

# Pricing, greening, and transparency decisions considering the impact of government subsidies and CSR behavior in supply chain decisions

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## Abstract

In this paper, we analytically model different government subsidy strategies in a supply chain manufacturing and selling a green product. We model the interaction between greening degree and transparency level set by a manufacturer and its impact on not only the supply chain, but also consumers and the government. The supply chain is composed of a manufacturer and a retailer. The manufacturer can choose two different strategies. First, he only cares about his production profit; and second, he concerns with CSR in addition to his production profit. We develop a new transparency-based index of consumer satisfaction to model how the market reacts to manufacturer CSR decisions. The government decide three different subsidy strategies. A three-stage Stackelberg game model is developed and solved to analytically derive managerial insights. As a result, if the transparency cost coefficient is sufficiently high, the greening degree and transparency level in CSR concerns strategy are higher than when the manufacturer is not concerned with corporate social responsibility. In addition, when the transparency cost coefficient is sufficiently high, the profit of supply chain members and government are equal in both strategies. We give a real-world example of Iranian brick industry.

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## 1 Introduction

The world is threatened by ecological and social issues such as: climate change, air pollution, energy consumption, and rising world population. Some may argue, that all societal parties: governments, individuals, and corporations, are responsible to mitigate these issues ([Goldsmith, 1980](#)). Government, interested in promoting and preserving social welfare, are already taking an active role in addressing the forementioned societal issues. For example, due to climate change, the Maldives is faced with complete submersion. In order to mitigate complete submersion, the Maldives government created United Nations climate legislation, and disbursed money to firms and consumers to make all parties aware of the issue and the actions each may take to decrease likelihood of complete submersion ([Mohamed and King, 2017](#); [Nachmany et al., 2017](#)). Just like the Maldives, China has realized that 28%, 42%, and 17% of the greenhouse gases,  $CO$ ,  $SO_2$ , and  $NO_x$ , respectively, emitted by the country ([Saikawa et al., 2017](#)) are due to the use of non-environmentally friendly products, also referred to as *non-green* products. Not only are green products necessary to address issues such as climate change, consumers must also trust and know which products are truly green, i.e., manufacturers must be *transparent* in their manufacturing practices ([Bemporad and Baranowski, 2007](#)). Governments can help firms become *greener*, develop environmentally friendly processes and products, via greening subsidies ([Sana, 2020](#); [Zhang et al., 2015](#)); governments can also help firms become *transparent*, make the environmental impact of their business practices and processes known to consumers, via transparency subsidies ([Yu et al., 2016](#); [Zhang et al., 2016b](#)). To help companies not only become greener, but also more transparent, from 1983 to 2015, the government of Canada gave \$915 million in subsidies to firms ([Rémillard, 2017](#)). Unfortunately, not all subsidies by governments are well spent. For example, \$2.3 billion of a total of \$9 billion of greening subsidies in the US had to be cut due to ineffectiveness ([Abdullah, 2010](#); [Gardner, 2011](#)). Clearly governments are already spending a significant amount of money on greening and transparency subsidies, unfortunately not all of these subsidies are effective. As such, in order to help address societal issues, such as climate change, we develop an analytical model of consumer behavior towards firms' greening and transparency decisions, and determine the profit (welfare) maximizing decisions a supply chain (government) make.

### 1.1 Sustainable development

As noted by [Goldsmith \(1980\)](#), addressing issues such as climate change, requires firms, governments, and citizens each to take an active role. Unfortunately, [Goldsmith \(1980\)](#) did not define the exact roles of each party when meeting environmental issues. Due to the urgency of environmental issues, world governments, industry leaders, and world citizens in a series of meetings defined their roles in order to address environmental issues, via a mutually developed framework referred to as

*Sustainable Development*. Sustainable Development (SD) is defined as “a development that fulfills the requirements of the present without jeopardizing the capability of next generations to meet their own needs” ([Brundtland et al., 1987](#)). However, to apply sustainable development, requirements of corporations (financial concerns) and citizens (social concerns) must also be considered, and not only environmental concerns. In order to combine environmental, societal, and financial concerns, firms are using the triple-bottom-line (TBL), proposed by [Elkington \(1997\)](#), to evaluate and determine their decisions. Even though the definition of TBL requires all three concerns (environmental, social, and financial) to be incorporated when firms make decisions, barring a few studies, the operation management sustainability literature focuses on only the environmental and financial aspects, thereby omitting any social aspects. In our paper, we contribute to the small, but growing, literature on using all three concerns, in the definition of the TBL, in a firm’s decision-making process.

## 1.2 Corporate social responsibility (CSR)

As previously discussed, social concern is a part of the TBL that firms consider. To consider social concerns, there are several responsibilities for firms referred to as *corporate social responsibility* (CSR). CSR, first defined by [Bowen \(1953\)](#), is the moral/legal operating constraints, in line with societal values and objectives, firms must consider when making decisions.

## 1.3 Transparency

An aspect of CSR is *transparency*, defined as the external impact of a firm’s actions is clear and available in the firm’s public reports ([Crowther and Martinez, 2004](#)). Just as CSR has moral and legal requirements, so does transparency ([de Mingo and Cerrillo-i-Martínez, 2018](#); [Grimmelikhuijsen and Kasymova, 2015](#)). Unfortunately, there are several definitions of transparency in the literature today based on the research area, with multiple authors proposing various valid definitions ([da Cruz et al., 2016](#); [Farrell, 2016](#); [Fritz et al., 2017](#)). For the remainder of this paper we use the [Crowther and Martinez \(2004\)](#) definition of transparency that is explained on the environmental transparency, stated at the start of this paragraph.

Enhancing transparency leads to benefit to Firms. When corporations disclose more information related to the influence of their actions on the environment, then customers can distinguish products that are ecologically friendly to those that are not, referred to as *green* and *non-green* products, respectively ([Zhang et al., 2020](#)). As transparency enables consumers to differentiate products based on their level of greenness, referred to as *greening degree*, corporations may now consider more expenses to increase greening degree of their products, as some buyers are agreeable to pay more money for such commodities ([An, 2013](#); [Egels-Zandén and Hansson, 2016](#)). A further byproduct of demand for green products and transparency is the greening of existing products as well as new ones. In this paper, we refer to the manufacturer’s determined level of transparency as *transparency level*.

Overall, sustainability is a very challenging concept these days which interests both academic and practical communities. As previously mentioned, sustainability has three aspects and CSR is an important concept, which play the social role of sustainability. As [Crowther and Martinez \(2004\)](#) mentioned, one of the most important parts of CSR is transparency, especially environmental transparency. Moreover Increasing transparency level can increase consumer satisfaction [Hegwer \(2015\)](#); [Simintiras et al. \(2015\)](#) argued that increasing transparency leads to an increase in consumer satisfaction. Hence, considering a consumer satisfaction index leads to having CSR measure, which supply chains can take into consideration. In this paper, we introduce an environmental transparency based index for consumer satisfaction, which makes a measure of CSR.

## **1.4 Literature review**

Our paper spans three streams of literature: corporate transparency, *green supply chain management*, which is defined as supply chain management using green products, and environmentally friendly processes ([Hervani et al., 2005](#)), and government intervention. In the next sections, we will first provide a summary of the work in each stream, identify the research gap presented in each stream, and discuss how our proposed work addresses the identified gap.

### **1.4.1 Transparency**

There are few papers on transparency on CSR and SD, some are related to the work we present in this paper. For example, [Haddad \(2015\)](#); [Langley \(2001\)](#); [Wognum and Bremmers \(2009\)](#) argue that sector-wide, such as food production and non-profit corporations, transparency results in all executives taking SD into account when making decisions. Some researchers take a firm-specific perspective and find that increased transparency increases SD ([Arena et al., 2015](#); [Li and Li, 2012](#)). [An \(2013\)](#); [Egels-Zandén et al. \(2015\)](#); [Vaccaro and Patiño Echeverri \(2010\)](#) empirically discover that transparency of supply chains has a favorable effect on willingness to pay of the customers for the supply chains commodities.

In the studies that focus on SD and use analytical modeling, none consider the impact of transparency, something we consider in this paper. As no existing work in SD considers transparency, it is also not surprising that consumer choice models also do not consider transparency. In this paper, we propose an analytical consumer choice model that accounts for not only a firm's SD decisions, but also the firm's transparency decision. Moreover, to the best of our knowledge, the effect of transparency on consumer satisfaction in analytical modeling has not been taken into account. We propose a new index of consumer satisfaction, which relies on transparency.

### **1.4.2 Green supply chain management**

As previously discussed, is also very important part of SD. Several researchers such as [Fang and Xu](#)

(2020); [Kumar et al. \(2017\)](#); [Liu and Chen \(2019\)](#); [Rajabion et al. \(2019\)](#), have been studied “green supply chain management” and argued that GSCM have a crucial rule in SD. For instance, [Jamali and Rasti-Barzoki \(2018\)](#) argued that greener products increase consumer demand. In the same papers, to the best of our knowledge, the authors determined the profit maximizing greening degree of the supply chain in a competitive environment.

Several studies in literature applied game theory to investigate green supply chain management. For example, surveying a green supply chain considering dual distribution way was taken into account by [Li et al. \(2016\)](#). They considered direct distribution method as well as using retailers to deliver a green product to customers. [Hafezalkotob \(2017\)](#) investigated the effect of government subsidies on applying energy saving technologies with three different approaches for the government. He applied game theory to analyze the competition between two supply chains. [Jamali and Rasti-Barzoki \(2019\)](#) studied the effect of using 3PL for transportation management in sustainable supply chain management. They considered a competition between a green and a non-green producer and analyzed the market in two scenarios. [He et al. \(2019\)](#) surveyed different channel structures in a closed-loop supply chain. They considered a dual-channel where the product can be received to the consumers using retailers or third parties. They applied game theory and reached the optimum pricing decisions in different channel structure scenarios. [Gao et al. \(2020\)](#) investigated eco-label policy in dual channel green supply chains as a new rule and compared the effect of eco-label policy on a manufacturer and a retailer which compete with each other in the supply chain. Studying the effect of different production policies on green supply chains was done by [Hadi et al. \(2020\)](#). They reach the conclusion that considering environmental production policy enhance the production in supply chains.

Nowadays, CSR has become a very important part of supply chains and several researchers surveyed the impact of CSR on decision making in green supply chains. For instance, [Ma et al. \(2017\)](#) examined CSR and asymmetric cost information in supply chain managements. They applied a game theoretic approach to model the problem and analyze it. [Omar et al. \(2019\)](#) investigated the relationship between CSR and green supply chain and examined the uncertainties of environmental situations. [Johari et al. \(2019\)](#) surveyed the effect of different CSR strategies of supply chain on the market and social behavior. They applied an evolutionary game theory to their problem to study the market. Examining the effect of CSR on the green supply chain management was done by [Wang et al. \(2020\)](#). They also surveyed the impact of CSR on the performance of supply chains and used big-data analysis to reach their goals.

However, none of the studies on green supply chain management considers transparency. In our study, the simultaneous effect of transparency level and greening degree of a supply chain on consumers’ purchase behavior is taken into account for the first time. In addition, we characterize how a supply chain, accounting for CSR, changes its profit maximizing greening degree and transparency level, relative to a supply chain not accounting for CSR.

### 1.4.3 Government intervention

Just as CSR may help firms accomplish SD, multiple authors in the literature suggest that governments may also help society reach its SD goals ([Hafezalkotob, 2018](#); [Madani and Rasti-Barzoki, 2017](#); [Mont and Dalhammar, 2005](#)). One approach to determining a government’s best course of action to meet SD commitments is to model a government as an active consumer ([Vermeulen, 2002](#)); particularly, a government’s action sets is leveraging tax/subsidy in a competitive environment composed of other governments and multiple firms ([Sheu and Chen, 2012](#)). Several studies in the literature survey government intervention strategies under a broad number of government objectives. As an example, [Al-Gwaiz et al. \(2017\)](#); [Choi and Luo \(2019\)](#); [Madani and Rasti-Barzoki \(2017\)](#); [Sana \(2020\)](#) argue that using subsidy/tax can convince corporations to account for environmental issues, by developing and selling green products. In addition, [Dai et al. \(2016\)](#); [Hafezalkotob \(2018\)](#); [Ji et al. \(2020\)](#); [Sheu and Chen \(2012\)](#) show that government intervention increases consumers’ social welfare. We follow the previous studies to consider the government interference into the market. But unlike the previous work, we consider subsidy for the environmental transparency. We also consider a combination of three different subsidy strategies, which have not been considered before.

Now to illustrate our novelty and compare the related literature works, we categorize the related literature into the following table.

**Table 1. Related studies in the literature which focused on the transparency compare to the present work**

Study	Sustainable Development		Game Theory	Effect of Transparency on Consumer Behavior	Transparency in Supply chain	Transparency as a variable	Greening degree as a variable	Government as a player in market
	Transparency related to Sustainability and CSR	Environmental Transparency						
<a href="#">Hsu et al. (2009)</a>					✓			
<a href="#">Keene and Pullin (2011)</a>	✓	✓						
<a href="#">David (2014)</a>	✓	✓						
<a href="#">Kanagaretnam et al. (2014)</a>			✓					
<a href="#">Arena et al. (2015)</a>		✓						
<a href="#">Haddad (2015)</a>	✓	✓						
<a href="#">Mol (2015)</a>	✓	✓						
<a href="#">Egels-Zandén et al. (2015)</a>	✓							
<a href="#">Egels-Zandén and Hansson (2016)</a>	✓			✓				
<a href="#">Shvarts et al. (2016)</a>		✓						

Study	Sustainable Development		Game Theory	Effect of Transparency on Consumer Behavior	Transparency in Supply chain	Transparency as a variable	Greening degree as a variable	Government as a player in market
	Transparency related to Sustainability and CSR	Environmental Transparency						
<a href="#">Zhang et al. (2016a)</a>	✓							
<a href="#">Mittal and Agrawal (2016)</a>				✓				
<a href="#">Tang and Luo (2016)</a>	✓	✓						
<a href="#">Schultz (2016)</a>			✓			✓		
<a href="#">Tamimi and Sebastianelli (2017)</a>	✓							
<a href="#">Lin et al. (2017)</a>		✓						
<a href="#">Leitch (2017)</a>	✓							
<a href="#">Fritz et al. (2017)</a>	✓							
<a href="#">Kim and Lee (2018)</a>	✓							
<a href="#">Ortiz-Rodríguez et al. (2018)</a>	✓							
<a href="#">Foscht et al. (2018)</a>	✓			✓				
<a href="#">Suning et al. (2018)</a>					✓			
<a href="#">Lee and Comello (2019)</a>	✓			✓				
<a href="#">Chen et al. (2019)</a>	✓		✓					
<a href="#">Khosroshahi et al. (2019)</a>	✓	✓	✓	✓	✓			
<a href="#">Bistline et al. (2020)</a>		✓		✓				
<a href="#">Wasiuzzaman and Wan Mohammad (2020)</a>	✓	✓				✓		
<b>Our Work</b>	✓	✓	✓	✓	✓	✓	✓	✓

### 1.5 Research gap and present study's contributions

To the best of our knowledge and as shown in [Table 1](#), greening degree, transparency level, and government subsidy have not been considered simultaneously in analytical models. In addition, most surveyed research papers, only consider retail price subsidy ([Hafezalkotob, 2018](#); [Madani and Rasti-Barzoki, 2017](#)). Considering analytical models related to social aspect of SD are performed only in two ways: fairness concerns ([Qin et al., 2016](#); [Yang et al., 2013](#)), and consumer surplus ([Panda, 2014](#); [Xie, 2016](#)). Unlike, previous studies, we not only consider product greening degree, transparency level, and three forms of government subsidy, but also we model the social aspect of SD using a new Consumer Satisfaction Index (CSI), defined in [Section 2.3](#). In particular, we examine the effect of transparency level and greening degree on the demand of a green product. We consider a green supply chain consisting of a manufacturer and a retailer. Two different strategies for the manufacturer are compared: concern with CSR and no-concern with CSR. When the manufacturer is concerned with CSR, his profit

is composed of a combination of his *production profit*, which is the profit from manufacturing the product and selling it to the consumers, and the *CSI profit*, which is the profit from CSR concerns. The analytical definitions of production profit and CSI profit are found in Section 3.1. In addition, a government determines market subsidies given an objective function composed of transparency benefit, social welfare, and subsidy costs. The main contributions of this paper are:

- Using a new transparency dependent demand function to model consumer behavior;
- Simultaneously consider transparency level and greening degree as the decision variables of a manufacturer in a supply chain in a competitive environment;
- Simultaneously using three types of government subsidy strategies;
- Proposing a new objective function consisting of transparency benefit, social welfare, and cost paid by the government;
- Comparing two different manufacturer's strategies: concern with CSR vs no-concern with CSR, using a new consumer satisfaction index as a CSR indicator.

The rest of this paper is categorized as follows. Section 2 presents some required preliminaries to formulate the problem. In Section 3, the problem is explained in detail and analytically modeled. Section 4 provides the game structures and equilibrium decision values. In addition, several parametric and numerical analyses are given. Finally, a summary of the paper and conclusions as well as some suggestion for further research are given in Section 5.

## 2 Preliminaries

In this section, three different concepts are defined and analytically modeled.

- Willingness to pay (WTP) demand model
- Consumer surplus (CS)
- Consumer satisfaction index (CSI)

Willingness to pay demand model is one of the popular demand models in the literature ([Huang et al., 2013](#)). As we use WTP demand model and to develop our demand function, we define it and extend it in this section. Consumer surplus is also defined before. However, as CS is used in governments' profit function, its definition is given in this section. CSI is a new transparency dependent index of CSR which we develop it in this section. This index is used to define the manufacturer's profit function who concerns about CSR. Below, these concepts are explained.

### 2.1 Willingness to pay demand model

*Willingness to pay* (WTP) related to a consumer is the highest price that he is pleasant to pay for buying a good or service, and if its price is more than the WTP of a consumer, then the consumer does not make a purchase ([Huang et al., 2013](#)). Assume that WTP of entire potential customers is a random



variable ( $V$ ) that follows probability density function (p.d.f)  $f_V(v)$ , then the demand function for a market with the market size  $\alpha$  is (Kalish, 1985):

$$D(p) = \alpha \int_{v \geq p} f_V(v) dv, \quad (1)$$

where  $p$  denotes the price of commodity in the market. The model in Eq. (1) is referred to as the willingness to pay demand model (Huang et al., 2013).

The model in Eq. (1) does not consider SD. However, as previously discussed, we account for SD in a supply chain by considering a manufacturer's greening degree and transparency level. Therefore, Eq. (1) cannot be used as greening degree and transparency level are not considered. Instead, we propose an extension of the WTP demand model, which considers greening degree and transparency level. Before presenting an analog of Eq. (1), we first must understand how consumers' WTP changes with both greening degree and transparency level. Zhao et al. (2018), in an empirical study, found if a firm increases its greening degree ( $\theta$ ), then the price consumers are willing pay for products by that firm will also increase. Similarly, consumers' WTP increases with a green product's transparency level ( $\mu$ ) (Egels-Zandén and Hansson, 2016). In addition, there are several studies, which consider a reference point in consumers' mind. For example, Baucells and Hwang (2017); Chen et al. (2017); Zhang et al. (2013) consider consumers purchasing goods and use empirical studies of Greenleaf (1995); Kalwani et al. (1990) to argue that consumers' actions to purchase or not are determined by the sign of the difference between a product's price and a consumer specific reference price. In this paper, we take the empirical finding of Greenleaf (1995); Kalwani et al. (1990); Zhao et al. (2018) and the analytical models of Baucells and Hwang (2017); Chen et al. (2017); Zhang et al. (2013) and develop a new analytical model of consumer utility by accounting for a consumer specific minimum transparency level, namely *reference transparency level*. In particular, each consumer,  $j \in J$ , has a reference transparency level of  $\mu_j$ , where  $J$  is the set of all potential consumers. The resulting consumer utility for consumer  $j$  is:

$$u_j = v_0 + \zeta_\mu(\mu - \mu_j) + \zeta_\theta\theta - p. \quad (2)$$

In Eq. (2),  $\zeta_\mu$  and  $\zeta_\theta$  denote the effects of transparency level and greening degree on WTP, respectively. In addition,  $v_0$  denotes the base product value before the impact of greening degree and transparency level are considered. One advantage of our model of consumer's utility, Eq. (2), is that a consumer may decide to buy a commodity even if  $\mu$  is lower than his reference transparency level, assuming greening degree is sufficiently high and price is sufficiently low.

Consequently, if the probability density function (p.d.f) of the reference transparency level is  $f_M(\cdot)$  and its cumulative distribution function (c.d.f) is  $F_M(\cdot)$ , the demand function is:

$$D(p, \mu, \theta) = \alpha \int_{v_0 + \zeta_\mu(\mu - \hat{\mu}) + \zeta_\theta \theta - p \geq 0} f_M(\hat{\mu}) d\hat{\mu}. \quad (3)$$

By the definition of a c.d.f and the definition of  $\mu_j$  in Eq. (3),

$$D(p, \mu, \theta) = \alpha \int_{v_0 + \zeta_\mu(\mu - \hat{\mu}) + \zeta_\theta \theta - p \geq 0} f_M(\hat{\mu}) d\hat{\mu} = \alpha F_M \left( \frac{v_0 + \zeta_\mu \mu + \zeta_\theta \theta - p}{\zeta_\mu} \right).$$

Therefore, to have demand defined, we need  $1 \geq F_M \left( \frac{v_0 + \zeta_\mu \mu + \zeta_\theta \theta - p}{\zeta_\mu} \right) \geq 0$ , implying:

$$D(p, \mu, \theta)|_{p=\mu=\theta=0} = \alpha \Rightarrow \alpha F_M \left( \frac{v_0}{\zeta_\mu} \right) = \alpha \Rightarrow F_M \left( \frac{v_0}{\zeta_\mu} \right) = 1 \Rightarrow \hat{\mu} \leq \frac{v_0}{\zeta_\mu}. \quad (4)$$

Eq. (4) is valid for all  $\mu$ , we can restate the condition as simply:  $\max_{j \in J} \mu_j \leq \frac{v_0}{\zeta_\mu}$ . The modified WTP in our paper, Eq. (2), is linear in greening degree ( $\theta$ ) and transparency level ( $\mu$ ). This is a common assumption in the literature where [Tirole \(1988\)](#); [Zhao et al. \(2012\)](#) do the same for quality and lead-time, respectively. We take a similar modeling perspective with greening degree and transparency level and the associated WTP demand model, Eq. (3).

## 2.2 Consumer surplus (CS)

Consumer surplus (CS) is the sum of deference between WTP of consumers and the market price ([Marshall, 2005](#)). Based on the definition of demand in Eq. (3), CS can be calculated by the following relation ([Panda, 2014](#); [Xie, 2016](#)).

$$CS(p, \mu, \theta) = \int_p^{p^{max}} D(\hat{p}, \mu, \theta) d\hat{p} \quad (5)$$

Just as [Panda \(2014\)](#); [Sheu and Chen \(2012\)](#); [Xie \(2016\)](#), we consider CS as a way to measure social welfare.

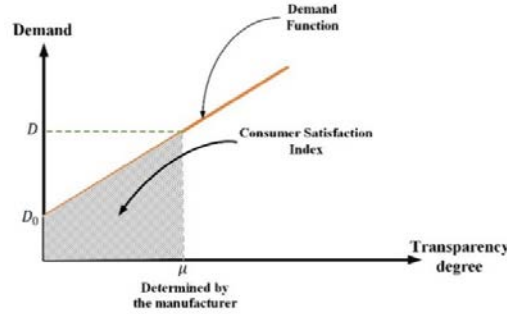
## 2.3 Consumer satisfaction index (CSI)

Increasing transparency level can increase consumer satisfaction ([Hegwer, 2015](#); [Simintiras et al., 2015](#)). In addition, as captured in our consumer utility model, Eq. (2), each consumer has her own unique reference transparency level. Supported by empirical work ([Johnson and Fornell, 1991](#)), our consumer utility model accounts for both positive and negative impacts on any given consumer's satisfaction given a firm's transparency level. To highlight the impact of a firm's transparency level on a given consumer, we propose a new transparency dependent CSI. As transparency is one of the most important aspects of CSR ([Crowther and Martinez, 2004](#)), CSI can be a measure of CSR. In defining CSI, we next define consumer satisfaction, and from there we formally define CSI.

**Definition 1** *Consumer satisfaction* ( $csa_j$ ) for each consumer,  $j$ , that purchases the product is the difference between his reference transparency level,  $\mu_j$ , and the firm's transparency level,  $\mu$ .

**Definition 2** *Consumer satisfaction index* (CSI) is defined as the sum of consumer satisfaction ( $csa_j$ ) for each consumer that purchases the item.

Based on [Definition 2](#), CSI is illustrated in [Fig. 1](#).



**Fig. 1.** Level of Consumer Satisfaction Index (CSI) in society

Therefore, CSI is calculated as:

$$CSI(p, \mu, \theta) = \int_0^{\mu} D(p, \dot{\mu}, \theta) d\dot{\mu}. \quad (6)$$

### 3 Modeling framework

In this section, we formally present the model we considering in our paper, using the definitions of WTP, CS, and CSI defined in [Section 2](#).

#### 3.1 Model Structure

Consider a supply chain that is comprised of a retailer and a manufacturer. The manufacturer manufactures a green commodity and sells it to customers through the retailer. The manufacturer has to decide the product wholesale price ( $w$ ) and greening degree ( $\theta$ ), and the manufacturer's transparency level ( $\mu$ ). The retailer decides the retail price ( $p$ ). We assume the manufacturer has two different strategies: no-concern with CSR ( $N$  strategy) and concern with CSR ( $C$  strategy). In the  $N$  strategy, the manufacturer's profit is only his production profit and in the  $C$  strategy, manufacturer's profit is his production profit as well as his CSI profit. Similar to the work of [Basiri and Heydari \(2017\)](#); [Jamali and Rasti-Barzoki \(2018\)](#); [Ma et al. \(2017\)](#), we assume that the manufacturer commits to his decisions before the retailer. Therefore, a Stackelberg competition is held between the manufacturer, as leader, and the retailer, as follower. In this paper, we consider an additional player, the government. Similar to the work of [Hafezalkotob \(2017\)](#); [Madani and Rasti-Barzoki \(2017\)](#); [Sheu and Chen \(2012\)](#), we assume that the government moves first and provides whatever subsidy it desires to the supply chain partners, manufacturer and retailer, in order to increase transparency benefit and social welfare, while accounting

for subsidy cost. In this study, three different subsidy strategies are available to the government: retail price subsidy ( $s_p$ ), transparency cost subsidy ( $s_\mu$ ), and manufacturing cost subsidy ( $s_c$ ). When determining the optimal subsidy, the government can use any combination of the three subsidies. Given the setting we construct, it follows that a Stackelberg game is held between the government, as leader, and the supply chain partners and their previously discussed Stackelberg game, as followers. Therefore, the two-stage Stackelberg game between and the government and the supply chain partners, and two-stage Stackelberg game between the supply chain's partners results in a single three-stage Stackelberg game. All notations are given in [Appendix A](#) (which is given in supplemental material).

### 3.1.1 Assumptions

In this section, we explicitly list the major assumptions made in the paper.

**Assumption 1** Similar to ([Konur and Geunes, 2016](#); [Xu et al., 2017b](#); [Zu-Jun et al., 2016](#)), all parameters, variables, profit functions and demand function are non-negative.

**Assumption 2** There are several studies that assumed WTP of potential consumers is a random variable with a uniform density function ([Chambers et al., 2006](#); [Ha et al., 2016](#); [Huang et al., 2013](#); [Lauga and Ofek, 2011](#); [Ronnen, 1991](#); [Zhao et al., 2012](#)). In this study, it is assumed that the reference transparency level, for consumers represented by  $M$ , is distributed according to a uniform density function between zero and  $\mu^m$ . Therefore:

$$M \sim \text{Uniform}(0, \mu^m) \rightarrow f_M(\mu) = \frac{1}{\mu^m}. \quad (7)$$

In addition, as mentioned before, maximum amount of  $\mu$  is  $\frac{v_0}{\zeta_\mu}$ . Therefore,  $\mu^m \leq \frac{v_0}{\zeta_\mu}$ .

**Assumption 3** Increasing a product's greening degree results in additional costs usually captured via a quadratic function ([Gao et al., 2016](#); [Li et al., 2016](#)). Similarly, increasing a firm's transparency level results in increased costs due to the need for experiments, certifications, labeling, etc. ([Mol, 2015](#)). However, there is no prior models of the costs of increasing transparency level in the literature, so we instead follow the approach of [Ma et al. \(2017\)](#); [Malekian and Rasti-Barzoki \(2019\)](#); [Xu et al. \(2017a\)](#) that consider other firm-wide actions, CSR effort, advertising cost and sustainability effort, respectively, that model these actions using a quadratic cost function. Therefore, we use the following relations.

$$TC_M = cD + k_\mu \frac{\mu^2}{2} + k_\theta \frac{\theta^2}{2}, \quad (8)$$

where  $TC_M$  denotes the manufacturer's total cost,  $c$  denotes production cost,  $D$  is the realized expected demand,  $k_\mu$  and  $k_\theta$  indicates the transparency level cost coefficient and greening degree cost coefficient, respectively.

### 3.1.2 Demand and profit functions

In this section, we analytically model the demand and profit functions considering the assumptions in Section 3.1.1 and using the definitions of WTP, CS, and CSI from Section 2.

#### *Demand function*

To calculate the demand function, we provide the following Lemma:

**Lemma 1** *Based on Assumptions 1 and 2, the demand function is formulated as the following relation.*

$$D = \alpha - \beta p + \zeta \mu + \gamma \theta \quad (9)$$

Proof of Lemma 1 is given in Appendix B (which is given in supplemental material).

#### *Government utility function*

We now discuss the government's utility function,  $\pi_G(s_p, s_\mu, s_c)$ . Where  $s_p$ ,  $s_\mu$ , and  $s_c$ , are the subsidies for retail price, transparency level cost, and product cost, respectively. The government's utility has three terms: 1) the transparency benefit (TB), 2) consumer surplus (CS), and 3) subsidy cost ( $C_s$ ). We now sequentially discuss each term.

The first profit term is the transparency benefit (TB). The concept of TB does not appear in the literature. However, other forms of benefit, e.g., environmental (Hafezalkotob, 2017; Sheu and Chen, 2012) are frequently discussed in the literature. Using the same approach of accounting for environmental benefits (Barbier et al., 1997; Hafezalkotob, 2018; Madani and Rasti-Barzoki, 2017; Mota et al., 2015) we too take a proportion of the total demand to define TB:

$$TB = \mu D. \quad (10)$$

Note that  $D$  considers only consumers that purchase the product. As such, even though each consumer has her own reference transparency level, once the item is purchased, the total transparency level experienced by consumers is the same and is  $\mu$ . Again, this definition is in line with existing SD literature.

The second term is consumer surplus, which is defined in Section 2.2. In particular, we rewrite  $CS(w, \mu, \theta)$  given in Eqs. (5) and (9) as:

$$CS(w, \mu, \theta) = \int_p^{\frac{\alpha + \zeta \mu + \gamma \theta}{\beta}} (\alpha - \beta p + \zeta \mu + \gamma \theta) dp = \frac{(\alpha - \beta p + \zeta \mu + \gamma \theta)^2}{2\beta} = \frac{(D(w, \mu, \theta))^2}{2\beta}. \quad (11)$$

The third term is subsidy cost. Similar to Hafezalkotob (2017, 2018); He and Zhao (2016); Sheu and Chen (2012) who use a linear model for per demand factors such as retail price and production cost subsidies and Guo et al. (2016); Xie (2016); Yang et al. (2013) who consider a multiplicative coefficient

for the subsidy of quadratic costs such as greening degree, advertising, and energy efficiency; we develop our model such that the government subsidy cost function is:

$$C_s = (s_p + s_c)D + s_\mu k_\mu \frac{\mu^2}{2}. \quad (12)$$

Hence, the government utility is:

$$\pi_G(s_p, s_\mu, s_c) = r_{TB}TB + r_{CS}CS - C_s. \quad (13)$$

Where  $r_{TB}$  and  $r_{CS}$  are conversion factors. The point to notice is that when the government provides market subsidies, total amount a consumer pays for a product changes from  $p$  to  $(p - s_p)$ . Hence, the demand function, defined in Eq. (9), changes to:

$$D = \alpha - \beta(p - s_p) + \zeta\mu + \gamma\theta. \quad (14)$$

In addition, when government uses subsidies, the manufacturer's cost function changes to:

$$TC_M = (c - s_c)(\alpha - \beta(p - s_p) + \zeta\mu + \gamma\theta) + (1 - s_\mu)k_\mu \frac{\mu^2}{2} + k_\theta \frac{\theta^2}{2} \quad (15)$$

As discussed in Section 3.1, the manufacturer has two strategies that may be used when determining  $\mu$ ,  $\theta$ , and  $w$ , the  $N$  strategy and the  $C$  strategy. As we will now discuss, each of these strategies leads to a different profit function for the manufacturer and in turn potentially different values of  $\mu$ ,  $\theta$ , and  $w$ . We first present the profit function of the  $N$  strategy, and use it as the basis for the profit function of the  $C$  strategy.

#### ***Manufacturer's profit function in N strategy***

Based on the above assumptions, the profits of the manufacturer from the  $N$  strategy,  $\pi_{MN}$ , is:

$$\pi_{MN}(w, \mu, \theta) = wD - TC_M = (w - (c - s_c))D - (1 - s_\mu)k_\mu \frac{\mu^2}{2} - k_\theta \frac{\theta^2}{2}. \quad (16)$$

Note that  $\pi_{MN}$  is the production profit, defined in Section 1.5 and is simply the manufacturer's profit from producing the product

#### ***Manufacturer's profit function in C strategy***

As previously discussed, the  $C$  strategy, accounts for CSR in the manufacturer's decisions. As such, we add an additional term to  $\pi_{MN}$  that accounts for CSR. This additive form is consistent with the approach taken by other researchers when modeling a firm accounting for social or environmental factors (e.g. [Choi and Messinger \(2014\)](#); [Panda \(2014\)](#); [Yang et al. \(2013\)](#)). In this paper, CSI is the added term and is, as previously discussed, a CSR measure. Therefore, if  $r_{CSI}$  is a conversion factor,

the manufacturer's profit under the  $C$  strategy is:

$$\pi_{M^c}(w, \mu, \theta) = \pi_{M^N}(w, \mu, \theta) + r_{CSI}CSI(w, \mu, \theta). \quad (17)$$

Note that  $r_{CSI}CSI(w, \mu, \theta)$  is the CSI profit, defined in Section 1.5, and is the manufacturer's profit from the CSI. With the formal definition of  $\pi_{M^c}$ , we now expand and simplify  $\pi_{M^c}$  given the previously discussed model parameters. In particular, we rewrite  $CSI(w, \mu, \theta)$ , given in Eq. (6), while accounting for demand, provided in Eq. (9), as:

$$CSI(w, \mu, \theta) = \frac{1}{2}\mu(2\alpha - 2\beta(p - s_r) + 2\gamma\theta + \zeta\mu). \quad (18)$$

Given Eqs. (15) and (12), we rewrite  $\pi_{M^c}$  as:

$$\pi_{M^c}(w, \mu, \theta) = (w - (c - s_c))D - (1 - s_\mu)k_\mu \frac{\mu^2}{2} - k_\theta \frac{\theta^2}{2} + \frac{r_{CSI}}{2}\mu(2\alpha - 2\beta p + 2\gamma\theta + \zeta\mu). \quad (19)$$

### Retailer's profit function

The profit of the retailer,  $\pi_R$ , as a function of the retail price,  $p$ , is:

$$\pi_R(p) = (p - w)D. \quad (20)$$

## 4 Game structures

Given the notation defined and discussed in Section 3, we represent the dynamics of the three-stage Stackelberg game we analyze in this section in Fig. 2 below.

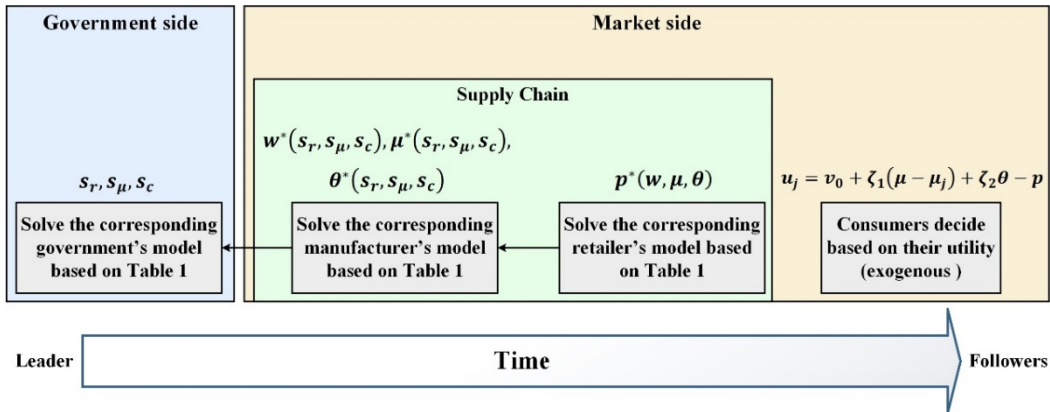


Fig. 2. The sequence of players' decisions based on backward induction technique

As discussed in Section 3, based on manufacturer's  $N$  and  $C$  strategies, two different game structures are held which are presented in Eqs. (21) and (22), respectively.

$$\begin{aligned}
& \underset{s_p, s_\mu, s_c}{Max} \pi_G = r_{TB} \mu D + r_{CS} CS - (s_p + s_c) D - s_\mu k_\mu \frac{\mu^2}{2} \\
& s. t \left\{ \begin{aligned} & \underset{w, \mu, \theta}{Max} \pi_{MN} = (w - (c - s_c)) D - (1 - s_\mu) k_\mu \frac{\mu^2}{2} - k_\theta \frac{\theta^2}{2} \\ & s. t \left\{ \underset{p}{Max} \pi_R = (p - s_p - w) D \right. \end{aligned} \right. \quad (21)
\end{aligned}$$

$$\begin{aligned}
& \underset{s_p, s_\mu, s_c}{Max} \pi_G = r_{TB} \mu D + r_{CS} CS - (s_p + s_c) D - s_\mu k_\mu \frac{\mu^2}{2} \\
& s. t \left\{ \begin{aligned} & \underset{w, \mu, \theta}{Max} \pi_{Mc} = (w - (c - s_c)) D - (1 - s_\mu) k_\mu \frac{\mu^2}{2} - k_\theta \frac{\theta^2}{2} + r_{CSI} CSI(w, \mu, \theta) \\ & s. t \left\{ \underset{p}{Max} \pi_R = (p - s_p - w) D \right. \end{aligned} \right. \quad (22)
\end{aligned}$$

Below, we calculate the supply chain members' equilibrium decisions in several Theorems. Proofs for all theorems are presented in [Appendix B](#) (which is given in supplemental material).

#### 4.1 Market sub-game

In this section, we firstly find the retailer's best response and then find the equilibrium manufacturer's decision values in different strategies.

**Theorem 1** *The best response of the retailer to the manufacturer's actions is:*

$$\hat{p}(w, \mu, \theta, s_p, s_\mu, s_c) = \frac{\alpha + (s_p + w)\beta + \gamma\theta + \zeta\mu}{2\beta}. \quad (23)$$

##### 4.1.1 C Strategy

In this strategy, the manufacturer has CSR concerns.

**Theorem 2** *The equilibrium decision variables of the manufacturer in the C strategy are:*

$$\begin{aligned}
& w_C^*(s_p, s_\mu, s_c) \\
& = c + \frac{2k_\mu k_\theta (1 - s_\mu) \left( \alpha - (c - s_p + s_c)\beta + \frac{s_c \gamma^2}{2k_\theta} \right) + r_{CSI} s_c \gamma^2 \zeta + k_\theta (\zeta - r_{CSI} \beta) (r_{CSI} (\alpha + (s_p - c)\beta) + s_c \zeta)}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - r_{CSI} \gamma^2 \zeta - k_\theta (\zeta - r_{CSI} \beta)^2}, \quad (24)
\end{aligned}$$

$$\mu_C^*(s_p, s_\mu, s_c) = \frac{k_\theta (\alpha - (c - s_p - s_c)\beta) (r_{CSI} \beta + \zeta)}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - r_{CSI} \gamma^2 \zeta - k_\theta (\zeta - r_{CSI} \beta)^2}, \quad (25)$$

$$\theta_C^*(s_p, s_\mu, s_c) = \frac{\gamma (\alpha - (c - s_p - s_c)\beta) (k_\mu (1 - s_\mu) + r_{CSI} \zeta)}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - r_{CSI} \gamma^2 \zeta - k_\theta (\zeta - r_{CSI} \beta)^2}. \quad (26)$$

Replacing the equilibrium manufacturer's decision variables, given in Eqs. (24)-(26), in the retailer best response, given in Eq. (23), we rewrite the equilibrium retail price in the C strategy as:



$$p_C^*(s_p, s_\mu, s_c) = c + \frac{3k_\mu k_\theta (1 - s_\mu) \left( \alpha - \left( c - s_p + \frac{s_c}{3} \right) \beta + \frac{s_c \gamma^2}{3k_\theta} \right) + s_c \zeta (r_{CSI} \gamma^2 - k_\theta \zeta) + r_{CSI} k_2 (\alpha + (s_p - c) \beta) (2\zeta - r_{CSI} \beta)}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - r_{CSI} \gamma^2 \zeta - k_\theta (\zeta - r_{CSI} \beta)^2} \quad (27)$$

#### 4.1.2 N strategy

In this strategy, the manufacturer has no CSR concerns. Hence, the difference between  $N$  strategy and  $C$  strategy is that in  $N$  strategy  $r_{CSI}$  equals to zero. Henceforth, replacing  $r_{CSI}$  into Eqs. (24)-(27) the equilibrium variables values in  $N$  strategy is as follows:

$$p_N^*(s_p, s_\mu, s_c) = c + \frac{k_1 (1 - s_\mu) (3k_2 \alpha - k_2 (3c - 3s_p + s_c) \beta + s_c \gamma^2) - k_2 s_c \zeta^2}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - k_\theta \zeta^2} \quad (28)$$

$$w_N^*(s_p, s_\mu, s_c) = c + \frac{k_\mu (1 - s_\mu) (2k_\theta (\alpha - (c - s_p + s_c) \beta) + s_c \gamma^2) - k_\theta s_c \zeta^2}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - k_\theta \zeta^2}, \quad (29)$$

$$\mu_N^*(s_p, s_\mu, s_c) = \frac{k_\theta (\alpha + (s_p + s_c - c) \beta) \zeta}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - k_\theta \zeta^2} \quad (30)$$

$$\theta_N^*(s_p, s_\mu, s_c) = \frac{k_\mu (1 - s_\mu) (\alpha + (s_p + s_c - c) \beta) \gamma}{k_\mu (1 - s_\mu) (4k_\theta \beta - \gamma^2) - k_\theta \zeta^2}. \quad (31)$$

#### 4.1.3 Analyses of market sub-game

In this section, we present sensitivity analysis results on the market sub-game. Based on our sensitivity analysis, we formally state corollaries and managerial insights regarding the two manufacturer strategies and different players' profits. We start by evaluating the effect of government's subsidies on the supply chain equilibrium actions in the  $N$  and  $C$  strategies. Then we compare the supply chain equilibrium actions under the  $N$  and  $C$  strategies, assuming there is no government subsidy in the market. In addition, we give several numerical examples for better understanding. The parameter values are based on the real word case study of [Chen and Wang \(2015\)](#) and examples used by [Ma et al. \(2017\)](#); [Sheu and Chen \(2012\)](#). Other papers also provide parameter values. The parameter values used in our examples are given in [Table 1](#). Note that in some cases, we fix some parameters and vary others to analyze trends. Note that we use  $(.)^N$  and  $(.)^C$  as the equilibrium values of variables in the  $N$  and  $C$  strategies, respectively. For example we use  $\mu^N$  and  $\mu^C$  as the transparency level in the  $N$  and  $C$  strategies, respectively.

**Table 2. The values of parameters used in numerical examples**

parameter	$\alpha$	$\beta$	$\zeta$	$\lambda$	$c$	$k_\mu$	$k_\theta$	$r_{CSI}$	$r_{TB}$	$r_{CS}$
amount	100	2	1	1.5	2	2	2	1	1	1

First, we examine the effect of the government's subsidies on the supply chain equilibrium actions under the  $N$  and  $C$  strategies.

**Corollary 1** Based on [Table 3](#), the government subsidies,  $s_p, s_\mu, s_c$ , has a positive effect on the equilibrium transparency level in the  $N$  and  $C$  strategies,  $\mu^N$  and  $\mu^C$ , respectively. Because the first order derivatives of their equilibrium values with respect to  $s_p, s_\mu$ , and  $s_c$  are positive.

**Table 3. The effect of  $s_p, s_\mu, s_c$  on  $\mu^N$  and  $\mu^C$**

case	Value	Positive (P) or negative (N)
$\frac{d\mu^N}{ds_p}$	$\frac{k_\theta\beta\zeta}{k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-k_\theta\zeta^2}$	P
$\frac{d\mu^N}{ds_\mu}$	$\frac{k_\mu k_\theta(\alpha+(s_c-c+s_p)\beta)(4k_\theta\beta-\gamma^2)\zeta}{(k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-k_\theta\zeta^2)^2}$	P
$\frac{d\mu^N}{ds_c}$	$\frac{k_\theta\beta\zeta}{k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-k_\theta\zeta^2}$	P
$\frac{d\mu^C}{ds_p}$	$\frac{k_\theta\beta(r\beta+\zeta)}{k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-r\gamma^2\zeta-k_\theta(\zeta-r\beta)^2}$	P
$\frac{d\mu^C}{ds_\mu}$	$\frac{k_\mu k_\theta(\alpha+(s_c-c+s_p)\beta)(4k_\theta\beta-\gamma^2)(r\beta+\zeta)}{(k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-r\gamma^2\zeta-k_\theta(\zeta-r\beta)^2)^2}$	P
$\frac{d\mu^C}{ds_c}$	$\frac{k_\theta\beta(r\beta+\zeta)}{k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-r\gamma^2\zeta-k_\theta(\zeta-r\beta)^2}$	P

**Corollary 2** Based on [Table 4](#), the government subsidies,  $s_p, s_\mu, s_c$ , has a positive effect on the equilibrium greening degree in the  $N$  and  $C$  strategies,  $\theta^N$  and  $\theta^C$ , respectively. Because the first order derivatives of their equilibrium values with respect to  $s_p, s_\mu$ , and  $s_c$  are positive.

**Table 4. The effect of  $s_p, s_\mu, s_c$  on  $\theta^N$  and  $\theta^C$**

case	Value	Positive (P) or negative (N)
$\frac{d\theta^N}{ds_p}$	$\frac{k_\mu(1-s_\mu)\beta\gamma}{k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-k_\theta\zeta^2}$	P
$\frac{d\theta^N}{ds_\mu}$	$\frac{k_\theta k_\mu(\alpha+(s_c-c+s_p)\beta)\gamma\zeta^2}{(k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-k_\theta\zeta^2)^2}$	P
$\frac{d\theta^N}{ds_c}$	$\frac{k_\mu(1-s_\mu)\beta\gamma}{k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-k_\theta\zeta^2}$	P
$\frac{d\theta^C}{ds_p}$	$\frac{\beta\gamma(k_\mu(1-s_\mu)+r\zeta)}{k_\mu(1-s_\mu)(4k_\theta\beta-\gamma^2)-r\gamma^2\zeta-k_\theta(\zeta-r\beta)^2}$	P

case	Value	Positive (P) or negative (N)
$\frac{d\theta^C}{ds_\mu}$	$\frac{k_\theta k_\mu (\alpha + (s_c - c + s_p)\beta)\gamma(r\beta + \zeta)^2}{k_\mu(1 - s_\mu)(4k_\theta\beta - \gamma^2) - r\gamma^2\zeta - k_\theta(\zeta - r\beta)^2}$	P
$\frac{d\theta^C}{ds_c}$	$\frac{\beta\gamma(k_\mu(1 - s_\mu) + r\zeta)}{k_\mu(1 - s_\mu)(4k_\theta\beta - \gamma^2) - r\gamma^2\zeta - k_\theta(\zeta - r\beta)^2}$	P

**Insight 1** Based on Corollaries [1](#) and [2](#), as government subsidies increase, the equilibrium transparency level and greening degree increase in both  $N$  and  $C$  strategies. In other words, the government increases the equilibrium transparency level and greening degree by using each type and each value of subsidy in both  $N$  and  $C$  strategies that manufacturer chooses.

For the remainder of this section, we calculate the equilibrium values of the variables given in Section [3](#) and illustrate them in [Table 5](#) (when all government subsidy decisions set to zero).

**Table 5. The equilibrium results in two market sub-game structures assuming no government subsidy**

case	$N$ Strategy	$C$ Strategy
$p^*$	$c + \frac{3k_\mu k_\theta (\alpha - c\beta)}{k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2}$	$c + \frac{k_\theta(\alpha - c\beta)(3k_\mu + r_{CSI}(2\zeta - r_{CSI}\beta))}{k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2}$
$w^*$	$c + \frac{2k_\mu k_\theta (\alpha - c\beta)}{k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2}$	$c + \frac{(\alpha - c\beta)(2k_\mu + r_{CSI}(\zeta - r_{CSI}\beta))}{k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2}$
$\mu^*$	$\frac{k_\theta(\alpha - c\beta)\zeta}{k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2}$	$\frac{k_\theta(\alpha - c\beta)(r_{CSI}\beta + \zeta)}{k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2}$
$\theta^*$	$\frac{k_\mu(\alpha - c\beta)\gamma}{k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2}$	$\frac{k_\theta\beta(\alpha - c\beta)(k_\mu + r_{CSI}\zeta)}{k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2}$
$D^*$	$\frac{k_\mu k_\theta\beta(\alpha - c\beta)}{k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2}$	$\frac{k_\theta\beta(\alpha - c\beta)(k_\mu + r_{CSI}\zeta)}{k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2}$
$\pi_R^*$	$\frac{k_\mu^2 k_\theta^2 \beta (\alpha - c\beta)^2}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	$\frac{k_\theta^2 \beta (\alpha - c\beta)^2 (k_\mu + r_{CSI}\zeta)^2}{(k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2)^2}$
$\pi_M^{N^*}$	$\frac{k_\mu k_\theta (\alpha - c\beta)^2 (4k_\mu k_\theta\beta - k_\mu\gamma^2 - k_\theta\zeta^2)}{2(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	$\frac{k_\theta(\alpha - c\beta)^2 (k_\mu^2(4k_\theta\beta - \gamma^2) + r_{CSI}^2\zeta(2k_\theta\beta(\zeta - r_{CSI}\beta) - \gamma^2\zeta))}{2(k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2)^2}$ $-\frac{k_\theta(\alpha - c\beta)^2 (k_\mu(k_\theta(\zeta - r_{CSI}\beta)(\zeta - 3r_{CSI}\beta) + 2r_{CSI}\gamma^2\zeta))}{2(k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2)^2}$
$\pi_{SC}^*$	$\frac{k_\mu k_\theta (\alpha - c\beta)^2 (6k_\mu k_\theta\beta - k_\mu\gamma^2 - k_\theta\zeta^2)}{2(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	$\frac{k_2(\alpha - c\beta)^2 (k_\mu^2(6k_\theta\beta - \gamma^2) + r_{CSI}^2\zeta(2k_\theta\beta(2\zeta - r_{CSI}\beta) - \gamma^2\zeta))}{2(k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2)^2}$ $-\frac{k_\theta(\alpha - c\beta)^2 (k_\mu(2r_{CSI}\gamma^2\zeta + k_\theta(3r_{CSI}^2\beta^2 - 8r\beta\zeta + \zeta^2)))}{2(k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2)^2}$

case	<i>N</i> Strategy	<i>C</i> Strategy
$CSI^*$	$\frac{k_2^2(\alpha - c\beta)^2\zeta(2k_1\beta - \zeta^2)}{2(k_1(4k_2\beta - \gamma^2) - k_2\zeta^2)^2}$	$\frac{k_\theta^2(\alpha - c\beta)^2(r_{CSI}\beta + \zeta)(2k_\mu\beta + (r_{CSI}\beta - \zeta)\zeta)}{2(k_\mu(4k_\theta\beta - \gamma^2) - r_{CSI}\gamma^2\zeta - k_\theta(\zeta - r_{CSI}\beta)^2)^2}$

Now, we give results and insights based on the equilibrium values for the market sub-game given in [Table 5](#).

**Corollary 3** If  $k_\mu > \frac{k_\theta(\zeta - r_{CSI}\beta)^2 + r_{CSI}\gamma^2\zeta}{4k_\theta\beta - \gamma^2}$  and  $r_{CSI} \geq \frac{2k_\theta\beta\zeta - \gamma^2\zeta}{k_\theta\beta^2}$ , then the transparency level ( $\mu$ ) and greening degree ( $\theta$ ) in the *C* strategy are greater than those in the *N* strategy, i.e.,  $\mu^C \geq \mu^N, \theta^C \geq \theta^N$ . In addition, the retail price ( $p$ ) and wholesale price ( $w$ ) in the *C* strategy are greater than those in the *N* strategy, i.e.,  $p^C \geq p^N, w^C \geq w^N$ .

**Insight 2** Based on Corollary 3, if  $k_\mu$  is not sufficiently high, then even if the manufacturer is not concerned with CSR, he chooses a high transparency level to increase his profit, as a higher  $\mu$  leads to a larger demand. However, when  $k_\mu$  and  $r_{CSI}$  are sufficiently high, when the manufacturer chooses the *N* strategy, he determines a lower transparency level than in the *C* strategy. The lower transparency level in the *N* strategy is due to the high value of  $k_\mu$ , as the manufacturer cares only about profit generated from selling the produced product in the *N* strategy. However, in the *C* strategy a sufficiently high level of  $r_{CSI}$  means that the manufacturer cares about both production and *CSI* profits, leading to a higher transparency level.

**Insight 3** Based on Corollary 3, when  $k_\mu$  and  $r_{CSI}$  are sufficiently high, the profit margins of the manufacturer and the retailer in the *C* strategy are greater than those in the *N* strategy. With  $k_\mu$  and  $r_{CSI}$  sufficiently high, the manufacturer's *C* strategy leads to a higher level of  $\mu$  and  $\theta$ . Hence, consumers are willing to pay more for the product (based on the Eq. (2)). Therefore, in the *C* strategy, consumers' willingness to pay is higher than it is in the *N* strategy. Consequently, the retailer is willing to pay a higher wholesale price in the *C* strategy than in the *N* strategy.

**Corollary 4** If  $k_\mu \geq \frac{k_\theta k_\theta(\zeta - r_{CSI}\beta)^2 + r_{CSI}\gamma^2\zeta}{4k_\theta\beta - \gamma^2} + \frac{2\zeta^2}{4k_\theta\beta - \gamma^2}$  and  $r_{CSI} \geq \frac{2k_\theta\beta\zeta - \gamma^2\zeta}{k_\theta\beta^2}$ , then the demand in the *C* strategy is more than that in the *N* strategy, i.e.,  $D^C \geq D^N$ .

**Insight 4** Based on Corollaries 3 and 4, if  $k_\mu$  is sufficiently high, then the manufacturer's *C* strategy leads to more product demand. When  $k_\mu$  is sufficiently high,  $p, \mu$  and  $\theta$  are higher in the *C* strategy than in the *N* strategy. Based on Eq. (2), when  $\mu$  and  $\theta$  in the *C* strategy are sufficiently higher than in the *N* strategy such that they dominate the difference of  $p$  in the *C* and *N* strategies, then the demand in the *C* strategy is higher than that in *N* strategy.

Now we define the *supply-chain-production profit* as the net production profit of the supply chain, which can be analytically defined as:

$$\pi_{SC}(p, \mu, \theta) = \pi_R + \pi_M^N = (p - c)D - k_\mu \frac{\mu^2}{2} - k_\theta \frac{\theta^2}{2}. \quad (32)$$

We now compare supply-chain-production profit in the  $C$  strategy ( $\pi_{SC}^C$ ) and in the  $N$  strategy ( $\pi_{SC}^N$ ).

**Corollary 5** If  $k_\mu > \frac{2k_\theta(r_{CSI}^2\beta^2\zeta - 2r_{CSI}\beta\zeta^2) + r_{CSI}\gamma^2\zeta^2}{8k_\theta\beta\zeta - 3k_2r_{CSI}\beta^2 - 2\gamma^2\zeta}$  and  $\frac{8k_\theta\beta\zeta - 2\gamma^2\zeta}{3k_\theta\beta^2} \geq r_{CSI} \geq \frac{2k_\theta\beta\zeta - \gamma^2\zeta}{k_\theta\beta^2}$ , then the supply-chain-production profit in  $C$  strategy is more than in  $N$  strategy, i.e.,  $\pi_{SC}^C \geq \pi_{SC}^N$ .

**Example 1.** Based on the parameter values given in [Table 2](#), the equilibrium supply-chain-production profits are 3724.54 and 5359.72 in the  $N$  and  $C$  strategies, respectively. Hence, if the manufacturer changes his choice from the  $N$  strategy to the  $C$  strategy, the supply-chain-production profit increases by 30%.

**Insight 5** Based on [Corollary 5](#) and [Example 1](#), when  $k_\mu$  is sufficiently high and  $r_{CSI}$  is between two specific level, the manufacturer's  $C$  strategy may lead to an increase in the supply-chain-production profit by 30%. Therefore, when the manufacturer chooses the  $C$  strategy, the supply-chain-production profit increases relative to the  $N$  strategy. However, if  $r_{CSI}$  is too high, then the supply-chain-production profit no longer increases. Low levels of  $r_{CSI}$  means that the  $N$  and the  $C$  strategy supply-chain-production profits are nearly similar.

**Corollary 6** If  $k_\mu \geq \frac{k_\theta(r_{CSI}^2\beta^2 + 2\zeta^2 - 2r_{CSI}\beta\zeta) + r_{CSI}\gamma^2\zeta}{8k_\theta\beta - 2\gamma^2}$  and  $r_{CSI} \geq \frac{2k_\theta\beta\zeta - \gamma^2\zeta}{k_\theta\beta^2}$ , then the retailer's profit in the  $C$  strategy is greater than that in the  $N$  strategy, i.e.,  $\pi_R^C \geq \pi_R^N$ .

**Corollary 7** If  $k_\mu > \frac{\zeta(r_{CSI}^2\beta^2 + 2(k_\theta - \zeta)\zeta)}{8k_\theta\beta - 2(r_{CSI}\beta^2 + \gamma^2 + 2\beta\zeta)}$  and  $r_{CSI} > \max\left\{\frac{2\zeta\beta - \gamma^2}{\beta^2}, \frac{2k_\theta\beta\zeta - \gamma^2\zeta}{k_\theta\beta^2}\right\}$ , then the CSI in the  $C$  strategy is greater than that in the  $N$  strategy, i.e.,  $CSI^C \geq CSI^N$ .

**Insight 6** Based on [Corollaries 7](#) and [8](#), when  $k_\mu$  and  $r_{CSI}$  are sufficiently high, in the manufacturer's  $C$  strategy, both consumers and the retailer are better off, relative to the  $N$  strategy. Even though the  $C$  strategy only considers consumer benefit, we notice that the retailer is better off too.

**Corollary 8** Based on [Table 6](#), the demand sensitivity with respect to transparency level,  $\zeta$ , has a positive effect on all equilibrium variables values in the  $N$  strategy. Because the first order derivatives of their equilibrium values with respect to  $\zeta$  are positive.

**Table 6. The effect of  $\zeta$  on equilibrium variables ( $\frac{d}{d\zeta}$ ) in  $N$  strategy**

case	$\frac{d}{d\zeta}$	Positive (P) or negative (N)
$p^*$	$\frac{6k_\mu k_\theta^2(\alpha - c\beta)\zeta}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	P

case	$\frac{d}{d\zeta}$	Positive (P) or negative (N)
$w^*$	$\frac{4k_\mu k_\theta^2(\alpha - c\beta)\zeta}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	P
$\mu^*$	$\frac{k_\theta(\alpha - c\beta)(4k_\mu k_\theta\beta - k_\mu\gamma^2 + k_\theta\zeta^2)}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	P
$\theta^*$	$\frac{2k_\mu k_\theta(\alpha - c\beta)\gamma\zeta}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	P
$D^*$	$\frac{2k_\mu k_\theta^2\beta(\alpha - c\beta)\zeta}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	P
$\pi_R^*$	$\frac{4k_\mu^2 k_\theta^3\beta(\alpha - c\beta)^2\zeta}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^3}$	P
$\pi_M^{N*}$	$\frac{k_\mu k_\theta^2(\alpha - c\beta)^2\zeta}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^2}$	P
$\pi_C^*$	$\frac{k_\mu k_\theta^2(\alpha - c\beta)^2\zeta(8k_\mu k_\theta\beta - k_\mu\gamma^2 - k_\theta\zeta^2)}{(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^3}$	P
$CSI^*$	$\frac{k_\theta^2(\alpha - c\beta)^2(2k_\mu^2\beta(4k_\theta\beta - \gamma^2) + 3k_\mu(-2k_\theta\beta + \gamma^2)\zeta^2 - k_\theta\zeta^4)}{2(k_\mu(4k_\theta\beta - \gamma^2) - k_\theta\zeta^2)^3}$	P if $(k_\mu \geq \frac{(3+\sqrt{17})\zeta^2}{8\beta})$

**Corollary 9** Based on [Table 6](#), as  $k_\mu$  increases, the retailer's profit, the manufacturer's production profit, and the supply-chain-production profit in the  $N$  and  $C$  strategies are equal. Because the following relations are held.

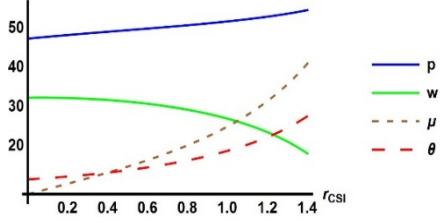
$$\lim_{k_\mu \rightarrow \infty} \frac{\pi_R^C}{\pi_R^N} = \lim_{k_\mu \rightarrow \infty} \frac{\pi_M^{NC}}{\pi_M^{NN}} = \lim_{k_\mu \rightarrow \infty} \frac{\pi_{SC}^C}{\pi_{SC}^N} = 1 \quad (33)$$

In addition, as  $k_\mu$  increases, the equilibrium transparency level is zero in the  $N$  and  $C$ . Because the following relations are held.

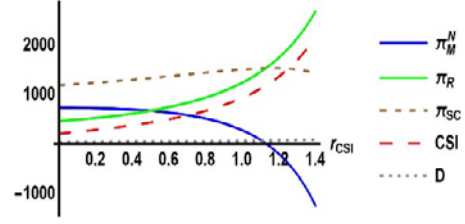
$$\lim_{k_\mu \rightarrow \infty} \theta^C = \lim_{k_\mu \rightarrow \infty} \theta^N = 0 \quad (34)$$

**Insight 7** Based on [Corollary 9](#), as  $k_\mu$  increases, the retailer's profit, the manufacturer's production profit, and the supply-chain-production profit in the  $C$  and  $N$  strategies are equal. As  $k_\mu$  increases, a large transparency level becomes prohibitively expensive, regardless of the selected strategy,  $C$  or  $N$ . Therefore, when  $k_\mu$  is large, the transparency level tends to zero in both the  $C$  and  $N$  strategies. Hence, the  $C$  and  $N$  strategies leads to the similar equilibrium profits as  $k_\mu$  grows.

**Example 2.** The following figure shows the effect of  $r_{SCI}$  on the variables in the  $C$  strategy.



5-a.  $r_{CSI}$  effect on the decision variables



5-b.  $r_{CSI}$  effect on the dependent variables

**Fig. 3.** The effect of  $r_{CSI}$  on the variables in  $C$  strategy

**Insight 8** As shown in [Fig. 3](#), increasing  $r_{CSI}$  may lead to an increase in the CSI. It is reasonable as in Eq. 18, we assume that the relation between CSI and the manufacturer's profit is linear. Increasing  $r_{CSI}$  results in the manufacturer accounting for CSI more when making production, transparency, and greening decisions. Accounting for CSI in decisions leads to an increase in the greening degree and transparency level,  $\theta$  and  $\mu$  respectively. Higher values of  $\theta$  and  $\mu$  result in greater demand, leading to an increase in supply-chain-production profit. Hence, increasing  $r_{CSI}$  leads to an increase in the supply-chain-production profit.

#### 4.2 Government sub-game

To determine the government's equilibrium decisions, based on the backward induction technique, which is illustrated in Eqs. [\(21\)](#) and [\(22\)](#), the government utility function must be maximized while accounting for the supply chain's members best response functions. Before continuing, we consider the concavity of the government utility function. Therefore, the Hessian matrix of the government utility function must be negative-definite. However, the Hessian matrix is very complicated and strongly depends on the parameter values. It may be positive-definite, negative-definite or indefinite. Hence, we will use Karush-Kuhn-Tucker (K.K.T) conditions to find the equilibrium government variables' values ([Kuhn, 2014](#)). We present the government's equilibrium decision variable values in the following theorems:

**Theorem 3** *If the manufacturer does not concern with CSR ( $N$  strategy), one of the following set points presented in [Table 8](#), achieves the largest government utility (thus is the government's equilibrium decisions) and satisfies the “no money-pump assumptions” particularly:  $p \geq s_p^* \geq 0$ ,  $1 \geq s_\mu^* \geq 0$  and  $c \geq s_c^* \geq 0$ .*

**Table 7. The KKT points of the government utility in  $N$  strategy**

Case	Name	Set point	Government utility ( $\pi_G^*$ )
$KKT_1^N$	Interior point	$s_p^* \geq 0, s_\mu^* = \frac{2r_{TB}\beta + \zeta}{2r_{TB}\beta + 3\zeta},$ $s_c^* = c - \frac{k_\theta(2r_{TB}\beta + 3\zeta)(2r_1\beta(\alpha + s_p^*\beta) + (\alpha + 2c\beta + 3s_p^*\beta)\zeta)}{\beta(4k_\mu k_\theta(-8 + r_{CS})\beta + 8k_\mu\gamma^2 + k_\theta(2r_{TB}\beta + 3\zeta)^2)}$ $- \frac{4k_\mu(k_\theta\beta((-4 + r_{CS})\alpha - 4c\beta + (-8 + r_{CS})s_p^*\beta) + (\alpha + (c + 2s_p^*)\beta)\gamma^2)}{\beta(4k_\mu k_\theta(-8 + r_{CS})\beta + 8k_\mu\gamma^2 + k_\theta(2r_{TB}\beta + 3\zeta)^2)}$	$\frac{2k_\mu k_\theta(\alpha - c\beta)^2}{4k_\mu k_\theta(8 - r_{CS})\beta - 8k_\mu\gamma^2 - k_\theta(2r_{TB}\beta + 3\zeta)^2}$
$KKT_2^N$	No transparency cost	$s_p^* \geq 0, s_\mu^* = 0,$ $s_c^* = \frac{1}{2}(c - 2s_p^* - \frac{\alpha}{\beta} - \frac{k_\theta(\alpha - c\beta)(k_\mu r_2 + 2r_{TB}\zeta)}{k_\mu k_\theta(-8 + r_{CS})\beta + 2k_\mu\gamma^2 + 2k_\theta\zeta(r_{TB}\beta + \zeta)})$	$\frac{k_\mu k_\theta(\alpha - c\beta)^2}{2k_\mu k_\theta(8 - r_{CS})\beta - 4k_\mu\gamma^2 - 4k_\theta\zeta(r_{TB}\beta + \zeta)}$
$KKT_3^N$	Maximum transparency cost	$s_p^* \geq 0, s_\mu^* = 1, s_c^* = c - \frac{\alpha + s\beta}{\beta}$	0
$KKT_4^N$	Only transparency cost	$s_p^* = 0, s_c^* = 0,$ $s_\mu^* = 1 - \frac{\zeta(k_\theta\zeta(2r_{CS}\beta + \zeta) - 2k_\mu(4k_\theta\beta - \gamma^2))}{k_\mu(\gamma^2(2r_{CS}\beta + \zeta) - 2k_\theta\beta(4r_{CS}\beta + (2 + r_{TB})\zeta))}$	$\frac{k_\theta^2(\alpha - c\beta)^2(4k_\mu r_{CS}\beta + (2r_{TB}\beta + \zeta)^2)}{8(k_\mu(4k_\theta\beta - \gamma^2)^2 + k_\theta\zeta(\gamma^2(2r_{TB}\beta + \zeta) - k_\theta\beta(8r_{TB}\beta + (4 + r_{CS})\zeta))}$
$KKT_5^N$	No retail price subsidy and maximum manufacturing cost	$s_p^* = 0, s_c^* = c,$ $s_\mu^* = 1 - \frac{\zeta(2k_\mu\alpha(4k_\theta\beta - \gamma^2) - k_\theta\zeta(2r_{TB}\alpha\beta + (\alpha + 2c\beta)\zeta))}{k_\mu(2k_\theta\beta(4r_{TB}\alpha\beta + (2 + r_{CS})\alpha\zeta - 4c\beta\zeta) - \gamma^2(2r_{TB}\alpha\beta + (\alpha - 2c\beta)\zeta))}$	$\frac{k_\theta(4k_\mu\alpha\beta(k_2r_{CS}\alpha - 8ck_\theta\beta + 2c\gamma^2) + k_\theta(2r_{TB}\alpha\beta + (\alpha + 2c\beta)\zeta)^2)}{8(k_\mu(4k_\theta\beta - \gamma^2)^2 + k_\theta\zeta(\gamma^2(2r_{TB}\beta + \zeta) - k_\theta\beta(8r_{TB}\beta + (4 + r_{CS})\zeta))}$
$KKT_6^N$	Only maximum manufacturing cost	$s_p^* = 0, s_\mu^* = 0, s_c^* = c$	$\frac{k_\mu k_\theta \alpha \beta (k_\mu(k_\theta r_{CS} \alpha - 8ck_\theta\beta + 2c\gamma^2) + 2k_\theta\zeta(r_{TB}\alpha + c\zeta))}{2(k_\theta\zeta^2 - k_\mu(4k_\theta\beta - \gamma^2))^2}$
$KKT_7^N$	No subsidy	$s_p^* = 0, s_\mu^* = 0, s_c^* = 0$	$\frac{k_\mu k_\theta^2 \beta (\alpha - c\beta)^2 (k_\mu r_{CS} + 2r_{TB}\zeta)}{2(k_\theta\zeta^2 - k_\mu(4k_\theta\beta - \gamma^2))^2}$

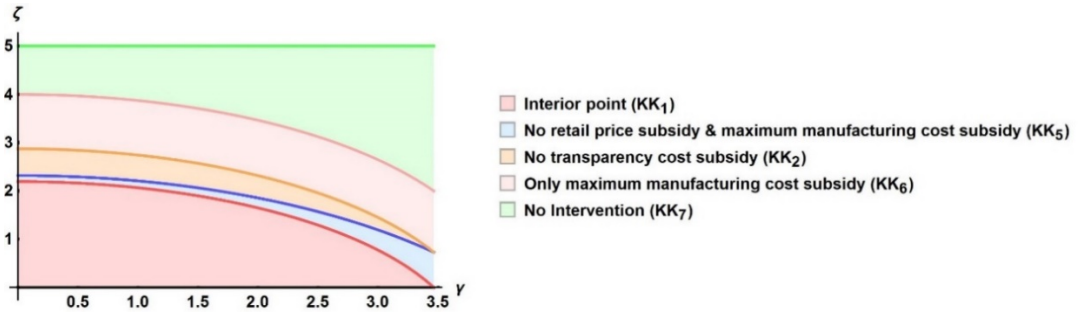


**Corollary 10**  $r_{CS}$  has a non-negative impact on the government utility function. The relationship between  $r_{CS}$  and  $\pi_G$  follow from the first-order derivatives of all of the KKT points given in [Table 8](#), all are non-decreases in  $r_{CS}$ . Therefore, if  $r_{CS}$  increases, the optimum government utility does not decrease.

**Corollary 11** If  $k_\mu = k_\theta = \beta = 2, r_{TB} = r_{CS} = 1, \alpha > c \rightarrow (\pi_G = f(\zeta, \gamma))$ , then:

$$\pi_G^* = \begin{cases} \pi_G(KK_1^N) & 0 < \zeta < \frac{2(\sqrt{28-2\gamma^2}-2)}{3} \text{ \& } 0 < \gamma < 2\sqrt{3} \\ \pi_G(KK_5^N) & \frac{2(\sqrt{28-2\gamma^2}-2)}{3} < \zeta < \frac{2\gamma^2-32+\sqrt{(24-\gamma^2)(\gamma^2-16)^2}}{20-\gamma^2} \text{ \& } 0 < \gamma < 2\sqrt{5} \\ \pi_G(KK_2^N) & \frac{2\gamma^2-32+\sqrt{(24-\gamma^2)(\gamma^2-16)^2}}{20-\gamma^2} < \zeta < \sqrt{15-\gamma^2}-1 \text{ \& } 0 < \gamma < \sqrt{14} \\ \pi_G(KK_6^N) & \sqrt{15-\gamma^2}-1 < \zeta < \sqrt{16-\gamma^2} \text{ \& } 0 < \gamma < 4 \\ \pi_G(KK_7^N) & o.w \end{cases} \quad (35)$$

**Corollary 12** Based on [Corollary 11](#), the area of optimum government strategies is:



**Fig. 4.** The optimum strategy environment of government

**Insight 9** As is shown in [Fig. 4](#), lower values of the demand sensitivity with respect to transparency level and greening degree,  $\zeta$  and  $\gamma$  respectively, the interior point, which contains all positive decision variables, is the optimum point of the government utility. As either  $\zeta$ ,  $\gamma$  or both increase, some subsidies become zero. In higher values of  $\zeta$  and  $\gamma$ , the optimum government strategy is to provide no subsidies by the government. This sequence is reasonable, because when the values of  $\zeta$  and  $\gamma$  are low, the consumers are not so sensitive to greening degree or transparency level and consumers care more about price than sustainability. Hence, if the government wants to increase the transparency level, he must provide several subsidies. However, if the values of  $\zeta$  and  $\gamma$  are high, the consumer's demand is highly sensitive to transparency level and greening degree and hence, the manufacturer decides a high transparency level and greening degree, independent of the government's subsidy decisions. Consequently, the government does not need to provide subsidies.

**Example 3.** Based on [Corollary 12](#), if  $r_{TB} = r_{CS} = 1, \gamma = \frac{3}{2}, k_\mu = k_\theta = \beta = c = 2, \alpha = 100$ , then:

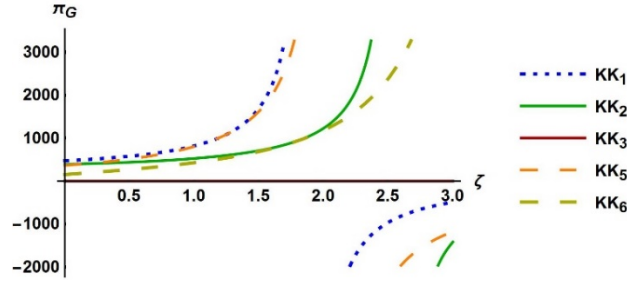


Fig. 5. The government utility function presented in [Example 3](#)

**Corollary 13** If  $r_{TB} = r_{CS} = \zeta = 1, k_{\mu} = k_{\theta} = 2, \alpha > \beta c \rightarrow (\pi_G = f(\beta, \gamma))$ , then:

$$\pi_G^* = \begin{cases} \pi_G(KK_5^N) & 0 < \beta < \frac{5 + 7\gamma^2 - \sqrt{25 + 22\gamma^2 + \gamma^4}}{48} \text{ \& } 0 < \gamma < 2\sqrt{3} \\ \pi_G(KK_6^N) & \frac{5 + 7\gamma^2 - \sqrt{25 + 22\gamma^2 + \gamma^4}}{48} < \beta < \frac{1 + \gamma^2}{8} \text{ \& } 0 < \gamma < 2\sqrt{5} \\ \pi_G(KK_2^N) & \frac{1 + \gamma^2}{8} < \beta < \frac{1 + \gamma^2}{6} \text{ \& } 0 < \gamma < \sqrt{14} \\ \max\{\pi_G(KK_5^N), \pi_G(KK_4^N)\} & \frac{1 + \gamma^2}{6} < \beta < \frac{5 + 7\gamma^2 + \sqrt{25 + 22\gamma^2 + \gamma^4}}{48} \text{ \& } 0 < \gamma < 4 \\ \pi_G(KK_7^N) & o.w \end{cases} \quad (36)$$

**Insight 10** Based on Corollaries [11](#) and [13](#), the government's equilibrium subsidy decisions are highly dependent parameter values. For instance, the point  $KK_5^N$  that is optimum in a range of parameters ([Corollary 11](#)), is never an optimum point when parameters are in the range of [Corollary 13](#). Hence, there is no unique suggestion or formulation for the government regarding his subsidy strategies and his decision is strongly dependent on the operating parameter values.

**Corollary 14** Based on [Corollary 13](#), if  $r_{TB} = r_{CS} = \zeta = 1, k_{\mu} = k_{\theta} = 2, \alpha > \beta c$ , then

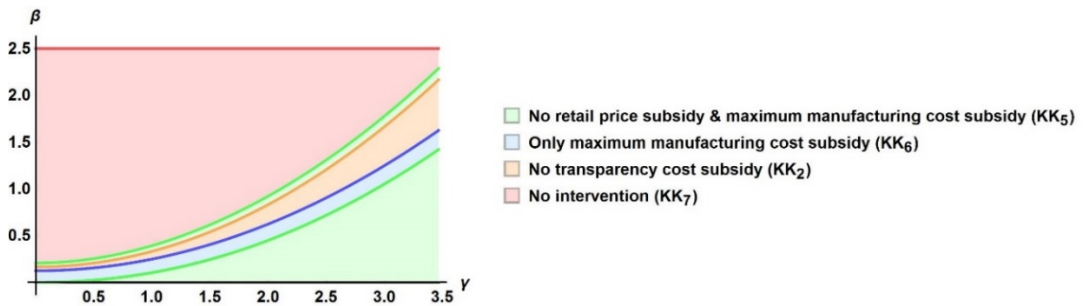
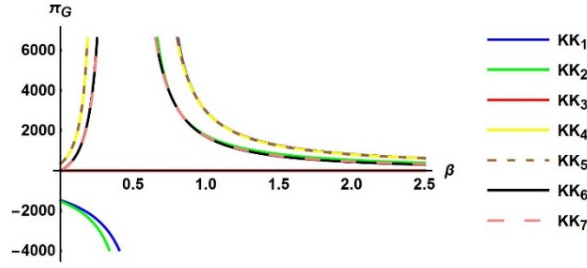


Fig. 6. The optimum strategy environment of government

**Insight 11** As shown in [Fig. 6](#), for any fixed value of  $\gamma$  at first when  $\beta$  is small, the strategy of no subsidy and optimum manufacturing cost subsidy ( $KK_5$ ) is the optimum strategy; as  $\beta$  increases,  $KK_5$  is dominated by other strategies; as  $\beta$  continue to increase,  $KK_5$  again dominates other strategy. Therefore, the domain over which a government's KKT point is optimal is not always convex, as shown by  $KK_5$ .

**Example 4.** Based on [Corollary 14](#), if  $r_{TB} = r_{CS} = \zeta = 1, \gamma = \frac{3}{2}, k_\mu = k_\theta = c = 2, \alpha = 100$ , then:



**Fig. 7.** The government utility function presented in [Example 4](#)

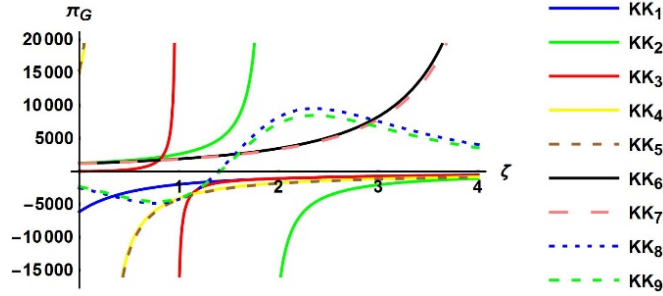
**Theorem 4** If the manufacturer concerns with CSR (*C* strategy), one of the following set points which achieves the most government utility and satisfied the assumptions, particularly  $p \geq s_r^* \geq 0, 1 \geq s_\mu^* \geq 0$  and  $c \geq s_c^* \geq 0$ , is the equilibrium solution of the government.

**Table 8.** The KKT points of the government utility in *C* strategy

Case	Set point
$KKT_1^N$	$s_p^* \geq 0, s_\mu^* = \frac{(r^\# \beta + 2r_1 \beta + \zeta)(k_\mu + r\zeta)}{k_1(3r\beta + 2r_1\beta + 3\zeta)}$
$s_c^*$	$= c + \frac{4k_\mu k_\theta \beta \left( (-4 + r_2^\#) \alpha - 4c\beta + (-8 + r_2) s_p^* \beta \right) + k_\theta (3r + 2r_1) \beta^2 \left( 2r_1 (\alpha + s_p^* \beta) + r (\alpha + 2c\beta + 3s_r \beta) \right) + 4k_\mu (\alpha + (c + 2s_p^*) \beta) \gamma^2}{\beta \left( 4k_\mu k_\theta (8 - r_2) \beta - 8k_\mu \gamma^2 - 8r\gamma^2 \zeta - k_\theta ((3r + 2r_1)^2 \beta^2 + 2(-7r + 6r_1 + 2rr_2) \beta \zeta + 9\zeta^2) \right)}$ $+ \frac{2(k_\theta \beta (4r_1 \alpha + r(-5 + 2r_2) \alpha - 2cr\beta + r(-7 + 2r_2) s_p^* \beta + 2r_1 (c + 3s_p^*) \beta) + 2r (\alpha + (c + 2s_p^*) \beta) \gamma^2) \zeta + 3k_\theta (\alpha + 2c\beta + 3s_p^* \beta) \zeta^2}{\beta \left( 4k_\mu k_\theta (8 - r_2) \beta - 8k_\mu \gamma^2 - 8r\gamma^2 \zeta - k_\theta ((3r + 2r_1)^2 \beta^2 + 2(-7r + 6r_1 + 2rr_2) \beta \zeta + 9\zeta^2) \right)}$
$KKT_2^N$	$s_p^* \geq 0, s_\mu^* = 0$
$s_c^*$	$s_c^* = \frac{1}{2} (c - 2s_p^* - \frac{\alpha}{\beta} - \frac{k_\theta (\alpha - c\beta) (2r_1 (r\beta + \zeta) + r_2 (k_\mu + r\zeta))}{k_\mu k_\theta (-8 + r_2) \beta + 2k_\mu \gamma^2 + 2r\gamma^2 \zeta + k_\theta (2r(r + r_1) \beta^2 + (2r_1 + r(-4 + r_2)) \beta \zeta + 2\zeta^2)})$
$KKT_3^N$	$s_p^* \geq 0, s_\mu^* = 1$
$s_c^*$	$s_c^* = c - \frac{-k_\mu k_\theta (\alpha + s_p^* \beta) (r\beta + \zeta)^2 + r^2 (\alpha + (c + 2s_p^*) \beta) \gamma^2 \zeta^2 + r\zeta \beta (\alpha + (c + 2s_p^*) \beta) \zeta^2}{\beta \left( k_\mu k_\theta (r\beta + \zeta)^2 - r\zeta (2r\gamma^2 \zeta + k_\theta (2r(r + r_1) \beta^2 + (2r_1 + r(-4 + r_2)) \beta \zeta + 2\zeta^2)) \right)}$ $+ \frac{r\zeta \left( k_\theta (r\beta^2 (2r_1 (\alpha + s_p^* \beta) + r (\alpha + c\beta + 2s_p^* \beta)) + \beta (2r_1 (\alpha + s_p^* \beta) + r ((-2 + r_2) \alpha - 2c\beta + (-4 + r_2) s_p^* \beta)) \zeta \right)}{\beta \left( k_\mu k_\theta (r\beta + \zeta)^2 - r\zeta (2r\gamma^2 \zeta + k_\theta (2r(r + r_1) \beta^2 + (2r_1 + r(-4 + r_2)) \beta \zeta + 2\zeta^2)) \right)}$
$KKT_4^N$	$s_p^* = 0, s_c^* = 0$
$s_\mu^*$	$s_\mu^* = 1 - \frac{r\gamma^2 \zeta (r\beta - 2r_2 \beta + \zeta) + k_\theta \beta^3 \zeta^3 r^2 \left( \left( \frac{(r+2r_2)}{\zeta^3} + \frac{(2rr_1+12r_2-r)}{r\beta\zeta^2} \right) + \left( \frac{(2rr_1+2r_2-r)^{-1}}{r^2\zeta\beta^3} \right) \right) - 2k_\mu (4k_\theta \beta - \gamma^2) (r\beta + \zeta)}{k_\mu (\gamma^2 (r\beta + 2r_2 \beta + \zeta) - 2k_\theta \beta (r(2 + r_1) \beta + 4r_2 \beta + (2 + r_1) \zeta))}$

Case	Set point
$KKT_5^N$	$s_p^* = 0, s_c^* = c$ $s_\mu^* = 1 - \frac{2k_\mu\alpha(4k_\theta\beta - \gamma^2)(r\beta + \zeta) + r\gamma^2\zeta(-2r_1\alpha\beta + r\beta(\alpha + 2c\beta) + (\alpha + 2c\beta)\zeta)}{k_\mu(2k_\theta\beta(4r_1\alpha\beta + r\beta((2 + r_2)\alpha - 4c\beta) + (2 + r_2)\alpha\zeta - 4c\beta\zeta) - \gamma^2(2r_1\alpha\beta + r\beta(\alpha - 2c\beta) + (\alpha - 2c\beta)\zeta))}$ $+ \frac{k_\theta(r^2\beta^3(2r_1\alpha + r(\alpha + 2c\beta)) + r\beta^2(12r_1\alpha + r(-1 + 2r_2)\alpha - 2c\beta\zeta) + \beta(2r_1\alpha + r(-1 + 2r_2)\alpha - 2c\beta)\zeta^2 + (\alpha + 2c\beta)\zeta^3)}{k_\mu(2k_\theta\beta(4r_1\alpha\beta + r\beta((2 + r_2)\alpha - 4c\beta) + (2 + r_2)\alpha\zeta - 4c\beta\zeta) - \gamma^2(2r_1\alpha\beta + r\beta(\alpha - 2c\beta) + (\alpha - 2c\beta)\zeta))}$
$KKT_6^N$	$s_p^* = 0, s_\mu^* = 0, s_c^* = c$
$KKT_7^N$	$s_p^* = 0, s_\mu^* = 0, s_c^* = 0$
$KKT_8^N$	$s_p^* = 0, s_\mu^* = 1, s_c^* = c$
$KKT_9^N$	$s_p^* = 0, s_\mu^* = 1, s_c^* = 0$
$\#r_{CS}, \dagger r_{TB}, \ddagger r_{CS}$	

**Example 5.** If  $r = r_{TB} = r_{CS} = 1, \gamma = \frac{3}{2}, k_\mu = k_\theta = \beta = c = 2, \alpha = 100$ , then



**Fig. 8.** The government utility function presented in [Example 5](#)

**Corollary 15** Based on the [Example 5](#), the optimum government utility is:

$$\pi_G^* = \begin{cases} \pi_G(KK_2^N) & 0 \leq \zeta \leq 2(-1 + \sqrt{2}) \\ \pi_G(KK_3^N) & 2(-1 + \sqrt{2}) \leq \zeta \leq \frac{122}{125} \\ \pi_G(KK_2^N) & \frac{122}{125} \leq \zeta \leq \frac{15}{8} \\ \pi_G(KK_8^N) & \frac{15}{8} \leq \zeta \leq 2.943 \\ \pi_G(KK_6^N) & \frac{15}{8} \leq \zeta \leq \frac{39}{8} \\ \pi_G(KK_8^N) & o.w \end{cases} \quad (37)$$

Based on Eq. (37), First,  $KK_2$  dominates other points. Then  $KK_3$  dominates  $KK_2$  and again,  $KK_2$  dominates other points. Like  $KK_2$ , in some  $\zeta$  values,  $KK_8$  dominates other points, then  $KK_6$  dominates  $KK_8$  and finally,  $KK_8$  again dominates other points. Hence, similar to  $N$  strategy, the domain over which a government's KKT point is optimal is not always convex.

## 5 Case study: Brick industry in Iran

In this section, we consider a real world example which is proposed by [Hafezalkotob \(2017\)](#). The case is about the brick industry in Iran. First, we describe the case and then analyze it.

### 5.1 Introducing the case and analyzing the results

The brick industry has a crucial impact of GDP of every country. However, in many countries, old and energy-intensive technologies are applied which is result in pollution. For instance, in Bangladesh, about 40% of greenhouse gases emission is made by brick industry ([World-Bank, 2011](#)). In India, brick industry has the third rank after power industry and steel industry in coal consumption ([Maithel et al., 1999](#)). Also in Iran, the old and energy intensive technologies are used in brick industries such that the brick industry's energy consumption in Iran is two times of universal average ([Hafezalkotob, 2017](#)).

On the other hand, construction industry is a very important industry in Iran which has an undeniable role in sustainable development ([Sattari and Avami, 2007](#)). Moreover, brick is a basis of construction industry and more than 6500 brick manufacturer exists in Iran which produce more than 53 million brick per year. However, most of these manufacturers use old and energy intensive technologies. There are two modern brick technologies: Hoffman and Tunnel which reduce the energy consumption if they are used instead of old technologies. Furthermore, environmental transparency has a very important and undeniable role in increasing the willingness to pay of the productions with green technologies ([GBC, 2009](#)). Hence, similar to ([Hafezalkotob, 2017](#)), we consider energy saving level as the greening degree. The data of parameters of this case is as follows ([Hafezalkotob, 2017](#)):

**Table 9. Parameters values in the Iranian brick industry case**

parameter	$\alpha$	$\beta$	$\zeta$	$\gamma$	$c$	$k_\mu$	$k_\theta$	$r_{CSI}$	$r_{TB}$	$r_{CS}$
amount	12	1	1	1.2	2	1.6	1.8	1	1	1

Considering Table 9, the following result are achieved in two situations: 1) without government intervention (when all government subsidy decisions set to zero); 2) with government intervention.

**Table 10. Equilibrium variable values for the case study**

case	Without Government intervention		With Government intervention	
	N Strategy	C Strategy	N Strategy	C Strategy
$p^*$	13.65	15.43	21.82	29.25
$w^*$	9.77	9.41	15.13	16.51
$\mu^*$	2.43	4.63	10.46	9.80
$\theta^*$	2.59	4.01	4.46	8.50
$D^*$	3.88	6.02	6.69	12.75

case	Without Government intervention		With Government intervention	
	<i>N</i> Strategy	<i>C</i> Strategy	<i>N</i> Strategy	<i>C</i> Strategy
$\pi_R^*$	15.08	36.22	44.81	162.44
$\pi_M^{N*}$	19.42	12.95	36.69	58.05
$\pi_{SC}^*$	34.50	49.17	81.51	220.49
$CSI^*$	6.48	17.15	15.32	81.21
$s_p^*$	0	0	0.7	10
$s_c^*$	0	0	0.26	1.18
$s_\mu^*$	0	0	0.6	0
$U_G^*$	-	-	33.47	63.73
$KKT$	-	-	$KK_1$	$KK_2$

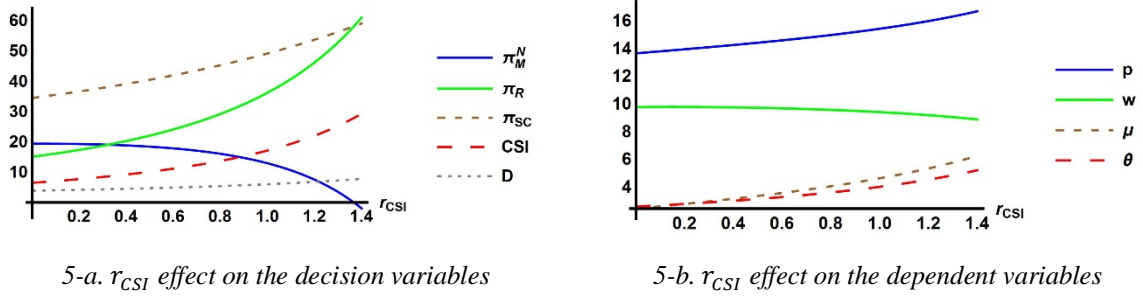
**Corollary 16** Considering [Table 11](#), when there is no government intervention, the prices, transparency and energy saving levels in *C* strategy are higher than in *N* strategy. In addition, the demand, the retailer's profit and supply chain profit in *C* strategy are higher than in *N* strategy and the manufacturer's profit in *C* strategy is lower than in *N* strategy. Moreover, the consumer satisfaction in *C* strategy is higher than in *N* strategy.

**Insight 12** When there is no government intervention, if manufacturer decide to choose *C* strategy, his profit decreases. However, he can gain much more demand, more consumer satisfaction and more total supply chain profit. In addition, the energy saving and transparency levels are higher. Therefore, energy consumption and pollution will decrease.

**Corollary 17** Considering [Table 11](#), when the government intervene the market,  $KK_1$  and  $KK_2$  are respectively the optimum point of government in *N* and *C* strategies.

**Insight 13** In  $KK_1$ , the government give subside for transparency cost and pay about 60% of transparency cost to the manufacturer and in  $KK_2$ , the government considers no transparency subsidy. Hence, as clear in [Table 10](#), the transparency level in *C* strategy is lower than in *N* strategy when the government intervene to the market. In addition, when the government intervenes the market and the manufacturer chooses *C* strategy, the consumer satisfaction index (CSI) strongly increases rather than all other situations.

**Corollary 18** The following figure shows the effect of  $r_{SCI}$  on the variables in the *C* strategy in the case study.



**Fig. 9. The effect of  $r_{CSI}$  on the variables in C strategy**

As it is clear, the manufacturer's profit decreases by increasing the  $r_{CSI}$ . The reason is that increasing  $r_{CSI}$  means that the manufacturer concerns more about CSR. Hence, his profit decreases by increasing  $r_{CSI}$ . In addition, transparency and energy saving levels increases by increasing  $r_{CSI}$ .

## 5.2 Comparing different subsidy strategies

In this section, we assume that the government aims to use only one subsidy strategy. Hence, we consider three policies for the government: retail price subsidy policy (RP): In this policy, the government only uses the retail price subsidy ( $s_p$ ) and two other subsidies are zero ( $s_\mu = s_c = 0$ ), transparency cost subsidy policy (TP): In this policy, the government only uses transparency cost subsidy ( $s_\mu$ ) and two other subsidies are supposed to be zero ( $s_p = s_c = 0$ ), and manufacturing cost subsidy policy (MP): In this policy, the government only uses transparency cost subsidy ( $s_c$ ) and two other subsidies are given zero ( $s_p = s_\mu = 0$ ). Therefore, we find out which policy is better with respect to different variables. The results of this consideration are summarized in the following table.

**Table 11. Equilibrium variable values for the case study in different government policies**

case	N Strategy			C Strategy		
	RP Policy	TP Policy	MP Policy	RP Policy	TP Policy	MP Policy
$p^*$	13.65	20.78	13.65	30.43	13.65	19.25
$w^*$	9.77	14.52	9.77	17.69	9.77	6.51
$\mu^*$	2.43	10.03	2.43	9.80	2.43	9.80
$\theta^*$	2.59	4.17	2.59	8.50	2.59	8.50
$D^*$	3.88	6.26	3.88	12.75	3.88	12.75
$\pi_R^*$	15.08	39.17	15.08	162.44	15.08	162.44
$\pi_M^{N*}$	19.42	31.29	19.42	58.05	19.42	58.05
$\pi_{SC}^*$	34.50	70.46	34.50	220.49	34.50	220.49

case	N Strategy			C Strategy		
	RP Policy	TP Policy	MP Policy	RP Policy	TP Policy	MP Policy
$CSI^*$	6.48	19.59	6.48	81.21	6.48	81.21
$s_p^*$	0	0	0	11.18	0	0
$s_c^*$	0	0	0	0	0	0
$s_\mu^*$	0	0.61	0	0	0	11.18
$U_G$	-	33.28	-	63.73	-	63.73

**Corollary 19** [Table 12](#) shows that in RP policy and MP policy, the optimum subsidies are zero. In other words, in  $N$  strategy, if the government plan to eliminate the transparency cost subsidy, paying other subsidies wont help government increase his utility.

**Insight 14** Based on [Corollary 19](#), if the government aim to consider subsidy in  $N$  strategy, it should be the transparency cost subsidy. Hence, the best policy for the government in  $N$  strategy is TP policy.

**Corollary 20** [Table 12](#) shows that in TP policy, the optimum subsidies are zero. In other words, when the supply chain concerns about CSR (i.e.,  $C$  strategy), the government don't have to pay transparency cost subsidy. It is reasonable because when the supply chain concerns about CSR (i.e.,  $C$  strategy), he decides to determine a high level of transparency. Therefore, the government does not need to pay subsidy to the supply chain to increase the transparency level. In addition, in  $C$  strategy, RP and MP policies have the same utility for the government, however, MP policies makes the smaller retail price, which helps the consumers more than RP policy. Hence, if the government wants to help the consumers, he is better to choose MP policy over the RP policy.

**Insight 15** Based on [Corollary 20](#), if the government aim to consider subsidy in  $C$  strategy, it should be the retail price subsidy or the manufacturing cost subsidy. However, it is better to pick the manufacturing cost subsidy over the retail price subsidy because it helps the consumers. Hence, the best policy for the government in  $C$  strategy is MP policy.

## 6 Managerial implications

We previously prepared several results and managerial insights. In this section, we gather all together and based on our findings, we propose some suggestions for supply chain members and the government. The following list is some suggestions for the supply chain members:

- If the manufacturer wants more willingness of the consumer to pay and more market share, then he should choose the strategy  $C$ , even selecting the strategy leads to lower monetary profit.
- If the manufacturer wants to sell his commodities with higher wholesale price to the retailer, he



has to pick strategy  $C$ . When he chooses strategy  $C$ , the optimum transparency level and greening degree increases and the consumers are more willing to pay for the products. Hence, the retailer sells his products in higher retail price and willing to buy products from the manufacturer in higher wholesale price.

- If the manufacturer wants to approach the centralized system, he should choose  $C$  strategy and make a contract such as two-part tariff contract with the retailer. Choosing strategy  $C$  leads to increase the supply-chain-production profit and making a contract with the retailer balance the manufacturer and the retailer profit.
- When the manufacturer picks strategy  $C$ , the retailer and the consumers are better off related to strategy  $N$ . In other words, the retailer earns more money and the consumers satisfied more in strategy  $C$  rather than in strategy  $N$ .

There are also several suggestions for the government.

- If the government wants to increase the transparency level or greening degree of the manufacturer, using all three types of subsidies works, and it does not matter what strategy the manufacturer picks. However, the government should consider the cost of subsidies and find the best package of subsidies based on market attributes.
- When the manufacturer chooses strategy  $N$  and does not concern about CSR, in the case that the unit cost of transparency is not high, the manufacturer decides a high transparency level. Hence, the government may give up using subsidies in this situation. However, if unit transparency cost is high, using subsidy is necessary for the government when strategy  $N$  is picked.
- To choose the best subsidy strategy, the government  $\zeta$  and  $\gamma$ . The more these two parameters increase, the less subsidy the government needs to improve the environmental and social benefits.
- The people more sensitive to the price, the more subsidy the government should consider to increase the environmental and social benefits. Because when the consumers are more sensitive to price, the manufacturer should decrease the transparency level and greening degree to reduce the retail price. Therefore, the government needs to intervene in the market to increase the transparency level and greening degree.
- In the case of the brick industry, the greening degree in strategy  $C$  is much more than in strategy  $N$ . However, the transparency level in strategy  $C$  is less than in strategy  $N$ . Hence, in this case, if the government is more interested in increasing transparency, he should consider it directly in his utility function and change his utility function.
- When the government intervenes in the market and the manufacturer chooses  $C$  strategy, the consumer satisfaction index (CSI) sharply increases rather than all other situations.

- If the government wants to consider only one type of subsidy in  $N$  strategy, it should be the transparency cost subsidy. In addition, if the government aims to consider only one type of subsidy in  $C$  strategy, it should be the manufacturing cost subsidy.

## 7 Conclusion and future work

In this study, we analytically determine a government's subsidy strategies in a green market in order to increase a manufacturer's transparency level and thereby increase social welfare. In fact, the government's subsidies strategies make the manufacturer increase the transparency level, which helps the environmental aspect of sustainability. In addition, it makes the product less expensive, which increases the social welfare of consumers. We assumed that a green supply chain including a manufacturer and a retailer sells a green product in the market. In addition, we assumed that potential consumers' purchasing behavior is determined by the transparency level and greening degree, determined by the manufacturer. Moreover, we analytically modeled each potential consumer having a reference transparency level that impacts the likelihood of that consumer purchasing the product. The manufacturer can choose two different strategies: he only concerns with his profit, the  $N$  strategy, or has concern with CSR in addition to his profit, the  $C$  strategy. A new transparency-dependent consumer satisfaction index is developed in this paper as the CSR indicator. The manufacturer determines the wholesale price, the transparency level, and greening degree. The retailer determines the retail price and sells products to consumers. The government chooses a combination of three different subsidies to provide to the market: retail price, transparency cost, and manufacturing cost subsidies. Using a three-layer Stackelberg game between the government, manufacturer, and retailer, we determine each party's equilibrium decisions as a function of the model parameters. We find multiple managerial insights in our work that may help governments and in turn business determine best courses of action in practice. We also give a real-world example of Iranian brick industry to fit the problem with the real word applications.

In the future work, several number of extensions are plausible. For example, multiple green and non-green production may be considered in the manufacturer's production portfolio. In addition, multiple supply chains competing with a market can be considered. Further, we assumed perfect knowledge of the game parameters, however some parameters may not be known exactly, but only their distributions or uncertainty sets may be known. Finally, the government's strategies were just a few of the viable strategies that could be used. As with each of the potential additional scenarios, additional government subsidy strategies are needed depending on the additional scenario.

## Appendix A. Notations

### *Parameters*

$\alpha$  Market size of product

$k_\mu$	Transparency cost coefficient
$k_\theta$	Greening cost coefficient
$r_{CSI}, r_{TB}, r_{CS}$	Conversion factors
$c$	Unit production cost paid by manufacturer
$\zeta_\mu$	Effect of transparency level on WTP
$\zeta_\theta$	Effect of Greening degree on the WTP

### ***Decision Variables***

$w$	Unit wholesale price of manufacturer's product
$p$	Unit retail price determined by retailer
$\mu$	Transparency level that manufacturer chooses
$\theta$	Greening degree that manufacturer chooses
$s_p$	Retail price subsidy level
$s_\mu$	Transparency cost subsidy level
$s_c$	Production cost subsidy level

### ***Dependent Variables***

$D$	Demand function of product
$\pi_R$	Profit function of retailer
$\pi_M^N$	Manufacturer's profit function in $N$ strategy (production profit)
$\pi_M^C$	Manufacturer's profit function in $C$ strategy
$\pi_{SC}$	supply chain's production profit function
$\pi_G$	Government utility function

## **Appendix B. Proof of Theorems**

### **Proof of [Lemma 1](#)**

**Proof.** By Merging the Eqs. (3) and (7), the following relation can be given.

$$D = D(p, \mu, \theta) = \alpha \int_{v_0 + \zeta_\mu(\mu - \bar{\mu}) + \zeta_\theta\theta - p > 0} \frac{d\dot{\mu}}{\mu^m} = \frac{\alpha(v_0 + \zeta_\mu\mu + \zeta_\theta\theta - p)}{\zeta_\theta \frac{v_0}{\zeta_\theta}} = \alpha - \frac{\alpha(p - \zeta_\mu\mu - \zeta_\theta\theta)}{v_0}$$

By replacing the relations  $\beta = \frac{\alpha}{v_0}$ ,  $\zeta = \frac{\alpha\zeta_\mu}{v_0}$ ,  $\gamma = \frac{\alpha\zeta_\theta}{v_0}$ , Eq. (9) is derived.  $\square$

### Proof of [Theorem 1](#)

As  $\frac{d^2\pi_R}{dp^2} = -2\beta$ , the retailer's profit function is concave. Therefore, the best response of retailer occurs in the extreme point that can be achieved as follows.

$$\frac{d\pi_R}{dp} = 0 \rightarrow \hat{p}(w, \mu, \theta, s_p, s_\mu, s_c) = \frac{\alpha + (s_r + w)\beta + \gamma\theta + \zeta\mu}{2\beta} \quad (38)$$

Hence, [Theorem 1](#) is proved.  $\square$

### Proof of [Theorem 2](#)

Using backward induction algorithm the equilibrium variables' values can be find. Firstly, the best response of retailer ( $\hat{p}$ ) is given in [Theorem 1](#). Replacing given  $\hat{p}$  into the manufacturer's profit function, it is updated. The Hessian matrix ( $H$ ) of updated manufacturer's profit ( $\hat{\pi}_M^C$ ) can be calculated as follows.

$$H = \begin{bmatrix} \frac{\partial^2 \hat{\pi}_M^C}{\partial \mu^2} & \frac{\partial^2 \hat{\pi}_M^C}{\partial \mu \partial \theta} & \frac{\partial^2 \hat{\pi}_M^C}{\partial \mu \partial w} \\ \frac{\partial^2 \hat{\pi}_M^C}{\partial \theta \partial \mu} & \frac{\partial^2 \hat{\pi}_M^C}{\partial \theta^2} & \frac{\partial^2 \hat{\pi}_M^C}{\partial \theta \partial w} \\ \frac{\partial^2 \hat{\pi}_M^C}{\partial w \partial \mu} & \frac{\partial^2 \hat{\pi}_M^C}{\partial w \partial \theta} & \frac{\partial^2 \hat{\pi}_M^C}{\partial w^2} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -2k_\mu(1-s_\mu) & r_{CS1}\gamma & -r_{CS1}\beta + \zeta \\ r_{CS1}\gamma & -2k_\theta & \gamma \\ -r_{CS1}\beta + \zeta & \gamma & -2\beta \end{bmatrix}$$

Considering assumptions, if  $|H_1| = -k_\mu(1-s_\mu) < 0$ ,  $|H_2| = 2k_\mu k_\theta(1-s_\mu) - \frac{(r_{CS1}\gamma)^2}{2} > 0$  and  $|H_3| = k_\mu(1-s_\mu)(4k_\theta\beta - \gamma^2) - k_\theta(\zeta - r\beta)^2 - r\gamma^2\zeta < 0$ ,  $\hat{\pi}_M^C$  is jointly concave in  $w$ ,  $\mu$  and  $\theta$ . Consequently, the interior point solution exists and hence, the first-order conditions conclude the unique best response given in Eqs. [\(24\)](#)-[\(26\)](#).  $\square$

### Proof of [Theorem 3](#)

As the Hessian matrix of government utility is strongly depends on the parameters values, it may be positive-definite, negative-definite or indefinite. Hence, Karush-Kuhn-Tucker (K.K.T) conditions should be used to find the equilibrium government variables' values ([Kuhn, 2014](#)). Based on (K.K.T), there are 18 points that a potential to be the optimum point of government utility function which are given below.

Case	Set point
------	-----------

$KKT_1^N$ 

$$s_p^* \geq 0, \quad s_\mu^* = \frac{2r_{TB}\beta + \zeta}{2r_{TB}\beta + 3\zeta}$$

$$s_c^* = c - \frac{k_\theta(2r_{TB}\beta + 3\zeta)(2r_1\beta(\alpha + s_p^*\beta) + (\alpha + 2c\beta + 3s_p^*\beta)\zeta)}{\beta(4k_\mu k_\theta(-8 + r_{CS})\beta + 8k_\mu\gamma^2 + k_\theta(2r_{TB}\beta + 3\zeta)^2)}$$

$$- \frac{4k_\mu(k_\theta\beta((-4 + r_{CS})\alpha - 4c\beta + (-8 + r_{CS})s_p^*\beta) + (\alpha + (c + 2s_p^*)\beta)\gamma^2)}{\beta(4k_\mu k_\theta(-8 + r_{CS})\beta + 8k_\mu\gamma^2 + k_\theta(2r_{TB}\beta + 3\zeta)^2)}$$

 $KKT_2^N$ 

$$s_p^* \geq 0, \quad s_\mu^* = 0,$$

$$s_c^* = \frac{1}{2}(c - 2s_p^* - \frac{\alpha}{\beta} - \frac{k_\theta(\alpha - c\beta)(k_\mu r_2 + 2r_{TB}\zeta)}{k_\mu k_\theta(-8 + r_{CS})\beta + 2k_\mu\gamma^2 + 2k_\theta\zeta(r_{TB}\beta + \zeta)})$$

 $KKT_3^N$ 

$$s_p^* \geq 0, \quad s_\mu^* = 1, \quad s_c^* = c - \frac{\alpha + s\beta}{\beta}$$

 $KKT_4^N$ 

$$s_p^* = 0, \quad s_c^* = 0,$$

$$s_\mu^* = 1 - \frac{\zeta(k_\theta\zeta(2r_{CS}\beta + \zeta) - 2k_\mu(4k_\theta\beta - \gamma^2))}{k_\mu(\gamma^2(2r_{CS}\beta + \zeta) - 2k_\theta\beta(4r_{CS}\beta + (2 + r_{TB})\zeta))}$$

 $KKT_5^N$ 

$$s_p^* = 0, \quad c_s^* = c,$$

$$s_\mu^* = 1 - \frac{\zeta(2k_\mu\alpha(4k_\theta\beta - \gamma^2) - k_\theta\zeta(2r_{TB}\alpha\beta + (\alpha + 2c\beta)\zeta))}{k_\mu(2k_\theta\beta(4r_{TB}\alpha\beta + (2 + r_{CS})\alpha\zeta - 4c\beta\zeta) - \gamma^2(2r_{TB}\alpha\beta + (\alpha - 2c\beta)\zeta))}$$

 $KKT_6^N$ 

$$s_p^* = 0, s_\mu^* = 0, s_c^* = c$$

 $KKT_7^N$ 

$$s_p^* = 0, s_\mu^* = 0, s_c^* = 0$$

 $KKT_8^N$ 

$$s_p^* = \frac{4k_\mu(k_\theta\beta((4 - r_{CS})\alpha + 4c\beta) - (\alpha + c\beta)\gamma^2) - k_\theta(2r_{TB}\beta + 3\zeta)(2r_{TB}\alpha\beta + (\alpha + 2c\beta)\zeta)}{\beta(4k_\mu k_\theta(-8 + r_{CS})\beta + 8k_\mu\gamma^2 + k_\theta(2r_{TB}\beta + 3\zeta)^2)}$$

$$s_\mu^* = \frac{2r_{TB}\beta + \zeta}{2r_{TB}\beta + 3\zeta}, \quad s_c^* = c$$

 $KKT_9^N$ 

$$s_p^* \geq 0, s_\mu^* = 0, c_s^* = \frac{1}{2}(c - 2s_r^* - \frac{\alpha}{\beta} - \frac{k_\theta(\alpha - c\beta)(k_\mu r_{CS} + 2r_{TB}\zeta)}{k_\mu k_\theta(-8 + r_{CS})\beta + 2k_\mu\gamma^2 + 2k_\theta\zeta(r_{TB}\beta + \zeta)})$$

 $KKT_{10}^N$ 

$$s_p^* = 0, s_c^* = \frac{(\alpha - c\beta)(4k_\mu(k_\theta(4 - r_{CS})\beta - \gamma^2) - k_\theta(2r_{TB}\beta + \zeta)(2r_{TB}\beta + 3\zeta))}{\beta(4k_\mu k_\theta(-8 + r_{CS})\beta + 8k_\mu\gamma^2 + k_\theta(2r_{TB}\beta + 3\zeta)^2)}, \quad s_\mu^* = \frac{2r_{TB}\beta + \zeta}{2r_{TB}\beta + 3\zeta}$$

 $KKT_{11}^N$ 

$$s_p^* = \frac{(\alpha - c\beta)}{2\beta} \left( \frac{k_\mu r_{TB} + 2r_{CS}\zeta}{k_\mu(8 - r_{TB}) - 2\left(\zeta r_{CS} - \frac{\zeta^2}{\beta} - \frac{k_\mu\gamma^2}{\beta k_\theta}\right)} - 1 \right), \quad s_\mu^* = 0, s_c^* = 0$$

 $KKT_{12}^N$ 

$$s_p^* = c - \frac{\alpha}{\beta}, s_\mu^* = 1, s_c^* = 0$$

$$KKT_{13}^N \quad s_p^* = \frac{k_\mu k_\theta \beta ((4 - r_{CS})\alpha + 4c\beta) - k_\mu (\alpha + c\beta)\gamma^2 - k_\theta \zeta (2r_{TB}\alpha\beta + (\alpha + c\beta)\zeta)}{\beta (k_\mu k_\theta (-8 + r_{CS})\beta + 2k_\mu \gamma^2 + 2k_\theta \zeta (r_{TB}\beta + \zeta))}, s_\mu^* = 0, s_c^* = c$$

$$KKT_{14}^N \quad s_p^* = -\frac{\alpha}{\beta}, s_\mu^* = 1, s_c^* = c$$

$$KKT_{15}^N \quad s_p^* = 0, s_\mu^* = 1 - \frac{\zeta (k_\theta \zeta (2r_{CS}\beta + \zeta) - 2k_\mu (4k_\theta \beta - \gamma^2))}{k_\mu (\gamma^2 (2r_{CS}\beta + \zeta) - 2k_\theta \beta (4r_{CS}\beta + (2 + r_{TB})\zeta))}, s_c^* = 0$$

$$KKT_{16}^N \quad s_p^* = 0, s_\mu^* = 1, s_c^* = c - \frac{\alpha}{\beta}$$

$$KKT_{17}^N \quad s_p^* = 0, s_\mu^* = 1, s_c^* = 0$$

$$KKT_{18}^N \quad s_p^* = 0, s_\mu^* = 1, s_c^* = c$$

By calculating the profit values in these points, some point does not satisfy the feasibility conditions. After removing these points, seven K.K.T points can be the optimum solution of government utility, which are given in [Table 8](#).

#### Proof of [Theorem 4](#)

Similar to [Theorem 3](#), as the Hessian matrix of government utility may be positive-definite, negative-definite or indefinite, Karush-Kuhn-Tucker (K.K.T) conditions should be used to find the equilibrium government variables' values ([Kuhn, 2014](#)). Based on (K.K.T), there also are 18 points that a potential to be the optimum point of government utility function. By calculating the profit values in these points, some point does not satisfy the feasibility conditions. After removing these points, nine K.K.T points can be the optimum solution of government utility, which are given in [Table 9](#).

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