in the beverage filling and packaging process, namely hot-filling technology and aseptic cold-filling technology. Hot-filling technology is used when the weight of the PET bottle is greater than or equal to 18 g and aseptic cold-filling technology is used when the weight is less than 18 g.

According to the internal statistics of the corporation, the costs and carbon emissions in the process of preform manufacturing are strongly correlated with the weight of PET bottle. The costs and carbon emissions in bottle manufacturing are constant and uncorrelated with the weight of PET bottle. The costs and carbon emissions in beverage filling and packaging are uncorrelated with the weight of PET bottle, but correlated with the filling technology used and the packaging process. In Fig. 2, the X-coordinate is the weight of PET bottle and the Y-coordinate is the fixed cost, variable cost and variable carbon emissions, respectively in the process of preform manufacturing. The blue lines are the original data directly extracted from the corporation's report, while the red lines are obtained by linear regression model, which are formulated as:

$$\begin{aligned} Y_{pmf} &= -39.424605X + 1632.004\left(R^2 = 0.9889\right), && \text{(fixed cost)} \\ Y_{pmv} &= 0.13437X - 0.0183348\left(R^2 = 0.9783\right), \text{ and} && \text{(variable cost)} \\ Y_{cmv} &= 0.03006X - 0.31561(R^2 = 0.9783). && \text{(variable carbon emissions)} \end{aligned}$$

It is noted that R^2 is significant and large; the regression lines can be used to represent the general linear relationship between the weight of PET bottle and the fixed cost, variable cost and variable carbon emissions. Besides, the gap between fixed cost, variable cost and variable carbon emissions by hot-filling and aseptic cold-filling should also be considered. The production cost function (1) and carbon emission function (2) are formulated as linear functions approximately as

$$mmc(\tau, Q) = \begin{cases} \alpha_0 + \alpha_1\tau + (\alpha_2 + \alpha_3\tau)Q & \tau \geq \tau^{(s)} \\ \alpha_0 + \alpha_4 + \alpha_1\tau + (\alpha_2 + \alpha_5 + \alpha_3\tau)\,Q & \tau < \tau^{(s)} \end{cases} \tag{1}$$

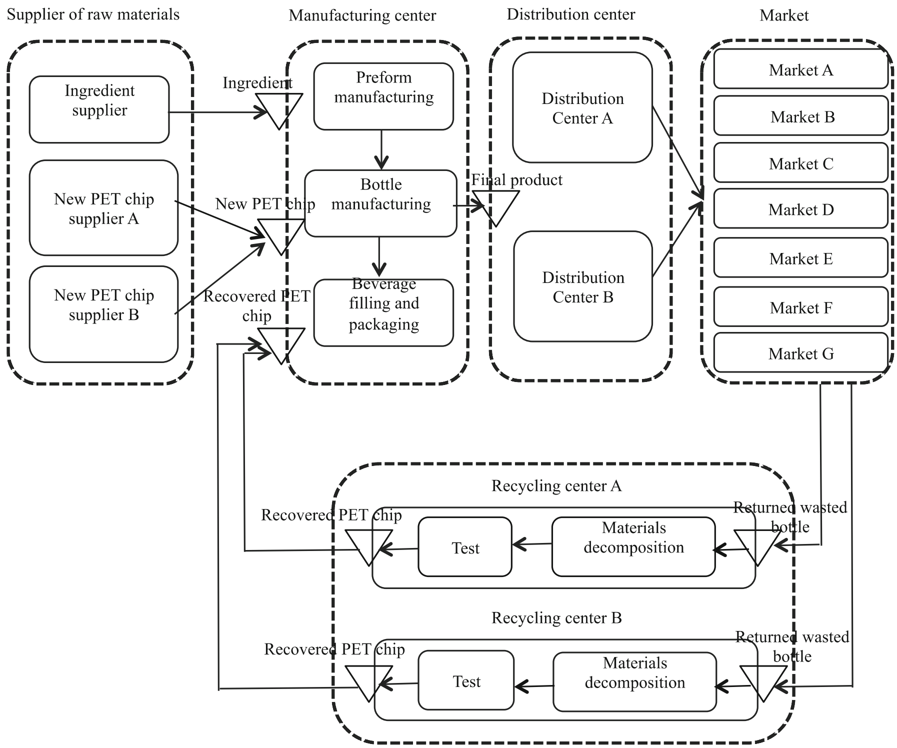

Fig. 3 Potential supply chain network of 500 ml PET-bottled soft drinks

$$cmc(\tau, Q) = \begin{cases} (\beta_0 + \beta_1\tau)Q & \tau \geq \tau^{(s)} \\ (\beta_0 + \beta_2 + \beta_1\tau)\,Q & \tau < \tau^{(s)} \end{cases} \quad (2)$$

where τ is the weight of PET bottle and Q is the number of PET-bottled soft drinks produced.

According to the estimated linear functions of fixed cost, variable cost and variable carbon emissions, parameters α_0, α_2 and β_0 denote the respective interceptions and parameters α_1, α_3 and β_1 denote the respective slopes. Besides, parameters α_4, α_5 and β_2 denote the gap between fixed cost, variable cost and variable carbon emissions of hot-filling and aseptic cold-filling respectively. $\tau^{(s)}$ is the critical weight of PET bottleonswitching beverage filling and packaging process.

A potential supply chain network of PET-bottled soft drinks each containing 500 milliliters of beverage is shown in Fig. 3. There are two kinds of raw materials, namely ingredients and PET chips. Since there is only one ingredient supplier having a long-term cooperation with the corporation and there is no correlation between ingredient purchasing and weight reduction problem, purchasing cost is ignored in this paper. There are two sources of PET chips: new PET chips and recovered PET chips. There are two suppliers of the new PET chips: A and B; there are also two recycling centers, Recycling center A and Recycling center B. All manufacturing processes are completed in an independent manufacturing center of the corporation and products are immediately sent to a distribution center after production. There are two distribution centers, Distribution center A and Distribution center B. The corporation supplies the products for regional markets. Detailed data are shown in "Appendix: Related data".

Before formulating any mathematical models, some assumptions are considered, and they are as follows. (1) All demands should be satisfied and all expected returnable products should be recycled; (2) the locations of markets are fixed and predefined; and (3) the inventory cost and related problems are simplified.

4 Models

In the following, indices, decision variables and key parameters are defined.Details of the following notations are given in "Appendix: Notations".

4.1 Deterministic model

A general multi-objective mix-integer linear programming (MOMILP) model of the supply chain network is constructed with two objective functions. The first objective (3) measures the total economic cost and the second objective (8) measures the total carbon emissions in the whole product life-cycle.

4.1.1 Economic objective

Total economic cost (TCF) can be evaluated by expenditure associated with four segments, which are procurement cost (PCF), manufacturing cost (MCF), distribution cost (DCF) and recycling cost (RCF).

$$\boldsymbol{Minimize}\ TCF = PCF + MCF + DCF + RCF \tag{3}$$

Procurement cost function (4) measures costs related to new and recovered PET chips. The first item is the total fixed cost of selecting some suppliers to establish a long-term business, the second item measures the purchasing and transportation cost of new PET chips, and the third item is the transportation cost of recovered PET chips.

$$\begin{aligned} PCF = & \sum_{i \in I} fs_i S_i + \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \left(ps_{ijt} + pt_t lsm_{ij} \right) PN_{ijt} \\ & + \sum_{m \in M} \sum_{j \in J} \sum_{t \in T} pt_t lrm_{mj} MR_{jmt} \end{aligned} \tag{4}$$

Manufacturing cost function (5) measures the costs of manufacturing the product. The first item is the cost of opening a manufacturing center, and the second item is the initial investment in production line and variable production cost of designing the PET bottle.

$$MCF = \sum_{j \in J} fm_j MC_j + \sum_{j \in J} \sum_{t \in T} mmc \left(\tau, \sum_{k \in K} MD_{jkt} \right) \tag{5}$$

Distribution cost function (6) measures the cost of distributing PET-bottled soft drinks from manufacturing centers to markets. The first item is the cost of opening a distribution center, the second item is the total processing cost in the distribution center, and the third and fourth items are the transportation cost of delivering PET-bottled soft drinks from manufacturing centers to distribution centers and from distribution centers to market, respectively.

$$DCF = \sum_{k\in K} fd_k DC_k + \sum_{k\in K}\sum_{j\in J}\sum_{t\in T} pp_{kt} MD_{jkt} + \sum_{k\in K}\sum_{j\in J}\sum_{t\in T} pt_t\,(\tau+\Delta)\,lmd_{jk} MD_{jkt} + \sum_{k\in K}\sum_{n\in N}\sum_{t\in T} pt_t\,(\tau+\Delta)\,ldx_{kn} DX_{knt} \tag{6}$$

Recycling cost function (7) measures the costs related to recycling returned PET bottles and discarding unusable recycled PET chip. The first item is the cost of opening a recycling center, the second item is the purchasing and transportation cost of collecting returned PET bottles from market, the third item is the cost of regenerating PET chips, and the fourth item is the disposal cost of unusable recycled PET chip

$$RCF = \sum_{m\in M} fr_m RC_m + \sum_{m\in M}\sum_{n\in N}\sum_{t\in T}\left(pr_{mnt} + pt_t \tau lxr_{nm}\right) RX_{mnt} + \sum_{m\in M}\sum_{j\in J}\sum_{t\in T} prr_{mt} MR_{jmt} + \sum_{m\in M}\sum_{t\in T} pd_{mt}\left(\tau \sum_{n\in N} RX_{mnt} - \sum_{j\in J} MR_{jmt}\right) \tag{7}$$

4.1.2 Environmental objective

Similarly, total carbon emissions (TEF) also can be considered from the procurement(PEF), manufacturing (MEF), distribution (DEF) and recycling (REF) process.

$$\textbf{\textit{Minimize}}\ TEF = PEF + MEF + DEF + REF \tag{8}$$

Procurement carbon emissions function (9) measures the carbon emissions related to acquisition of new and recovered PET chips. The first item is the purchasing carbon emissions of new PET chips, and the second and third items are the transportation carbon emissions of new and recovered PET chips, respectively.

$$PEF = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} cn_{ijt} PN_{ijt} + \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} ct_t lsm_{ij} PN_{ijt} + \sum_{m\in M}\sum_{j\in J}\sum_{t\in T} ct_t lrm_{mj} MR_{jmt} \tag{9}$$

Manufacturing carbon emissions function (10) measures the carbon emissions of manufacturing of the product. Distribution carbon emissions function (11) measures the carbon emissions of delivering PET bottles from manufacturing centers to distribution centers and from distribution centers to markets. Besides, in recycling carbon emission function (12), the first item is the transportation carbon emissions of returned PET bottles from market, the second item is the carbon emissions of regenerating PET chips, and the third item is the carbon emissions of discarding unusable recycled PET chip

$$MEF = \sum_{j\in J}\sum_{t\in T} cmc\left(\tau, \sum_{k\in K} MD_{jkt}\right) \tag{10}$$

$$DEF = \sum_{k\in K}\sum_{j\in J}\sum_{t\in T} ct_t\,(\tau+\Delta)\,lmd_{jk} MD_{jkt}$$

$$+\sum_{k\in K}\sum_{n\in N}\sum_{t\in T} ct_t\,(\tau+\Delta)\,ldx_{kn}DX_{knt} \tag{11}$$

$$REF=\sum_{m\in M}\sum_{n\in N}\sum_{t\in T} ct_t\tau lxr_{nm}RX_{mnt}+\sum_{m\in M}\sum_{j\in J}\sum_{t\in T} crr_{mt}MR_{jmt}$$
$$+\sum_{m\in M}\sum_{t\in T} crd_{mt}\left(\tau\sum_{n\in N}RX_{mnt}-\sum_{j\in J}MR_{jmt}\right) \tag{12}$$

4.1.3 Constraints

For the MOMILP model, many constraints should be considered, for instance, capacity constraints, material transformation constraints, product flow balance constraints, distribution and demand satisfaction constraints, and recyclable products constraints.

Capacity constraints (13)–(16) ensure that actual workload in each supplier, manufacturing center, distribution center and recycling center should not exceed the maximum processing capacities.

$$\sum_{j\in J} PN_{ijt}\le \overline{msc}_{it}S_i \quad \forall i\in I,t\in T \tag{13}$$

$$\sum_{k\in K} MD_{jkt}\le \overline{mmc}_{jt}MC_j \quad \forall j\in J,t\in T \tag{14}$$

$$\sum_{n\in N} DX_{knt}\le \overline{mdc}_{kt}DC_k \quad \forall k\in K,t\in T \tag{15}$$

$$\sum_{n\in N} MR_{jmt}\le \overline{mrc}_{mt}RC_m \quad \forall m\in M,t\in T \tag{16}$$

Constraint (17) ensures the full transformation from new and recovered PET chips to PET bottles, constraint (18) restricts the highest proportion of reused chips in a bottle and constraint (19) ensures the part transformation from returned PET bottles to recovered PET chips.

$$\sum_{i\in I} PN_{ijt}+\sum_{m\in M} MR_{jmt}=\gamma\tau\sum_{k\in K} MD_{jkt} \quad \forall j\in J,t\in T \tag{17}$$

$$\sum_{m\in M} MR_{jmt}\le \omega\left(\sum_{i\in I} PN_{ijt}+\sum_{m\in M} MR_{jmt}\right) \quad \forall j\in J,t\in T \tag{18}$$

$$\sum_{j\in J} MR_{jmt}\le (1-\sigma_{mt})\,\tau\sum_{n\in N} RX_{mnt} \quad \forall m\in M,t\in T \tag{19}$$

As for the distribution and demand satisfaction constraints, constraint (20) ensures the product flow balance in each distribution center, and constraint (21) ensures that all market demands are satisfied.

$$\sum_{j\in J} MD_{jkt}=\sum_{n\in N} DX_{knt} \quad \forall k\in K,t\in T \tag{20}$$

$$\sum_{k\in K} DX_{knt}\ge d_{nt} \quad \forall n\in N,t\in T \tag{21}$$

Recyclable products constraint (22) ensures that the number of collected PET bottles is equal to the expected recyclable PET bottlesin the market in the last period.

$$\sum_{m \in M} RX_{mnt} = \theta_t d_{n(t-1)} \quad \forall n \in N, t \in T \tag{22}$$

Besides, constraints (23)–(24) enforce the binary and non-negativity restrictions on the correspondingdecision variables.

$$S_i, MC_j, DC_k, RC_m \in \{0, 1\} \quad \forall \in I, j \in J, k \in K, m \in M \tag{23}$$

$$PN_{ijt}, MD_{jkt}, DX_{knt}, RX_{mnt}, MR_{jmt} \geq 0 \quad \forall i \in I, j \in J, k \in K, m \in M, n \in N, t \in T \tag{24}$$

4.2 Robust optimization model

Robust optimization, first proposed by Soyster (1973), incorporates an uncertain data set to deal with uncertain parameters by considering the worst case scenario. Robust optimization has been successfully implemented to deal with uncertain data in the design of supply chain network (Mulvey et al. 1995; Bertsimas and Sim 2004; Iyengar 2005), which cope with uncertainties in the dynamic and competitive supply chain network environment (Lalmazloumian et al. 2016; Sabri and Beamon 2000). Yu and Li (2000) formulated a highly efficient robust optimization model which can generate solutions less sensitive to data in the scenario set and demonstrate the computational efficiency of the model based on two logistics examples; the model has been further applied to solve product planning by Leung et al. (2007). However, the magnitude of uncertainty of stochastic parameters and systemic uncertainty level cannot be under control in the scenario set. A min-max criterion, which means the cost function is minimized against the worst case, is used in robust optimization for multi-period stochastic operations management problems by Ben-Tal et al. (2005). Pishvaee et al. (2011) further proposed a robust optimization model based on the concept of min-max criterion to handle the inherent uncertainty of input data in a closed-loop supply chain network design problem, and compared the solutions obtained from the deterministic and robust optimization model under different systemic uncertainty levels. The methodology of min-max criterion on robust optimization model is inherited inour research.

With increasing degree of weight reduction, some customers may prefer the product with a lighter bottle for environmental consideration, while other customers may prefer the feeling of a heavier bottle in their hands and thus not support the energy saving efforts with their buying patterns, nor support the bottle weight reduction. Therefore,larger fluctuations in the demand of the product may result from the increasing degree of weight reduction. Similarly, according to the internal statistics of the corporation, the increasing degree of weight reduction may lead to larger fluctuations in the recovery rate, discarding rate and the ratio of recovered chips contained in a bottle too. Therefore, the demand, average recovery rate, discarding rate and proportion of recovered chips contained are treated as uncertain parameters in the proposed MOMILP model. With the increasing level of weight reduction, the uncertainty scale may also increase.

Thus, the uncertainty scale of these parameters is assumed to be in positive proportion to the level of weight reduction and varies in a specified closed bounded set (Ben-Tal et al. 2005).The general form of this uncertainty set is represented as

$$\mu_{Set} = \left\{ \xi \in \boldsymbol{R}^{+} : \left| \xi^{(\tau)} - \xi^{(\bar{\tau})} \right| \leq \rho_{\xi} \left(\bar{\tau} - \tau \right), \underline{\tau} \leq \tau \leq \bar{\tau} \right\},$$

where $\xi^{(\bar{\tau})}$ is the nominal value of the $\xi^{(\tau)}$ as the highest bottle weight of vector ξ and $\rho_\xi > 0$ represents the uncertainty level caused by per unit weight of reduction. The uncertainty set μ_{Set} indicates that the variation of vector ξ is in positive proportion to the level of weight reduction.

The inquality (18) and (19) contain the vector of uncertain parameters, which can be rewriten as

$$\sum_{m\in M} MR_{jmt} \le \left(\omega^{(\bar{\tau})} + \rho_\omega(\bar{\tau}-\tau)\right)\left(\sum_{m\in M} MR_{jmt} + \sum_{i\in I} PN_{ijt}\right) \quad \forall j \in J, t \in T \tag{23a}$$

$$\sum_{m\in M} MR_{jmt} \le \left(\omega^{(\bar{\tau})} - \rho_\omega(\bar{\tau}-\tau)\right)\left(\sum_{m\in M} MR_{jmt} + \sum_{i\in I} PN_{ijt}\right) \quad \forall j \in J, t \in T \tag{23b}$$

$$\sum_{j\in J} MR_{jmt} \le \left(1-\sigma_{mt}^{(\bar{\tau})} - \rho_\sigma(\bar{\tau}-\tau)\right)\tau \sum_{n\in N} RX_{mnt} \quad \forall m \in M, t \in T (24.1) \tag{24a}$$

$$\sum_{j\in J} MR_{jmt} \le \left(1-\sigma_{mt}^{(\bar{\tau})} + \rho_\sigma(\bar{\tau}-\tau)\right)\tau \sum_{n\in N} RX_{mnt} \quad \forall m \in M, t \in T \tag{24b}$$

Similarly, for inquality (21) we have

$$\sum_{k\in K} DX_{knt} \ge d_{nt}^{(\bar{\tau})} + \rho_d(\bar{\tau}-\tau)\, \forall n \in N, t \in T \tag{25}$$

Also, the equaltiy constraint (22) can be converted to its tracable equivalent equations as

$$\sum_{m\in M} RX_{mnt} \ge \theta_t^{(\bar{\tau})} d_{n(t-1)}^{(\bar{\tau})} + \rho_d\rho_\theta(\bar{\tau}-\tau)^2 - \left(\rho_d\theta_t^{(\bar{\tau})} + \rho_\theta d_{n(t-1)}^{(\bar{\tau})}\right)(\bar{\tau}-\tau) \quad \forall n \in N, t \in T \tag{26a}$$

$$\sum_{m\in M} RX_{mnt} \le \theta_t^{(\bar{\tau})} d_{n(t-1)}^{(\bar{\tau})} + \rho_d\rho_\theta(\bar{\tau}-\tau)^2 + \left(\rho_d\theta_t^{(\bar{\tau})} + \rho_\theta d_{n(t-1)}^{(\bar{\tau})}\right)(\bar{\tau}-\tau) \quad \forall n \in N, t \in \tag{26b}$$

5 Computational analysis

Both the deterministic and robust models are solved by CPLEX12 in the GAMS 23.8 modeling environmenton a Intel(R) Core(TM) 2.40 GHz computer with 4 GB RAM.All solutions in the above models are optimally solved.

An augmented ε-constraints method proposed by Mavrotas (2009) guarantees the efficiency of the obtained solution and accelerates the whole process by avoiding redundant iterations.Following the augmented ε-constraints method, we obtain unique efficient Pareto-optimal solutions and show them as a Pareto frontier on the perspective of economic cost and carbon emissions. Both economic performance and enviromental sustainability are measured in the determinisitc and robust models.

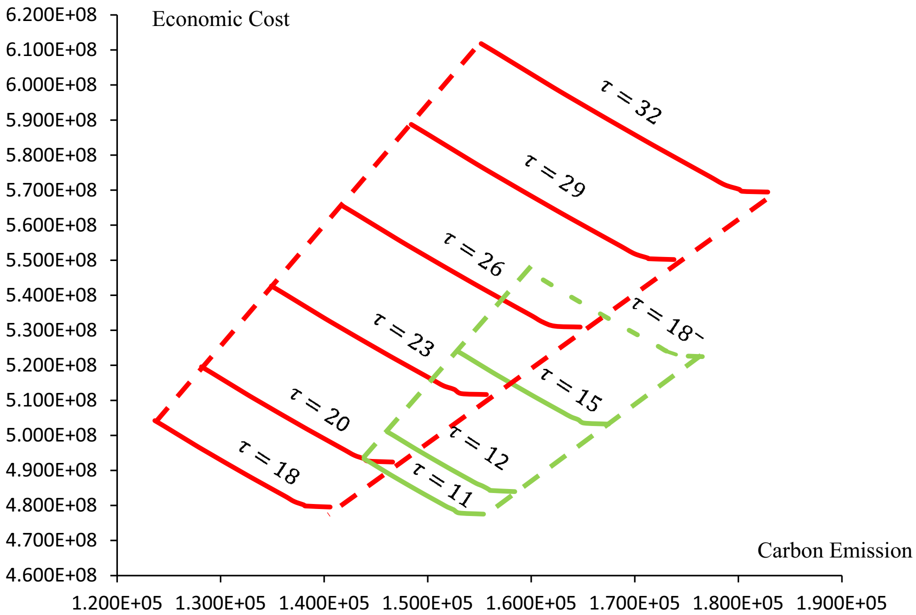

Fig. 4 Pareto frontier in the deterministic model

5.1 Deterministic model

5.1.1 Pareto frontier on economic and carbon emission

Some Pareto frontiers obtained from the deterministic model are shown in Fig. 4. In general, the economic cost and carbon emissions are in conflict regardless of what the weight of a PET bottle τ is. When weight reduction begins and the weight of a PET bottle reduces from 32 to 18 g, the Pareto-frontier shifts to the left and a set of solutions leading to lower economic cost and carbon emissions is obtained, as denoted by the red solid line. However, when weight reduction of PET bottle continues, additional fixed cost, variable cost and variable carbon emissions may lead to a significant increase in the economic cost and carbon emissions because the beverage filling process has switched from hot-filling to aseptic cold-filling. The red Pareto-frontier $\tau = 18$ will therefore move to the green Pareto-frontier $\tau = 18^{-}$. But after the process switching, weight reduction will still be cost-effective and environmentally beneficial.

All Pareto-frontiers can be classified into red ($\tau \geq 18$) or green($\tau < 18$) Pareto-areas. In the deterministic model, the optimal weight of a PET bottle is always either 18 or 11 g, which is the bottom line for the red as well as the green areas. Currently, when the volume of carbon emissions is restricted to less than 1.519E+5, the optimal weight of a PET bottle is 18 g; otherwise when the restricted volume of carbon emissions is greater than 1.519E+5,the optimal weight of a PET bottle is 11 g.

In future, when weight reduction technology is feasible for PET bottles to weigh even less than 11 g, the threshold of the restricted volume of carbon emissions will decrease. However, irrespective of how low the weight of a PET bottle can be, the optimal weight of a PET bottle might still be 18 g when the volume of carbon emissions is comparatively small. However, when the restricted volume of carbon emissions is less than 1.236E+5, all decisions on weight reduction technology selection and network design will become infeasible. Moreover, for switching from hot-filling to aseptic cold-filling the location of green Pareto-area affects the selected weight of a PET bottle(still 11 or 18 g) and the corresponding network design strategy may also change.

Another interesting conclusion is that the feasible trade-off between economic cost and carbon emission declines with weightreduction. This means that when the weight of a PET bottle is small, greater concern about carbon emissions will not result in a very high increase (decrease) in economic cost. Thus, re-designing the supply chain network on purchasing, manufacturing, distribution and recycling processes has less impact on adjustment between economic costs and carbon emissions.

5.1.2 Strategic decisions on facility location

The critical point of switching the strategic decisions on facility location is shown in Table 1. In general, regardless of the feasible weight of a PET bottle, selection of facility location has a significant impact on economic costs and carbon emissions of the supply chain network. As the point moves along each Pareto-frontier from a low total economic cost (TCF) solution point to a low total carbon emission (TEF) solution point, this means higher restriction on carbon emissions on the supplier selection will change from B to A, the distribution center selection will change from A alone to both A and B, and the recycling center selection will change from B to A.

Figures 5 and 6 represent the trends of cost and carbon emissions on the procurement, manufacturing, distribution and recycling processes changing with the weight of a PET bottle when economic cost (CM, solid line) and carbon emissions (EM, dash line) are minimized.

In the purchasing process, both economic cost and carbon emission significantly decrease with weight reduction. Since it is assumed that demand does not change with weight reduction, when the proportion of virgin PET chips in a PET bottle decreases, the purchase of new PET chips is gradually reduced to obtain a lower cost and carbon emissions. Besides, we observe that the trade-off between economic cost and carbon emission is significant in the purchasing process, which means the selection of supplier plays an important role in balancing between the economic cost and carbon emissions.

In the manufacturing process, there is a complete overlap between the solid and dash lines, meaning conflict between economic costs and carbon emissions barely exists. When weight reduction leads to lower variable cost and higher fixed cost, the overall result is a higher manufacturing cost. It is especially true when the cost incurred from switching the beverage filling process from hot-filling to aseptic cold-filling is considered, the manufacturing cost increases greatly at $\tau = 18$. Carbon emissions from the manufacturing process decrease with weight reduction because variable carbon emissions decrease with weight reduction. Similarly, large amounts of carbon emissions result from additional input in switching the beverage filling process from hot-filling to aseptic cold-filling. But after that, carbon emissions in the manufacturing process continue to decrease.

In the distribution process, since weight reduction technology reduces the weight of a PET bottle, the total weight of PET-bottled soft drinks shipped to the market decreases. Thus, the economic cost and carbon emissions in the distribution process gradually decrease. However, the declines are not apparent, and the reason is that the reduced weight of a PET bottle is relatively small in proportion to the total weight of a PET-bottled soft drink.

In the recycling process, under the condition of unchanged recovery rate, the number of returned PET bottles remains the same irrespective of the weight of a PET bottle. But

Table 1 Estimated critical point of facility location switching

Weight of a PET bottle $\boldsymbol{\tau}$			32 g		26 g	
Supplier	Distribution center	Recycling center	TCF	TEF	TCF	TEF
B	A	B	5.695×10^8	1.828×10^5	5.309×10^8	1.647×10^5
B	A and B	B	5.697×10^8	1.804×10^5	5.312×10^8	1.623×10^5
A and B	A and B	B	5.702×10^8	1.801×10^5	5.324×10^8	1.611×10^5
A and B	A and B	A	5.715×10^8	1.787×10^5	5.340×10^8	1.601×10^5
A	A and B	A	6.118×10^8	1.552×10^5	5.657×10^8	1.417×10^5

18 g		18^- g		15 g		11 g	
TCF	TEF	TCF	TEF	TCF	TEF	TCF	TEF
4.796×10^8	1.406×10^5	5.225×10^8	1.76510^5	5.032×10^8	1.675×10^5	4.775×10^8	1.554×10^5
4.799×10^8	1.382×10^5	5.228×10^8	1.741×10^5	5.035×10^8	1.651×10^5	4.779×10^8	1.530×10^5
4.801×10^8	1.380×10^5	5.231×10^8	1.740×10^5	5.045×10^8	1.645×10^5	4.788×10^8	1.525×10^5
4.824×10^8	1.363×10^5	5.254×10^8	1.723×10^5	5.053×10^8	1.638×10^5	4.795×10^8	1.519×10^5
5.042×10^8	1.236×10^5	5.471×10^8	1.596×10^5	5.241×10^8	1.528×10^5	4.933×10^8	1.438×10^5

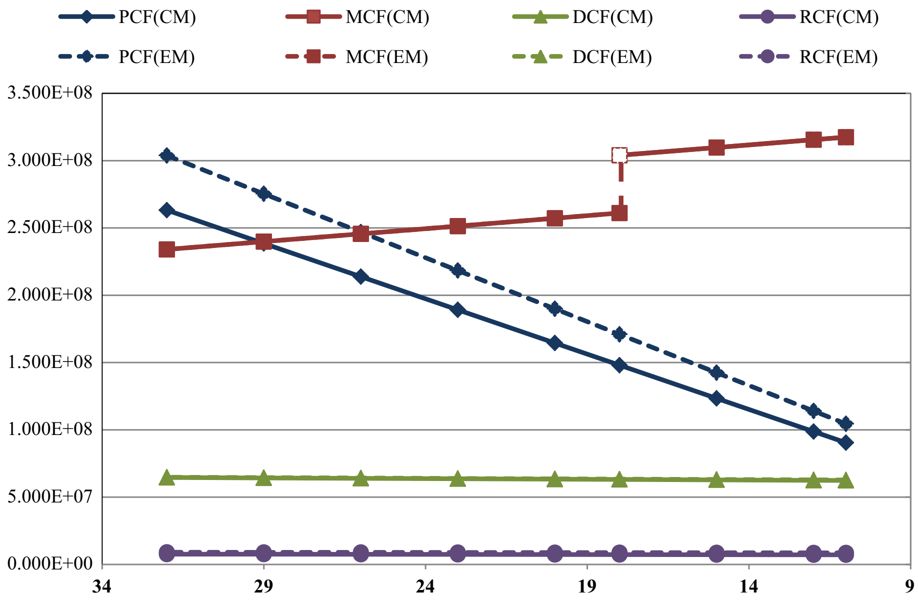

Fig. 5 Relationship between economic cost in the four processes and the weight of a PET bottle

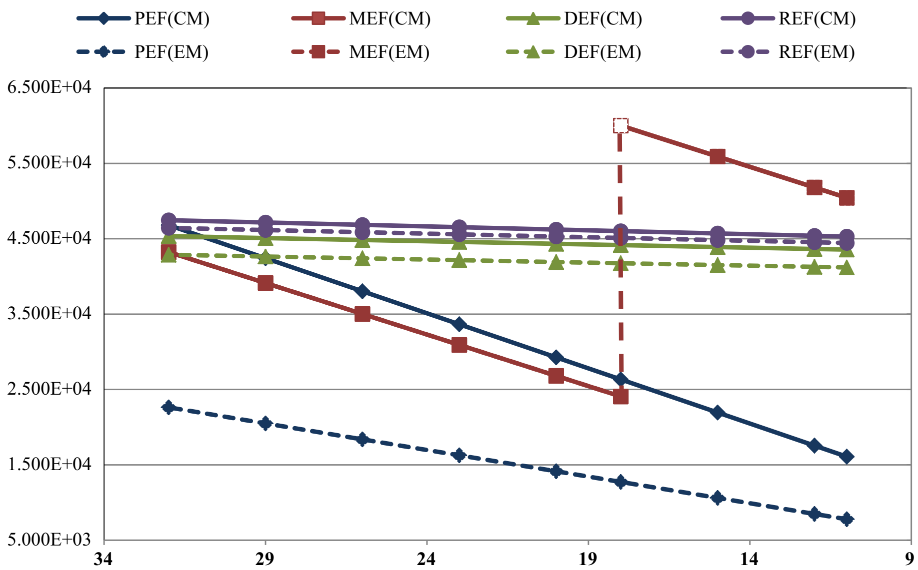

Fig. 6 Relationship between carbon emissions in the four processes and the weight of a PET bottle

the quantity of PET chips recovered from the returned PET bottles decreases with weight reduction because the amount of PET chips used in a PET bottle decreases. Thus, the amount of recovery of PET chips and the total weight of PET bottled soft drinks shipped back to manufacturing center decrease, and economic cost and carbon emissions in the recycling process decrease. However, the declines are also not apparent.

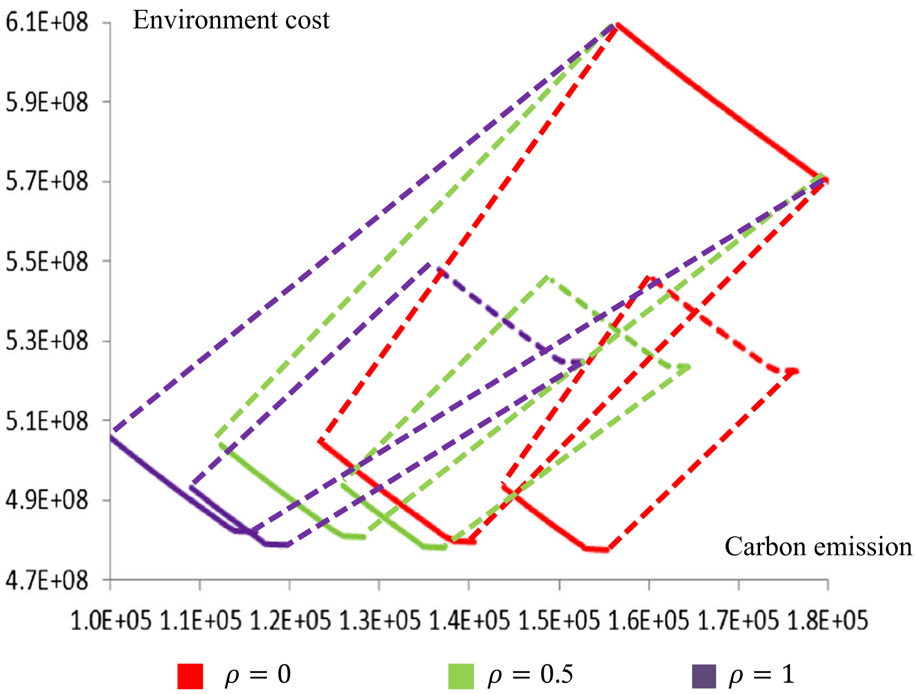

Fig. 7 Pareto frontier on economic and carbon emission perspectives in the robust model

5.2 Robust optimization model

The systemic uncertainty level ρ ranges from 0 to 1, when uncertainty level ρ equals to 0, it means that all uncertain parameters are assumed to be deterministic. Several representative uncertainty levels, such as 0, 0.5 and 1, are selected to analyze the robust optimization model. All data of certain parameters in the deterministic model are also used in the robust model, and the data of uncertain parameters in the deterministic model are treated as the mean value in the robust model.

The Pareto frontier on economic and carbon emission perspective in robust optimization model is reported in Fig. 7. We observe that with the increase inthe systemic uncertainty level, each point shifts to the upper left, which means that with increasing systemic uncertainty level, the economic cost increasesand the carbon emissions decrease on each weight of a PET bottle.With the increasing of systemic uncertainty level, the recycling process will be affected greatly. As a result, the corporation will reduce the usage of recovered PET chip and increase the purchase new PET chips, leading to an increase of cost and carbon emissions in the procurement and a decrease of cost and carbon emissions in the recycling. The demand may lead to larger fluctuations with the increasing of systemic uncertainty level, more products should be maufactured in order to satisfy the the deamands of customers, so the manufacturing cost and carbon emissions, distribution cost and carbon emission will increase. The decrease in the recycling cost is less than the increase in the manufacturing cost and distribution cost, therefore the total economic costs increase with the increase of the systemic uncertainty level. The decreasein the recycling carbon emissions is more than the carbon emissions in themanufacturing of the productand the carbon emissions in the distribution of the product, therefore the total carbon emissionsdecrease with the increase in the systemic uncertainty level.

In addition, the movement of the Pareto-area also affects the decision on the selection of weight reduction technology. Considering the uncertainty resulting from weight-reduction, the optimal weight of a PET bottle is still either 18 or 11 g. When the systemic uncertainty level $\rho = 0$, if the carbon emission restriction is less than 1.519E5, the optimal bottle weight is 18; if the carbon emission restriction is more than 1.519E5, the optimal bottle weight is 11g. When the systemic uncertainty level $\rho = 0.5$, if the carbon emission restriction is less than 1.428E5, the optimal bottle weight is 18 g; if the carbon emission restriction is more than 1.428E5, the optimal bottle weight is 11g. When the systemic uncertainty level $\rho = 1$, if the carbon emission restriction is less than 1.157E5, the optimal bottle weight is 18 g; if the carbon emission restriction is more than 1.157E5, the optimal bottle weight is 11 g. The threshold of restricted volume of carbon emission will decrease with the increase inthe systemic uncertainty level, which is approximately from 1.519E+5 ($\rho = 0$) to 1.428E+5 ($\rho = 0.5$) to 1.157E+5 ($\rho = 1$).

6 Conclusion

The conflict between economic performance and environmental regulation when selecting product technology and designing network is examined. Data from a corporation in China which produces and sells PET-bottled soft drinks and also recycles bottles, are used with the consideration of future regulationof carbon emissions. A mixed-integer linear programming model is developed for anlayzing the selection of weight reduction technology and decision making in raw material purchasing, vehicle routing, facility location, manufacturing and recycling plans which affect the economic cost and carbon emissions of supply chain network. In addition, a robust mixed-integer linear programming model is applied to deal with the uncertainty of supply chain network resulting from weight-reduction.After computional experiments, we observe that there is a significant trade-off between economic cost and carbon emissions. A series of conclusions are obtained as follows.

In the derterministic model, firstly, we find that although weight reduction is cost-effective and environmentally beneficial, increasing cost and carbon emissions in switching the beverage filling process from hot-filling to aseptic cold-filling divide the Pareto-area into two parts, which makes the original Pareto frontiers move to the upper right. By comparing the bottom line of the two obtained Pareto-areas, the optimal weight of a PET bottle is always either 18 or 11 g. Currently, when the volume of carbon emissions is restricted to less than 1.519E+5, the optimal weight of a PET bottle is 18 g; otherwise when the restricted volume of carbon emissions is greater than 1.519E+5, the optimal weight of a PET bottle is 11 g. Secondly, the feasible trade-off between economic cost and carbon emission declines with weight reduction. This means that when the weight of a PET bottle is small, greater concern about carbon emissions will not result in a very high increase (decrease) in economic cost. Thus, when the weight of a PET bottle is small, re-designing supply chain network on purchasing, manufacturing, distribution and recycling processes has less impact on the adjustment between economic costs and carbon emissions.Lastly, we also find that weight reduction technology has significant impact on the manufacturing and purchasing processes, but little impact on the distribution and recycling processes, therefore we should pay more attention to the manufacturing and purchasing processes.

In the robust model, we find that uncertainty has impact on the economic cost and carbon emissions on each weight of the PET bottle, with the increased systemic uncertainty level, the economic cost increases and the carbon emissions decrease on each weight of the PET bottle. As the threshold of the restricted volume of carbon emissions will decrease with the increase in the systemic uncertainty level, we should pay more attention to the selection of weight reduction technology when the uncertainty level is high.

7 Discussion, limitation and future research

There is still room for improvement and some aspects of the work in this paper can be extended. First,volume discounts on purchasing, inventory policy, multiple products and transportation modes are not considered in this paper; these factors should be taken into account to bring the model closer to the real world situation in future research. Second, this paper does not consider the uncertainties that result from external factors,such as fluctuations in raw material prices, as well as government policies, carbon emissions tax, trading schemes;future research should includethese elements. Third, innovative ideas from competitors and entry of third party logistics and independent recyclers are not considered in our paper, in the future these factors should also be considered.

Acknowledgements This work described in this paper was partially supported by National Scientific Foundation of China (Project No. 71671152 Grant No. 61750110536),Guangdong Natural Science Foundation fund (2015A030313782), SUSTech Startup fund (Y01236215), National Scientific Foundation of Fujian Province (Project No. 2015J01288), the Program for New Century Excellent Talents in University (NCET-12-0321) andthe Fundamental Research Funds for the Central Universities (No. 20720151004).

Appendix: Related parameters

Other parameters	
$m\bar{s}c_{it}$	Maximal supply capacity of new PET chips from supplier i in period t
$m\bar{m}c_{jt}$	Maximal production capacity of PET bottles at manufacturing center j in period t
$m\bar{d}c_{kt}$	Maximal distribution capacity of PET bottles at distribution center k in period t
$m\bar{r}c_{mt}$	Maximal processing capacity of returned PET bottles at recycling center k in period t
fs_i	Fixed cost of selecting supplier i to establish a long-term business
fm_j	Fixed cost of opening manufacturing center j
fd_k	Fixed cost of opening distribution center k
fr_m	Fixed cost of opening recycling center m
ps_{ijt}	Unit purchase price of new PET chips from supplier i to manufacturing center j in period t
pp_{kt}	Unit processing cost in distribution center k
pr_{mnt}	Unit repurchase price of returned PET bottles from market n torecycling center m in period t
pt_t	Unit cost of delivering cargoes (chips or bottles) per unit weight per unit distance in period t
pd_{mt}	Unit cost of discarding unusable recycling PET chips at recycling center m in period t
prr_{mt}	Unit cost of regenerating recovery PET chips at recycling center m in period t
lsm_{ij}	Shortest shipping distances from supplier i to manufacturing center j
lmd_{jk}	Shortest shipping distances from manufacturing center j to distribution center k
ldx_{kn}	Shortest shipping distances from distribution center k to market n
lxr_{nm}	Shortest shipping distances from market n torecycling center m
lrm_{mj}	Shortest shipping distances from recycling center m to manufacturing center j
cn_{ijt}	Unit carbon emission of purchasing new PET chips from supplier i to manufacturing center j in period t
crr_{mt}	Unit carbon emission of regenerating recovery PET chips at recycling center m in period t
crd_{mt}	Unit carbon emission of discarding unusable recycling PET chips at recycling center m in period t
ct_t	Unit carbon emission of delivering cargoes (chips or bottles) per unit weight per unit distance in period t

Appendix: Related data

See Tables 2, 3, 4, 5, 6 and 7.

Table 2 Data on purchasing process

	Period	PET chip supplier A	PET chip supplier B
Unit purchase price of new PET chips from supplier (Yuan/Ton)	1	11,700	9460
	2	10,700	8450
	3	10,695	8400
	4	10,688	8370
	5	10,688	8300
	6	10,680	8290
Unit carbon emission of purchasing new PET chips from supplier (Ton/Ton)	1	0.7782	0.9478
	2	0.7782	0.9478
	3	0.7782	0.9478
	4	0.7782	0.9478
	5	0.7782	0.9478
	6	0.7782	0.9478
Maximal supply capacity of new PET chips from supplier (Ton)	1	5000	6000
	2	5000	6000
	3	8000	9000
	4	8000	9000
	5	8000	9000
	6	8000	9000
Fixed cost of establishing a long-term business (Yuan)		55,000	75000

Table 3 Data on distribution process

	Period	Distribution center A	Distribution center B
Unit circulation cost in distribution center (Yuan/Unit)	1	0.135	0.155
	2	0.145	0.165
	3	0.155	0.175
	4	0.165	0.185
	5	0.175	0.195
	6	0.185	0.205
Maximal distribution capacity of PET bottles (Unit)	1	250,000,000	300000000
	2	250,000,000	300,000,000
	3	250,000,000	300,000,000
	4	250,000,000	300,000,000
	5	250,000,000	300,000,000
	6	250,000,000	300,000,000
Fixed cost of opening distribution center (Yuan)		1,750,000	2,700,000

Table 4 Data on recycling process

	Period	Recycling center A	Recycling center B
Discarding rate of unusable recycling PET chips at recycling center	1	0.1	0.08
	2	0.1	0.08
	3	0.1	0.08
	4	0.1	0.08
	5	0.1	0.08
	6	0.1	0.08
Maximal processing capacity of returned PET bottles at recycling center (Unit)	1	50,000,000	60,000,000
	2	50,000,000	60,000,000
	3	50,000,000	60,000,000
	4	50,000,000	60,000,000
	5	50,000,000	60,000,000
	6	50,000,000	60,000,000
Unit cost of discarding unusable recycling PET chips at recycling center (Yuan/Unit)	1	0.0145	0.0118
	2	0.0133	0.0103
	3	0.0132	0.0102
	4	0.0139	0.0102
	5	0.0137	0.01
	6	0.0135	0.0098
Unit cost of regenerating recovery PET chips at recycling center (Yuan/Ton)	1	2200	1700
	2	2150	1650
	3	2100	1620
	4	2000	1550
	5	1950	1500
	6	1900	1400
Unit carbon emission of regenerating recovery PET chips at recycling center (Ton/Ton)	1	2	2.5
	2	2	2.5
	3	2	2.5
	4	2	2.5
	5	2	2.5
	6	2	2.5
Unit carbon emission of discarding unusable recycling PET chips at recycling center (Ton/Unit)	1	0.000565	0.000575
	2	0.000562	0.000572
	3	0.000561	0.000571
	4	0.000559	0.000569
	5	0.000558	0.000568
	6	0.000556	0.000566
Fixed cost of opening recycling center (Yuan)		1,200,000	1,000,000

Table 5 Demand of each market (Unit)

Period	Market A	Market B	Market C	Market D	Market E	Market F	Market G
1	14,000,000	10,500,000	14,000,000	10,500,000	10,500,000	3,500,000	7,000,000
2	15,000,000	11,000,000	15,000,000	11,000,000	11,500,000	4,000,000	7,500,000
3	15,500,000	12,000,000	15,500,000	12,000,000	12,000,000	5,000,000	9,000,000
4	16,000,000	13,000,000	16,000,000	12,000,000	13,000,000	5,500,000	9,000,000
5	14,000,000	12,000,000	15,000,000	11,000,000	11,000,000	4,500,000	8,500,000
6	12,000,000	11,000,000	14,000,000	9,000,000	10,000,000	5,000,000	8,000,000

Table 6 Unit purchase price of returned product from market (Yuan/unit)

	Period	Market A	Market B	Market C	Market D	Market E	Market F	Market G
Recycling center A	1	0.061	0.058	0.058	0.055	0.056	0.054	0.051
	2	0.059	0.057	0.056	0.054	0.055	0.053	0.049
	3	0.058	0.055	0.054	0.053	0.054	0.052	0.048
	4	0.058	0.054	0.053	0.051	0.052	0.051	0.047
	5	0.057	0.053	0.051	0.049	0.051	0.049	0.046
	6	0.056	0.053	0.051	0.048	0.049	0.047	0.045
Recycling center B	1	0.051	0.049	0.051	0.047	0.046	0.045	0.041
	2	0.050	0.048	0.049	0.046	0.045	0.044	0.040
	3	0.049	0.047	0.048	0.045	0.043	0.043	0.039
	4	0.048	0.046	0.047	0.043	0.042	0.041	0.038
	5	0.046	0.044	0.046	0.042	0.041	0.039	0.037
	6	0.044	0.043	0.044	0.041	0.040	0.038	0.036

Table 7 Data about transportation

Period	1	2	3	4	5	6
Unit cost of delivering cargoes (Yuan/(Tons*KM))	0.98	0.98	0.98	0.98	0.98	0.98
Unit carbon emission of delivering cargoes (Tons/(Tons*KM))	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008

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