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Citation:

DING, Huiping, WANG, Li and ZHENG, Lucy (2018). Collaborative mechanism on profit allotment and public health for a sustainable supply chain. European Journal of Operational Research, 267 (2), 478-495. [Article]

Collaborative Mechanism on Profit Allotment and Public Health for a Sustainable Supply Chain

Huiping Ding[a,1] Li Wang [a] Lucy Zheng[b]

[a] School of Economics and Management, Beijing Jiaotong University, Beijing 100044, China
[b]Wolverhampton Business School, University of Wolverhampton, Wolverhampton WV1 1AD, UK

Abstract：This paper explores the collaborative mechanism that motivates supply chain firms to collectively invest in environmental technology and produce environmental friendly products (EFPs) to reduce pollutant emissions and negative impacts on environment and public health. Our paper investigates how such firms can achieve the balance between economic feasibility and environmental and social sustainability under multiple sustainable constraints in terms of the triple bottom line dimensions. The work also describes the impacts of interrelated multiple sustainable constraints on optimal policy for the supply chain transfer price and profit allotment decisions. Our findings suggest that government intervention plays a dominant role in governing the supply chain firms' behaviors in the context of environmental and public health sustainability. The profit allotment is determined through the process of negotiation of the transfer price interrelated with the government subsidy sharing between the supply chain firms.

Keywords: Supply chain management; Sustainable constraints; Public health; Transfer price; Profit allotment.

1. Introduction

Sustainable supply chain management (SSCM) has attracted increasing attention from both academics and practitioners. The focal issue has been how to identify optimal solutions that balance environmental, social, and economic benefits (Quariguasi et al., 2009). Sustainable supply chains are viewed as encompassing components of this triple bottom line, for which supply chain firms need to be engaged in the process (Elkington, 1997). Sustainable development related to environmental, social, and economic issues advocates firms to improve environmental practices and social responsibilities across their supply chains. A balance among the three pillars of the triple bottom line (economics, environment, and society) requires a good understanding as to how industrial activities affect the current and future environment (Hutchins et al., 2008). Thus, by taking stakeholders' environmental and social interests as sustainable constraints, the purpose of the research at hand is to investigate the mechanism of balance between financial feasibility and environmental protection and public health in the context of the supply chain, and to gain insight into collaborative transfer price decision and profit allotment between supply chain firms.

The existing literature has not yet given enough attention to the interactive effects between environmental and social externalities, government policies, and stakeholders' environmental and public health interests. The environmental behavior of partner firms may have influences on the supply chain's value transformation process (Klassen and Vachon, 2003). It is likely for those supply chain members with higher levels of social performance to seek to strengthen their partnership with influencing stakeholders. From the perspective of triple bottom line dimensions, some questions can be raised: which trade-offs occur between the environmental, public health, and economic impacts of supply chain firms' activities? How do the sustainable constraints that represent stakeholders' environmental and public health interests affect supply chain firms' decision behaviors? How can the government subsidy sharing interrelated with the transfer price decision and profit allotment be effectively used to motivate supply chain firms'

[1]Corresponding author. Tel.: +86 10 51687177
E-mail addresses:hpding@bjtu.edu.cn, hpdding@sina.com

collaborative investment in green technology? What are the best solutions that balance ecological, social (public health), and economic concerns?

More recently, Ding et al. (2016) developed an environmentally sustainable supply chain model in which stakeholders' interests (environmental carrying capacity, government policies, and customer environmental concerns) are considered as multiple environment constraints, and the operations strategy decision and economic performance of an integrated environmentally sustainable supply chain for producing environmental friendly products (EFPs) is analyzed. However, while considering the firms' environmental behaviors the collaborative mechanism between the supply chain firms in terms of the transfer price decision and profit allotment has not yet been investigated. With government intervention, the profit allotment, including government policy incentive (subsidy) sharing between the sustainable supply chain partners, is a key issue that requires further study.

Built upon the latest research and taking the view of triple bottom line, this study extends the research by including social aspect as a new dimension and examines the externality of environmental pollution, namely, the negative impact of environmental pollution on healthcare costs by introducing public health as a new constraint to accommodate the social aspect. Our work investigates the optimal policy for collaborative supply chain profit allotment subject to sustainable constraints in view of the triple bottom line dimensions. In particular, our paper seeks to fill the literature gaps concerning the interplay effects of incorporating the triple-dimension sustainable constraints interrelated to the supply chain transfer price and profit allotment decisions. From the perspective of a sustainable supply chain, we introduce government intervention, including both subsidy and penalty, as an effective driver that motivates supply chain firms to collaboratively make their commitment towards pollution prevention and public health assurance via EFPs production. Our model reflects stakeholders' interests from both environmental and public health (social aspect interrelated to environmental pollution) perspectives; analyzes the joint effects of multiple sustainable constraints and their interplay relations on supply chain transfer price and profit allotment decisions; and explicates the environmental, public health, and economic performances of the collaborative supply chain. A key issue worthy of exploration for the success of sustainable supply chain collaboration is to determine the transfer price interrelated with sharing of government policy incentives between supply chain firms, which is more challenging since it involves the allocation of government policy incentives between the supply chain firms as well as compliance with sustainable constraints. Therefore, our main contribution to the field is the development of an analytical framework for characterizing a sustainable supply chain by encompassing transfer pricing, supply chain collaboration, public intervention, and triple-dimension sustainable constraints.

The remainder of the paper is organized as follows. Section 2 reviews the existing literature. Section 3 formulates a collaborative sustainable supply chain model with sustainable constraints in the triple bottom line dimensions. Section 4 develops a solution structure to sustainable supply chain collaborative mechanism on profit allotment through model analysis. Section 5 provides the numerical results and discussion. Section 6 presents the supply chain model with two suppliers, assuming that they are not competitors to one another. The final section draws conclusions and ends with further research directions.

2. Literature Review

SSCM has received increased attention from academics, policy-makers, and practitioners in the past decades (Reed, 2008; Bai and Sarkis, 2010; Gold et al., 2010; Ilgin and Gupta, 2010; Barker and Zabinsky, 2011; Dekker, et al. 2012; Mallidis et al., 2012; Seuring, 2013; Brandenburg et al., 2014; Devika et al., 2014; Kumar et al., 2014; Fahimnia et al., 2015). With an increasing awareness of and the need for environmental protection, firms are compelled by pressure from the stakeholders to incorporate "green" practices into their SSCM (Gold et al., 2010). Firms can improve not only their economic benefits but also the environmental and social impacts through their internal production processes (Gimenez et al., 2012).

Stakeholders' environmental interests and green technology investment

The school advocating stakeholders' environmental and social interests argues that firms should take the liability to reduce environmental externalities via green technology investments (Chiu and Yong, 2004; Ding et al., 2014; Matthews and Lave, 2000; Holmgren and Amiri, 2007; Longa, et al. 2008). The supply chain firms are under the pressure from environmental stakeholders such as consumers, societies, and governments for producing environmental friendly products and services. While complying with government regulations in relation to the socio-environmental impacts of the supply chain, the firms need to achieve consumer satisfaction for green preference and social wellbeing (Gopalakrishnan et al., 2012). With their green preference the consumers have a tendency to pay a price premium when they prefer environmentally friendly products (Loureiro and Lotade, 2005). The pressure affects the firms' technology adoptions to become environmentally friendly (Luken and Rompaey, 2008).

Yalabik and Fairchild (2011) examined the impact of pressures from the stakeholders on firms' green technology investment in order to achieve environmental friendly production. They argued that the government subsidies are more effective than environmental fines in encouraging firms to invest in environmental innovation, especially in those "dirty" industries. Their findings suggest that the incentive policy is a stronger driving force for firms' environmental innovation than the penalty policy. Employed a lifecycle approach, Ding et al. (2014) focused on the impact of government policies on the environmental friendly product (EFP) projects' performance and their commercial feasibility. Based on their findings, they drew policy implications on how to motivate firms reducing their pollution externalities by producing EFPs. Kumar et al. (2014) proposed an environment friendly approach using green data envelopment analysis for supplier selection. The approach took regional emission standards into account to encourage suppliers going "green" by cutting their carbon footprints. Using a strategic decision-making model, Tseng and Hung (2014) considered both operational and social costs incurred by carbon emissions in the context of a supply chain network. They suggested that government legislation is an effective way to force firms bearing the social costs of their carbon dioxide emissions and improving their environmental and social performances. Barari et al. (2012) studied a synergetic alliance concerning environmental and economic trade-offs with the maximization of business profits by leveraging the product's "greenness." They argued that coordination between supply chain firms helps with initiating and adapting their green strategies and practices.

Environmental sustainability and supply chain perspective

Though scholars have paid much attention on corporate governance's impact on promoting sustainability, there is limited research on the issue in this regard from a supply chain perspective (Vermeulen and Seuring, 2009; Alvarez et al., 2010). Employing case study method, Formentini and Taticchi (2015) investigated governance mechanisms that are associated with supply chains and sustainability. They considered contingency factors from strategic alignment perspective with resource-based view. Ding et al. (2015) studied business performance of supply chain firms by considering environmental externality and government regulation impact in their model. They investigated optimal operations strategy of environmental friendly product in the supply chain context. However, it still remains unclear how corporate sustainability approaches are implemented and aligned with governance mechanisms at the supply chain level (Formentini and Taticchi, 2015). Therefore, there is a need for a better understanding as to how the corporate governance can motivate supply chain collaboration considering both sustainability and economic trade-offs.

A firm can gain the maximum benefit only when its sustainable operational strategies are aligned with those of its suppliers and customers (Tang and Zhou, 2012). The internalization of environmental externalities relies on each firm and the interactive cooperation between the firms within the supply chain network. In the context of supply chain management, an important issue is to identify a contract mechanism that benefits to all supply chain members with coordinate profits, so that the members are willing to participate in the coordination and optimization. As the supply chain members have different costs and revenue structures, they will have different gains and benefits from the collaboration (Simatupang and Sridharan, 2005). With respect to profit allotment among the supply chain firms, there have been a growing number of studies in the arena. Research on profit sharing among the supply chain members has emerged to address the decisions regarding optimal pricing, optimal margin, order and production quantities, and the number of shipments, that will maximize the total profit of the whole supply chain (Batarfi et al. 2016). Giannoccaro and Pontrandolfo (2004), Cachon and Lariviere (2005) proposed revenue-sharing contracts under which suppliers sell their products to distributors at a low wholesale price and they share supply chain sales revenue. The proposed revenue-sharing contracts maximize the performance of the whole supply chain, and the benefits of each party are adjusted by the distribution coefficient of the neighboring nodes. The distribution coefficient is to provide a reasonable profit allotment between supply chain members to ensure the supply chain coordination, and also encourage the members to carry out technological innovation and operational risks sharing. However, the determination of the distribution coefficient between suppliers and distributors has not yet been explored.

Chauhan and Proth (2005) presented a provider–retailer partnership model that not only maximizes the total combined profit but also optimizes the shared profit to each partner proportional to their risk and investment. Lakhal (2006) proposed a mathematical model for profit sharing and transfer pricing between network firms, enabling maximization of operating profits via the manufacturing-network within its supply chain. The study considered the factors including multiple suppliers and retailers, costs differentia, resources availability and sharing, and competition with subcontracting option. The model that the study employed calculates transfer price of the manufacturing product, based on each firm's contribution, for the way of sharing operating profits between the firms in the supply chain network. Wei and Choi (2010) explored the wholesale pricing and profit sharing scheme for coordinating supply chains under the mean–variance decision framework. The study showed that a unique equilibrium solution to the leader–follower Stackelberg game will exist, if the demand satisfies the increasing generalized failure rate, in the decentralized setting with a pre-negotiated and determined profit sharing ratio. The manufacturer acts as the leader who offers the contract while the retailer is the follower who reacts to the offer. Ding et al. (2011) developed a graphic model with three-dimensions to depict the possible cooperative solutions of profit allotment between partners in the context of three-echelon supply chain. They applied a game approach and analyzed how the profit allotment can effectively motivate partners for collaboration with each other. Feng et al. (2014) studied a revenue-sharing contract in an N-stage supply chain using a two-round profit allocation mechanism. They argued that it is a flexible method for adjusting the profits in the second round by considering the reliability of all of the members. Saha et al. (2015) developed multi-item multi-objective manufacturer–retailer supply chain models, considering risk and budget constraints for long-term contracts. They also considered a profit sharing scheme in a fuzzy-stochastic environment, at which the manufacturing costs of the items are fuzzy, and the demands for the items are random during each of periods. Arani et al. (2016) modelled a mixed revenue-sharing option contract. Using a game theoretic approach, they examined several possible situations to obtain the retailer's order quantity and the manufacturer's production quantity in the Nash equilibrium. Becker-Peth and Thonemann (2016) extended the classical normative decision model by integrating reference-dependent valuation. They showed how behavioral aspects of revenue-sharing affect inventory decisions. Cruz et al. (2008, 2009) investigated the interplay between the heterogeneous decision-makers and the equilibrium pattern of product outputs, transaction pricing, and levels of social responsibility activities. They considered the multi-criteria decision-making approach that includes the maximization of net return and the minimization of emissions and risks. However, these studies failed to take environmental or social performances into account.

Ageron et al. (2012) developed a theoretical SSCM framework. They identified the enabling conditions and critical success factors, such as performance criteria, greening supply chains, characteristics of suppliers, managerial approaches, barriers, benefits, and motivations. Silvestre (2015) explored how supply chain sustainability can be implemented and managed in developing countries, especially in the emerging economies like BRICs. They pointed out that developing economies face more barriers for SSCM due to the complexity and uncertainty of business environment and institutional voids. However, these studies neglect the impact of corporate social responsibility (CSR) on firms' decision-making process in reducing environmental pollution. When taking environmental and social impact into consideration, supply chain firms' business behavior will be affected owing to the additional costs for pollution abatement, which further affect the profit sharing scheme between supply chain firms.

CRS behavior and public health

CSR refers to a firm's business practices involving self-regulations that benefit society for a greener business operation (Andersen et al., 2009). Combining case study and survey approaches, Carter and Jennings (2002) established a relationship between CSR and supply chain. Hsueh (2008) developed mathematical models to investigate firms' CSR behaviors and their profits in decentralized and centralized supply chain networks. CSR ensures firms with a responsible business venture to reduce negative environmental footprints and potential health and safety risks, and to gain acceptance from local societies (Wirth et al., 2016). The environmental problems such as high level air pollution not only result in health risks, but also incur real costs on the citizens, the societies, and the economy as a whole (Matus et al. 2012). Norris (2006) examined the relationship between gross national product (GNP) per capita and environmental pollution, and the impact of increasing or decreasing in GNP per capita on public health. Public health impact assessment identifies any negative health impacts, based on which the government policies are to be set accordingly to protect public health (Mittelmark, 2001). It becomes possible to analyze the cost effectiveness of pollution abatement strategies and to set air quality standards by quantifying the impact of air pollution on public health (Aunan and Pan, 2004). Using different approaches such time-series, cross-sectional, panel, case-crossover, cohort, and intervention designs, a number of epidemiological studies on air pollution and public health in China have been conducted (Kan et al., 2012; Aunan and Pan, 2004; Wang and Mauzerall, 2006). The increased health risks observed among Chinese population are much higher than that in developed countries (Kan et al., 2012). Aunan and Pan (2004) proposed exposure-response functions to detect the impact of PM10 and SO2 pollution on public health in China. Using an integrated assessment approach combining engineering, epidemiology, and economics, Wang and Mauzerall (2006) developed air quality and meteorological models to establish the link between energy consumption, technologies, air pollution concentrations, and their impacts on public health in the Eastern China. Most of these studies have focused on negative public health impact of air pollution using either damage function approach or point estimate. However, there has been little attention to be paid for reflecting how supply chain firms commit themselves to reduce public health loss.

A limited SSCM studies have considered multiple sustainable constraints from the triple bottom line dimensions, and the research on how stakeholders' environmental and social interests can be balanced with green investments' financial feasibility in the supply chain remains rear. In addition, the issues concerning how to effectively enable supply chain firms to go for green investments have not yet investigated sufficiently. It is still a key issue requiring a further investigation as to how the mechanism for supply chain profit sharing would change if the environmental and public health are included into consideration. A further study is essential, from eco-efficiency perspective by integrating organizational interdependencies, to focus on balancing supply chain firms' business profits and social interests in the environment protection and public health. The present study seeks to fill the literature gaps, using a supply chain model that incorporates multiple sustainable constraints to represent stakeholders' interests from perspective of the triple bottom line including environment and public health. In order to assess green investment performance of a supply chain, our model considers not only the environment constraint, but the joint impact of other factors including government policies, public healthcare cost, and consumers' environmental awareness. In particular, comparing with previous study (for example, Ding et al., 2014, 2015, 2016), the contributions of this study lie in two areas by: (1) introducing public health factor to represent social interests; (2) exploring the joint impact of environmental and social responsibility constraints on supply chain coordination for profit sharing through transfer price negotiation between supply chain firms. The impact of government incentive policy is also integrated into our model. Our study is different from previous studies because of our multiple sustainable constraints model, which has introduced public health constraint into our equation from the triple bottom line dimensions. Our study can, therefore, combine broader aspects of sustainable supply chain system. We emphasize both perspectives of supply chain firms' decision-making and policy-making for reducing pollutant emissions. In doing so, our study will focus on the mechanism as to how to motivate supply chain firms to improve their environmental and social performances as well as their investment decisions in responding to the sustainable constraints. Table 1 summaries the main studies in the area for comparison.

➢ The Table outlining the comparison of this work with respect of the other published studies (especially the Ding et al. (2016)) is greatly recommended to clearly mark the contribution of this paper. Table should be included at the end of literature section. This will clearly help out the reader to the view the contribution of this paper.**(reviewer 2#)**

Table 1 Comparison between this research and previous studies

This research work	Contributions
Collaborative mechanism on profit allotment and public health for a sustainable supply chain	This study investigates how firms can achieve the balance between economic feasibility and environmental and social sustainability in the triple bottom line dimensions. It investigates the joint impact of multiple sustainable constraints on optimal policy through supply chain transfer pricing and profit allotment decisions that are interrelated with the government policies. In particular, social responsibility in terms of public health cost constrain is incorporated into our model.
Journal publications	
Assessing the economic performance of an environmental sustainable supply chain in reducing environmental externalities (Ding et al., 2016, EJOR)	The paper formulated a quantitative model of an integrated supply chain that incorporates only environmentally sustainable constraint to optimize supply chain firms' operational strategies of producing environmental friendly products. However, the supply chain transfer price and profit allotment decisions, and social responsibility dimension are not considered in the study.
Pricing strategy of environmental sustainable supply chain with internalizing externalities (Ding et al., 2015, IJPE)	The paper focused on optimal pricing strategies for environmentally sustainable supply chains and the relationship between firms' environmental performance and government policies, without considering a sustainable constraint.
Lifecycle approach to assessing environmental friendly product project with internalizing environmental externality (Ding et al., 2014, JCP)	The paper focused on the mechanism of how firms can voluntarily produce the environmental friendly product (EFP) to remedy negative externalities. It examined the relationship between policy incentives and economic performance of the EFP, and the impact of the government polices on the EFP's commercial feasibility and process of internalizing externalities. However, supply chain models were not their focal point.

Quariguasi et al., 2009, EJOR; Klassen and Vachon, 2003, Production and Operations	The papers investigated the environmental behavior of partner firms in the supply chain and optimal solutions balancing environmental, social, and economic benefits. However, the studies did not consider the interactive effects of government policy, or stakeholders' environmental and public health interests.
Kumar et al., 2014, Omega; Yalabik and Fairchild, 2011, IJPE; Chiu and Yong, 2004, JCP; Matthews and Lave, 2000, Environmental Science & Technology; Holmgren and Amiri, 2007, Energy Policy; Longa, et al. 2008, Ecological Economics	The papers examined the impacts of consumer, regulatory, and competitive pressures on supply chain firms' green technology investment to reduce environmental externalities. They suggested that government legislation is an effective way to force firms bearing the social costs and improving their environmental and social performances. However, the supply chain transfer price and profit allotment decisions were not considered by these studies.
Formentini and Taticchi, 2015, JCP	The paper proposed an empirical investigation using seven case studies on the governance mechanisms that are associated with supply chains and sustainability. However, it is unclear in relation to how corporate sustainability approaches are implemented and aligned with governance mechanisms at the supply chain level.
Arani et al., 2016, IJPE; Becker-Peth and Thonemann, 2016, EJOR; Batarfi et al. 2016, Applied Mathematical Modelling; Feng et al., 2014, IJPE; Wei and Choi, 2010, EJOR; Lakhal, 2006, EJOR; Giannoccaro and Pontrandolfo, 2004,IJPE	The papers proposed frameworks and methodology for profit sharing and transfer pricing among the supply chain members. They addressed the decisions regarding optimal pricing, enabling maximization of the total profit of the whole supply chain. Pricing and profit sharing scheme were explored under the mean-variance decision framework, and revenue-sharing option contracts were introduced to coordinate supply chains. However, they did not consider a sustainable constraint.
Cruz et al., 2008, IJPE	The paper developed a framework to analyze the optimal allocation of resources to corporate social responsibility activities in a supply chain network. However, the environmental and social performances of production behavior were not considered.
Hsueh, 2008, EJOR; Carter and Jennings, 2002, Transportation Research; Matus et al., 2012, Global environmental change; Kan et al., 2012, Environment international	The papers established a relationship between CSR and supply chain combining case study and survey approaches. They evaluated the profit of coordination between manufacturers on CSR using mathematical models. Most of the studies on public health focused on its negative impact of air pollution. But the issue as to how supply chain firms are committed to reduce public health loss was not studied.

3. Sustainable supply chain collaborative mechanism on profit allotment

In the following section, we formulate supply chain models in the cases of non-cooperation and collaborative decision-making while introducing the EFPs, in which the supply chain firms' business decisions are subject to constraints representing stakeholders' sustainability interests in view of the triple bottom line dimensions. We also discuss how the constraints affect government subsidy rates, supply chain firms' decision behaviors concerning the EFPs' sales quantities, price, and supply chain profit allotment.

3.1 Description of Triple-dimension Sustainable Constraints

In this study, we consider the communities, government, and consumers as the major stakeholders, and characterize their environmental preferences and social interests by means of multiple sustainable constraints that may be classified into two types: the first one represents environmental sustainable aspects including environment carrying capacity (environmental standards), regulation, market preference (consumers' environmental awareness); the second represents social aspect in terms of public health safety responsibility. For eco-environment to be sustainable, supply chain firms' business activities must comply with the sustainable constraints. However, in a supply chain this is not an individual firm's responsibility; rather, it needs collaboration among all supply chain partners. We take it for granted that each of the supply chain partners must comply with the sustainable constraints that affect its and also other partners' behaviors, environmental and social performances as well. The sustainable constraints that characterize the environmental and social interests of the stakeholders are presented in the following sections.

3.1.1 Environmental sustainable constraints

Ding et al. (2016) presented the environmental sustainable constrains including three views: environmental carrying capacity, regulation and consumers' preference. This study will use the definitions including environmental constraint (presented by environmental carrying capacity), regulation constraint, and market constraint that are defined in Ding et al (2016). Without environmental standards, the financial burdens of environmental cleaning and restoring on the government are substantial. The government accordingly imposes penalties on pollution and provided subsidies to green investments to drive and motivate the firms' improvement in their environmental and social performances. The pollutants can then be prevented at the source so that their destructive impacts on society are significantly reduced or eliminated. From the perspective of market demand, a consumer's preference reflects the market constraint in the sense that EFPs' total costs of purchase and usage do not exceed that of environmentally unfriendly products (EUFPs). In reality, consumers who are environmental awareness exert pressure on supply chain firms to improve their sustainable practices, and they have a trade-off between buying EFPs and paying an affordable price premium.

- not convinced that the current paper leads us to have **new insights into the roles of CSR in a supply chain system** ……. should consider a more realistic supply chain system (e.g., two suppliers-one manufacturer or so) to make a good contribution as it addresses the interaction between multiple participants given this CSR context. **(reviewer 3#)**

3.1.2 Public health constraint

From the perspective of social society, our research adds a new sustainable constraint. Public health constraint refers to government policy that guides supply chain firms to perform their corporate social responsibility by being environmentally friendly and reducing negative externality impacts on the public health so that loss of public health caused by pollutants can be reduced in the long run. Increased public healthcare cost is the result of decreasing environment quality caused by polluting production of the supply chain firms. Imposing a public health constraint will compel supply chain firms to reduce public health loss with their environmental commitment. In doing so, we can analyze the impact of public healthcare constraint on the supply chain firms' CSR behavior and decision and social impact. We assume that without the environmental legislations, public healthcare cost will increase due to supply chain firms' environmentally unfriendly behaviors. These increased public healthcare costs are partially borne by the government subsidy supporting medical expenses.

3.2 Modelling Assumptions and Notations

3.2.1 Assumptions

(1) Consider a two-echelon supply chain that consists of one manufacturer with one supplier and produces a single product. The manufacturer sells finished goods to the market (consumers), the supplier provides intermediate products to the manufacturer, and correspondingly, one unit of the finished goods consumes v units of the intermediate products. The manufacturer's production is operated on the basis of make-to-order strategy.

(2) Consider two situations: 1) Assume that without sustainability constraints, the supply chain firms only produce EUFPs and sell them in the competitive market, and EUFPs' production runs at capacity in accordance with the market share; 2) Enforced by government policies, the supply chain firms would collaboratively introduce EFPs by engaging in green technology investment. Such additional investment

increases the cost of producing the EFPs, resulting in a cost disadvantage when compared with the EUFP in the competitive market.

(3) To motivate supply chain firms to actively improve their environmental and social performances, the government imposes penalty for EUFPs' production and provides subsidies to encourage green investment, thereby reducing the EFP's cost disadvantage in the marketplace. By taking corporate social responsibility into account in terms of preventing the loss of public health, we assume that the government also levies tax on loss of public health to compensate for increased public healthcare cost. Based on the logic that only the additional costs of pollution prevention are to be compensated, we assume that the government subsidies should only partially compensate supply chain firms' average incremental costs for producing EFPs and are only granted until the supply chain firms' breaks-even. We also assume that the government subsidies are granted to the manufacturer by going through the consumers (i.e., the manufacturer obtains the subsidy only after it has sold the products to the consumers), and the manufacturer shares the subsidies with the supplier through adjustment of the transfer price.

(4) We assume that the EFPs' sales quantities are unlikely to run at the full production capacity of manufacturer when it is still new to the market. Instead, upon expecting promotion by government policies and consumers' changing environmental preferences, they will increase gradually with a forecasted growth rate through its diffusion process. Meanwhile, the EFPs will gradually replace the EUFPs in the marketplace. As the EFPs' sales quantities increase, the EUFPs' sales decrease until they are fully replaced. We also assume that, with an additional investment in production of the EFPs, the manufacturer operates in a flexible manufacturing system in which production capacity is compatible with its market share, so that a flexible change of production quantity of the EFPs becomes possible.

- assume that the firms can flexibly change Q_t^e at each time. In fact, changing from EUFP to EFP sometimes needs extra process or equipment, which may yield a constraint that Q_t^e is limited to a certain capacity related to the process or equipment. What do the authors think about the firms' model of controlling Q_t^e? **(reviewer 1#)**

(5) To analyze the sustainable supply chain, we consider the two situations of either non-cooperation supply chain or collaborative supply chain. In the non-cooperation case, the supply chain firms make their decision independently. There are no environmental constraints. The supply chain firms only produce the EUFPs and sell them in the competitive market, implying that without any environmental and social concerns, the supply chain firms are unlikely to have any motivation to cooperatively improve their environmental and social performances. In a collaborative case, government enforces legislation by setting environment standard constraints that represent the maximum levels of pollutant allowed at an environmentally acceptable level, and also provides incentives so that the manufacturer and supplier collaboratively introduce production of the EFPs through environmental technology investment.

It maybe not common assuming a supply chain with one manufacturer and one supplier. Considering the complexity with multiple suppliers, our study would be advanced in handling both cases with one and multiple suppliers. Based on one supplier case analysis, the multiple suppliers' case will be addressed in Section 6 for gaining the insight of the problem solution.

- assumption that the supply chain consists of one manufacturer and one supplier is not common …… justify the assumption and discuss effects in case of multiple suppliers. **(reviewer 1#)**

3.2.2 Parameter notations

Based on the notions used in previous studies (Ding et al., 2014, 2016), we add new notations following:

Q = EUFPs' average annual demand (market share) that matches production capacity of manufacturer

Q^u = EUFPs' sales quantity ($Q^u = Q$ without EFPs; $Q^u = Q - Q^e$ with EFPs)

P_m^u = Sales price of EUFPs

P_s^u = Transfer price for EUFPs (i.e., manufacturer's unit purchase cost)

B_m = Government incentive policy to EFPs per unit in proportion to average incremental cost for environmental protection under collaborative supply chain

I_m, I_s = Initial investment of green project from the manufacturer and supplier

C_m^u, C_m^e = Variable cost of manufacturer per unit of EUFPs and EFPs

W_m^u, W_m^e = Pollutant disposal cost of manufacturer per unit of EUFPs and EFPs

E_m^u, E_m^e = Pollutant emission of manufacturer per unit of EUFPs and EFPs

C_s^u, C_s^e = Variable cost of supplier per unit of intermediate products for EUFPs and EFPs

W_s^u, W_s^e = Pollutant disposal cost of supplier per unit of intermediate products for EUFPs and EFPs

E_s^u, E_s^e = Pollutant emission of supplier per unit of intermediate products for EUFPs and EFPs

F_m^u, F_s^u = Government penalties imposed on EUFPs per unit output of manufacturer and supplier

Y = Environmental carrying capacity (representing emission standards) allocated to supply chain system

Z^u, Z^e = Environmental cleaning and restoring costs borne by government to keep the environment at a self-healing standard for EUFPs and EFPs

U^u, U^e = Lifecycle usage cost per unit of EUFPs and EFPs

H_m^u, H_s^u = Total healthcare cost for loss of public health caused by pollutant emission per unit of EUFPs by manufacturer and supplier respectively

θ_m^u, θ_s^u = Pollution tax levied on public health loss caused per unit of EUFPs by manufacturer and supplier respectively

V_m, V_s = Government healthcare subsidy to the healthcare cost of public health loss caused per unit of EUFPs by manufacturer and supplier respectively

k = Sensitivity rate of consumer to environmental quality ($0 \le k < 1$)

g = Average annual growth rate of EFPs' sales quantities

n_1 = Time point at which supply chain reaches economic break-even with the EFPs

r = Interest rate

b = Total coefficient of government incentive policy

$\Delta NPV_m, \Delta NPV_s, \Delta NPV_{sc}$ = Net present value of EFPs for manufacturer, supplier, and supply chain system

3.2.3 Decision variable notations

Q^e = Annual sales quantity (EFP) of manufacturer

P_m^e = Annual sales price (EFP) of manufacturer

α = Annual coefficient of government subsidy per unit of EFPs

β = Incentive policy transmitted to supplier based on the average incremental cost per unit of its output for EFPs

$P_s^e(b)$ = Transfer price for EFP

In the following sections, we present a model framework that explicitly incorporates the sustainable constraints in view of triple bottom line dimensions and helps explore stakeholders' interrelations and supply chain firms' decision behaviors aligned with replacing EUFPs by EFPs when encouraged by government incentive policy.

3.3 Structure of the Constraints

Referring to Ding et al. (2014, 2016), the environmental constraint presents the following inequality meaning that the supply chain firms' total pollution cannot exceed the emission allowance (regulation standards) allocated to the supply chain system:

$$Q_t^e E_{mt}^e + \nu Q_t^e E_{st}^e + (Q - Q_t^e) E_{mt}^u + \nu (Q - Q_t^e) E_{st}^u \leq Y, \qquad t = 1, 2, \ldots, n \qquad (1.1)$$

where $Q - Q^e$ is EUFPs' annual sales of product quantity that have not yet been replaced by EFPs. Taking into account social welfare and environmental externalities, regulations should conform to ecological sustainability (represented by the environmental carrying capacity). In order to allow for EFPs' self-sustaining marketing programs of promoting green products need to remain in place for a sufficiently long period of time.

Distinct from previous studies, the corporate social responsibility constraint (in terms of public health) is included in our mode that can be presented as follows:

$$(Q - Q_t^e)[H_{mt}^u + \nu H_{st}^u] \leq Q(V_{mt} + \nu V_{st}) \qquad t = 1, 2, \ldots, n \qquad (1.2)$$

By assuming that the government offers a limited amount of healthcare subsidy to compensate the public healthcare cost caused by EUFPs, the inequality Eq. (1.2) states that in the supply chain the total healthcare cost for loss of public health caused by EUFPs that have not yet been replaced (on the left hand side) should not be over the government healthcare subsidy allocated on the basis of the supply chain's production capacity (on the right hand side). We also assume that collected public health taxes levied on the EUFPs are fully used to compensate the public healthcare cost in terms of the healthcare subsidy. The implication of the corporate social responsibility (public health) constraint is that without the enforced environmental legislation, the increased public healthcare cost caused by the EUFPs is not accounted for by firms; as we infer, it is partially borne by the government healthcare subsidy that supports the increased medical expenses. On the contrary, if the inequality Eq. (1.2) does not hold, it then means that for a given level of government healthcare subsidy, the public health condition will be getting worse with high healthcare costs caused by the pollution. With the introduction of EFPs motivated by the government policies and as the EUFPs are replaced, the healthcare cost is reduced and must be confined to the limited amount of government healthcare subsidy allocated to the supply chain system.

Considering the important role of government policies in reducing environmental externalities, government subsidy is explicitly introduced into the sustainable supply chain model to evaluate the financial feasibility of EFPs' production in terms of reaching a break-even, and to asses its effectiveness of enabling supply chain firms' improvement in their environmental and social performances. In reality, however, the government subsidy to firms' green investments is restricted by financial burdens and should therefore be subject to an upper limit. Thus, the regulation constraint need to reflect the financial feasibility that the government subsidy offered must be less than the government's savings in environmental externality cost, which can be presented as follows:

$$\begin{aligned} B_{mt} Q_t^e \leq b[&(Z_t^u - Z_t^e) + (Q(V_{mt} + \nu V_{st}) - (Q - Q_t^e)(V_{mt} + \nu V_{st})) \\ &- (Q(F_{mt}^u + \nu F_{st}^u + \theta_{mt}^u + \nu \theta_{st}^u) - (Q - Q_t^e)(F_{mt}^u + \nu F_{st}^u + \theta_{mt}^u + \nu \theta_{st}^u))] \end{aligned} \qquad t \leq n_1 \qquad (2.1)$$

As seen above, on the right-hand side of the inequality, the first item presents the government's saved environmental cleaning and restoring costs, the second item group is the government's saved healthcare subsidy to the healthcare cost caused by pollution, the third item group is the reduced penalty cost and public health tax due to replacement of EUFPs by EFPs. Parameter b (b < 1) ensures that the amount of government subsidy is less than the reduced environmental externality costs. $t \le n_1$ means the government subsidy only applies until the supply chain firms reach break-even. As presumed above, the manufacturer obtains subsidy from the government through consumers and part of this subsidy is passed on to the supplier through transfer price negotiation. Following the study of Ding et al. (2014), with the consideration that the additional cost of producing the EFPs should only be partially compensated, we consider that the government subsidy per unit is proportional to (with α_t <1) average incremental cost of the manufacturer for producing the EFPs, which is presented following:

$$B_{mt} = \alpha_t \frac{\sum_{t=1}^{t=n_1}[C_{mt}^{e} + vP_{st}^{e}(\beta) - (C_{mt}^{u} + vP_{st}^{u})]Q_t^e + I_m}{\sum_{t=1}^{t=n_1} Q_t^e} \tag{2.2}$$

where $P_{st}^{e}(\beta)$ is the EFPs' transfer price, including compensation for the supplier's incremental cost for environmental protection. In a sustainable supply chain, the supplier should also take its responsibility for collaborative investment in green technologies. In order to compensate for its incremental cost, the supplier likely increases the transfer price (i.e., $P_s^e(\beta) > P_s^u$) through negotiations with the manufacturer (Ding et al., 2015). For simplicity, by taking annual mean values of other parameters, it is defined as follows:

$$P_s^e(\beta) = P_s^u + \beta[(C_s^e - C_s^u) + I_s / v\textstyle\sum_{t=1}^{t=n_1} Q_t^e] \tag{3}$$

where P_s^u, C_s^u, and C_s^e are estimated based on their mean values, and Q_t^e is determined by either the environmental constraint or the public health constraint (see Section 4). By simplifying Eq. (2.2), substituting Eq. (3) into it, and combing with Eq. (2.1), the regulation constraint is rewritten as the following:

$$\alpha_t \le \frac{b[(Z_t^u - Z_t^e)/Q_t^e + (V_{mt} + vV_{st}) - (F_{mt}^u + vF_{st}^u + \theta_{mt}^u + v\theta_{st}^u)]\sum_{t=1}^{t=n_1} Q_t^e}{[\sum_{t=1}^{t=n_1}(C_{mt}^e + vP_s^e(\beta) - C_{mt}^u - vP_{st}^u)Q_t^e + I_m]} \tag{4}$$

- First, why does not the government enter the negotiation process? Second, the government can decide β by maximizing the social welfare, is it better than the process of negotiation of the transfer price interrelated with the government subsidy sharing between the supplier and the manufacturer? **(reviewer 2#)**

Our model assumes that the government subsidy goes to the manufacturer only when its final products are purchased and consumed by the customers. The government negotiates subsidy rate α_t (decision variable) with the manufacturer every year, α_t decreases as Q_t^e increases. Based on which, the determination of α_t in Eq. (4) depends on how the government subsidy (measured per unit of the EFPs) is shared (via negotiation) between supply chain firms. In other words, the manufacturer is willingly to share the government subsidy with the supplier at what portion (represented by β as decision variable), that also satisfies the supplier. The transfer price can be then determined based upon negotiating β and optimizing sales quantity of the EFPs.

For different types of consumers in the process of making purchasing decisions, environmental consciousness may differ. More often, consumers balance a trade-off concerning whether to buy the EFPs (paying a price premium) or not, which depends on how they are environmentally conscious or price sensitive. The consumers who are price sensitive likely choose the EUFPs (even though they may be environmental awareness) when they feel paying a higher price is unaffordable. For having EFPs gain market acceptance, their cost disadvantage due to additional investment needs to be diminished in a way during their lifecycle. We thus assume that, for an individual consumer, the total purchase and usage costs for EFPs do not exceed that of EUFPs. Accordingly, taking into account the consumers' environmental interests, the market constraint is written as follows:

$$P_{mt}^{e}(1-k)+U_{t}^{e} \le P_{mt}^{u}+U_{t}^{u} \tag{5}$$

where k denotes the consumer's sensitivity to environmental quality ($0 \le k < 1$), the situation for k=1 is uncommon (only sensitive to environmental quality) in reality and thus is not considered in our study. The higher the value of k, the more concerned consumers are with environmental awareness and the less sensitive they are to price premiums. The market constraint implies $P_{mt}^{e} > P_{mt}^{u}$, and preferably with $U_{t}^{e} < U_{t}^{u}$.

3.4 Structure of the Objective Functions

Referring to Ding et al. (2015), we formulate the objective functions of producing EFPs by considering the cases of non-cooperation and collaborative supply chains. In the case of non-cooperation, the manufacturer and the supplier make the decision to maximize their own profits. In this case we assume that, owing to lack of environmental pressures, the supply chain firms only produce the EUFP, and with no environmental sustainable constraints, government policy does not play a role either. As mentioned above, due to EFPs' cost disadvantage compared to EUFPs in the competitive market, supply chain firms would not have an intention to produce EFPs. In order to have supply chain firms collaboratively engage in green investments of EFPs, the government offers a subsidy to EFPs and imposes a penalty and public health tax for EUFPs in the direction of reducing pollutant emissions. In this way, the supply chain firms are motivated to work together, in the case of collaboration, as an integrated system to comply with the sustainable constraints. With introducing the EFPs and also taking into account the opportunity cost (lost revenue) and savings (saved penalty cost and public health tax) arising from replacing the EUFPs by the EFPs, the incremental net present values of the manufacturer, supplier, and collaborative supply chain during finite time periods n are presented respectively as follows:

$$\Delta NPV_{m} = \sum_{t=1}^{n}[(P_{mt}^{e} - \nu P_{st}^{e}(\beta) - C_{mt}^{e} - W_{mt}^{e} + B_{mt})Q_{t}^{e} - (P_{mt}^{u} - \nu P_{st}^{u} - C_{mt}^{u} - W_{mt}^{u} - F_{mt}^{u} - \theta_{mt}^{u})Q_{t}^{e}]e^{-rt} - I_{m} \tag{6.1}$$

$$\Delta NPV_{s} = \sum_{t=1}^{n}[(P_{st}^{e}(\beta) - C_{st}^{e} - W_{st}^{e})\nu Q_{t}^{e} - (P_{st}^{u} - C_{st}^{u} - W_{st}^{u} - F_{st}^{u} - \theta_{st}^{u})\nu Q_{t}^{e}]e^{-rt} - I_{s} \tag{6.2}$$

$$\Delta NPV_{sc} = \sum_{t=1}^{n}\left\{\begin{array}{l}[(P_{mt}^{e} - P_{mt}^{u}) - (C_{mt}^{e} - C_{mt}^{u}) - (W_{mt}^{e} - W_{mt}^{u}) + B_{mt} - \nu(C_{st}^{e} - C_{st}^{u}) - \\ - \nu(W_{st}^{e} - W_{st}^{u}) + (F_{mt}^{u} + \nu F_{st}^{u}) + (\theta_{mt}^{u} + \nu\theta_{st}^{u})]Q_{t}^{e}]\end{array}\right\}e^{-rt} - I_{s} - I_{m} \tag{6.3}$$

From above we note that the supply chain firms' operating profits consist of two parts, i.e., profits earned from the EFPs and profits lost (deduction) due to the replacement of the EUFPs by the EFPs. To simplify the calculation, following the study of Ding et al (2014), we assume that, stimulated by government incentive policy and consumers' preference of environmental quality, the EFPs' sales quantities go through their initial development period by increasing with a growth rate g. With market diffusion the EFPs' sales quantities follow the relations of $Q_{t}^{e} = Q_{(t-1)}^{e}(1+g)$ for any of two consecutive time periods and $Q_{t}^{e} = (1+g)^{t-1}Q_{1}^{e}$ for n_1 time periods, Q_{1}^{e} is the sales quantity of the EFPs in the first time period. By substituting Q_{t}^{e} with its relation of Q_{1}^{e} and rewriting the EFPs' accumulative sales quantities during the initial development period as $\sum_{t=1}^{t=n_1} Q_{t}^{e} = Q_{1}^{e}[(1+g)^{n_1} - 1]/g$, and on the substitution of Eqs. (2.2) and (3) into Eqs. (6.1)–(6.3), together with Eqs. (1.1)–(1.2), (4), and (5), the maximized objective function represented by the incremental net present value of the collaborative supply chain that produces the EFPs during n_1 time periods is formulated as the following:

$$
Max\Delta NPV = \sum_{t=1}^{n_1} \begin{bmatrix} (P_{mt}^e - C_{mt}^e - W_{mt}^e - mC_{st}^e - mW_{st}^e \\ + \alpha_t \dfrac{\sum_{t=1}^{t_N} [C_{mt}^{\mathrm{e}} + mP_s^{\mathrm{e}}(\beta) - (C_{mt}^u + mP_{st}^u)](1+g)^{t-1} Q_1^e + I_m}{Q_1^e[(1+g)^{t_{n_1}} - 1]/g}) \\ -(P_{mt}^u - C_{mt}^u - mC_{st}^u - W_{mt}^u - mW_{st}^u - F_{mt}^u - mF_{st}^u - \theta_{mt}^u - m\theta_{st}^u) \\ \end{bmatrix} (1+g)^{t-1} Q_1^e e^{-rt} - I_s - I_m \tag{7.1}
$$

$$
st. \quad Q\left(E_{mt}^u + vE_{st}^u\right) - (1+g)^{t-1} Q_1^e \left(E_{mt}^u + vE_{st}^u - E_{mt}^e - vE_{st}^e\right) \leq Y \tag{7.2}
$$

$$
(Q - (1+g)^{t-1} Q_1^e)[H_{mt}^u + vH_{st}^u] \leq Q(V_{mt} + vV_{st}) \tag{7.3}
$$

$$
\alpha_t \leq \frac{b[(Z_t^u - Z_t^e)/Q_t^e + (V_{mt} + vV_{st}) - (F_{mt}^u + vF_{st}^u + \theta_{mt}^u + v\theta_{st}^u)] \sum_{t=1}^{t=n_1} Q_t^e}{[\sum_{t=1}^{t=n_1} (C_{mt}^e + vP_s^e(\beta) - C_{mt}^u - vP_{st}^u) Q_t^e + I_m]} \tag{7.4}
$$

$$
P_{mt}^e (1-k) + U_t^e \leq P_{mt}^u + U_t^u \tag{7.5}
$$

$$
Q_1^e \geq 0, P_{mt}^e \geq 0, \alpha_t \geq 0, \beta > 0 \tag{7.6}
$$

where $0 \leq \alpha_t < 1$, $0 < \beta < 1$. We study the financial feasibility of producing the EFPs under sustainable constraints while explicitly incorporating effects of the government's environmental and public health policies. ΔNPV is a net profit (or loss) due to replacing the EUFPs with the EFPs, where the opportunity costs for replacing EUFPs (including lost revenues and saved penalty costs) are taken into account. However, it should be noted that annual fixed costs in terms of depreciations of the uncovered investment of the EUFPs are not considered here, therefore, the lost revenues are overestimated. Noting that the EFPs' operations actually go through a dynamic process along with its market diffusion, there is a need to determine the EFP's optimal sales quantities during a transition period toward break-even. The motive of the current study is to address the EFPs' optimal sales quantity, sales price, transfer price, and government subsidy sharing that push ΔNPV of the collaborative supply chain to reach its break-even ($\Delta NPV = 0$) during finite time periods n_1. The model analysis will be presented in the next section.

4. Model Analysis

The overall objective is to cognize operational strategies for optimizing the supply chain firms' business policies and the stakeholders' interests, and address the profit allotment and the transfer price in sustainable supply chain collaboration, which are presented in the optimization model by maximizing the net present value of a collaborative supply chain with the sustainable constraints including emission standard, public health, regulation, and consumer's preference. By formulating the Lagrange function with the Kuhn–Tucker conditions, also together with game approach, the supply chain firms' optimal decisions complying with the sustainable constraints that include the new dimension of public health are derived below.

4.1 Manufacturers' Price Decisions

Using the Kuhn–Tucker conditions, it can be shown that the manufacturers' optimal sales price P_{mt}^{e*} is determined as follows:

$$
P_{mt}^{e*} = (P_{mt}^u + U_t^u - U_t^e)/(1-k) \tag{8}
$$

The equation above indicates the sales price of EFPs is no less than EUFPs with $k \geq 0$. This means that the higher the consumers' environmental quality concern and the lower the lifecycle usage costs of EFPs, the higher their preferences are for EFPs. That is to say, the consumers that prefer EFPs are often willing to pay a price premium.

4.2 Manufacturers' Product Quantity Decisions

Notice that manufacturers' product quantity decision needs to match the consumers' demand with purchased finished goods. According to the complementary conditions, distinct from previous studies by introducing public health constraint, we can show that the initial optimal sales quantity (t=1), denoted by Q_1^{e*}, can be determined by either of the following equations that has a larger quantity as shown in Eq. (9.3):

$$Q_1^{e*} = Q_{1E}^{e*} = \frac{Q(E_{mt}^u + vE_{st}^u) - Y}{(E_{mt}^u + vE_{st}^u - E_{mt}^e - vE_{st}^e)} \tag{9.1}$$

$$Q_1^{e*} = Q_{1H}^{e*} = \frac{Q[H_{mt}^u + vH_{st}^u - (V_{mt} + vV_{st})]}{(H_{mt}^u + vH_{st}^u)} \tag{9.2}$$

$$Q_1^{e*} = Max[Q_{1E}^{e*}, Q_{1H}^{e*}] \tag{9.3}$$

where Q_{1E}^{e*} and Q_{1H}^{e*} stand for the optimal initial sale quantity of the EFPs derived from Eq. (9.1) and Eq. (9.2) respectively. As shown above, Q_1^{e*} is determined by the larger among Eqs. (9.1) and (9.2). We can observe that both the constraints of environmental standard and public health affect the manufacturers' initial optimal sales quantities, it means that Q_1^{e*} depends on either the total pollutant emissions or the total healthcare costs for loss of public health that need to be reduced for compliance with either the environmental standard constraint or the public health constraint. We should notice that the larger initial sale quantity among Q_{1E}^{e*} and Q_{1H}^{e*} will satisfy both the constraints. Eq. (9.1) shows that emission allowance allocated to the supply chain system is fully consumed by emissions from both EFPs and EUFPs, which implies that the emissions become restrained with compliance of the environmental constraint. Similarly Eq. (9.2) shows that during the first production period of the EFPs, the healthcare cost for loss of public health caused by the EUFPs also simply consumes the entire government healthcare subsidy allocated.

4.3 Government Incentive Policy Decisions

The government incentive policy in terms of subsidy is offered to compensate for supply chain firms' incremental costs incurred for the reduction of pollutants and public health losses, its purpose is to help the firms overcome EFPs' cost disadvantage during the market diffusion period. The analytical results show that the net present value of a supply chain increases for a marginal increase in the net environmental cost savings of government by reducing pollutant emissions and public health losses. This implies that both regulations and incentive policy jointly make essential efforts in enabling supply chain firms to invest in green technologies. The optimal value of government subsidy rate α_t^* is determined as follows:

$$\alpha_t^* = \frac{b\{(Z_t^u - Z_t^e) + [(V_{mt} + vV_{st}) - (F_{mt}^u + vF_{st}^u + \theta_{mt}^u + v\theta_{st}^u)]Q_1^{e*}(1+g)^{t-1}\}[(1+g)^{n_1} - 1]}{(1+g)^{t-1} g[\sum_{t=1}^{t=n_1}(C_{mt}^e + vP_s^e(\beta) - C_{mt}^u - vP_{st}^u)(1+g)^{t-1}Q_1^{e*} + I_m]} \tag{10}$$

where Q_1^{e*} is determined by Eq. (9), and $P_s^e(\beta)$ is determined by Eq. (3), in turn depending on the optimal value of β. As mentioned above, it can be seen that the annual coefficient of the government subsidy is negatively related to the accumulative incremental costs of supply chin firms. This implies that the less the value of α_t, the longer the EFPs need to take to reach break-even. Generally speaking, α_t will decrease as the EFPs' sales quantity gradually increases by time periods. This is intuitively true since with growth of the EFPs' sales through market diffusion the less government subsidy is needed for compensating incremental costs of the EFPs' production. The government will reduce the subsidy by time periods and cease it when the NPVs of supply chain firms reach break-even at time point $t = n_1$. The transfer price decision is based on negotiations of government subsidy sharing between supply chain members, i.e., the determination of the optimal value of β.

4.4 Transfer Price Decision in Collaborative Supply Chains

Substituting Eq. (9.3) into Eq. (6.1) and (6.2), we can obtain the incremental net present values of the manufacturer and supplier in collaboration (with the optimal sales quantity) denoted by ΔNPV_m^* and ΔNPV_s^*. As the overall benefit of the integrated supply chain system is optimum, the supply chain members will collaborate only if all the individual members are satisfied, i.e., the following inequalities must hold:

$$\Delta NPV_m^* \geq 0 \text{ and } \Delta NPV_s^* \geq 0 \tag{11}$$

Eq. (11) means that, when compared with the non-cooperation case, a collaborative supply chain producing the EFPs will have better incremental net present values for both the manufacturer and the supplier; this implies that the above inequalities are the necessary prerequisites for a lasting collaborative relationship between the manufacturer and supplier. The manufacturer and supplier have to coordinate the transfer price $P_s^e(\beta)$ or negotiate a unique value of β that satisfies them both. Since the determination of β goes through a negotiation process between the supply chain partners, we employ the Rubinstein game approach (1982) to characterize the bargaining process. For simplicity of calculation, we use the annual mean value for the costs and sales price. From Eq. (11) we can obtain the lower and upper bounds of β denoted by β_{min} (from $\Delta NPV_s^* \geq 0$) and β_{max} (from $\Delta NPV_m^* \geq 0$) as follows:

- On Eq. (12.1) and (12.2) in Section 4.3, I have no idea of why \beta_min is always smaller than \beta_max. Assuming very large values for Is and Im, we can find that \beta_min gets larger than \beta_max. **(reviewer 1#)**

$$\beta_{\min} = \frac{(I_s/Q_{m1}^{e*}) + v\sum_{t=1}^{n_1}(C_s^e - C_s^u + W_{st}^e - W_{st}^u - F_{st}^u - \theta_{st}^u)(1+g)^{t-1}e^{-rt}}{\left[I_s g/Q_{m1}^{e*}[(1+g)^{n_1}-1] + v(C_s^e - C_s^u)\right]\sum_{t=1}^{n_1}(1+g)^{t-1}e^{-rt}} \tag{12.1}$$

$$\beta_{\max} = \frac{\sum_{t=1}^{n_1}[(P_{mt}^{e*} - P_{mt}^u) - (C_m^e - C_m^u) - (W_{mt}^e - W_{mt}^u) + F_{mt}^u + \theta_{mt}^u + \frac{b[(Z_t^u - Z_t^e) + [(V_{mt}^u + vV_{st}^u) - (F_{mt}^u + vF_{st}^u + \theta_{mt}^u + v\theta_{st}^u)](1+g)^{t-1}Q_{m1}^{e*}]}{(1+g)^{t-1}Q_{m1}^{e*}}](1+g)^{t-1}e^{-rt} - \frac{I_m}{Q_{m1}^{e*}}}{\left[I_s g/Q_{m1}^{e*}[(1+g)^{n_1}-1] + v(C_s^e - C_s^u)\right]\sum_{t=1}^{n_1}[(1+g)^{t-1}e^{-rt}]} \tag{12.2}$$

where [β_{min}, β_{max}] is the feasible interval for finding the optimal value of β. β_{min} is the lowest portion of the government subsidy that the supplier would accept to reach its NPV break-even, at which the losses of the EFPs just offset by the profits earned from the EUFPs; β_{max} is the highest portion of the government subsidy that the manufacturer would share with the supplier, at which the manufacturer only gains its NPV break-even without earning any extra profits. Let x^* ($0 \leq x^* \leq 1$) be the manufacturer's share of the profits while $1 - x^*$ is the supplier's share. Assuming an indefinite bargaining game between the manufacturer and supplier in our case, the manufacturer's optimum profit-sharing ratio is expressed as $x^* = (1 - \delta_2)/(1 - \delta_1\delta_2)$, where δ_1 and δ_2 are the discount factors of the manufacturer and supplier respectively (here, the discount factor is the patience degree of participants for $0 \leq \delta \leq 1$, which can be seen as the cost of bargaining). With the members in collaboration, the optimal value of β is obtained in terms of the ratio of the profit allocation between the supply chain members in the following manner:

$$\beta^* = \frac{(\delta_2 - \delta_1\delta_2)\beta_{max} + (1-\delta_2)\beta_{min}}{1-\delta_1\delta_2} = (1-x^*)\beta_{max} + x^*\beta_{min} \tag{13}$$

where β^* denotes the optimal value of the coefficient of government subsidy to the supplier, and β_{max} and β_{min} are as shown in Eqs. (12.1) and (12.2). Based on determination of optimal value β^*, the transfer price and government subsidy rates can then be determined. To ensure $\beta_{max} > \beta_{min}$, from Eqs. (12.1)-(12.2) we can obtain the following:

$$\beta_{\max}-\beta_{\min}= \tag{14}$$

$$=\frac{\sum_{t=1}^{n_1}\{[(P_{mt}^{e*}-P_{mt}^{u})-(C_m^e-C_m^u)-(W_{mt}^e-W_{mt}^u)+F_{mt}^u+\theta_{mt}^u]+\frac{b[(Z_t^u-Z_t^e)+[(V_{mt}^u+\nu V_{st}^u)-(F_{mt}^u+\nu F_{st}^u+\theta_{mt}^u+\nu\theta_{st}^u)](1+g)^{t-1}Q_{m1}^{e*}]}{(1+g)^{t-1}Q_{m1}^{e*}}\}(1+g)^{t-1}e^{-rt}}{\left[I_s g/Q_{m1}^{e*}[(1+g)^{n_1}-1]+\nu(C_s^e-C_s^u)\right]\sum_{t=1}^{n_1}(1+g)^{t-1}e^{-rt}}-$$

$$-\frac{\sum_{t=1}^{n_1}\nu[(C_s^e-C_s^u)+(W_{st}^e-W_{st}^u)-(F_{st}^u+\theta_{st}^u)](1+g)^{t-1}e^{-rt}+\frac{I_m+I_s}{Q_{m1}^{e*}}}{\left[I_s g/Q_{m1}^{e*}[(1+g)^{n_1}-1]+\nu(C_s^e-C_s^u)\right]\sum_{t=1}^{n_1}(1+g)^{t-1}e^{-rt}}=\frac{\Delta NPV_{sc}/Q_{m1}^{e*}}{\left[I_s g/Q_{m1}^{e*}[(1+g)^{n_1}-1]+\nu(C_s^e-C_s^u)\right]\sum_{t=1}^{n_1}[(1+g)^{t-1}e^{-rt}]}>0$$

By rewriting Eq.(14) we have the following:

$$I_m+I_s<Q_{m1}^{e*}\sum_{t=1}^{n_1}\left\{\begin{array}{l}[(P_{mt}^{e*}-P_{mt}^{u})-(C_m^e-C_m^u)-(W_{mt}^e-W_{mt}^u)+F_{mt}^u+\theta_{mt}^u]+\\ +\frac{b[(Z_t^u-Z_t^e)+[(V_{mt}^u+\nu V_{st}^u)-(F_{mt}^u+\nu F_{st}^u+\theta_{mt}^u+\nu\theta_{st}^u)](1+g)^{t-1}Q_{m1}^{e*}]}{(1+g)^{t-1}Q_{m1}^{e*}}-\\ -\nu[(C_s^e-C_s^u)+(W_s^e-W_s^u)-(F_s^u+\theta_s^u)]\end{array}\right\}(1+g)^{t-1}e^{-rt} \tag{15}$$

The above inequalities mean that the initial investments I_m and I_s have to be confined and should not be over the total of the supply chain's accumulated incremental profit margins (including the government subsidies). Given other parameters, the supply chain will be able to achieve $\Delta NPV_{SC}>0$ corresponding to $\beta_{max}>\beta_{min}$. In other words, a very large initial investment without government subsidy is more likely to be financially infeasible for the EFPs.

5. Numerical Analysis

- ➢ introduce the **real business scenario** to match with the math model. In other words, are they representing a **realistic/general case**? Can the authors provide **real industry examples representing the cases?** It would strengthen the practical value of the work if the author provide real industry examples.**(reviewer 2#)**

In this section, using hybrid vehicles as a case example we present numerical analysis to quantify the interplay effects of multiple sustainable constraints on the environmental behavior of supply chain firms, and assess the impact of government incentive policy on a surviving collaborative sustainable supply chain. The analytical model is applied to a project investment of hybrid vehicle that is carried out by an automobile manufacturer, and the managerial insights of supply chain firms' environmental decisions on sustainable practice are provided.

5.1 Data Generation

The data employed (see Table 2) were calculated (proportionally or average???) based on the real market data of an automobile company that was involved in this research project. The company produces not only conventional vehicles, but also hybrid vehicles which has been gradually replacing the conventional ones. Therefore, the data employed is validity and reliability reflecting real business scenario. Using the real industrial example, the data analysis examines the effectiveness of the government policies that motivate the supply chain firms jointly investing in the hybrid vehicle production. The firms can then share the government subsidy through the transfer price negotiation. Our numerical example provides the insight of the effectiveness of government policies for given cost and price parameters of the EFPs, and illustrating the mechanism of supporting supply chain sustainability from the triple bottom line dimensions.

Table 2. Initial investment cost and operating parameters

Pollution prevention initial investment cost items					Thousand		
Manufacturer's investment (I_m) Supplier's investment (I_s)					4,000,000 3,000,000		
Operating data items							
Item	Thousand /Unit	Item	Thousand /Unit	Item	Item	Item	Thousand /Year

P_m^u	120	P_s^u	30	b	0.1	Y	12,000	Z^u	5,000,000
C_m^e	50	C_s^e	15	r	10%	E_m^e	0.02/unit	Z^e	500,000
C_m^u	30	C_s^u	10	v	2	E_s^e	0.01/unit		
F_m^u	7	F_s^u	5	k	0.1	E_m^u	0.05/unit	Item	Quantity
W_{mt}^u	5	W_{st}^u	3	g	8%	E_s^u	0.03/unit	Q	140,000
W_{mt}^e	4	W_{st}^e	2						
U^e	15	U^u	30						
H_m^u	3.75	H_s^u	2.5						
θ_m^u	2.70	θ_s^u	1.80						
	2.43		1.63						
	1.49		0.99						
V_m	2.60	V_s	1.75						
	2.43		1.63						
	1.49		0.99						

By using the Rubinstein game approach, in the bargaining process between the supply chain members, the patience degrees (cost of bargain) of the manufacturer and the supplier are $\delta_1 = 0.2$ and $\delta_2 = 0.5$ respectively (here we assume the manufacturer is less patient than the supplier in the bargaining process, which means the manufacturer's bargain cost is higher for $\delta_1 < \delta_2$). Based on the reality that the impact of pollutant emissions on environment is often regionally dispersed, the public healthcare cost H_m^u and H_s^u are estimated based on a regional survey with the assumption that they are in proportion to regional GDP, automotive vehicle volume, and automotive vehicles' contribution to emissions. Public health tax and government public health subsidy are then estimated in proportion to the healthcare cost caused by environmental pollution. As for the public health tax and government public health subsidy, their parameters are given at three different levels, illustrated in three scenarios respectively, in order to see if there is any impact on optimal solution to the product quantity. In scenario 1 (corresponding to Table 3), public health subsidy is set to be 70% of healthcare cost with V_m = 2.6, V_s = 1.75, θ_m = 2.7, and θ_s = 1.8; in scenario 2 and 3 (corresponding to Table 4 and 5), the public health subsidy is 65% and 40% of healthcare cost with V_m = 2.43, V_s = 1.63, θ_m = 2.43, θ_s = 1.63 and V_m = 1.49, V_s = 0.99, θ_m = 1.49, θ_s = 0.99 respectively. As mentioned earlier, the collected public health taxes levied on the EUFPs are used to compensate the public healthcare cost in terms of the healthcare subsidy. In the numerical analysis, the optimal solutions to the hybrid vehicle project are quantified in terms of government subsidy rate, EFPs' sales quantities, time to break-even, and self-sustainability.

5.2 Results and Discussion

Table 3, 4 and 5 present the results with time periods, including the EFPs' optimal initial sales quantities until the break-even. As mentioned above, the optimal initial quantity of the EFPs equals the larger of either Q_{1E}^{e*} or Q_{1H}^{e*} according to Eq. (9.3). In our numerical illustration as shown in Table 3 (scenario 1), with estimation of larger values of the government healthcare subsidy, we obtain $Q_1^{e*} = Q_{1E}^{e*} > Q_{1H}^{e*}$ in accordance with Eq. (9.1); in Table 4 and 5 (scenario 2 and 3), with estimation of lower values of the government healthcare subsidy at different tow levels and other things being equal, we have $Q_1^{e*} = Q_{1H}^{e*} > Q_{1E}^{e*}$ in accordance with Eq.(9.2).

Table 3 Numerical results of optimal solutions (Scenario 1, $n_1 = 6$ years)

	$P_s^{e*}(\beta)$ =34.16 thousand, β*=0.452, $Q_1^{e*} = Q_{1E}^{e*} > Q_{1H}^{e*}$ (V_m =2.6, V_s =1.75; θ_m =2.7, θ_s =1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48,571	52,457	56,654	61,186	66,081	71,367	77,077	83,243	89,902	97,095
P_{mt}^{e*} (thousand)	150	150	150	150	150	150	150	150	150	150
a_t^*	0.213	0.194	0.176	0.159	0.144	0.130	0	0	0	0
B_{mt} (thousand)	7.545	6.858	6.223	5.635	5.090	4.585	0	0	0	0
ΔNPV_{sc} (million)	-5,505.56	-4,068.04	-2,683.71	-1,349.13	-61.17	**1,183.05**	2,223.28	3,244.60	4,247.35	5,231.86
ΔNPV_m (million)	-3,120.47	-2,286.69	-1,495.12	-742.52	-25.96	**657.25**	1,146.67	1,627.19	2,098.98	2,562.19
ΔNPV_s (million)	-2,385.08	-1,781.35	-1,188.59	-606.61	-35.21	**525.80**	1,076.61	1,617.40	2,148.37	2,669.67

Table 4 Numerical results of optimal solutions (Scenario 2, n_1 = 6 years)

	$P_s^{e*}(\beta)$ =34.19 thousand, β*=0.457, $Q_1^{e*} = Q_{1H}^{e*} > Q_{1E}^{e*}$ (V_m =2.43, V_s =1.63; θ_m =2.43, θ_s =1.63)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48,960	52,877	57,107	61,675	66,610	71,938	77,693	83,909	90,622	97,871
P_{mt}^{e*} (thousand)	150	150	150	150	150	150	150	150	150	150
a_t^*	0.212	0.193	0.175	0.158	0.143	0.129	-	-	-	-
B_{mt} (thousand)	7.491	6.810	6.180	5.596	5.056	4.555	-	-	-	-
ΔNPV_{sc} (million)	-5,523.14	-4,102.88	-2,735.49	-1,417.55	-145.92	**1,082.26**	2,106.49	3,112.10	4,099.43	5,068.81
ΔNPV_m (million)	-3,130.24	-2,306.04	-1,523.88	-780.53	-73.04	**601.26**	1,081.68	1,553.36	2,016.48	2,471.17
ΔNPV_s (million)	-2,392.90	-1,796.83	-1,211.61	-637.02	-72.88	**481.00**	1,024.82	1,558.74	2,082.96	2,597.64

Table 5 Numerical results of optimal solutions (Scenario 3, n_1 = 4 years)

	$P_s^{e*}(\beta)$ =33.72 thousand, β*=0.416, $Q_1^{e*} = Q_{1H}^{e*} > Q_{1E}^{e*}$ (V_m =1.49, V_s =0.99; θ_m =1.49, θ_s =0.99)									
	t=1	t=2	t=3	**t=4**	t=5	t=6	t=7	t=8	t=9	t=10
Q_t^{e*}	84,480	91,238	98,537	106,420	114,934	124,129	134,059	140,000	140,000	140,000
P_{mt}^{e*} (thousand)	150	150	150	150	150	150	150	150	150	150
a_t^*	0.106	0.094	0.084	0.074	-	-	-	-	-	-
B_{mt} (thousand)	3.63	3.23	2.87	2.53	-	-	-	-	-	-
ΔNPV_{sc} (million)	-4,918.97	-2,905.54	-955.75	**933.99**	2,608.93	4,253.41	5,868.00	7,400.85	8,794.35	10,061.17
ΔNPV_m (million)	-2,796.39	-1,644.42	-540.44	**518.88**	1,378.50	2,222.48	3,051.12	3,837.81	4,552.98	5,203.14
ΔNPV_s (million)	-2,122.58	-1,261.12	-415.32	**415.11**	1,230.43	2,030.93	2,816.88	3,563.04	4,241.37	4,858.03

As can be seen in Table 3, the NPVs of the supply chain firms break-even and begin to earn profits in year t = 6. The EFPs' optimal sales price is 150 thousand RMB/vehicle. For given a relatively higher level of the government healthcare subsidy the annual optimal initial sales quantity is determined by environmental constraint with $Q_1^{e*} = Q_{1E}^{e*} = 48571 > Q_{1H}^{e*}$, and the optimal subsidy rate α^* gradually decreases from 0.213 to zero soon after $\Delta NPV = 0$. That is, beyond the 6th year the government ceases its subsidy as soon as the supply chain becomes to earn a profit. The transfer price $P_s^{e*}(\beta)$ = 34.16 thousand RMB/unit with β^* = 0.452.

In Table 4 and 5, with the same optimal product price, the NPVs of the supply chain system break-even in year 6 with $Q_1^{e*} = Q_{1H}^{e*} = 48960 > Q_{1E}^{e*} = 48571$ (scenario 2), and in year 4 with $Q_1^{e*} = Q_{1H}^{e*} = 84480 > Q_{1E}^{e*}$ (scenario 3), respectively. Numerical results show that, for given relatively lower levels of the government healthcare subsidy and pollution tax, a larger initial sales quantity of the EFPs is produced with a smaller government subsidy required so that the optimal subsidy rate α^* decreases from 0.212 (scenario 2) or 0.106 (scenario 3) (lower than 0.213 in scenario 1) to zero when ΔNPV reaches zero. The transfer price $P_s^{e*}(\beta)$ = 34.19 thousand RMB/unit with β^* = 0.457 in scenario 2. With even lower level of the government and healthcare subsidy and pollution tax, scenario 3 shows the initial sales quantity of the EFPs becomes even larger, therefore, the supply chain system reaches to its breaks-even much earlier in year 4, and the transfer price $P_s^{e*}(\beta) =$ 33.72 thousand RMB/unit with β^* = 0.416 (lower than scenario 2). This implies that the supply chain system can reach break-even earlier and the transfer price tends to decrease along with a lower portion of the government subsidy transmitted to the supplier, when a larger optimal initial quantity of the EFPs determined by public health constraint corresponding to lower values of the government healthcare subsidy and pollution tax. As expected, during the first production period of the EFPs, the increased healthcare cost caused by the EUFPs consumes all of government healthcare subsidy. With the increase of the EFPs, the healthcare cost reduces and less government subsidy is consumed.

From the results as shown above, some non-trivial findings are obtained reflecting interplay relations between the sustainable constraints. Particularly, the optimal initial sales quantities of the EFPs are affected by both the constraints of environmental standard and public health. Moreover, supply chain firms have trade-offs in determining the EFPs' optimal operational strategy which reflects the insight of reducing environmental effects by replacing EUFPs with EFPs. That is, impelled by complying with the sustainable constraints and induced by government incentive policy, supply chain firms' optimal operational decisions make a balance between gaining benefits from the government incentive policy and losing the profits of the EUFPs replaced by the EFPs through market diffusion periods. As for the regulation constraint, as EFPs' production continues with increasing in sales volumes, the government subsidy per unit α_t falls and reduces to zero when the EFP project breaks-even. As a crucial factor that affects supply chain firms' environmental behavior, the government incentive policy is the key driver for motivating supply chain firms to take part in the green investments and improve their environmental and social performances. It needs to be emphasized that the government subsidy should not apply to any circumstances where profits are gained, and not to fully compensate the firms' incremental cost either. The amount of subsidies sharing needs to be properly justified in order to effectively drive supply chain firms to innovate on their green and social activities and increase the eco-efficiency of the society. As for the market constraints, being aware of consumers' environmental quality concerns, for given values of k (<1), the firms will likely charge a price premium as long as it is acceptable to the consumers. As for the consumers, they will be content using green products that comfort their green preferences with affordable total purchase and usage costs.

In order to see the effect of incorporating public health factors on business behaviors of the supply chain firms, Table 6 presents the results in scenario 4 excluding public health factors.

Table 6 Numerical results of optimal solutions excluding public health factors (Scenario 4, n_1 = 7 years)

	$P_s^{e*}(\beta)$ =34.54 thousand, β*=0.537, $Q_1^{e*}=Q_{1E}^{e*}$									
	t=1	t=2	t=3	t=4	t=5	t=6	**t=7**	t=8	t=9	t=10
Q_t^{e*}	48571	52457	56654	61186	66081	71367	77077	83243	89902	97095
P_{mt}^{e*} (thousand)	150	150	150	150	150	150	150	150	150	150
a_t^*	0.224	0.204	0.185	0.167	0.151	0.136	0.123	0	0	0
B_{mt} (thousand)	7.565	6.878	6.243	5.655	5.110	4.605	4.138	0	0	0
ΔNPV_{sc} (million)	-5,782.86	-4,617.60	-3,500.57	-2,428.44	-1,398.16	-406.93	**547.80**	1,324.47	2,087.02	2,835.70
ΔNPV_m (million)	-3,272.10	-2,587.19	-1,941.78	-1,332.69	-757.03	-212.16	**304.34**	650.73	990.83	1,324.74
ΔNPV_s (million)	-2,510.76	-2,030.41	-1,558.79	-1,095.75	-641.13	-194.77	**243.47**	673.74	1,096.19	1,510.96

As for the impact of considering public health factors on the optimal operations policy, we obtain an important finding by comparing with the results in Table 3, 4 and 5, we can see that by including public healthcare factor so that driven by double effects from both environmental and public health constraints together with the saved penalties by replacing the EUFPs the time periods required for break-even of the supply chain tends to become short, as shown in Table 3, 4 and 5 (one year or three years shorter than the scenario 4 excluding public health factors in Table 6). This is intuitively true in the sense that the inclusion of public healthcare cost into the constraint actually has an active effect of internalizing environmental externality caused by the EUFPs, which drives the supply chain firms to be environmentally friendly with more production of the EFPs. an increase of the EFPs' initial optimal sales quantity is driven by including public healthcare constraint, the values of α* in scenarios 1-3 (Table 3, 4, and 5) are less than that in the case of excluding public healthcare cost as shown in scenario 4 (Table 6). The optimal portion of the supplier sharing the government subsidy and the transfer price in the scenario 1-3 including public healthcare constraint are smaller than those in scenario 4 excluding public health factors. The implication is that internalization of public healthcare cost increases initial production of the EFPs so that more EUFPs are replaced, which leads to less requirement for government subsidy.

- According Table 2 and 3, \Delata NPV is negative for the first 5 years, and tuned into positive for the rest 5 years. During the ten years, total of \Delata NPV is not so large. What if the manufacture makes only EUFP against the policy of the government? **(reviewer 1#)**

However, a question can be raised what if the manufacture only produces EUFPs rather than follows the government environmental policy. The manufacture has to then pay the penalty charges for its EUFPs production. Meanwhile, its sales quantities of the EUFPs must comply with the environmental constraint, therefore, its production quantities of the EUFPs maybe below its full production capacity. The production of the EUFPs per period complying with the environment constraint can be expressed as follows:

$$Q_t^u E_{mt}^u + vQ_t^u E_{st}^u \le Y \quad \text{or} \quad Q_t^u \le Y/(E_{mt}^u + vE_{st}^u), \qquad t = 1, 2, \ldots, n \tag{16}$$

The manufacturer would produce EUFPs at the allowed maximum quantity which is equal to $Q_t^u = Y/(E_{mt}^u + vE_{st}^u) < Q$. In this case, when the manufacturer only produces the EUFPs with sales quantity Q_t^u during n periods, the net present values of the accumulated annual profits of the supply chain denoted by NPV_{sc}^u can be expressed as follows:

$$NPV_{sc}^u = \sum_{t=1}^{n}[P_{mt}^u - C_{mt}^u - W_{mt}^u - F_{mt}^u - \theta_{mt}^u - \nu(C_{st}^u + W_{st}^u + F_{st}^u + \theta_{st}^u)]Q_t^u e^{-rt} \quad (17)$$

where $Q_t^u = Y/(E_{mt}^u + \nu E_{st}^u)$. However, without entering into the EFPs business, the manufacture will strategically lose an opportunity obtaining a long term benefit to gain business competitive advantage along with the triple dimensions. This can be illustrated by comparing NPV_{sc}^u and NPV_{sc}^e, the later is the net present value of the accumulated annual profits of producing the EFPs with the EUFPs gradually replaced (Ding et al., 2016), it can be expressed below:

$$NPV_{sc}^e = \sum_{t=1}^{n}\begin{bmatrix}[P_{mt}^e + B_{mt} - C_{mt}^e - W_{mt}^e - \nu(C_{st}^e + W_{st}^e)]Q_t^e \\ +[P_{mt}^u - C_{mt}^u - W_{mt}^u - F_{mt}^u - \theta_{mt}^u - \nu(C_{st}^u + W_{st}^u + F_{st}^u + \theta_{st}^u)](Q - Q_t^e)\end{bmatrix}e^{-rt} - I_s - I_m \quad (18)$$

where on the right hand side of the equation, the first and second item groups respectively stand for the annual profits of the EFPs and the EUFPs that has not yet replaced. Comparing Eq.(17) and Eq.(18) we obtain the following:

$$NPV_{sc}^e - NPV_{sc}^u = \sum_{t=1}^{n}\begin{bmatrix}[P_{mt}^e + B_{mt} - C_{mt}^e - W_{mt}^e - \nu(C_{st}^e + W_{st}^e)]Q_t^e \\ +[P_{mt}^u - C_{mt}^u - W_{mt}^u - F_{mt}^u - \theta_{mt}^u - \nu(C_{st}^u + W_{st}^u + F_{st}^u + \theta_{st}^u)][(Q - Q_t^e) - Ye^{-rt}/(E_{mt}^u + \nu E_{st}^u)]\end{bmatrix}e^{-rt} \quad (19)$$
$$- I_s - I_m$$

For comparison, other things being equal, in the case of Scenario 1 with $Q_1^{e*} = Q_{1E}^{e*} = 48571$ our results in Table 7 show that $Q_t^u = 109091$, and in year t=3 the case of producing the EFPs to gradually replace the EUFPs becomes better than only producing the EUFP, which means that only producing EUFPs will lose a long term benefit.

Table 7 Comparison of NPV_{sc}^u and NPV_{sc}^e (Scenario 1)

	$Q_1^{e*} = Q_{1E}^{e*} = 48571$, $Q_t^u = 109091$ (V_m =2.6, V_s =1.75; θ_m =2.7, θ_s =1.8)									
	t=1	t=2	**t=3**	t=4	t=5	t=6	t=7	t=8	t=9	t=10
NPV_{sc}^e	-961.92	4,606.17	9,745.58	14,493.86	18,885.18	22,950.64	26,718.53	30,214.58	33,462.24	36,482.81
NPV_{sc}^u	3540.50	6759.13	9685.16	12345.19	14763.39	16961.76	18960.28	20777.11	22428.78	23930.30
$NPV_{sc}^e - NPV_{sc}^u$	-4502.42	-2152.95	**60.42**	2148.67	4121.79	5988.88	7758.25	9437.47	11033.46	12552.51

What does "the time periods required for break-even ... become short" mean in p. 17? I understand that the parameter n_1 is given. However, this sentence implies that n_1 is determined by \Delta NPV, which depends on public health factors. **(reviewer 1#)** **(Addressed in the revision report, see comment 6)**

- should perform the worst-case analysis. **(reviewer 1#)**
- The analysis is based on 8% of the growth rate. How is the result when the growth rate is decreased from 8% to 0% every year? The parameter k that is customers' positive impression on price of EFP is set to 0.1. How does a more negative parameter, e.g. 0.01, affect the result? **(reviewer 1#)**

  The most concern for the supply chain firms to produce EFPs is their potential business risks, i.e. how soon they can achieve at least a break-even within a certain time period. Considering the government intervention for reducing the externality impact of environmental pollution and public health cost, the worst case would be that the EFPs can only reach the break-even point when the sales quantities reach their market share. The question is for how long the supply chain is willing to wait until reaching the break-even, the longer the risker that the manufacturer (the final product provider) will be. For instance, in our numerical analysis, the growth rate of the EFPs, *g*, is based on 8%, and the customers' positive impression on price of the EFP, *k*, is set to 0.1 (see Table 2), which obtains positive results. We can expect that when *g* and *k* become lower, the time for the supply chain to reach break-even will be longer (see Table 8 and 9). The results show that the time for supply chain to make break-even is more sensitive to *k* (the consumers' positive impression on price of the EFP) than to the growth rate *g*. This may explains that when *k* becomes lower, the consumers' willingness to purchase the EFPs will reduce, as well as the EFP's purchase price and sales, which has stronger negative impact on the supply chain's profits. As for *g*, though the EFP's sales quantities reduce as it decreases, both the sales and costs of the EFPs are influenced in a similar way, thus the growth rate has less impact on the profits.

Table 8 Numerical results of sensitivity analysis (Scenario 1, *g* decreases from 0.08 to zero)

	(g=0.08) $P_s^{e*}(\beta)$=34.16 thousand, β*=0.452, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48571	52457	56654	61186	66081	**71367**	77077	83243	89902	97095
ΔNPV_{sc} (million)	-5,505.56	-4,068.04	-2,683.71	-1,349.13	-61.17	**1,183.05**	2,223.28	3,244.60	4,247.35	5,231.86
	(g=0.06) $P_s^{e*}(\beta)$=34.23 thousand, β*=0.449, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48,571	51,486	54,575	57,849	61,320	**65,000**	68,899	73,033	77,415	82,060
ΔNPV_{sc} (million)	-5,505.56	-4,087.77	-2,741.83	-1,463.27	-247.97	**907.89**	1,837.77	2,733.82	3,597.30	4,429.37
	(g=0.04) $P_s^{e*}(\beta)$=34.30 thousand, β*=0.446, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48,571	50,514	52,535	54,636	56,822	**59,095**	61,458	63,917	66,473	69,132
ΔNPV_{sc} (million)	-5,505.56	-4,107.51	-2,799.24	-1,574.62	-427.98	**645.95**	1,475.40	2,259.60	3,001.03	3,702.02
	(g=0.02) $P_s^{e*}(\beta)$=34.38 thousand, β*=0.443, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48,571	49,543	50,534	51,544	52,575	**53,627**	54,699	55,793	56,909	58,047
ΔNPV_{sc} (million)	-5,505.56	-4,127.24	-2,855.93	-1,683.22	-601.39	**396.68**	1,134.91	1,819.44	2,454.20	3,042.78
	(g=0.01) $P_s^{e*}(\beta)$=34.42 thousand, β*=0.441, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48,571	49,057	49,548	50,043	50,544	**51,049**	51,560	52,075	52,596	53,122
ΔNPV_{sc} (million)	-5,505.56	-4,137.11	-2,884.00	-1,736.50	-685.67	**276.63**	972.48	1,611.40	2,198.04	2,736.69
	(g=0) $P_s^{e*}(\beta)$=34.46 thousand, β*=0.439, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
Q_t^{e*}	48571	48571	48571	48571	48571	**48571**	48571	48571	48571	48571
ΔNPV_{sc} (million)	-5,505.56	-4,146.98	-2,911.90	-1,789.10	-768.38	**159.55**	815.07	1,411.00	1,952.76	2,445.26

Table 9 Numerical results of sensitivity analysis (Scenario 1, *k* decreases from 0.08 to 0.01)

	(k=0.08, g=0.08) P_m^{e*}=146.74 thousand, $P_s^{e*}(\beta)$=33.44 thousand, β*=0.373, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
ΔNPV_{sc} (million)	-5,649.54	-4,353.40	-3,107.86	-1,909.56	-755.40	**357.46**	1,268.71	2,163.40	3,041.82	3,904.27
	(k=0.05, g=0.08) P_m^{e*}=142.11 thousand, $P_s^{e*}(\beta)$=32.41 thousand, β*=0.281, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	t=6	**t=7**	t=8	t=9	t=10
ΔNPV_{sc} (million)	-5,854.16	-4,758.90	-3,710.60	-2,705.96	-1,741.93	-815.75	**75.12**	789.86	1,491.60	2,180.59
	(k=0.02, g=0.08) P_m^{e*}=137.76 thousand, $P_s^{e*}(\beta)$=31.44 thousand, β*=0.180, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	**t=9**	t=10
ΔNPV_{sc} (million)	-6,046.24	-5,139.58	-4,276.45	-3,453.59	-2,668.06	-1,917.12	-1,198.32	-509.38	**151.77**	677.91
	(k=0.01, g=0.08) P_m^{e*}=136.36 thousand, $P_s^{e*}(\beta)$=31.13 thousand, β*=0.141, $Q_1^{e*}=Q_{1E}^{e*}>Q_{1H}^{e*}$ (V_m=2.6, V_s=1.75; θ_m=2.7, θ_s=1.8)									
	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	**t=10**
ΔNPV_{sc} (million)	-6,107.68	-5,261.34	-4,457.44	-3,692.74	-2,964.29	-2,269.42	-1,605.65	-970.74	-362.64	**220.52**

Another issue that needs to be addressed concerns the way of granting the government subsidy, which is explored as a unique finding of our study. There is an argument regarding whether it is better to grant the government subsidy directly to a supply chain firm (manufacturer) or not, which is not intuitively sensed. As mentioned earlier, we assume that the government grants the subsidy to a manufacturer by going through the consumers; this means the manufacturer will obtain a subsidy only after selling the products to the consumers. This is so because there is the need for ensuring that in practice the EFPs must be used by consumers to replace the EUFPs so that the reduction of pollutant emissions can be realized. Moreover, one may argue that if the government subsidies are granted directly to the manufacturer without going through the consumers in a local country, the manufacturer may sell its product overseas allowing the overseas consumers to benefit from the government subsidy. This would not be the intention of the government in any country, particularly where environmental pollution is happening locally. In this sense, the government policy incentives should normally go to subsidizing local consumers to reduce environmental pollutions and public health losses locally.

From views of environmental and social societies, another aspect that remains to be examined is how to properly set environmental standards and healthcare subsidies to the healthcare cost of public health loss. Since the status quo of environmental carrying capacity and public health naturally depend on the circumstances and characteristics of the local environment, the environmental standards should be set low enough in order to safely protect the environment; as for public healthcare subsidies to the healthcare cost incurred by environmental pollution, its setting might be much more complicated. These issues need further investigation.

6. Sustainable supply chain modeling with multiple suppliers

We will develop our above analysis in the current section by addressing the case with multiple suppliers sustainable supply chain, which consists of one manufacturer and two suppliers. Between the two suppliers, we assume that one provides intermediate products for the EFPs and another for the EUFPs. Considering that the EFPs gradually replace the EUFPs, the business strategies for the two suppliers can be totally different. The supplier providing the EFPs' intermediate products will more likely win its business contracts from the manufacturer. While the other supplier will more likely lose its business as the manufacturer replaces the EUFPs by the EFPs. However, in reality, the supplier would seek for gaining the EFP's business rather than to be the loser by only providing the EUFPs' intermediate products. Therefore, an alternative case can be that two suppliers provide intermediate products for both the EFPs and EUFPs. In this case, the suppliers' strategic positions will depend on the types of intermediate products (e.g. similar or different) and the levels of quality and price they can provide to win the contracts from the manufacturer. Therefore, the two suppliers are more likely to be involved in competition with market demand uncertainties. However, this case with multiple competitive suppliers is not the focal point for this current study, but an interesting direction for future research.

Costs structure and transfer prices with multiple suppliers

In order to avoid complexity with competition issue, we will focus on the case including multiple suppliers who provide different intermediate products for both the EFPs and EUFPs. Therefore, there will be no competition between the suppliers due to providing different products. The suppliers would win their business based on their production strategy and position, assuming the suppliers run their operations independently within the supply chain. The manufacturer can deal the multiple suppliers as individuals within a single group. Based on the assumptions, the two-echelon supply chain model with multiple suppliers can be formulated in the similar way to the above modeling, but with different price and cost items associated with to the different suppliers. Let i be the number of the suppliers (i=1,2…,l), one unit of the finished goods consumes ν_i units of ith intermediate products. Since the suppliers are treated as similar individuals within a single group in our model, thus, in the model formulae of the above sections, each of the items associated with single supplier is replaced by accumulated term $\sum_{i=1}^{l}(.)_{si}$ for including multiple suppliers. Eqs. (7.1)-(7.4) will be rewritten by replacing the items of the supplier with the accumulated terms, together with renumbering Eqs. (7.5)-7.6), we obtain the following:

$$Max\Delta NPV=\sum_{t=1}^{n_1}\left[\begin{array}{l}(P_{mt}^{e}-C_{mt}^{e}-W_{mt}^{e}-\sum_{i=1}^{l}\nu_i(C_{sit}^{e}-W_{sit}^{e})\\ +\alpha_t\dfrac{\sum_{t=1}^{t_N}[C_{mt}^{e}-C_{mt}^{u}+\sum_{i=1}^{l}\nu_i(P_{sit}^{e}(\beta)-P_{sit}^{u})](1+g)^{t-1}Q_1^{e}+I_m}{Q_1^{e}[(1+g)^{t_{n_1}}-1]/g})\\ -(P_{mt}^{u}-C_{mt}^{u}-W_{mt}^{u}-F_{mt}^{u}-\theta_{mt}^{u}-\sum_{i=1}^{l}\nu_i(C_{sit}^{u}+W_{sit}^{u}+F_{sit}^{u}+\theta_{sit}^{u}))\end{array}\right](1+g)^{t-1}Q_1^{e}e^{-rt}-\sum_{i=1}^{l}I_s-I_m \tag{20.1}$$

$$st.\quad Q\left(E_{mt}^{u}+\sum_{i=1}^{l}\nu_iE_{sit}^{u}\right)-(1+g)^{t-1}Q_1^{e}\left(E_{mt}^{u}-E_{mt}^{e}+\sum_{i=1}^{l}\nu_i(E_{sit}^{u}-E_{sit}^{e})\right)\le Y \tag{20.2}$$

$$(Q-(1+g)^{t-1}Q_1^{e})[H_{mt}^{u}+\sum_{i=1}^{l}\nu_iH_{sit}^{u}]\le Q(V_{mt}+\sum_{i=1}^{l}\nu_iV_{sit}) \tag{20.3}$$

$$\alpha_t\le\frac{b[(Z_t^{u}-Z_t^{e})/Q_t^{e}+(V_{mt}+\sum_{i=1}^{l}\nu_iV_{sit})-(F_{mt}^{u}+\theta_{mt}^{u}+\sum_{i=1}^{l}\nu_i(F_{sit}^{u}+\theta_{sit}^{u}))]\sum_{t=1}^{t=n_1}Q_t^{e}}{[\sum_{t=1}^{t=n_1}[C_{mt}^{e}-C_{mt}^{u}+\sum_{i=1}^{l}\nu_i(P_{sit}^{e}(\beta)-P_{sit}^{u})]Q_t^{e}+I_m]} \tag{20.4}$$

$$P_{mt}^{e}(1-k)+U_t^{e}\le P_{mt}^{u}+U_t^{u} \tag{20.5}$$

$$Q_1^{e}\ge 0,P_{mt}^{e}\ge 0,\alpha_t\ge 0,\beta>0 \tag{20.6}$$

The same way applies to other relevant formulae in the above sections. The multiple suppliers are interrelated for determining the transfer prices, at which the manufacturer shares the government subsidies with the suppliers. Due to that fact that the multiple suppliers provide different intermediate products with no competition, the government subsidies can therefore be distributed from the manufacturer and shared among the suppliers in a similar way, for example, with the same proportion to their individual average incremental costs for producing the EFP's intermediate products (Ding et al. 2015). Thus, Eq.(3) can be rewritten as follows:

$$P_{si}^{e}(\beta) = P_{si}^{u} + \mu_i \beta[(C_{si}^{e} - C_{si}^{u}) + I_{si} / v_i \textstyle\sum_{t=1}^{t=n_1} Q_t^e] \qquad i = 1,2,\ldots, l \tag{21.1}$$

$$\mu_i = [(C_{si}^{e} - C_{si}^{u}) + I_{si} / v_i \textstyle\sum_{t=1}^{t=n_1} Q_t^e] \Big/ \textstyle\sum_{i=1}^{l} [(C_{si}^{e} - C_{si}^{u}) + I_{si} / v_i \textstyle\sum_{t=1}^{t=n_1} Q_t^e] \tag{21.2}$$

where μ_i is the distribution coefficient of the government subsidies for supplier *i*, it is measured by the ratio of the incremental cost of individual supplier *i* to the total incremental costs of the all suppliers for producing the EFP's intermediate product.

Numerical illustration

Considering the case with two suppliers for *i*=1, 2, the data for manufacturer and supplier 1 was maintained as the same as in Table 2, while the data for supplier 2 was estimated relative to supplier 1 (see Table 10).

Table 10 Suppliers' investment costs and operating parameters

Pollution prevention initial investment cost items						Thousand	
Supplier's investment I_{si}				(*i*=1) (*i*=2)		3,000,000 1,000,000	
Operating data items							
Item (*i*=1)	Thousand /Unit	Item (*i*=2)	Thousand /Unit	Item (*i*=1)	Thousand /Unit	Item (*i*=2)	Thousand /Unit
P_s^u	30	P_s^u	15	F_s^u	5	F_s^u	2.5
C_s^e	15	C_s^e	7.5	H_s^u	2.5	H_s^u	1.25
C_s^u	10	C_s^u	5	E_s^e	0.01/unit	E_s^e	0.005/unit
W_s^u	3	W_s^u	1.5	E_s^u	0.03/unit	E_s^u	0.015/unit
W_s^e	2	W_s^e	1	ν	2	ν	2
θ_s^u	1.63	θ_s^u	0.82	V_s	1.63	V_s	0.82
	1.80		0.90		1.75		0.88
	0.99		0.49		0.99		0.49

The results with two suppliers are presented in Tables 11-14 for the four scenarios described above, respectively. By assuming no competition between the suppliers, the results show the similar pattern to the case with one supplier, except that the government subsidies shared from the manufacturer need to be distributed between the suppliers, with individual shared portion via the transfer prices. The transfer price determination is based on the ratio of the incremental costs of each individual supplier to the total incremental costs of the all suppliers for producing the EFP's intermediate product. The transfer prices need to be satisfied by the supply chain firms. Moreover, adding more suppliers without increasing environmental carrying capacity for pollution emission that allocated to supply chain system, the initial sales quantities of the EFPs tend to become larger with the EUFPs even more quickly replaced. The rationale is when the total amount of allowed emissions allocated to a supply chain system is strict, more suppliers mean potentially more total emissions in the supply chain so that, more EFPs need to be produced to replace the EUFPs for complying with regulation standard.

Table 11 Numerical results of optimal solutions with two suppliers (Scenario 1, n_1 = 4 years)

$P_{s1}^{e*}(\beta)$ =32.81 thousand, $P_{s2}^{e*}(\beta)$ =15.77 thousand, β*=0.515, $\mu_1 = 0.61$, $\mu_2 = 0.39$, β_1=0.314, β_2=0.201 $Q_1^{e*} = Q_{1E}^{e*} > Q_{1H}^{e*}$ (V_m =2.6, V_{s1} =1.75, V_{s2} =0.88; θ_m^u =2.7, θ_{s1}^u =1.8, θ_{s2}^u =0.9)										
	t=1	t=2	t=3	**t=4**	t=5	t=6	t=7	t=8	t=9	t=10
Q_t^{e*}	84444	91200	98496	**106376**	114886	124077	134003	140000	140000	140000

P_{mt}^{e*} (thousand)	150	150	150	**150**	150	150	150	150	150	150
a_t^*	0.082	0.072	0.062	**0.053**	0	0	0	0	0	0
B_{mt} (thousand)	3.105	2.710	2.345	**2.006**	0	0	0	0	0	0
ΔNPV_{sc} (million)	-5,527.70	-3,130.10	-803.15	**1,456.91**	3,532.76	5,570.86	7,571.91	9,472.47	11,200.24	12,770.94
ΔNPV_m (million)	-2,721.75	-1,496.50	-320.57	**809.39**	1,775.69	2,724.42	3,655.90	4,540.60	5,344.87	6,076.02
ΔNPV_{s1} (million)	-2,138.57	-1,292.81	-462.42	**352.87**	1,153.33	1,939.24	2,710.87	3,443.74	4,109.98	4,715.66
ΔNPV_{s2} (million)	-667.38	-340.80	-20.16	**294.65**	603.73	907.20	1,205.15	1,488.13	1,745.39	1,979.26

Table 12 Numerical results of optimal solutions with two suppliers (Scenario 2, $n_1 = 4$ years)

$P_{s1}^{e*}(\beta)$=32.88 thousand, $P_{s2}^{e*}(\beta)$=15.78 thousand, β*=0.527, $\mu_1 = 0.61$, $\mu_2 = 0.39$, β_1=0.321, β_2=0.206

$Q_1^{e*} = Q_{1E}^{e*} > Q_{1H}^{e*}$ (V_m=2.43, V_{s1}=1.63, V_{s2}=0.82; θ_m^u=2.43, θ_{s1}^u=1.63, θ_{s2}^u=0.82)

	t=1	t=2	t=3	**t=4**	t=5	t=6	t=7	t=8	t=9	t=10
Q_t^{e*}	84444	91200	98496	**106376**	114886	124077	134003	140000	140000	140000
P_{mt}^{e*} (thousand)	150	150	150	**150**	150	150	150	150	150	150
a_t^*	0.083	0.072	0.063	**0.054**	0	0	0	0	0	0
B_{mt} (thousand)	3.129	2.734	2.369	**2.030**	0	0	0	0	0	0
ΔNPV_{sc} (million)	-5,584.97	-3,243.60	-971.85	**1,234.01**	3,254.93	5,239.10	7,187.21	9,037.47	10,719.52	12,248.66
ΔNPV_m (million)	-2,753.57	-1,559.55	-414.29	**685.56**	1,620.58	2,538.60	3,439.93	4,295.99	5,074.23	5,781.72
ΔNPV_{s1} (million)	-2,154.51	-1,324.40	-509.38	**290.82**	1,076.48	1,847.84	2,605.19	3,324.50	3,978.41	4,572.88
ΔNPV_{s2} (million)	-676.89	-359.65	-48.18	**257.62**	557.87	852.66	1,142.09	1,416.98	1,666.88	1,894.06

Table 13 Numerical results of optimal solutions with two suppliers (Scenario 3, $n_1 = 4$ years)

$P_{s1}^{e*}(\beta)$=33.13 thousand, $P_{s2}^{e*}(\beta)$=15.85 thousand, β*=0.575, $\mu_1 = 0.61$, $\mu_2 = 0.39$, β_1=0.351, β_2=0.224

$Q_1^{e*} = Q_{1H}^{e*} > Q_{1E}^{e*}$ (V_m=1.49, V_{s1}=0.99, V_{s2}=0.49; θ_m^u=1.49, θ_{s1}^u=0.99, θ_{s2}^u=0.49)

	t=1	t=2	t=3	**t=4**	t=5	t=6	t=7	t=8	t=9	t=10
Q_t^{e*}	84622	91392	98703	**106600**	115128	124338	134285	140000	140000	140000
P_{mt}^{e*} (thousand)	150	150	150	**150**	150	150	150	150	150	150
a_t^*	0.081	0.071	0.061	**0.053**	0	0	0	0	0	0
B_{mt} (thousand)	3.118	2.724	2.359	**2.021**	0	0	0	0	0	0
ΔNPV_{sc} (million)	-5,802.30	-3,674.32	-1,612.07	**388.10**	2,207.40	3,993.61	5,747.36	7,409.52	8,920.58	10,294.27
ΔNPV_m (million)	-2,874.31	-1,798.84	-769.97	**215.61**	1,038.77	1,846.95	2,640.45	3,392.51	4,076.20	4,697.74
ΔNPV_{s1}	-2,211.81	-1,437.94	-678.15	**67.83**	800.24	1,519.34	2,225.36	2,894.52	3,502.84	4,055.87

(million)										
ΔNPV_{s2} (million)	-716.19	-437.54	-163.95	**104.66**	368.39	627.32	881.55	1,122.50	1,341.54	1,540.67

Table 14 Numerical results of optimal solutions excluding public health factors with two suppliers (Scenario 4, $n_1 = 5$ years)

$P_{s1}^{e*}(\beta)$=33.36 thousand, $P_{s2}^{e*}(\beta)$=15.94 thousand, β^*=0.687, $\mu_1 = 0.61$, $\mu_2 = 0.39$, β_1=0.419, β_2=0.268, $Q_1^{e*} = Q_{1H}^{e*}$										
	t=1	t=2	t=3	t=4	**t=5**	t=6	t=7	t=8	t=9	t=10
Q_t^{e*}	84,444	91,200	98,496	106,376	**114,886**	124,077	134,003	140,000	140,000	140,000
P_{mt}^{e*} (thousand)	150	150	150	150	**150**	150	150	150	150	150
a_t^*	0.085	0.075	0.065	0.055	**0.047**	0	0	0	0	0
B_{mt} (thousand)	3.129	2.734	2.369	2.030	**1.717**	0	0	0	0	0
ΔNPV_{sc} (million)	-6,147.68	-4,358.78	-2,629.46	-956.18	**664.34**	2,135.14	3,579.19	4,950.72	6,197.57	7,331.07
ΔNPV_m (million)	-3,038.54	-2,124.31	-1,253.76	-423.62	**369.08**	1,027.11	1,673.17	2,286.79	2,844.63	3,351.75
ΔNPV_{s1} (million)	-2,330.19	-1,672.56	-1,026.89	-392.95	**229.46**	840.55	1,440.53	2,010.38	2,528.42	2,999.37
ΔNPV_{s2} (million)	-778.95	-561.91	-348.82	-139.61	**65.81**	267.48	465.49	653.56	824.53	979.95

7. Conclusions

The supply chain management practice towards eco-sustainability in terms of reducing environmental and social externalities is more often complex in reality and expects long run tasks. One of the crucial issues in supply chain management is the trade-off between economic objective and environmental sustainability and social responsibility. By taking perspectives from supply chain firms and stakeholders including governments, communities, and consumers, this study constructs a sustainable supply chain framework with multiple sustainable constraints in view of the triple bottom line dimensions to evaluate the economic, environmental, and social performances of a supply chain. In addition, the case for the sustainable supply chain with multiple supplies assuming no competitions between suppliers has been also addressed.

Our study contributes to the literature in several ways: (1) we have explored the mechanism that motivates supply chain firms to collaboratively reduce the impacts of pollutant emissions on environment and public health by producing EFPs through environmental technology investments under sustainable constraints with triple bottom line dimensions representing stakeholder's sustainable interests; (2) we have examined the impacts of interplay and interrelation of the multiple sustainable constraints representing environmental and social interests on the supply chain transfer price and profit allotment decisions when taking government intervention into consideration; (3) we have extended the research by incorporating public health factor into our model from social dimension to analyze the joint effects of multiple factors on supply chain firms' performance from triple bottom line dimensions; (4) we have addressed the multiple suppliers case assuming no competitions between them.

Our findings suggest that supply chain firms' environmental decisions interplay with the trade-offs between financial feasibility of their green investments and stakeholders' interests of environmental and public health represented by the sustainable constraints. Through the government subsidy sharing negotiations between the supply chain members, the transfer price is collaboratively determined, which is crucial to sustain the supply chain. Distinct from the previous studies that consider only economic and environmental aspects (two dimensions), in view of triple bottom line the inclusion of the third dimension of social aspect (public healthcare cost) generates the double effects, the implication is that the optimal decision policy for operating the EFPs is not only affected by the environmental constraint but also the public health constraint. As for supply chain operations, to motivate supply chain firms to invest in EFPs, collaboratively realizing break-even in a finite time period through supply chain profit allotment that is interrelated with sharing of government incentive policy forms the backbone of supply chain sustainability.

Based on our findings, we can draw the following conclusions. First, the profit allotment is determined through the negotiation of the transfer price interrelated with the government subsidy sharing between the supply chain members. Second, consumers' environmental awareness that represents the market constraint depends on their living standards. It is also affected by the government incentive policy, which has a stronger impact on EFPs' market diffusion process and manufacturer's price decisions. Third, the EFPs' optimal operational decisions are jointly affected by multiple factors such as the environmental standards, the level of public healthcare cost for loss of human health caused by pollution, and the level of supply chain firms' pollutant emissions. The government policies, together with the support of consumers' environmental awareness, play the key role to help the supply chain firms gain the EFPs' market position by overcome the cost disadvantage and ultimately become self-sustaining. Fourth, in the case when the suppliers provide different intermediate products respectively without competition between them, they can be treated as a single group to negotiate the transfer price in terms of sharing the government subsidy with the manufacturer. The shared portion of the government subsidy to the supply chain group is distributed between the suppliers based on the ratios of the incremental cost of individual supplier to the total incremental costs of the all suppliers for producing the EFP's intermediate product.

There are issues that need to be explored in future studies. For instance, the research would conduct the question of how supply chain firms can be effectively driven or motivated to collaboratively initiate their environmental technology innovation for pollution prevention in the competitive market. Another avenue for future research could be extending the model into a supply chain with multiple suppliers involving supply competitions.

Acknowledgements

This research is supported by the NSFC with Grant NO.71372012, partially supported by the National Basic Research Program of China (973 Program) with Grant No 2013CB329101.

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