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Highlights

- We evaluate environmental economic performance of environmentally friendly product in the context of supply chain.
- We develop a supply chain model incorporating environmental policies with multiple environmental sustainable constraints.
- Stakeholders' Environmental interests are reflected by constructing environmental sustainable constraints.
- We investigate interrelation among supply chain firms, government and consumers in reducing environmental externalities.
- The government policy incentives for sustainable supply chain to be cost competitive is quantitatively assessed.

Assessing the Economic Performance of an Environmental Sustainable Supply Chain in Reducing Environmental Externalities

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Abstract: This study investigates the mechanism that motivates supply chain firms to reduce environmental externalities while balancing the economic feasibility of the supply chain system under environmentally constrained circumstances in a competitive market. Taking government policy incentives into account, a quantitative model of an integrated supply chain that incorporates sustainable constraints is formulated to optimize supply chain firms' operational strategies of producing environmental friendly products (EFPs). This study contributes to the literature with a better understanding the interplay and interrelation of multiple sustainable constraints and their impact on supply chain firms' collaborative decisions. Our findings suggest that the decisions of operating EFPs are subject to sustainable constraints and that the government policy incentives play a dominant role overseeing supply chain firms' environmental behaviors toward sustainability.

Keywords: sustainable supply chain; environmental externality; sustainable constraint; environmental friendly products; stakeholders.

1 Introduction

Over the past few decades, economic development has caused many environmental issues that our society currently faces, including climate change, ozone decline, nuclear radiation, industrial toxins, widespread air and water pollutions (Cohen and Winn, 2007). Similar to climate change, most negative externalities can be traced back to market failure (Coase, 1960). To a large extent, environmental pollution and damage caused by firms' production processes and the use of their products are not directly captured in the market; i.e., they are "external" to private sectors and are therefore potential sources of market inefficiency. Since the costs of repairing the environment and/or removing the damages are not recognized or accounted for by the supply chain firms, the real problem created in the free-market economy is that they do not have to subtract these costs from their overall revenues. Consequently, private costs of production

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tend to be lower than related social costs, which can lead to inefficiency in the resource allocation. The question of how to resolve these issues of environmental externalities has become the subject of worldwide debate. Thus, the purpose of this research is twofold: 1) to investigate the mechanism of economic feasibility that reduces environmental externalities in the context of the supply chain system while taking stakeholders' environmental interests as sustainable constraints and 2) to gain insight into the balance between economic development and environmental protection.

With increasing awareness of the need for environmental protection and sustainability as well as pressures from governments, customers, and various stakeholder groups, companies are being urged to effectively incorporate sustainability issues into their supply chain management (SCM) schemes (Gold et al., 2010). In addition, the issue of supply chain sustainability combining sustainable development and supply chain management has been receiving increased attention (Dyllick and Hockers, 2002).

Sustainable development is often described as a combination of environmental, social, and economic issues involved in human development (Zailani et al., 2012). As corporations attempt to move toward environmental sustainability, management must extend their efforts to improve environmental practices across their supply chains (Vachon and Klassen, 2008). One of the most important issues in green logistics is how to identify preferred solutions that balance environmental and business concerns (Quariguasi et al., 2009). Previous studies have addressed sustainability in SCM from different perspectives, including green product design (Mallidis et al., 2012), green purchasing and supplier selection (Bai and Sarkis, 2010; Rao, 2002; Kumar et al., 2014), manufacturing (Ilgin and Gupta, 2010), remanufacturing (Mitra and Webster, 2008), reverse logistics (Barker and Zabinsky, 2011), closed-loop logistics (Devika et al., 2014), and supply chain design (Chaabane et al., 2011). Although the literature regarding environmental management in the supply chain context has been growing in recent years (Tseng and Hung, 2014), the interplay effects that incorporate environmental externalities, government policy incentives, and stakeholders' environmental interests (as sustainable constraints in this domain) have not been given sufficient attention. Since they are important for both environmental and economic sustainability, they require theoretical and empirical investigations.

Negative externalities resulting from the poor environmental performance of supply chain firms can have a destructive impact on environmental sustainability (Delucchi, 2000). Thus, firms have been increasingly under pressure to achieve a balance between profitability and sustainability. Maintaining such a balance in the long run requires firms to take a holistic approach toward sustaining financial flow (profit), resource flow (planet), and development flow (people) (Tang and Zhou, 2012). In this study, we refer to "reducing environmental externalities" as the efforts that firms make (under government enforcement and incentives) to reduce environmental pollution through improvements in their production processes or product usage. In other words, it involves transformation processes that attempt to effectively control and prevent pollution from the manufacturing source. In doing so, environmental externalities can be internalized by the development of a sustainable supply chain among partner firms not only for economic development but also for environmental and socially sustainable development (Seuring and Müller, 2008; Erol et al., 2011).

The internalization (reduction) of externalities is one of the necessary paths for achieving sustainability (Bithas, 2011). However, reducing externalities comes with financial burdens (attributed as additional expenses) when attempting to manufacture products that ensure ecological sustainability. This includes additional investments incurred because of greening and the penalties levied for not meeting certain standards (Barari et al., 2012). With a profit-driven nature that favors their own interests, firms inevitably seek trade-offs by balancing conflicting pressures that are often connected with sustainable development, i.e., firm-level economic performance versus environmental degradation and social disruption (Matos and Hall, 2007). Moreover, firms are compelled to reduce their impact on the environment by both regulatory and non-regulatory pressures from the government, market, and community (Hall, 2000).

The environmental behaviors of partner firms may have influences on the supply chain's value transformation process (Klassen and Vachon, 2003). Changes in value transformation represent opportunities for supply chain members' reconsideration of collaborative relationships. Contracts and supply chain cooperation should be further understood so that sustainability issues are not simply viewed as trade-offs (Seuring, 2013). These issues raise the following questions:

How can supply chain firms manageably deal with the complex and dynamic nature of reducing environmental externalities?

Which trade-offs occur between the environmental impacts of supply chain firms' economic activities and their costs, and what are the best solutions that balance ecological and economic concerns (Dekker, 2012)?

What factors influence supply chain members' collaborative relationships when they face the challenge of improving their environmental performance?

What are the sustainable constraints that represent environmental externalities and stakeholders' environmental interests, and how do they affect supply chain firms' decision behaviors?

Would government policy incentives help motivate supply chain firms to make environmental technology investments in the competitive market?

The present study seeks to address these issues by introducing multiple sustainable constraints in a quantitative model of an integrated supply chain that reflects stakeholders' environmental interests, analyzing the joint effects of the multiple sustainable constraints and their interrelation on supply chain firms' decision behaviors, and explicating the environmental and economic performance of the supply chain system. By constructing an integrated supply chain model while considering government policies, our research investigates a supply chain system's evolving path towards environmental sustainability.

The remainder of this paper is organized as follows. Section 2 reviews the existing literature. Section 3 describes the sustainable constraints while taking stakeholders' environmental interests into account. Section 4 formulates an integrated environmental sustainable supply chain model with multiple sustainable constraints and analyzes the solution structure. Section 5 provides the results and discussion. The final section draws the conclusions and presents future research directions.

2 Literature review

There have been numerous literature reviews on green or sustainable supply chain research (e.g., Bloemhof-Ruwaard et al., 1995; Reed, 2008; Quariguasi et al., 2009; Gold et al., 2010; Ilgin and Gupta, 2010; Dekker, 2012; Seuring and Müller, 2008; Seuring, 2013; Brandenburg et al., 2014; Fahimnia et al., 2015). Bloemhof-Ruwaard et al. (1995) observed the earliest studies on the application of operational research (OR) optimization models to environmental management (e.g., Böttcher and Rembold, 1977; Das and Haimes, 1979; Batta and Chiu, 1988; Ellis, 1988; Bouzaher et al., 1990). Brandenburg et al. (2014) observed that, among the extant research related to the SCM perspective, sustainability is often externally motivated by the government, the customers or stakeholders (e.g., Gold et al. 2010; Seuring and Müller, 2008), and a vertical coordination for improving environmental performance among supply chain firms is required (Carter and Rogers, 2008). Fahimnia et al. (2015) presented an excellent structured review of green SCM literature and stated the following:

"Sustainable and green supply chain management is necessarily globalized. Broadening the number and location of countries where green supply chain management is investigated is required. Without the voices of less-developed countries amongst the researchers portends a major weakness and belies a multi-culturally and globally relevant viewpoint."

They also observed that conceptual and empirical studies represent the most influential works, and prescriptive, normative, and quantitative modeling have begun to take on greater importance. In particular, opportunities abound for additional research in the formal modeling of green SCM with practical applications (Fahimnia et al., 2015). As environmental issues become a worldwide concern, within the field of OR, research combining environmental issues and OR models has been growing rapidly.

Through our literature survey, we found that the related literature may be classified as two different schools: 1) the study of supply chain firms' decision-making processes interrelated with environmental responsibility (i.e., eliminating pollution at its source), from the perspective of stakeholders' environmental interests; and 2) the integration of environmental issues in supply chain optimization through a quantitative model-based approach, which can be found in the studies on green/sustainable/reverse/closed-loop supply chains.

Externality costs occur when the private calculation of costs differs from (usually much less than) society's valuation of costs (Griffin and Steele, 1980). The school of stakeholders' environmental interests argues that firms should accept liability for environmental externalities through environmental technology investments (Matthews and Lave, 2000; Ding et al., 1999, 2008; Ding and Xu, 2010; Holmgren and Amiri, 2008; Nguyen, 2008; Longoa, 2008). In addition, the environmental and social impacts of supply chains are becoming increasingly important and influential. Thus, firms are under pressure to become environmentally friendly, especially from the government, the community, and the customers, all of which are the main stakeholders that affect their technology adoptions (Luken and Rompaey, 2008).

To the government, environmental quality is a public good that must be protected from damage created by any private agents (Owen, 2004). However, markets cannot meet the requirements of Pareto efficiency when fully defined and enforceable property rights are absent. Thus, it is necessary for the government to tax and regulate the environmental damage caused by production (Common, 1979). Previous studies have shown that firms' initial environmental performance is influenced by governmental regulation (Laplante and Rilstone, 1996; Gray and Deily, 1996). In this regard, the stricter the regulation, the more effort the firms will exert to reduce pollution.

For consumers, their purchasing choices exert market pressure on firms (York and Venkataman, 2010). When consumers prefer environmentally friendly products (EFPs), they have a tendency to pay price premiums (Loureiro and Lotade, 2005). While the government and consumers are the external drivers, supply chain partner firms may provide internal pressure on firms' environmental behaviors. Firms' environmental proactivity can also act as a source of strategic resources, capabilities, and differentiation competitive advantages (González-Benito et al., 2005). Moreover, an individual firm's sustainable operational strategies can generate the largest benefits only when the strategies are aligned with those of their upstream suppliers and downstream customers (Tang and Zhou, 2012). The solution to internalizing environmental externality not only involves individual firms, but also the participation and cooperation among supply chain members. The related literature shows the consensus that firms' business activities should comply with environmental regulations and improve their environmental performance.

Following up on the related literature, further study on quantitatively modeling sustainable supply chain management (SSCM) into the supply chain level is necessary, particularly from the prospective of resolving conflicts between supply chain members' self-interests and the social interests of environment protection. Such resolutions can be achieved by integrating inter-organizational interdependencies, which have a strong focus on aspects of eco-efficiency. It is still rare in the existing literature to use quantitative method to address the effects of government policies on supply chain firms' environmental performance, the studies that jointly consider multiple sustainable constraints in a quantitative optimization model creatively add to the field of study. More specifically, since studies that examine the supply chain's integrated decision-making process (incorporating stakeholders' environmental interests as sustainable constraints) are limited, the present study aims to fill this research gap.

It is evident from the literature that studies considering environmental issues in supply chains are popular (Osmani and Zhang, 2014; Leigh and Li, 2014; White and Lee, 2009). As for the integration of environmental issues through supply chain optimization, previous studies have employed different methods to evaluate environmental investment decisions. For example, one study formulated a multi-objective model using mathematical programming for environmental investment decision-making (Higgins et al., 2008), while another study employed the lifecycle assessment method to evaluate potential environmental costs and impacts associated with products or processes throughout its lifecycle (Gaterell and Lester, 2000). Ding et al. (2014) explored the motivation factors that drive firms to produce environmentally friendly products, using the lifecycle approach to assess the performance of internalizing environmental externalities. Yalabik and Fairchild (2011) developed an economic analysis to examine the effects of consumer, regulatory, and competitive pressures on two firms' investments toward environmentally friendly production as they compete for environmentally sensitive customers. Their results suggest that policy incentives are stronger drivers of environmental innovation than penalties, particularly when dealing with "dirty" industries. They also found that subsidies offered to encourage firms to invest in environmental innovation were more effective than actions that simply increase environmental fines. Rădulescu et al. (2009) studied a multi-objective programming approach for production planning processes that incorporates a single type of constraint on pollutant emissions. In their study, two alternative optimization problems of either minimum pollution penalties or maximum expected returns were considered. These studies, however, are only based on the context of individual manufacturers.

Hasan (2013) examined whether the adoption of environmental practices in SCM can have a positive impact on the environmental and operational performance of companies, where descriptive case studies were only presented without using a quantitative model-based approach. Wu and Pagell (2011) employed a theory-building approach through case studies to address the issues of balancing short-term profitability and long-term environmental sustainability when making supply chain decisions under uncertain conditions. Kumar et al. (2014) proposed a green data envelopment analysis approach that incorporates heterogeneous suppliers and took into account regional emission compliance standards and laws to encourage suppliers to go "green" and cut down on carbon footprints. Devika et al. (2014) proposed a multi-objective optimization model with mixed integer linear programming formulation for a general closed-loop supply chain network, which includes the environmental and social impacts of the network for minimizing the total costs of the network. Tseng and Hung (2014) proposed a strategic decision-making model by considering both the operational costs and social costs caused by carbon dioxide emissions from a supply chain network that incorporates sustainability driven by pressure from the government and various stakeholders. In this case, the social costs of carbon emissions caused by the products' production process and transportation are included as the components of the total costs of the objective function. They suggested that a legislation that forces firms to bear the social costs of carbon dioxide emissions is an effective way to reduce carbon dioxide emissions resulting from their business activities. Barari et al. (2012) investigated a synergetic alliance between the environmental and commercial benefits, based on the argument that coordination between manufacturers and retailers helps adapt their strategies of initiating green practices, while maximizing economic profits by leveraging the product's "greenness." Here, the evolutionary game approach is used to arrive at the optimal strategy set (which is economically beneficial for supply chain firms) and thus, it establishes equilibrium. Overall, the literature reveals that non-single type joint constraints of environmental sustainability have been rarely considered. Therefore, our model contributes to the literature by introducing joint multiple sustainable constraints as an extension to the extant literature in order to shed light on the economic feasibility of producing green products that are interrelated to supply chain firms' decisions.

Environmental collaboration is defined as a specific focus on inter-organizational interactions between supply chain members, including joint environmental goal setting, shared environmental planning, and working together to reduce environmental pollution, which can be directed either upstream toward suppliers or downstream toward customers (Vachon and Klassen, 2008). In their study, the relationship between environmental collaboration in the supply chain and manufacturing performance (including cost, quality, delivery, flexibility, and environment) is empirically examined using a sample of firms in the package printing industry. However, most empirical studies lacked an investigation into the interplay and interrelation among supply chain firms' economic-environmental trade-off decision behaviors, which opens the possibility of applying a quantitative model of optimization in order to gain more insight into this issue.

As for operational research, the most common purpose is to illustrate how supply chains can operate with the coordination of both environmental and economic targets. For example, Cruz (2008) modeled the multi-criteria (the maximization of profit and the minimization of emission and risk) decision-making behaviors of various decision-makers (manufacturers, retailers, and consumers) in supply chains, while Although profit indicators are more direct in reflecting the economic performance of the supply chain (taking externalities into account), it lacks the lifecycle perspective. In comparison, the net present value method is more commonly used for evaluating an investment project (e.g., an investment in environmental technologies) where its lifecycle effects can be incorporated. The related literature mainly focuses on specific operational problems, such as decisions on production planning, logistics, location, allocation, inventory control, and information sharing. From the viewpoint of green investment decisions at the corporate level, studies that examine how various stakeholders' interests concerning environmental issues can coordinately balance the economic feasibility of green investments in the supply chain are relatively rare. In addition, the issue regarding how supply chain firms can be effectively motivated to make green investments have yet to be sufficiently examined.

Although the empirical research on SSCM primarily focuses on the intra-organizational level, they neglect to investigate inter-organizational aspects (e.g., Carter and Easton, 2011). Unlike empirical research, formal SSCM models integrate inter-organizational interdependencies, including the perspective of legal authorities. Hence, they are capable of reflecting external triggers of sustainability (Gold et al., 2010; Seuring and Müller, 2008). The open question is whether model-based research takes into account the intercompany perspective. Moreover, if the role and influence of stakeholders is adequately reflected in quantitative SSCM models, then quantitative models could be employed to elaborate on the interplay of regulatory decisions made by managers of supply chains or industries (Brandenburg et al., 2014). The main studies reviewed above especially those published in the main OR journals are listed in Table 1.

Table 1 Summary of the main previous studies in the main OR journals

Authors	Focus (Journals)	Approaches/Models
Bai & Sarkis(2010)	Supplier selection (IJPE)	Grey system and rough set approach
Barker & Zabinsky (2011).	Reverse logistics (Omega)	Analytical hierarchy process
Brandenburg et al. (2014)	Analytical modeling research (EJOR)	Literature review
Dekker et al. (2012	Highlight contribution of OR to green logistics (EJOR)	A review
Caniëls et al. (2013)	Driver factors of supplier participation in SCM (JP&SM)	Partial least squares methodology
Chung et al. (2013)	Pollution taxes in supply chain networks (EJOR)	Dynamic game
Devika et al. (2014)	Closed loop supply (EJOR)	Hybrid meta heuristic methods
Ding et al. (2014)	Reducing environmental externalities (JCP)	Green investment valuation with lifecycle approach
Hasan, M. (2013)	environmental practices in SCM (AJIBM)	Literature review and case study
Higgins, AJ., Hajkowicz, S., Bui, E. (2008)	Environmental investment decision (Computers & OR)	multi-objective integer programming
Kumar, A., Jain, V., Kumar, S. (2014)	Supplier selection (Omega)	Green DEA (GDEA)
Matos, S., Hall, J. (2007)	Supply chain sustainable development (JOM)	life cycle assessment
Osmani & Zhang(2014)	Environmental supply chain (Applied Energy)	two-stage stochastic optimization model
Rădulescu, M., Rădulescu, S., Rădulescu, C. Z. (2009)	Production planning under environmental constraints (EJOR)	multi-objective programming approach
Seuring, S. (2013)	Review of modeling approaches for SSCM (Decision Support System)	Literature review
Tang, CS., Zhou, S. (2012)	Classify and summarize recent OR/MS research developments (EJOR)	Literature review
Yalabik & Fairchild(2011)	Relationship between government regulations and firms' emissions (IJPE)	Economic analysis
Tseng, SC., Hung, SW. (2014)	Sustainable supply chain management (Journal Environmental Management)	Strategic decision-making model
White, L., Lee, J. (2009)	OR and sustainable development (EJOR)	Literature review and case study
Wu, ZH., Pagell, M. (2011)	Decision-making in SSCM (JOM)	Theory-building through case studies

Concurring with these arguments, this study explores the mechanism of reducing the environmental externalities in the supply chain context. Relative to concepts of the green supply chain, internalizing supply chain environmental externality has its unique view in which it is a process that drives supply chain firms' collaborative environmental investments under the pressure and influence of stakeholders' environmental interests, which are guided by government policies to reduce/eliminate environmental damages and pollution. In this regard, our study also focuses on the mechanism of how supply chain firms can be motivated to improve their environmental performance and investment decision behaviors, both of which are subject to stakeholders' environmental interests. Different from the previous supply chain models, our study incorporates multiple sustainable constraints and establishes a model-based framework in order to quantitatively assess the supply chain's environmental investment performance. In addition, it incorporates the effects of government policies (both penalties and incentives) and consumers' environmental awareness while emphasizing the reduction of environmental externalities from both perspectives of policy-making and supply chain members' decision-making. In this case, the overall goal is to collaboratively fulfill the requirements of environmental sustainability. Our research contributes to (from the viewpoint of the supply chain's prospects) understanding the impact of multiple constraints on environmental investment's economic feasibility and its potential in reducing externalities. Considering the environmental investment project's economic break-even as a milestone and incorporating the timing factors that affect the process of internalizing externalities, our model provides a balanced and economically feasible decision-making framework for a supply chain to make optimal price and product quantity decisions, and for the government to make optimal subsidy decisions.

3 Environmentally sustainable constraints

In order to structure a constrained framework for an environmental supply chain model, we must first introduce the environmental sustainable constraints that characterize stakeholders' environmental interests. In regard to stakeholders, they play important roles in reducing environmental externalities (Buysse and Verbeke, 2003; Reed, 2008; Tseng and Hung, 2014). In our study, by considering the government, consumers, and supply chain firms as the major stakeholders, we characterize their environmental interests through multiple sustainable constraints in terms of environment carrying capacity as well as regulation and market preferences (representing consumers' environmental awareness). The process of reducing environmental externalities is accompanied by game playing and collaborating among the stakeholders and, although their collective objective is the same, in order to reduce pollution and protect the environment, each individual stakeholder may have its own specific interest. We take it for granted that the decision baseline of each game player must follow the aforementioned sustainable constraints, which affects its and also other players' behaviors and their environmental performance. These constraints correspondingly characterize the environmental behaviors of the supply chain firms, the government, and the consumers.

Supply chain firms, as major pollution generators, are profit-driven in the pursuit of economic benefits, and yet, due to the pressure from governments, consumers, environmental organizations, and communities, they have to accept their social responsibilities and be environmentally friendly. A government (particularly in a developing country) that is responsible for the sustainability of both the economy and the environment, not only promotes the country's economic development, but also regulates firms to accept their environmental responsibilities. These two missions may, however, conflict with one another since the government has to balance the short-term declination in economic growth as well as long-term environmental sustainability. Consumers who are influenced by their living environment also exert pressure on firms to engage in environmental supply chain practices. Based on their knowledge, individual characteristics, and preferences, consumers make a trade-off between buying more EFPs (environmental conscience) and paying higher prices. The sustainable constraints are presented in the following section.

3.1 Environmental constraint

In our model, environmental constraint is presented by environmental carrying capacity, an ecological concept defined as the population of organisms that can be sustained at a steady state considering the resources available in the ecosystem in which they reside (U.S. Environmental Carrying Capacity Project, 2009). However, in population biology, environmental carrying capacity is defined as the environment's maximal load (Hui, 2006). In the present study, we refer to environmental carrying capacity as the maximum load of environmental contamination carrying capacity under which the environment can clean up the pollution itself without deteriorating. Nevertheless, environmental carrying capacities are not static since they are contingent on technology, preferences, and the structure of production and consumption. They are also contingent on the interactions between physical and biotic factors of the environment (Arrow et al., 1995). One idea for establishing environmental regulations is based on a volume control policy that regulates the upper limit of allowed emissions volumes. With the assumption that the volume control policy is effective, this study uses the pollution emission standard, set by the environmental regulator (the government) for each of the firms, as their assigned share of environmental carrying capacity. For a supply chain system, its environmental carrying capacity is the sum of the assigned capacities of all of the supply chain partners. In our model, environmental constraint is defined as the requirement in which the total pollution emitted by a supply chain system cannot exceed its environmental carrying capacity. Supply chain firms have to either reduce production quantities or invest in environmental technologies in order to reduce emissions. Moreover, the process of reducing environmental externalities must satisfy the environmental constraint.

3.2 Regulation constraint

Regulation constraint refers to government policies that guide government decisions and supply chain firms' business activities. Without internalizing externalities, the financial burdens on the government of environmental cleaning and restoring can be substantial. When firms are motivated or pressured to make investments in environmental technologies, pollution can be prevented at the source so that the burden of externality costs on communities can be significantly reduced. Accordingly, the government sets policies, including both regulations and incentives, both of which are necessary for enforcing and motivating firms to improve their environmental performance. More specifically, the government imposes penalty costs on pollution and offers subsidies to environmental technology investments. In regard to the latter, the government subsidy should only compensate, to a certain extent, supply chain firms' incremental costs associated with the reduction of environmental externalities.

3.3 Market constraint

Market constraint refers to a consumer's preference, which depends on the total purchase price and usage cost of a product. The price of an EFP is more expensive than a traditional product due to the additional investment in environmental technologies and processes. Considering that the market is competitive and an EFP competes with an environmentally unfriendly product (EUFP), consumers prefer both a clean environment and an acceptable price premium for the EFP. However, consumers have a trade-off between environmental quality concern and price sensitivity because of their income budget constraints. In addition, their different preferences depend on the product's total cost of purchase and usage. In our model, the market constraint reflects the requirement that the total purchase and usage costs of EFPs should not exceed that of EUFPs.

Moreover, an inventory management policy in terms of vendor managed inventory (VMI) is considered in our model as an additional constraint, since one may argue that it is usually a part of the supply chain process and its impact on operations strategies should not be neglected in the supply chain's decision-making process.

4 Environmentally sustainable supply chain modeling

In this section, we discuss the following three questions: 1) What is the impact of supply chain firms' green investment decisions on their business performance? 2) To what extent do government policy incentives motivate supply chain firms to undertake environmental-friendly activities? and 3) How do the constraints representing stakeholders' environmental interests affect their decision behaviors? In the supply chain process of reducing environmental externalities, we address collaborative operational decisions related to EFPs' sales quantities and price, government subsidy rates, and VMI delivery policies. In our problem setting, we formulate an integrated supply chain model that maximizes the supply chain system's total net present value in which the firms' business decisions are subject to environmental sustainable constraints. Under the pressures of stakeholders' environmental interests and enforced legislation, supply chain firms face the challenge of cost disadvantages and break-even uncertainties when making environmental technology investments in a competitive market.

In the following sections, we present the framework of a constrained model that explicitly incorporates the environmental sustainable constraints in order to explore the logical decision-making process of replacing EUFPs with EFPs when motivated by government policy incentives.

4.1 Modeling assumptions and notations

4.1.1 Assumptions

(1) We assume that a two-echelon supply chain involves a single product that consists of one manufacturer and supplier. As a core member of the supply chain, the manufacturer sells its final products directly to the market (consumers) while the supplier provides intermediate products to the manufacturer. The manufacturer produces products based on the make-to-order strategy, and one unit of the final product consumes m units of intermediate products from the supplier.

(2) We assume that the products produced are EUFPs before the supply chain introduces EFPs, and the production runs at capacity in accordance with the market share. Under the enforcement of regulations and policy incentives, the supply chain firms introduce EFPs through investments in environmental

technologies. The sales quantities of the EFPs are unlikely to run at the manufacturer's production capacity from the start. Instead, they increase through its diffusion process and gradually replace the EUFPs with its quantities produced in each period. As the EFPs' sales quantities increase toward the production capacity, the EUFPs' quantities decrease until they are completely replaced.

(3) For the purpose of motivating supply chain firms to improve their environmental performance, we assume that the government charges penalties for the production of EUFPs and provides subsidies to encourage environmental technology investments. The subsidies are only granted until the supply chain's business break-even is reached, which are proportional to the incremental costs associated with producing EFPs. We also assume that the government grants the subsidy directly (or alternatively, through consumers) to the manufacturer, and the manufacturer takes the initiative to create a sustainable supply chain and share the subsidy with the supplier by adjusting the transfer price.

(4) We assume that the manufacturer's inventory is managed using the VMI model in order to minimize inventory costs, and the economic order quantity (EOQ) model is used as an inventory cost minimization constraint. The supplier manages the inventory level without stock-out and bears the inventory costs. The inventory is replenished in batches by delivering them several times annually (on average), assuming that the annual demand information is available to the supplier and the final output of the EFPs is produced based on the make-to-order strategy.

4.1.2 Parameter notations and definitions

The following notations are used in our model:

R_m^u, R_m^e = Manufacturer's annual net profit of EUFPs and EFPs

R_s^u, R_s^e = Supplier's annual net profit of EUFPs and EFPs

R^u = Integrated supply chain's annual net profit of EUFPs

B_m = Government subsidy per unit of output of EFPs

NPV^u, NPV^e = Net present value (NPV) of the integrated supply chain's profit for EUFPs and EFPs

ΔNPV = Incremental net present value of the integrated supply chain when introducing EFPs

Q = Manufacturer's production capacity (equal to its market demand)

Q^u = Sales quantity of EUFPs (Q^u =Q before introducing EFPs, $Q^u = Q - Q^e$ after introducing EFPs)

P_m^u = Sales price of EUFPs

I_m, I_s = Project's initial investment on pollution reduction and prevention from the manufacturer and supplier

C_m^u, C_m^e = Manufacturer's variable cost per unit of EUFPs and EFPs

W_m^u, W_m^e = Manufacturer's pollutant disposal costs per unit of EUFPs and EFPs

E_m^u, E_m^e = Pollution emitted by manufacturer per unit of EUFPs and EFPs

P_s^u, P_s^e = Supplier's sales price (transfer price) per unit of intermediate products for EUFPs and EFPs (manufacturer's purchase cost per unit)

C_s^u, C_s^e = Supplier's variable cost per unit of intermediate products for EUFPs and EFPs

W_s^u, W_s^e = Supplier's pollutant disposal costs per unit of intermediate products for EUFPs and EFPs

E_s^u, E_s^e = Pollution emitted by the supplier per unit of intermediate products for EUFPs and EFPs

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

C_h^u, C_h^e = Supplier's average inventory holding cost of intermediate products per unit for EUFPs and EFPs with VMI mode

C_o^u, C_o^e = Supplier's average ordering cost of intermediate products for EUFPs and EFPs per batch delivery with VMI mode, assuming both intermediate products for EFPs and EUFPs are delivered in the same batch during the process of gradually replacing EUFPs with EFPs

q = Annual ordering times of the supplier

Y = Environmental carrying capacity allocated to the supply chain system

Z^u, Z^e = Government's environmental cleaning and restoring costs for keeping the environment to a self-healing standard for EUFPs and EFPs

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

k = Consumer's environmental quality sensitivity rate ($0 \leq k < 1$; when $k = 1$, consumer is only sensitive to environment quality. This situation is not considered in this study)

g = Average annual growth rate of EFP sales quantities

r = Risk adjusted discount rate

4.1.3 Decision variable notations and definitions

Q^e = Sales quantities of EFPs

P_m^e = Sales price of EFPs

α = Cost factor of government subsidy per unit of output of EFPs

4.2 Structure of the objective function and constraints

4.2.1 Profit functions of EUFPs and EFPs

In our model, we consider environmental effect as the sole contributor to effectively measure the ecological effects accompanying supply chain activities, which is understandable since reducing environmental pollution is a high priority worldwide, particularly in developing countries. With the intention of motivating supply chain firms' green initiatives, the government provides a subsidy for EFPs and imposes a penalty for EUFPs. For the EUFPs, we assume that the annual sales quantity is at capacity $Q^u = Q$ in order to satisfy a relatively stable market demand. The annual profits of the manufacturer, supplier, and the integrated supply chain from producing EUFPs during time period t can be expressed as follows:

$$R_{mt}^u = (P_{mt}^u - mP_{st}^u - C_{mt}^u - F_{mt}^u - W_{mt}^u)Q \tag{1}$$

$$R_{st}^u = m(P_{st}^u - C_{st}^u - F_{st}^u - W_{st}^u)Q - \left(q_t C_o^u + mQC_h^u / 2q_t\right) \tag{2}$$

$$R_t^u = (P_{mt}^u - C_{mt}^u - mC_{st}^u - F_{mt}^u - mF_{st}^u - W_{mt}^u - mW_{st}^u - mC_h^u / 2q_t)Q - q_t C_o^u \tag{3}$$

where R_t^u is the sum of R_{st}^u and R_{mt}^u. The net present value (NPV) of the integrated supply chain's profit for EUFPs during its lifecycle N (with finite time periods) is then expressed as follows:

$$NPV^u = \sum_{t=1}^{N}\left[(P_{mt}^u - C_{mt}^u - mC_{st}^u - F_{mt}^u - mF_{st}^u - W_{mt}^u - mW_{st}^u - mC_h^u / 2q_t)Q - q_t C_o^u\right]e^{-rt} \quad (4)$$

Due to its additional investment cost, EFPs are at a disadvantage compared to EUFPs. To make up the incremental cost incurred by the environmental technology investment, supply chain firms usually increase the sales price. The higher price then brings a reduction in sales quantities in the competitive market, especially when EFPs have not yet been widely accepted by the market. Consequently, there is a reduction in overall profits. In such a circumstance, supply chain firms have no intention to produce EFPs. Since governments have the responsibility for pollution reduction and prevention, they should enforce regulations and offer policy incentives in order to drive supply chain firms' business activities in the direction of reducing environmental externalities. Taking government policies into account, the manufacturer's total profit during finite time period N can then be expressed as follows:

$$R_m^e = \sum_{t=1}^{N}[(P_{mt}^e + B_{mt} - mP_{st}^e - C_{mt}^e - W_{mt}^e)Q_t^e + (P_{mt}^u - mP_{st}^u - C_{mt}^u - W_{mt}^u - F_{mt}^u)(Q - Q_t^e)] - I_m \quad (5)$$

where Q_t^e is the EFP sales quantity during t time period, and $Q - Q^e$ stands for the annual product quantity of EUFPs that have not yet been replaced by EFPs. It is noted that the manufacturer's operating profits consist of two parts from the EFPs and the EUFPs that are not yet replaced (presented by the first and second groups of the above items). The government subsidy can be offered in different ways, such as tax deductions, tax exemptions, and financial subsidies, which may be granted directly to the supply chain firms or the consumers. As assumed, the government subsidy goes to the manufacturer who produces EFPs, and the manufacturer shares the subsidy with the supplier through the transfer price adjustment. We also assume that the EFPs and EUFPs are ordered in the same batch and the average ordering cost for each batch is facilitated as C_o^e. The supplier's total profit associated with producing components for the EFPs and EUFPs (not yet replaced during finite time period N) can be expressed as follows:

$$R_s^e = \sum_{t=1}^{N}[m(P_{st}^e - C_{st}^e - W_{st}^e - C_h^e / 2q_t)Q_t^e + m(P_{st}^u - C_{st}^u - W_{st}^u - F_{st}^u - C_h^u / 2q_t)(Q - Q_t^e)] - q_t C_o^e - I_s \quad (6)$$

where the supplier's operating profits also come from two parts that are presented by the first two groups of the above items (the first one from the EFPs, and the second one from the EUFPs not yet replaced). By summing Equations (5) and (6), we obtain the NPV of the integrated supply chain as follows:

$$NPV^e = \sum_{t=1}^{N}\begin{bmatrix}\left(P_{mt}^e + B_{mt} - C_{mt}^e - W_{mt}^e - mC_{st}^e - mW_{st}^e - mC_h^e / 2q_t\right)Q_t^e - q_t C_o^e \\ + \left(P_{mt}^u - C_{mt}^u - mC_{st}^u - F_{mt}^u - mF_{st}^u - W_{mt}^u - mW_{st}^u - mC_h^u / 2q_t\right)\left(Q - Q_t^e\right)\end{bmatrix}e^{-rt} - I_s - I_m \quad (7)$$

Comparing Equations (7) and (4), we obtain an incremental net present value of the integrated supply chain from producing the EFPs as follows:

$$\Delta NPV = \sum_{t=1}^{N} \begin{bmatrix} \left(P_{mt}^{e} + B_{mt} - C_{mt}^{e} - W_{mt}^{e} - mC_{st}^{e} - mW_{st}^{e} - mC_{h}^{e}/2q_{t}\right)Q_{t}^{e} - P_{mt}^{u}Q_{t}^{e} \\ + (C_{mt}^{u} + mC_{st}^{u} + W_{mt}^{u} + mW_{st}^{u} + F_{mt}^{u} - mF_{st}^{u} + mC_{h}^{u}/2q_{t})Q_{t}^{e} \\ - q_{t}\left(C_{o}^{e} - C_{o}^{u}\right) \end{bmatrix} e^{-rt} - I_{s} - I_{m} \qquad (8)$$

where, within the above summation, the first group of items presents the profit of the EFPs, the second item is the lost opportunity sales due to the replacement of the EUFPs, and the third group of items presents the opportunity savings from replacing the EUFPs with the EFPs.

4.2.2 Structure of the constraints

Our model is formulated to maximize objective function ΔNPV in Equation (8) by optimizing the sales quantities and price of the EFPs as well as the government subsidy during the finite initial periods up to t = t_N (< N). While also complying with the three sustainable constraints, t_N is the time point at which ΔNPV reaches its break-even (ΔNPV =0). The environmental constraint states that the supply chain system's pollution cannot exceed the environmental carrying capacity, which is described as follows:

$$Q_t^e E_{mt}^e + mQ_t^e E_{st}^e + (Q - Q_t^e)E_{mt}^u + m(Q - Q_t^e)E_{st}^u \leq Y \qquad t=1,2,\ldots,N \qquad (9)$$

where Y is environmental carrying capacity, which is assumed to be constant. Since governments have the responsibility for maintaining environmental sustainability, they must regulate supply chain firms' business activities without harming the environment. With the consideration of social welfare, regulations should conform to environmental sustainability balanced with economic development. The EFPs potentially offer a pathway to reduce externalities such as emissions and pollution but producing the EFPs may not gain profits due to their cost (price) disadvantage (because of additional investments) in the competitive market without government policies. Extant literature is unclear on whether green practices are economically profitable (Caniëls et al., 2013). A number of barriers exist for the implementation of EFPs due to their high initial capital costs, additional costs to consumers, limit market availability, and commercial feasibility (Banister, 2005; Romm, 2006; Struben and Sterman, 2008). Thus, it was concluded that marketing programs and subsidies must remain in place for a sufficiently long period of time in order to allow for EFPs' diffusion to become self-sustaining.

Concurring with the results revealed in the literature, we explicitly introduce the government subsidy into the supply chain model to investigate the economic feasibility of producing EFPs under environmental sustainable constraints. In addition, we quantify to what extent the government subsidy can effectively motivate supply chain firms to improve their environmental performance (balanced with EFPs' break-even point). In reality, restricted by financial burdens, the government subsidy offered to supply chain firms should also be subject to an upper limit. To be economically feasible, the regulation constraint should reflect the requirement that the government's net environmental disposal cost savings (the reduced environmental externality cost minus the reduced penalty cost) must be high enough compared with the government subsidy, which is expressed as follows:

$$B_{mt}Q_t^e \le b[(Z_t^u - Z_t^e) - (Q(F_{mt}^u + mF_{st}^u) - (Q - Q_t^e)(F_{mt}^u + mF_{st}^u))], \quad t \le t_N \tag{10}$$

where on the right-hand side, the first item group is the government's saved restoration cost, and the second item is the reduced penalty cost due to replacing EUFPs with EFPs. Parameter b (b < 1) is the coefficient of the government policy incentives, which is introduced here to ensure that the government subsidy to supply chain firms is less than the reduced environmental externality costs. $t \le t_N$ implies that the government subsidy is only provided before the firms reach break-even. Equation (10) can be simplified as follows:

$$B_{mt} \le b[(Z_t^u - Z_t^e)/Q_t^e - (F_{mt}^u + mF_{st}^u)] \tag{11.1}$$

With the consideration that the government subsidy should only compensate for the costs, it may be determined proportionally to the supply chain firm's average incremental costs incurred for environmental technology investments. Following the work of Ding et al. (2014), we assume that the government subsidy per unit is proportional to the manufacturer's average incremental cost of the EFPs, which can be expressed as follows:

$$B_{mt} = \alpha_t \frac{\sum_{t=1}^{t_N}[C_{mt}^e + mP_{st}^e - (C_{mt}^u + mP_{st}^u)]Q_t^e + I_m}{\sum_{t=1}^{t_N} Q_t^e} \tag{11.2}$$

where α $(0 \le \alpha \le 1)$ is the cost factor of government subsidy per unit, and P_{st}^e is the transfer price that includes the supplier's incremental cost associated with producing intermediate products for the EFPs. As a member of the sustainable supply chain, the supplier also needs to collaboratively invest in environmental technology. In order to compensate for its increased costs, the supplier is likely to increase the transfer price, i.e., $P_s^e > P_s^u$, through negotiating the transfer price with the manufacturer. We define P_s^e by adding the average incremental cost per unit of intermediate products for the EFPs to P_s^u as follows:

$$P_s^e = P_s^u + \left(C_s^e - C_s^u\right) + I_s/m\sum_{t=1}^{t_N} Q_t^e \tag{12}$$

where P_s^u, C_s^u, and C_s^e are estimated by their mean values, and Q_t^e is determined by the environmental constraint (see Subsection 4.3.3). By substituting Equation (11.2) into Equation (11.1), the regulation constraint can be rewritten as follows:

$$\alpha_t \le \frac{b[(Z_t^u - Z_t^e)/Q_t^e - (F_{mt}^u + mF_{st}^u)]\sum_{t=1}^{t_N} Q_t^e}{[\sum_{t=1}^{t_N}(C_{mt}^e + mP_{st}^e - C_{mt}^u - mP_{st}^u)Q_t^e + I_m]} \tag{13}$$

For different types of consumers, while making purchasing decisions, their focus point on the products may differ. Moreover, the consumers who are environmentally aware may tend to buy the EFPs and pay a price premium, whereas the consumers who are price sensitive (even though they may be concerned with environmental issues) may feel that they cannot afford to pay higher prices. Thus, the latter group will eventually choose the EUFPs. Generally speaking, for EFPs to gain market acceptance, an individual consumer's total purchase and usage costs for such products cannot exceed that of EUFPs. In this sense, by taking the consumers' environmental quality preference into consideration, the market constraint can be described as follows:

$$P_{mt}^{e}(1-k)+U_{t}^{e} \le P_{mt}^{u}+U_{t}^{u} \tag{14}$$

where k represents the consumer's environmental awareness and it measures the consumer's sensitivity to environmental quality ($0 \le k < 1$). The higher the value of k is, the less that consumers are sensitive to price premiums and the more they are concerned with environmental quality. The market constraint implies that $P_{mt}^{e} > P_{mt}^{u}$ and preferably, with $U_{t}^{e} < U_{t}^{u}$.

According to the EOQ model, inventory costs are minimized when inventory holding costs are equal to ordering costs. Thus, the incremental inventory cost minimization constraint can be written as follows:

$$q_t (C_o^e - C_o^u) = m(C_h^u - C_h^e)Q_t^e / 2q_t \tag{15}$$

By combining Equations (8) and (9) with (13) to (15), we can construct a model that maximizes the NPV of the integrated supply chain that produces the EFPs as follows:

$$\begin{aligned}
\mathrm{Max}\,\Delta NPV = \sum_{t=1}^{N} & \left[\begin{array}{l} (P_{mt}^{e} - C_{mt}^{e} - W_{mt}^{e} - mC_{st}^{e} - mW_{st}^{e} - mC_{h}^{e}/2q_t \\ + \alpha_t \dfrac{\sum_{t=1}^{t_N}[C_{mt}^{e} + mP_{st}^{e} - (C_{mt}^{u} + mP_{st}^{u})]Q_t^e + I_m}{\sum_{t=1}^{t_N} Q_t^e}) \\ -(P_{mt}^{u} - C_{mt}^{u} - mC_{st}^{u} - W_{mt}^{u} - mW_{st}^{u} - F_{mt}^{u} - mF_{st}^{u} - mC_{h}^{u}/2q_t) \end{array} \right] Q_t^e e^{-rt} - I_s - I_m \\
& - q_t (C_o^e - C_o^u) e^{-rt} \\
\text{st.} & \begin{cases} Q_t^e (E_{mt}^{e} + mE_{st}^{e}) + (Q - Q_t^e)(E_{mt}^{u} + mE_{st}^{u}) \le Y \\ \alpha_t \le \dfrac{b[Z_t^u - Z_t^e - (F_{mt}^{u} + mF_{st}^{u})Q_t^e]\sum_{t=1}^{t_N} Q_t^e}{Q_t^e[\sum_{t=1}^{t_N}(C_{mt}^{e} + mP_{st}^{e} - C_{mt}^{u} - mP_{st}^{u})Q_t^e + I_m]} \\ P_{mt}^{e}(1-k) + U_t^e \le P_{mt}^{u} + U_t^u \\ q_t (C_o^e - C_o^u) = \dfrac{mQ_t^e (C_h^e - C_h^u)}{2q_t} \\ Q_t^e \ge 0, P_{mt}^{e} \ge 0, \alpha_t \ge 0, q_t^e \ge 0 \end{cases}
\end{aligned} \tag{16}$$

where sales quantity Q_t^e, sales price P_{mt}^{e}, government subsidy rate α_t, and ordering times q_t are decision variables. The motive of this study is to find the EFPs' optimal operational strategy (sales quantity, sales price, government subsidy rate, and ordering times) that leads the incremental NPV of the integrated supply chain to reach break-even during a finite time period. We also assume that, stimulated by policy incentives and consumers' environmental preferences, the sales quantities of the EFPs increase with a constant growth rate g during t_N time periods through its diffusion process. In addition, the sales quantities of two consecutive time periods follow the relation of $Q_t^e = Q_{(t-1)}^e(1+g)$ and then, we have $Q_t^e = (1+g)^{t-1}Q_1^e$, where Q_1^e is the sales quantity of the first time period. After the diffusion process, the EFPs' sales quantities first reach production capacity (market share) and then continue with constant volume during subsequent periods. By replacing Q_t^e with its relation of Q_1^e and rewriting $\sum_{t=1}^{t_N} Q_t^e = Q_1^e[(1+g)^{t_N} - 1]/g$, Equation (16) can be rewritten as follows:

$$\mathrm{Max}\Delta NPV = \sum_{t=1}^{N}\left[\begin{array}{l}(P_{mt}^e - C_{mt}^e - W_{mt}^e - mC_{st}^e - mW_{st}^e - mC_h^e/2q_t \\ + \alpha_t \dfrac{\sum_{t=1}^{t_N}[C_{mt}^e + mP_{st}^e - (C_{mt}^u + mP_{st}^u)](1+g)^{t-1}Q_1^e + I_m}{Q_1^e[(1+g)^{t_N} - 1]/g}) \\ -(P_{mt}^u - C_{mt}^u - mC_{st}^u - W_{mt}^u - mW_{st}^u - F_{mt}^u - mF_{st}^u - mC_h^u/2q_t)\end{array}\right](1+g)^{t-1}Q_1^e e^{-rt} - \quad (17.1)$$
$$- q_t\left(C_o^e - C_o^u\right)e^{-rt} - I_s - I_m$$

$$\text{st.} \quad Q\left(E_{mt}^u + mE_{st}^u\right) - (1+g)^{t-1}Q_1^e\left(E_{mt}^u + mE_{st}^u - E_{mt}^e - mE_{st}^e\right) \le Y \quad (17.2)$$

$$\alpha_t \le \frac{b[Z_t^u - Z_t^e - \left(F_{mt}^u + mF_{st}^u\right)(1+g)^{t-1}Q_1^e][(1+g)^{t_N} - 1]}{(1+g)^{t-1}g\left[\sum_{t=1}^{t_N}(C_{mt}^e + mP_{st}^e - C_{mt}^u - mP_{st}^u)(1+g)^{t-1}Q_1^e + I_m\right]} \quad (17.3)$$

$$P_{mt}^e(1-k) + U_t^e \le P_{mt}^u + U_t^u \quad (17.4)$$

$$q_t\left(C_o^e - C_o^u\right) = [mQ_1^e(1+g)^{t-1}\left(C_h^e - C_h^u\right)]/2q_t \quad (17.5)$$

$$Q_1^e \ge 0, P_{mt}^e \ge 0, \alpha_t \ge 0, q_t^e \ge 0 \quad (17.6)$$

In the next section, we will present the model analysis.

4.3 Model analysis

The overall objective is to achieve the optimization of both the supply chain system's profits and the stakeholders' interests, which are specifically manifested in the model by maximizing the NPV of the integrated supply chain system with the constraints of the environmental standard, regulation, market, and inventory policy. The model's Lagrange function is formulated as follows:

$$
\begin{aligned}
L = \sum_{t=1}^{N} & \left[\begin{array}{l} P^e_{mt} - C^e_{mt} - W^e_{mt} - mC^e_{st} - mW^e_{st} - mC^e_h / 2q_t \\ + \alpha_t \dfrac{\sum_{t=1}^{t_N}[C^e_{mt} + mP^e_{st} - (C^u_{mt} + mP^u_{st})](1+g)^{t-1} Q^e_1 + I_m}{Q^e_1[(1+g)^{t_N} - 1]/g} \\ - \left(P^u_{mt} - C^u_{mt} - mC^u_{st} - W^u_{mt} - mW^u_{st} - F^u_{mt} - mF^u_{st} - mC^u_h / 2q_t\right) \end{array} \right] (1+g)^{t-1} Q^e_1 e^{-rt} \\
& - q_t\left(C^e_o - C^u_o\right)e^{-rt} - I_s - I_m \\
& + \lambda_{1t}[Y - Q\left(E^u_{mt} + mE^u_{st}\right) + (1+g)^{t-1} Q^e_1 (E^u_{mt} + mE^u_{st} - E^e_{mt} - mE^e_{st})] \\
& + \lambda_{2t} \left\{ \begin{array}{l} b[Z^u_t - Z^e_t - (F^u_{mt} + mF^u_{st})(1+g)^{t-1} Q^e_1][(1+g)^{t_N} - 1] \\ - \alpha_t g \ (1+g)^{t-1}[\sum_{t=1}^{t_N}(C^e_{mt} + mP^e_{st} - C^u_{mt} - mP^u_{st})(1+g)^{t-1} Q^e_1 + I_m] \end{array} \right\} \\
& + \lambda_{3t}[P^u_{mt} + U^u_t - P^e_{mt}(1-k) - U^e_t] + \lambda_{4t}\left[\frac{mQ^e_1 (1+g)^{t-1}\left(C^e_h - C^u_h\right)}{2q_t} - q^e_t\left(C^e_o - C^u_o\right)\right]
\end{aligned} \tag{18}
$$

where λ_{jt} (j = 1, 2, 3, 4; t = 1, 2,…, N) are Lagrange multipliers. The Kuhn–Tucker conditions for optimization are as follows:

$$
\begin{aligned}
\partial L / \partial Q^e_1 = & \sum_{t=1}^{N} \left[\begin{array}{l} \left(P^e_{mt} - C^e_{mt} - W^e_{mt} - mC^e_{st} - mW^e_{st} - \dfrac{mC^e_h}{2q_t}\right) \\ - \left(P^u_{mt} - C^u_{mt} - mC^u_{st} - W^u_{mt} - mW^u_{st} - F^u_{mt} - mF^u_{st} - \dfrac{mC^u_h}{2q_t}\right) \end{array} \right] (1+g)^{t-1} e^{-rt} \\
& + \sum_{t=1}^{t_N} \alpha_t \frac{(1+g)^{t-1} e^{-rt} \sum_{t=1}^{t_N}[C^e_{mt} + mP^e_{st} - (C^u_{mt} + mP^u_{st})](1+g)^{t-1}}{[(1+g)^{t_N} - 1]/g} \\
& + \lambda_{1t}(1+g)^{t-1}(E^u_{mt} + mE^u_{st} - E^e_{mt} - mE^e_{st}) \\
& - \lambda_{2t} \left[\begin{array}{l} b(F^u_{mt} + mF^u_{st})(1+g)^{t-1}[(1+g)^{t_N} - 1] \\ + \alpha_t g \ (1+g)^{t-1} \sum_{t=1}^{t_N}(C^e_{mt} + mP^e_{st} - C^u_{mt} - mP^u_{st})(1+g)^{t-1} \end{array} \right] \\
& + \lambda_{4t} \frac{m(1+g)^{t-1}\left(C^e_h - C^u_h\right)}{2q_t} = 0
\end{aligned} \tag{19.1}
$$

$$
\partial L / \partial \alpha_t = \frac{1}{(1+g)^{t_N} - 1} e^{-rt} - \lambda_{2t} = 0 \tag{19.2}
$$

$$
\partial L / \partial P^e_{mt} = (1+g)^{t-1} Q^e_1 e^{-rt} - \lambda_{3t}(1-k) = 0 \tag{19.3}
$$

$$
\begin{aligned}
\partial L / \partial q_t = & \left[\frac{m\left(C^e_h - C^u_h\right) Q^e_1 (1+g)^{t-1}}{2q_t^2} - \left(C^e_o - C^u_o\right)\right] e^{-rt} - \\
& \lambda_{4t}\left(\frac{mQ^e_1 (1+g)^{t-1}\left(C^e_h - C^u_h\right)}{2q_t^2} + \left(C^e_o - C^u_o\right)\right) = 0
\end{aligned} \tag{19.4}
$$

$$\lambda_{1t}\left(\partial L/\partial \lambda_{1t}\right) = \lambda_{1t}[Y - Q\left(E^u_{mt} + mE^u_{st}\right) + (1+g)^{t-1}Q^e_1(E^u_{mt} + mE^u_{st} - E^e_{mt} - mE^e_{st})] = 0 \tag{19.5}$$

$$\lambda_{2t}\left(\partial L/\partial \lambda_{2t}\right) = \lambda_{2t}\begin{Bmatrix} b[Z^u_t - Z^e_t - (F^u_{mt} + mF^u_{st})(1+g)^{t-1}Q^e_1][(1+g)^{t_N} - 1] \\ -\alpha_t g \ (1+g)^{t-1}[\sum_{t=1}^{t_N}(C^e_{mt} + mP^e_{st} - C^u_{mt} - mP^u_{st})(1+g)^{t-1}Q^e_1 + I_m] \end{Bmatrix} = 0 \tag{19.6}$$

$$\lambda_{3t}\left(\partial L/\partial \lambda_{3t}\right) = \lambda_{3t}[P^u_{mt} + U^u_t - P^e_{mt}(1-k) - U^e_t] = 0 \tag{19.7}$$

$$\lambda_{4t}\left(\partial L/\partial \lambda_{4t}\right) = \lambda_{4t}\left[q_t\left(C^e_o - C^u_o\right) - \frac{mQ^e_t\left(C^e_h - C^u_h\right)}{2q_t}\right] = 0 \tag{19.8}$$

$$\alpha_t\left(\partial L/\partial \alpha_t\right) = 0 \tag{19.9}$$

where Equations (19.1) to (19.4) are necessary conditions for optimality, and Equations (19.5) to (19.9) are complimentary conditions. When $\lambda_{jt} > 0$, $\partial L/\partial \lambda_{jt} = 0$; otherwise, when $\lambda_{jt} = 0$, $\partial L/\partial \lambda_{jt} > 0$. Next, we show the optimal decision processes of supply chain firms under the environmental sustainable constraints.

4.3.1 Manufacturers' price decisions

With the consideration of consumers' environmental quality concerns, λ_{3t} measures the increase in the NPV of the supply chain system for a marginal increase in consumers' total cost of purchasing and using EFPs. According to Equation (19.3), λ_{3t} can be calculated as follows:

$$\lambda_{3t} = \frac{(1+g)^{t-1}Q^e_1 e^{-rt}}{1-k} > 0 \tag{20}$$

λ_{3t} is positive and it increases with t, which is in accordance with the increase in EFP sales through the diffusion periods, as assumed by $Q^e_t = (1+g)^{t-1}Q^e_1$. k and λ_{3t} are positively related, which means that the higher the consumers' environmental quality concerns are, the higher their preferences are for EFPs. With $\lambda_{3t} > 0$, it can be seen from the complementary condition (19.7) that the market constraint is active. Thus, we have:

$$P^u_{mt} + U^u_t - P^e_{mt}(1-k) - U^e_t = 0 \tag{21}$$

In this case, the total cost of the purchase and usage of EFPs equals that of EUFPs, which means that the purchase price of EFPs is no less than EUFPs with k ≥ 0. This implies that, with environmental quality concerns, consumers prefer EFPs and they are willing to pay a price premium. This may also be explained by the fact that, since the opportunity cost of EFPs is the lost sale of replaced EUFPs, in reality, due to their profit-driven nature, supply chain firms would charge a price premium as high as possible, as long as it is accepted by consumers based on their environmental preferences. The manufacturers' optimal sales price, denoted by P_{mt}^{e*}, is as follows:

$$P_{mt}^{e*} = \frac{P_{mt}^{u} + U_{t}^{u} - U_{t}^{e}}{1-k} \tag{22}$$

As shown above, the manufacturers' price decision is influenced by consumers' environmental awareness and EFPs' usage costs. In addition, the higher the consumers' environmental awareness and the lower the usage costs, the higher the possibility for more expensive EFPs to be accepted by the market.

4.3.2 Manufacturers' (consumers') product quantity decisions

It should be mentioned that manufacturers' product quantity decisions are rather the consumers' product quantity decisions since consumers (ultimately) purchase finished goods based on price and subsidies. λ_{1t} measures the increase in the NPV of the supply chain system for a marginal increase in the environmental carrying capacity. When $\lambda_{1t} > 0$, the environmental constraint is active, and according to the complementary condition (19.5), the following equation is established:

$$Y - Q(E_{mt}^{u} + mE_{st}^{u}) + (1+g)^{t-1} Q_{1}^{e} (E_{mt}^{u} + mE_{st}^{u} - E_{mt}^{e} - mE_{st}^{e}) = 0 \tag{23}$$

The above shows that pollution emitted by both EFPs and EUFPs simply consume all of the environmental carrying capacity allocated to the supply chain system. This implies that the pollution becomes controlled and balanced by introducing EFPs in order to comply with the environmental constraint. Assuming that the environmental constraint set by the government is unchanged, we may infer that the supply chain system should pursue maximum profits with production quantities to consume all of the allowed environmental tolerances. Consequently, in the first period, the environmental constraint would be active with λ_{1t} > 0. In subsequent periods, however, since the total emissions of the supply chain system are reduced by the gradually increasing replacement of EUFPs with EFPs, the environmental constraint becomes inactive with λ_{1t} = 0 for t > 1, meaning that the pollution emitted by the supply chain system is under the environmental constraint. By rewriting Equation (23), the initial optimal sales quantity, denoted by Q_{1}^{e*}, is as follows:

$$Q_{1}^{e*} = \frac{Q\left(E_{mt}^{u} + mE_{st}^{u}\right) - Y}{(E_{mt}^{u} + mE_{st}^{u} - E_{mt}^{e} - mE_{st}^{e})} \tag{24}$$

As shown above, the numerator denotes the pollutant emissions that need to be reduced in order to comply with regulation standards, while the denominator denotes the pollutant emissions that can be reduced per unit of the final product through the supply chain system. We can see that the determination of manufacturers' initial optimal sales quantities is affected by the environmental constraint and it depends on the total pollutant emissions that need to be reduced to comply with the environmental constraint. In addition, the more pollutants there are, the larger the EFPs' initial sales quantities would be. This implies that more pollutant emissions over the environmental standard (caused by EUFPs) require larger initial sales quantities of EFPs, which coincides with intuition. Conversely, we also see that, with larger differences between pollutant emissions of EUFPs and EFPs (i.e., low emissions of E_m^e and E_s^e), the optimal initial sales quantities become smaller. This is because the environmental constraint (Y) is fixed so that less EFP quantities are required to replace the EUFPs when complying with the environmental standard.

4.3.3 Government subsidy decisions

λ_{2t} measures the increase in the NPV of a supply chain system for a marginal increase in the government's net environmental disposal cost savings by reducing environmental externalities. This implies that the joint efforts of both regulations and government policy incentives play an important role in enabling supply chain firms to take initiatives to participate in environmental technology investments. From Equation (19.2), we can obtain the following:

$$\lambda_{2t} = \frac{e^{-rt}}{(1+g)^{t_N} - 1} > 0 \quad \text{for } \alpha_t > 0 \tag{25}$$

We can see that, according to the complementary condition (19.6), the regulation constraint is active. Therefore, the optimal government subsidy rate denoted by α_t^* can be calculated as follows:

$$\alpha_t^* = \frac{b[Z_t^u - Z_t^e - (F_{mt}^u + mF_{st}^u)Q_1^e(1+g)^{t-1}][(1+g)^{t_N} - 1]}{(1+g)^{t-1} g[\sum_{t=1}^{t_N}(C_{mt}^e + mP_{st}^e - C_{mt}^u - mP_{st}^u)(1+g)^{t-1}Q_1^e + I_m]} \tag{26}$$

where Q_1^{e*} is determined by Equation (24), and P_{st}^{e*} is determined by Equation (12). The purpose of the government subsidy is to compensate for the incremental costs incurred for reducing environmental externalities, and it intends to help supply chain firms overcome the cost disadvantage of EFPs in the competitive market during the initial period. Eventually, the environmental restoration cost can be significantly reduced through the replacement of EUFPs by EFPs. From Equation (26), we can see that the cost factor of the government subsidy per unit is negatively related to supply chain firms' accumulated incremental costs. The implication is that the longer that the EFPs take to reach break-even, the less the value of α_t will be, i.e., α_t will decrease by time periods as the sales quantities of EFPs gradually increases. In our model, the optimal subsidy rate may vary annually depending on changes in the sales volumes. With a steady increase in EFPs' sales volumes and the decline in the incentive impact of the government subsidy, the government will reduce or cease the subsidy at the proper time. When the supply chain system's NPV reaches break-even at time point t = t_N, there will be no subsidy ($\alpha = 0$ and $B_m = 0$). Consequently, the constraint (17.3) becomes inactive so that $\lambda_{2t_N} = 0$ for t > t_N.

4.3.4 Suppliers' order quantity decisions

λ_{4t} measures the increase in the NPV of the supply chain system for a marginal decrease in inventory costs. Using the EOQ method, the inventory policy is optimum when the inventory holding costs are equal to the ordering costs. According to Equation (19.8), when the ordering costs are equal to the inventory holding costs, we have $\lambda_{4t} > 0$, which means that, as the marginal inventory costs decrease, the NPV of the supply chain increases. The optimal ordering time is computed as follows:

$$q_t^* = \sqrt{\frac{m\left(C_h^e - C_h^u\right)(1+g)^{t-1}Q_1^{e*}}{2\left(C_o^e - C_o^u\right)}} \quad (27)$$

where the optimal initial product quantity of EFPs is determined from Equation (24). The ordering time also depends on the growth rate of the EFPs and the incremental costs of both inventory holding and ordering. As analyzed above, we show that the supply chain system's NPV of producing EFPs is maximized by optimizing the EFPs' optimal operations strategies characterized by sales quantities, sales price, and government subsidy rates, where the environmental constraint determines the initial sales quantities, the market constraint determines the sales price, and the regulation constraint determines the government subsidy rates.

5 Numerical analysis

In this section, we present a case analysis to quantify the impact of government policy incentives (penalties for EUFPs and subsidies for EFPs) on surviving an integrated environmental sustainable supply chain using hybrid vehicles as an example. A case study can be comprehended as a particularly useful approach for assessing "real world" example allowing direct observation of the field, which is an empirical enquiry that investigates a contemporary phenomenon within its real life context (Seuring, 2008; Yin, 2003). Our case example conducts the contemporary phenomenon in its real life context in China concerning the impact of firms' business behaviors on the environment. The purpose here is to provide managerial insights into supply chain firms' environmental decisions. Based on the analytical work above, we apply the model to an invested hybrid vehicle project that is carried out by an automobile manufacturer. Our numerical analysis quantifies the optimal solutions to the hybrid vehicle's commercial feasibility, market diffusion, break-even, and self-sustainability throughout its lifecycle. In this case, the products are mainly hybrid passenger vehicles with energy saving features and emission reductions, which present a typical case of an EFP investment project.

5.1 Data generation

In our numerical study the related information and estimated data are based on real-world data that were gathered through the interview with the management staffs of the company, which is helped with the relations built with the case company. In the case reality, the hybrid vehicles produced by the automotive manufacturer are used for the public transportation in large cities with the intention of reducing vehicle emissions, and the governments provide subsidy to the case company for compensating its increased costs for producing the hybrid vehicle. The employed data (see Table 2) are estimated (on average) based on the market situation of an automobile company that produces conventional vehicles and is also engaged in hybrid vehicle production in order to replace the conventional ones. Though the data presented in the numerical example are relatively proportional in a way to those obtained from the interview, but they are ensured for their validity and reliability in the sense that the real matter concerned is that how much of the government subsidy offered would be just enough to effectively motivate the company to invest in the production of hybrid vehicle. Our numerical example using the gathered data works properly for gaining the insight of the effectiveness of government policies for given cost and price parameters of any type of the EFPs, providing an illustration of the logic thinking concerning the mechanism of internalizing environmental externality from both views of the government and the business firms.

Insert Table 2 here

Note that the transfer price of the EFPs is estimated by adding the average incremental cost per unit of the EFPs to the transfer price of the EUFPs, i.e., $P_s^e = P_s^u + \left(C_s^e - C_s^u\right) + I_s / m\sum_{t=1}^{t_N} Q_t^e$.

5.2 Results and discussion

Table 3 presents the results using the Solver Tool in Excel, with time periods including the EFPs' initial development periods.

Insert Table 3 here

As seen in Table 3, in year t = 8, the NPV of the supply chain system reaches zero, becomes break-even, and begins to earn a profit. For the given usage cost of the EFPs, the optimal product price is 1.23 million RMB/vehicle, the annual optimal initial sales quantity is Q_1^{e*} = 3500, and the optimal subsidy rate gradually decreases from 0.27 to zero soon after $\Delta NPV = 0$; i.e., beyond the 8th year, the supply chain system earns a profit and the government ceases its subsidy. The numerical results show that the inventory delivery time varies from 30 to 45 times per year with an ordering interval of approximately 8–10 days on average, thus implying that a change in EFP sales quantities does not have much influence on inventory delivery times. The entire process of the supply chain collaboratively reducing environmental externalities can be divided into two stages, i.e., the initial development stage for $t \le t_N$ ($\Delta NPV \le 0$), followed by growth to a steady stage for $t > t_N$ ($\Delta NPV > 0$). The evolving path of the sustainable constraints is shown in Table 4.

Insert Table 4 here

From the numerical analytic results, we obtain some non-trivial findings that reflect the interplay and interrelation of the environmental sustainable constraints. As shown in Table 4, we can see that, with constant emission tolerance, the environmental constraints turn out to be inactive during the initial periods of EFP project development (except for the first period), which may not be intuitively sensed. The implication here is that supply chain firms have a trade-off in determining the initial optimal sales quantities of EFPs while complying with the environmental constraints. Rationally, they will continue to pursue, not only to be economically optimal, but also environmentally feasible. Driven by the nature of maximizing their own benefits, supply chain firms try to create a balance between gaining benefits from the government subsidy and losing the profits of the EUFPs as they are replaced by the EFPs. Since the marginal profits of the EUFPs are larger than the marginal benefits of the government subsidy (α<1), the firms often fully utilize the constrained emission tolerance by producing as many EUFPs as possible. This means that, in the first period (t=1), the EUFPs that have to be replaced is just enough to fulfill the environmental constraint. During subsequent periods, as the environmental standards (assuming they are unchanged) do not become tighter for t>1, the environmental constraints become inactive since more EFPs are produced with less pollutant emissions.

As for the regulation constraint, we can see from Equation (25) that, as operational processes continue with increases in sales volumes, the value of λ_{2t} decreases, meaning that the regulation constraint will gradually become inactive. The implication is that, as EFP quantities increase, the regulation constraint becomes inactive when the EFP project reaches break-even. The government subsidy per unit α_t decreases with time (market diffusion) and reduces to zero soon after ΔNPV becomes positive. As shown in Table 3, for instance, after the 8th year in which the supply chain reaches break-even, $\alpha_9 = 0$ in the 9th year. This is because the purpose of the government subsidy is to compensate for the incremental costs associated with producing EFPs. In addition, the government will stop providing the subsidy when the EFP project reaches break-even, i.e., the government subsidy does not apply to any circumstances in which a profit is gained.

The results in Table 4 show that the market constraints tend to remain active due to the firms' profit-driven nature. According to Equation (14), for given values of k (< 1), U_t^e, and U_t^u (preferably with $U_t^e \leq U_t^u$), we have $P_{mt}^e > P_{mt}^u$. Consequently, the firms will likely charge a higher price premium for maximizing their marginal profits, as long as the price premium is acceptable to the consumers. This implies that the total purchase and usage costs of the EFPs per unit will be no less than (i.e., equal to) that of the EUFPs.

In our model's setting, some factors that have relatively important impacts on supply chain firms' environmental decision-making behaviors are assumed to be unchanged. These factors, however, may be dynamically adjusted in practice. For instance, as the reduction of environmental externalities gradually improves, the environmental constraint regulated by the government (Y) may then be adjusted to become stricter. By choosing the parameters, such as the coefficient of government policy incentives (b), government penalties (F_{mt}^u, F_{st}^u), environmental constraint (Y), and consumers' sensitivity to environmental quality (k), sensitivity analysis is performed to gain insights into their dynamic impacts on optimal solutions. The results are shown in Tables 5–9.

Insert Tables 5–9 here

Table 5 presents the impact of policy incentives on optimal decision outcomes. More specifically, it shows that, as the coefficient of the government policy incentives (b < 1) increases, B_{mt}, α_t, and ΔNPV_t all increase, the time to economic break-even t_N becomes shorter, and vice versa. When b = 0.15, for instance, the government total subsidies are $\sum_{t=1}^{t_N} Q_t^e B_{mt} = 2040.526$ million RMB for t_N = 8 and when b = 0.5, the government total subsidies are $\sum_{t=1}^{t_N} Q_t^e B_{mt} = 5361.717$ million RMB for t_N = 6, with an additional expenditure of 3321.201 million RMB. However, through experimental tests, we find that when b = 0.5, the supply chain system reaches break-even in six years. However, there would be $\alpha_{t=1}$ = 0.72, which is considered rather high. This implies that, if the total government subsidy per year is set to be one-half of the annually reduced environmental externality costs, then the government subsidy in the first year would be a quite high amount that compensates for over 70% of the manufacturer's average incremental costs of the EFPs per unit. However, it is questionable whether supply chain firms could be effectively motivated to become innovative in such a case. In this sense, the value of the coefficient b should be set relatively low enough to achieve eco-effectiveness.

Table 6 presents the impact of government penalties (F_{mt}^u, F_{st}^u) on the optimal decision outcomes. As shown in the table, we can see that, as the penalty increases, the required B_{mt} becomes less, which is consistent with Equation (11.1). This implies that stricter supervision measurement has an effect on urging supply chain firms to improve their environmental performance while less government subsidies are being spent. The computation results also show that increasing of penalties has a positive impact on ΔNPV_t, which is consistent with Equation (8). In this case, the higher the penalties, the larger the NPV of the supply chain and the shorter the time it takes to reach break-even. This is because when we introduce EFPs, the same quantity of EUFPs is replaced, meaning that the penalties on the replaced EUFPs are saved as opportunity revenues. The implication here is that by imposing heavy penalties on EUFPs, it has a double dividend effect on driving supply chain firms to reduce the production of EUFPs.

Table 7 presents the impact of environmental standards, denoted by Y on the optimal decision outcomes. As shown in the table, it can be seen that, the stricter the environmental standards, the more actively supply chain members are required to invest in EFP production. This is consistent with the intuition that, whenever environmental carrying capacity is challenged by severely increased pollutant emissions, the more environmentally friendly activities (e.g., environmental investments) are required along with stricter environmental standards to improve the environmental state. It is noted that the environmental carrying capacity is naturally determined depending on local environmental circumstances. To have a safeguard for keeping the level of pollutant emissions away from environmental carrying capacity, environmental standards should be set below environmental carrying capacity. Thus, in reality, the level of the environmental constraint (environmental standards) that the firms must comply with should actually be set lower than the environmental carrying capacity. Conversely, if the environmental constraint is relaxed, for instance, up to the level of Y = 28000, as shown in Table 7 (although, in reality, such a loose level of environmental standards unlikely represents a true environmental carrying capacity), the results show that with such a loose environmental constraint, even with a high amount of the government subsidy the EFP sales quantities are much less than they should be. Consequently, since the investment payback period becomes much longer, supply chain firms do not have any incentive to invest in EFPs. This is because few EFPs are legislatively enforced for reducing pollutant emissions when the environmental standards are very loosely set. In response, the firms would simply continue to produce EUFPs, which implies that it would not make any sense to have the firms invest in EFPs when the environmental standards are loosely set, especially since they are not under pressure to improve their environmental performance. This demonstrates that the level of the environmental standards that firms need to comply with are necessarily be set low enough to drive the improvement of the firms' environmental performance.

Table 8 presents the impact of pollution emitted by supply chain firms' EFPs per unit (E_m^e and E_s^e) on their optimal decision outcomes. E_m^e and E_s^e reflect the emission levels of manufacturers and suppliers when they produce EFPs. In this case, the lower the emission levels of E_m^e and E_s^e, the more efficient the environmental technology (normally, high green investments are required). For a given level of the environmental constraint (environmental standard), with lower emission levels of E_m^e and E_s^e, the less quantities of EFPs are required for complying with the environmental standard. That is, the less that EFPs are produced for replacing EUFPs, the longer it takes to reach break-even when additional investments and incremental costs do not decrease. As shown in Table 8, for E_m^e = 0.5 (lower emissions), the optimal sales quantities become less (which is consistent with Equation (24)), which is accompanied with increased government subsidies and a longer time to reach break-even (t_N = 9). This may increase the possibility of unacceptable commercial feasibility. On the contrary, when E_m^e =1.5 (higher emissions), for the same environmental standard, the optimal sales quantities become larger so that the government subsidy decreases and the time to reach break-even shortens (t_N = 6), which, in turn, increases overall commercial feasibility. The implication here is that (from the commercial feasibility viewpoint) when enforcing a stricter environmental standard we also need to consider that, for an advanced environmental technology to be used, whether the required high capital investment and incremental cost are acceptable for the market, it depends on the level of the environmental standard that must be complied with. That is, reducing the emissions levels of E_m^e and E_s^e should be accompanied with an acceptable level of additional investments and incremental costs required to become commercially feasible, especially since the firms' willingness to take the initiative greatly depends on their economic trade-offs due to their profit-driven nature. In order to promote supply chain firms' environmental behavior and further improve their environmental performance, the government may adjust the environmental constraint (environmental standard) according to the firms' environmental performance and regional environmental conditions. As the regional environmental conditions and the firms' environmental performance improve, the government may even enforce stricter emission standards. As a feasible approach, the government may implement a step-wise policy in which environmental standards are periodically tightened depending on regional environmental conditions, which may particularly suit developing countries. Since pollutant emissions are high in developing countries, it is often difficult to enforce local firms to reduce their pollutant emissions while complying with new, stricter environmental standards, due to the high capital investments and incremental costs of green initiatives that local firms are unwilling to accept (or unaffordable). In such circumstances, periodically tightening the environmental standard would be easier for a government to implement environmental policies on the one hand; while on the other hand, it would be easier for supply chain firms to cooperatively improve their environmental performance in a step-by-step approach. In sum, based on the tightening of the environmental standard, supply chain firms will significantly improve their environmental performance and overcome the challenge of economic feasibility during the process of reducing environmental externalities.

Table 9 presents the impact of consumers' sensitivity to environmental quality (k) on the optimal decision outcomes. As shown in the table, k directly affects product price decisions. The more that consumers prefer a product's environmental quality, the more likely the firms will charge a higher price for the EFPs, and vice versa. For instance, for k = 0.15, the sales price of the EFP is P_{mt}^{e} = 1305.88 with a higher price premium, and the time to reach break-even is reduced to seven years. Naturally, how likely the EFPs can be sold with a price premium in the market depends on the tendency of consumers' environmental quality preference. For instance, for k = 0.05, the sales price of the EFP is comparatively much lower (P_{mt}^{e} = 1168.42) with a lower price premium, thus implying that, when consumers have less environmental awareness, the EFPs are less acceptable in the competitive market and it will take longer to reach break-even. In other words, it is the consumers' environmental awareness that differentiates the EFPs from the competitive market, but the consumers' tendency of environmental awareness also depends on their living standards that are interrelated with price sensitivity. This, in turn, depends on local economic development. This intrinsic causality reflects the essence of the conflicts behind the trade-off between economic development and environmental production.

There are several insights gained from the aforementioned sensitivity analysis. As an important factor that impacts supply chain firms' eco-efficiency behaviors, the optimal decision policy of the government subsidy needs more attention. Government policy incentives play a key role for motivating supply chain firms to reduce their environmental impacts via investments in green technology. However, the amount of subsidies needs to be properly justified so that the firms can be effectively driven to innovate their environmental activities and increase eco-efficiency.

When marketing EFPs, we should be aware of the interplay effects of consumers' environmental awareness on the EFPs' market diffusion. In addition, the tendency of consumers' environmental awareness is interrelated with their living standards, price sensitivity, and local economic development state, which reflects the causality of the conflicts behind the trade-off between economic development and environmental protection.

Another aspect that needs to be examined is the setting of proper environmental standards. Since environmental carrying capacity naturally depends on the characteristics of local environmental circumstances, the environmental standards complied by firms' business activities should be set low enough in order to keep the level of pollutant emissions away from environmental carrying capacity and safely protect the environment.

Whenever the environmental constraint changes, the supply chain system has to redo the optimization, which leads to changes in supply chain members' optimal sales quantities decisions and government policy incentives. Through the adjustment of the environmental constraint, firms have to continually improve their environmental technologies in order to comply with the tightened environmental standards, and enlarge their friendlier production volumes to be consistent with the environmental ecosystem. In this regard, government regulation policies play a leading role that oversees the evolving path of the environmental constraint and guides the reduction of the pollution emitted by supply chain firms.

Another interesting finding is that, for given constant EFPs' usage costs over periods of time, the market constraint tends to be active throughout the project's entire lifecycle. This actually reflects firms' business nature of profit-driven maximization. This may also be explained by the example of an individual consumer who is concerned with environmental quality. In this case, he/she would tend to buy the EFP by paying a price premium, as long as its total purchase and usage cost does not exceed that of the EUFP. However, being aware of this, the supply chain system should optimize the final product price to maximize its NPV so that the total purchase and usage cost of the EFP remains the same as that of the EUFP. As for the consumers, they will be content with the use of green products that comfort their environmental preferences without paying more total costs.

We can also think of a situation in which the EFP usage cost tends to decrease when the market gradually becomes mature, thus leading to the possibility that the use of EFPs is cheaper than EUFPs. The reduction of usage cost requires a mature market condition for EFPs to be acceptable in terms of consumers' usability. For instance, by looking at an example of a hybrid vehicle, a more developed infrastructure, such as a charging station network, etc., helps reduce the usage cost of the hybrid vehicle. As the usage cost decreases, another issue may appear: owing to their profit-driven nature, firms may price EFPs even higher in order to balance the reduction of the usage cost with the intention of keeping the constraint to remain at $P_{mt}^{e}(1-k)+U_{t}^{e}=P_{mt}^{u}+U_{t}^{u}$. However, in a competitive market, this may not be realistic, since the firms often have limited room to differentiate their product prices from other competitive products. For this reason, with the reduction of usage costs and limited room for price adjustments, the market constraint may favor EFPs, especially after the firms reach steady production.

6 Conclusion

By introducing multiple constraints (i.e., the environmental externalities and stakeholders' environmental interests) in the model, this study analyzes the economic performance of an environmental sustainable supply chain from the perspectives of supply chain firms and the government. The main contributions of this study include: (1) Delving into the mechanism for the government to drive businesses (producers in the supply chain context) to take initiatives to effectively control and prevent pollution and (2) Analyzing supply chain firms' operations strategy decisions for producing EFPs through the development of an integrated supply chain model that incorporates government regulation and incentives as well as consumers' environmental concerns. It is even more important in promoting the producer responsibility principle on environment protection through collaboration among supply chain firms, as environmental protection is never a single party's responsibility. Supply chain firms' environmental decisions are not only interrelated with the economic feasibility of their green investments but also they are driven by the sustainable constraints that represent stakeholders' environmental interests. For motivating supply chain firms to engage in the investment of EFPs, realizing break-even (in the competitive market) within a finite time period is the backbone of self-sustainability along with environmental sustainability.

From the research findings we can conclude the following. First, manufacturer's price decisions are mainly determined by the market constraint that represents consumers' environmental awareness. This is intuitively true since, in reality, consumers who have environmental preferences will accept a price premium. However, for those who have less environmental consciousness, being price sensitive is the normal case. There also exists an interplay effect of consumers' environmental awareness on the market diffusion of EFPs, which interrelates consumers' environmental quality concerns with their living standards and local economic development. This actually indicates the important role of government incentives for helping EFPs go through its market diffusion process. Second, decisions regarding EFPs' optimal initial quantities are constrained by the total environmental carrying capacity allowed for the integrated supply chain. Moreover, the sequence of EFPs' sales quantities goes through an initial development (market diffusion) period toward break-even. The determination of optimal product quantities is also jointly affected by the environmental standard and the pollutant emission level of supply chain firms. Third, the government's optimal subsidy decision is influenced by both the supply chain firms' additional (green) investments and incremental operating costs, and the government's environmental rehabilitation cost savings are brought about by reducing environmental externalities. Furthermore, the government subsidy rate reduces over time and eventually down to zero soon after the ΔNPV becomes positive, implying that, as the EFPs' sales quantities increase, the subsidy rate decreases. This is natural since, with more sales quantities, EFPs hold a better position in the market. Consequently, there is less cost disadvantage with a higher likelihood of self-sustainability so that less subsidy is required to reach break-even. From the above analysis, we can see that the key role of the government subsidy is to help supply chain firms overcome the cost disadvantage of implementing EFPs in the competitive market and ultimately become self-sustaining after going through the initial EFP diffusion period.

In sum, our findings indicate that the mechanism of reducing environmental externalities embodies supply chain firms' collaboration of making green investments motivated by the government policy incentives, which, in turn, improves eco-efficiency and environmental protection. This also provides insights into achieving Pareto optimality with the unification of supply chain firms' decision behaviors, stakeholders' environmental interests, and social welfare.

Finally, for further study, it would be interesting to explore how to smooth out the collaboration between various partners within a supply chain system. In other words, we should investigate how to effectively mediate any conflicts and unify the interests among the individual supply chain partners in order to reduce environmental externalities. Another research potential would extend the model into a multi-echelon supply chain system or integrating the social dimension into the model.

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Table 2 Initial investment cost and operating parameters

Pollution prevention initial investment cost items	Million
Investment of manufacturer (I_m)	4000
Investment of supplier (I_s)	3500

Operating data items

Item	Thousand/Unit	Item	Thousand/Unit	Item		Item		Item	Million/Year
P_m^u	1100	P_s^u	300	b	0.15	Y	25,000	Z^u	3000
C_m^e	350	C_s^e	250	r	5%	E_m^e	1/unit	Z^e	600
C_m^u	300	C_s^u	200	m	2	E_s^e	0.5/unit		
F_m^u	60	F_s^u	30	k	0.1	E_m^u	2/unit	Item	Quantity
W_{mt}^u	30	W_{st}^u	30	g	0.15	E_s^u	1/unit	Q	8000
W_{mt}^e	10	W_{st}^e	10						
C_o^e	10	C_h^u	1.0			$P_s^e = P_s^u + \left(C_s^e - C_s^u\right) + I_s / m \sum_{t=1}^{t_N} Q_t^e$			
C_o^u	8	C_h^e	1.5						

Table 3 Numerical results of optimal solutions

	t=1	t=2	t=3	t=4	t=5	t=6	t=7	**t=8**	t=9	t=10
Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
α_t	0.27	0.23	0.19	0.16	0.13	0.11	0.09	0.09	0.00	0.00
B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	27.00	0.00	0.00
P_{mt}^e (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
q_t	30	31	33	34	36	38	39	41	43	45

ΔNPV (million)	-6672.82	-5815.84	-4923.87	-3991.38	-3012.37	-1980.42	-898.44	**132.03**	974.18	1776.24

Table 4 Evolution of the environmental sustainable constraints

	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
Environment constraint-	+	-	-	-	-	-	-	-	-	-
Regulation constraint	+	+	+	+	+	+	+	+	-	-
Market constraint	+	+	+	+	+	+	+	+	+	+
Inventory constraint	+	+	+	+	+	+	+	+	+	+

Note: "+"refers to the constraint is active, "**-**"refers to the constraint is inactive.

Table 5 Impact of policy incentives (b) on the optimal decision outcomes

		t=1	t=2	t=3	t=4	t=5	t=6	t=7	**t=8**	t=9	t=10
b=0.15 (Base level)	Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.27	0.23	0.19	0.16	0.13	0.11	0.09	0.09	0	0
	B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	27.00	0	0
	P_{mt}^{e} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	q_t	30	31	33	34	36	38	39	41	43	45
	ΔNPV (million)	-6672.82	-5815.84	-4923.87	-3991.38	-3012.37	-1980.42	-898.44	**132.03**	974.18	1776.24
		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	**t=10**
b=0.05	Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.10	0.09	0.07	0.06	0.05	0.04	0.03	0.03	0.03	0.03
	B_{mt} (thousand)	28.29	23.81	19.92	16.54	13.60	11.05	9.00	9.00	9.00	9.00
	P_{mt}^{e} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	q_t	30	31	33	34	36	36	39	41	43	45
	ΔNPV (million)	-6861.39	-6178.29	-5445.66	-4658.06	-3809.55	-2893.65	-1914.00	-981.01	-92.44	**753.82**
		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	**t=9**	t=10
b=0.10	Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000

	α_t	0.20	0.17	0.14	0.12	0.09	0.08	0.06	0.06	0.06	0
	B_{mt} (thousand)	56.57	47.63	39.85	33.09	27.21	22.09	18.00	18.00	18.00	0
	P^e_{mt} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	q_t	30	31	33	34	36	36	39	41	43	45
	ΔNPV (million)	-6767.11	-5997.06	-5184.77	-4324.72	-3410.96	-2437.04	-1406.22	-424.49	**510.49**	1312.60
b=0.20		t=1	t=2	t=3	t=4	t=5	t=6	t=7	**t=8**	t=9	t=10
	Q^{e*}_t	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.36	0.31	0.26	0.21	0.18	0.14	0.12	0.12	0	0
	B_{mt} (thousand)	113.14	95.25	79.70	66.17	54.41	44.18	36.00	36.00	0	0
	P^e_{mt} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	q_t	30	31	33	34	36	36	39	41	43	45
	ΔNPV (million)	-6578.54	-5634.61	-4662.98	-3658.04	-2613.79	-1523.81	-390.65	**688.54**	1530.70	2332.81
b=0.25		t=1	t=2	t=3	t=4	t=5	t=6	**t=7**	t=8	t=9	t=10
	Q^{e*}_t	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.30	0.26	0.21	0.18	0.15	0.12	0.10	0	0	0
	B_{mt} (thousand)	141.43	119.07	99.62	82.72	68.01	55.23	45.00	0	0	0
	P^e_{mt} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	q_t	30	31	33	34	36	36	39	41	43	45
	ΔNPV (million)	-6484.25	-5453.39	-4402.08	-3324.70	-2215.20	-1067.19	**117.13**	1001.39	1843.55	2645.66
b=0.5		t=1	t=2	t=3	t=4	t=5	**t=6**	t=7	t=8	t=9	t=10
	Q^{e*}_t	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.72	0.60	0.50	0.42	0.34	0.28	0	0	0	0
	B_{mt} (thousand)	282.86	238.14	199.25	165.43	136.03	110.46	0	0	0	0
	P^e_{mt} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33

	q_t	30	31	33	34	36	36	39	41	43	45
	ΔNPV (million)	-6012.82	-4547.27	-3097.61	-1657.98	-222.26	**1215.88**	2144.36	3028.62	3870.78	4672.89

Table 6 Impact of penalties on the optimal solution ΔNPV (Million)

	b=0.15, F_s^u =30 Thousand/Unit									
	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
F_{mt}^u =50	-6701.16	-5875.20	-5017.22	-4121.96	-3183.72	-2196.42	-1162.76	-178.32	**759.23**	1512.23
F_{mt}^u =55	-6686.99	-5845.52	-4970.55	-4056.67	-3098.05	-2088.42	-1030.60	-23.15	**936.33**	1713.88
F_{mt}^u =60	-6672.82	-5815.84	-4923.87	-3991.38	-3012.38	-1980.42	-898.44	**132.02**	974.18	1776.29
F_{mt}^u =65	-6658.66	-5786.15	-4877.20	-3926.09	-2926.70	-1872.42	-766.28	**287.20**	1155.14	1981.80
F_{mt}^u =70	-6644.49	-5756.47	-4830.52	-3860.80	-2841.03	-1764.42	-634.11	**442.37**	1336.10	2187.32
	b=0.15, F_m^u =60 Thousand/Unit									
	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
F_{st}^u =30	-6672.82	-5815.84	-4923.87	-3991.38	-3012.38	-1980.42	-898.44	**132.02**	974.18	1776.29
F_{st}^u =35	-6644.49	-5756.47	-4830.52	-3860.80	-2841.03	-1764.42	-634.11	**442.37**	1336.10	2187.32
F_{st}^u =40	-6616.16	-5697.11	-4737.17	-3730.23	-2669.69	-1548.43	-369.79	**752.72**	1698.02	2598.35
F_{st}^u =45	-6587.82	-5637.74	-4643.82	-3599.65	-2498.34	-1332.43	-105.47	**1063.07**	2059.93	3009.38
F_{st}^u =50	-6559.49	-5578.38	-4550.46	-3469.08	-2327.00	-1116.43	**158.86**	1259.71	2308.14	3306.70

Table 7 Impact of environmental constraint (Y) on the optimal decision outcomes

	b=0.15, F_{mt}^u =60 Thousand/Unit, F_{st}^u =30 Thousand/Unit										
		t=1	t=2	t=3	t=4	t=5	t=6	t=7	**t=8**	t=9	t=10
Y=25000 (Base level)	Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.27	0.23	0.19	0.16	0.13	0.11	0.09	0.09	0.00	0.00
	B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	27.00	0.00	0.00
	P_{mt}^e (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	ΔNPV (million)	-6672.82	-5815.84	-4923.87	-3991.38	-3012.37	-1980.42	-898.44	**132.03**	974.18	1776.24
Y=200		t=1	t=2	t=3	t=4	t=5	t=6	**t=7**	t=8	t=9	t=10

00	Q_t^{e*}	6000	6600	7260	7986	8000	8000	8000	8000	8000	8000
	α_t	0.14	0.12	0.09	0.09	0.09	0.09	0.09	0	0	0
	B_{mt} (thousand)	42.00	34.17	27.37	27.00	27.00	27.00	27.00	0	0	0
	P_{mt}^{e} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	ΔNPV (million)	-6326.83	-5090.91	-3783.91	-2531.37	-1338.49	-202.40	**879.58**	1763.85	2606.00	3408.11
Y=23000		t=1	t=2	t=3	t=4	t=5	t=6	**t=7**	t=8	t=9	t=10
	Q_t^{e*}	4500	5175	5951	6844	7871	8000	8000	8000	8000	8000
	α_t	0.14	0.12	0.09	0.09	0.09	0.09	0.09	0	0	0
	B_{mt} (thousand)	62.00	51.57	42.49	34.60	27.74	27.00	27.00	0	0	0
	P_{mt}^{e} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	ΔNPV (million)	-6534.43	-5525.87	-4467.89	-3353.57	-2175.43	-1039.34	**42.64**	926.91	1769.06	2571.17
Y=24000		t=1	t=2	t=3	t=4	t=5	t=6	t=7	**t=8**	t=9	t=10
	Q_t^{e*}	4000	4600	5290	6084	6996	8000	8000	8000	8000	8000
	α_t	0.14	0.12	0.09	0.09	0.09	0.09	0.09	0.09	0	0
	B_{mt} (thousand)	72.00	60.26	50.05	41.18	33.46	27.00	27.00	27.00	0	0
	P_{mt}^{e} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	ΔNPV (million)	-6603.63	-5670.85	-4695.88	-3672.48	-2593.90	-1457.82	-375.83	**654.63**	1496.78	2298.89
Y=26000		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	**t=9**	t=10
	Q_t^{e*}	3000	3450	3968	4563	5247	6034	6939	7980	8000	8000
	α_t	0.34	0.29	0.24	0.20	0.17	0.14	0.11	0.09	0.09	0
	B_{mt} (thousand)	102.00	86.35	72.74	60.90	50.61	41.66	33.88	27.11	27.00	0
	P_{mt}^{e}	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	ΔNPV (million)	-6742.02	-5960.82	-5151.86	-4310.28	-3430.85	-2507.95	-1535.52	-507.02	**474.37**	1276.48
Y=28000		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
	Q_t^{e*}	2000	2300	2645	3041.75	3498.01	4022.71	4626.12	5320.04	6118.05	7035.75
	α_t	0.53	0.46	0.39	0.33	0.28	0.23	0.20	0.16	0.13	0.11

	B_{mt} (thousand)	162.00	138.52	118.11	100.35	84.92	71.49	59.82	49.67	40.84	33.17
	P_{mt}^{e} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	ΔNPV (million)	-6880.40	-6250.77	-5607.81	-4948.04	-4267.74	-3562.93	-2829.37	-2062.49	-1257.37	-408.67

Table 8 Impact of pollutant emissions on the optimal decision outcomes

	b=0.15, F_{mt}^{u} =60 Thousand/Unit, F_{st}^{u} =30 Thousand/Unit, Y=25000, E_{s}^{e} =0.5										
		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
E_{m}^{e} = 1 (Base level)	Q_{t}^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_{t}	0.27	0.23	0.19	0.16	0.13	0.11	0.09	0.09	0.00	0.00
	B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	27.00	0.00	0.00
	ΔNPV (million)	-6672.82	-5815.84	-4923.87	-3991.38	-3012.37	-1980.42	-898.44	**132.03**	974.18	1776.24
E_{m}^{e} = 1.5	Q_{t}^{e*}	4666.67	5366.67	6171.67	7097.42	8000	8000	8000	8000	8000	8000
	α_{t}	0.19	0.16	0.13	0.11	0.09	0.09	0.09	0	0	0
	B_{mt} (thousand)	59.14	49.08	40.33	32.72	27.00	27.00	27.00	0	0	0
	ΔNPV (million)	-6511.36	-5477.54	-4391.89	-3247.27	-2054.38	-918.30	**163.69**	1047.95	1890.11	2692.21
E_{m}^{e} = 0.5	Q_{t}^{e*}	2800.00	3220.00	3703.00	4258.45	4897.22	5631.80	6476.57	7448.06	8000	8000
	α_{t}	0.35	0.30	0.25	0.21	0.18	0.15	0.12	0.10	0.09	0
	B_{mt} (thousand)	110.57	93.80	79.22	66.54	55.51	45.92	37.58	30.33	27.00	0
	ΔNPV (million)	-6769.70	-6018.81	-5243.06	-4437.84	-3598.24	-2718.96	-1794.30	-818.13	**163.26**	965.37
	b=0.15, F_{mt}^{u} =60 Thousand/Unit, F_{st}^{u} =30 Thousand/Unit, Y=25000, E_{m}^{e} =1.0										
E_{s}^{e} = 0.5		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
	Q_{t}^{e*}	3500	4025	4628.7	5323.0	6121.5	7039.7	8000	8000	8000	8000

(base level)				5	6	2	5				
	α_t	0.27	0.23	0.19	0.16	0.13	0.11	0.09	0.09	0.00	0.00
	B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	27.00	0.00	0.00
	ΔNPV (million)	-6672.82	-5815.84	-4923.87	-3991.38	-3012.37	-1980.42	-898.44	**132.03**	974.18	1776.24
E_s^e = 1.0		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
	Q_t^{e*}	7000	8000	8000	8000	8000	8000	8000	8000	8000	8000
	α_t	0.11	0.09	0.09	0.09	0.09	0.09	0	0	0	0
	B_{mt} (thousand)	33.43	27.00	27.00	27.00	27.00	27.00	0	0	0	0
	ΔNPV (million)	-6188.44	-4807.52	-3492.36	-2239.83	-1046.94	**89.15**	1017.62	1901.89	2744.04	3546.15
E_s^e = 0.1		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
	Q_t^{e*}	2500	2875.00	3306.25	3802.19	4372.52	5028.39	5782.65	6650.05	7647.56	8000
	α_t	0.42	0.36	0.30	0.26	0.21	0.18	0.15	0.12	0.10	0.09
	B_{mt} (thousand)	126.00	107.22	90.88	76.68	64.33	53.59	44.26	36.13	29.07	27.00
	ΔNPV (million)	-6811.21	-6105.80	-5379.85	-4629.18	-3849.32	-3035.47	-2182.48	-1284.79	-336.42	**598.30**

Table 9 Impact of consumers' environmental awareness on the optimal decision outcomes

	b=0.15, F_{mt}^u =60 Thousand/Unit, F_{st}^u =30 Thousand/Unit, Y=25000, E_m^e =1, E_s^e =0.5										
		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
k=0.05	Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.35	0.29	0.24	0.20	0.17	0.14	0.11	0.11	0.11	0.11
	B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	27.00	27.00	27.00
	P_{mt}^e (thousand)	1168.42	1168.42	1168.42	1168.42	1168.42	1168.42	1168.42	1168.42	1168.42	1168.42
	ΔNPV (million)	-6889.19	-6269.17	-5636.74	-4988.51	-4320.83	-3629.85	-2916.90	-2237.91	-1591.24	-975.32
k=0.1		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10

(Base level)	Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.27	0.23	0.19	0.16	0.13	0.11	0.09	0.09	0.00	0.00
	B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	27.00	0.00	0.00
	P_{mt}^{e} (thousand)	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33	1233.33
	ΔNPV (million)	-6672.82	-5815.84	-4923.87	-3991.38	-3012.37	-1980.42	-898.44	**132.03**	974.18	1776.24
		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
k=0.15	Q_t^{e*}	3500	4025	4628.75	5323.06	6121.52	7039.75	8000	8000	8000	8000
	α_t	0.25	0.21	0.17	0.14	0.12	0.10	0.08	0	0	0
	B_{mt} (thousand)	84.86	71.44	59.77	49.63	40.81	33.14	27.00	0	0	0
	P_{mt}^{e} (thousand)	1305.88	1305.88	1305.88	1305.88	1305.88	1305.88	1305.88	1305.88	1305.88	1305.88
	ΔNPV (million)	-6430.98	-5309.12	-4127.06	-2876.84	-1549.85	-136.76	**1357.72**	2634.83	3851.13	5009.57