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Compensation and information disclosure strategies of a green supply chain under production disruption

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ABSTRACT

This paper considers a manufacturer who produces and sells green products directly to customers via an online channel. We investigate the price compensation and information disclosure strategies to cope with a green production break. To this end, we first model the dynamic post-disruption customer behavior, considering the "observational learning" interactions facilitated by sales quantity information. Encountering the stock-out caused by production disruption, customers may leave or place backorders, depending on the factors including information learning, customer characters (sensitivities to time, price, and green level), disruption length, green level of the product, and price compensation. Then, by comparing and analyzing the optimal price compensation strategies with and without quantity information disclosure, we provide managerial insights on whether or not to disclose information during disruption, and how to adjust compensation price. The value of exposing quantity information and reducing the price is further analyzed via a numerical analysis. The results also indicate that the manufacturer could benefit more from the service of disclosing information than reducing the price in a hedge against short disruptions under some circumstances.

1. Introduction

Nowadays, various environmental challenges such as global climate and carbon emission, have resulted in the growing attention of enterprises and organizations with respect to sustainable supply chain development (Bian et al., 2017; Lyu et al., 2018). A remarkable number of consumers have also changed their purchase towards environmentally friendly products at a slightly higher price. In fact, by realizing efforts such as attaching the carbon footprint label with products to disclose the green level, some retailers could inspire a particular brand "reputation" from greening, and thus attract more customers (Mondal and Giri, 2020). Therefore, now many companies tend to engage in a green supply chain, not only because of the requirements of governmental and international legislations, but also to improve their profitability and substantial competitiveness (Ghosh and Shah, 2012).

Unexpected events such as natural catastrophes, machine breakdowns, etc., might disrupt the green supply chain and result in supply shortages, production interruptions, or direct demand disruptions. All types of disruptions ultimately lead to changes in demand, resulting in two types of losses: a short-term profit loss in terms of lose sales, and a long-term profit loss in terms of reduced future demand (Kuksov and Xie, 2010). To be specific, due to reputation/brand damages, the likelihood of receiving future orders from the customers who have undergone experienced stock-outs is reduced. Furthermore, the possibility of other customers' ordering could also be affected due to their social interactions through "word of mouth" (denoted as WOM hereafter) or "observational learning" (denoted as OL hereafter) (Zinn and Liu, 2008; Wang et al., 2019). Note that, in WOM, consumers normally obtain information from other buyers directly. In OL, consumers infer information from others' previous behaviors indirectly, such as through online product reviews.

In order to maintain business continuity and mitigate devastating profit losses, researchers and practitioners have developed a fruitful body of knowledge on disruption management in the context of non-green supply chains. For example, from the proactive aspect, the approaches of enhancing supply reliability and thus reducing supply risk are proposed, including supplier selection that diversifies suppliers and optimizes the order allocation pattern (Arabsheybani et al., 2018; Vahidi et al., 2018), contracting between

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suppliers and manufacturers (Li et al., 2020), etc. From the reactive aspect, coordination modes are established to guarantee the members' profit of a supply chain after a demand disruption (Liu et al., 2016) or a supply disruption (Aslani and Heydari, 2019), contingent sourcing is developed indicating how to emergently utilize backup suppliers coping with supply failures (Li et al., 2017; He et al., 2020), etc. However, research is limited in green supply chain disruption management, taking into consideration customers' preference or manufacturers'/retailers' efforts towards green.

In fact, the post-disruption demand exhibits different dynamics due to the customers' preference towards green. In other words, greening could play a considerable role affecting the negative impact caused by a disruption, thus influences the design of disruption mitigation strategies. A few recent researches start to argue for and against a finding that greening might be supportive for the disruption mitigation of green supply chains (Fahimnia et al., 2018). Therefore, it is essential to explore effective strategies coping with disruptions in green supply chains, based on customers' reaction (demand) management.

To this end, we consider a green manufacturer who produces a single kind of green product, and the production is interrupted accidently. In recent years, the development of e-commerce has significantly changed customers' purchasing patterns. As early predicted, the total retail e-commerce sales could reach \$4.058 trillion by 2020 (Rahmani and Yavari, 2019). Consequently, many green manufacturers have established direct online sales channels. Thus, we focus on the following setting: the manufacturer sells the green product directly to customers via an online channel, and the information regarding the green level and the sales record can be directly disclosed on the sales website (platform). To alleviate the profit losses incurred from disruptions, the green manufacturer could adopt proactive or reactive countermeasures. Nonetheless, the perfect proactive strategy is barely possible or economically infeasible to reach in reality (Kim et al., 2010). Hence, we employ reactive policies to manage customers' reaction in this study.

A common reactive strategy in both service and manufacturing industries is to compensate customers for the loss caused by the disruptions. For instance, in 2011, due to the lack of preparation for the surging demand in Touch Pad, HP and its partners failed to fulfill a number of orders in time. In order to reduce the damage of this stock-out, its retailers employed multiple forms of compensation service, including offering apologies, free service of future deliveries, future discounts, etc. (Dong et al., 2015).

In addition to providing incentives such as compensation, information also affects customers' reactions to disruptions through the mechanisms such as WOM and OL. The increasing convenience of surfing the Internet and e-commerce prompts information dissemination easily via both sales websites and online social media (Yu et al., 2015). For example, a product review online can be easily viewed by tens of thousands of prospective consumers (Motyka et al., 2018). As a result, these customers' purchasing behavior can be significantly affected due to an OL effect. In fact, according to a recent survey, 71% of U.S. adults who purchase online use consumer product reviews for their purchases, and 42% of them trust such a source (Chen et al., 2011). In other words, while selling green products via online channels, firms can directly facilitate an OL interaction among customers by disclosing the information of past buyers' purchase actions on their sales websites, and thus significantly interfere with customers' reaction to disruption.

To our best knowledge, little work takes into consideration customers' information-driven responses or focuses on informational benefits, in the process of mitigating disruptions, particularly regarding green production. Therefore, in order to bridge this gap, this paper studies how the green manufacturer strategically implements information disclosure and price reduction to maximize the profits during the disruption period. Two important research questions are addressed: Firstly, in view of consumers' OL interactions, does a green manufacturer/retailer disclose the information about how the previous customers react to the compensation policy during the out-of-stock period? Secondly, how to design effective compensation prices in the cases with and without information disclosure, taking into consideration customers' preferences towards green and information?

Our paper contributes to the literature in the following ways. First, two types of compensation strategies are proposed for mitigating stock-outs of green products: a pure price compensation policy without disclosing information, and a combined policy composed of disclosing sales quantity information and providing price reduction. The results guide how to adjust compensation price according to contributing factors such as information value, customer sensitivities (to price, time, and green level), disruption duration, green level, etc. Second, incorporating the OL effect from information, we bring forward the importance of information disclosure in alleviating disruption impact in a green production, and how the role of information disclosure changes with respect to customers' preference towards green level. Third, the findings also point out that the manufacturer might benefits from pure information disclosure without reducing the price when coping with short disruptions under some circumstances. Furthermore, increasing green could be a complementary for disruption mitigation, when the green level of the product is low.

The rest of this paper is organized as follows. The related work is briefly reviewed in Section 2. Section 3 describes the problem and analyzes the dynamics of how customers react to the services of information disclosure and price compensation. Two optimal strategies are proposed in Section 4. Via a numerical analysis, Section 5 presents the value of strategically disclosing information and reducing the price. Conclusions are drawn and future research work is suggested in Section 6. The calculations of Eqs. 8–10 and Table 2, as well as the proof of Proposition 1, can be found in the appendix.

2. Related literature

This study mainly relates to three streams of research: production disruption of green products, compensation pricing for stock-outs, and information disclosure.

2.1. Production disruption of green products

Generally, green supply chain management involves green strategies related to the entire operation process, including product and process design, procurement, processing, delivery, etc. Comprehensive reviews summarize the existing studies from a wide perspective (Agi et al., 2020).

However, only a little literature has been found addressing disruptions in green supply chains, mainly focusing on a closed loop supply chain (Yavari and Zaker, 2020). For instance, considering lateral transshipment as a resilient strategy coping with disruptions, Jabbarzadeh et al. (2018) design a closed-loop supply chain under disruptions risk and develop a stochastic robust optimization model to minimize the total cost. Different from them, our paper focuses more on green but not closed loop supply chains. The following several papers are related. By addressing a regression analysis on empirical data collected from 165 Finnish companies, Lintukangas et al. (2016) examine the possible link between supply risk management and green supply management practices. They find that quality and brand risk management ability are positively related to green supply management, while price and cost risk management ability show the opposite effect. On the other hand, through a non-fuzzy optimization modeling approach, Fahimnia et al. (2018) also investigate whether or not the greening and the robustness against disruption can be mutually supportive in a SC, and indicate that green supply chains are most sensitive to disruption. Considering a dual channel supply chain under channel disruption, Aslani and Heydari (2019) propose a new transshipment contract to maximize the profit for the supply chain and the members.

Furthermore, specific to the disruption management of green production, no relevant literature is found to our best knowledge. Most of the existing research on green production focuses on the individual or collaborative green activities of supply chain members, such as the coordination between manufacturers and retailers to tap the demand for green products. For example, based on a three-level green supply chain where the level of demand depends upon the green degree of products, Zhang and Liu (2013) address the comparative analysis of four decision-making models and point out that the cooperative model results in more benefit. Considering both a green and a non-green supply chain, Madani and Rasti-Barzoki (2017) investigate pricing and greening decisions with the government as the leader. Song and Gao (2018) examine the influence of customer sensitivity to greening on the decisions of green supply chain participants. Integrating both price differentiation and demand leakage for green and regular products, Raza and Govindaluri (2019) study a single channel coordination problem, and reveal that selling green and regular products at differentiated prices can significantly improve the profitability of both the manufacturer and retailer.

2.2. Compensation pricing for stock-outs

Various forms of compensation are studied to mitigate customer dissatisfaction or motivate backorders, including price discounts, rain checks, home delivery or reduced shipping charges, etc. (Anderson et al., 2006). All these efforts are costly to the providers (retailers/manufacturers), thus also referred to as financial compensation in most literature (Bhargava et al., 2006). By considering the demand shift from congested to uncongested periods, Keon and Anandalingam (2005) explored an approach for optimal dynamic discounts. Based on a duopoly model with two competitive e-retailers, Sun et al. (2008) investigate whether the stock-outs compensation can be a viable online operation model under competition, and find that some e-retailers have even moved to a "stockless" operation mode, fully relying on providing discounts to compensate consumers. Naming incentive compensations (monetary payments, store credit, and other forms of goodwill services) as availability guarantees, Su and Zhang (2009) compare it with commitment guarantee and find that the seller has an incentive to overcompensate consumers and a combination of these two commitments provides first-best outcomes. Later, through the comparison between four strategies (standard, substitute, backorder, and financial compensation), Kim and Lennon (2011) confirm that compensation exhibits the highest effectiveness in controlling customer reactions to stockouts. Dong et al. (2015) consider that the manufacturer compensates for the retailer's stock-out recovery effort and refers to such an incentive policy as a failure-recovery mechanism. By comparing it with stock-out prevention mechanisms (return policy and vendor-managed inventory), they find that the recovery mechanisms improve channel profitability under certain conditions, and may outperform prevention mechanisms. Chen et al. (2015) propose two compensation policies, namely uniform compensation and priority auction, and explore the optimal stockout price and base stock level under each mechanism. Based on a decentralized lateral system with two manufacturers (one disrupted and one requested), Shao (2018) studies the compensation rate and the transshipment price for both manufacturers.

As can be seen from the brief review above, extant research work on compensation has mainly focused on comparing it with other stock-out countermeasures, or the optimal decision (such as optimal price discount and compensation rate). Little research work has been done considering the service of information disclosure.

2.3. Information disclosure

Information disclosure has been largely discussed in terms of social learning/OL (He and Chen, 2018), WOM (Cascio et al., 2015; Xiang et al., 2017), and its impact on sales and consumer behavior (Shi et al., 2019). For example, considering that consumers can choose early uninformed purchases or late but informed purchases through social learning, Jing (2011) analyzes how social learning among peer consumers drives the dynamic pricing and adoption of durable experience goods. The results point out that the firm might benefit from informative advertising to initiate more social learning. Through an experimental setting resulting from information policy shifts at Amazon.com, Chen et al. (2011) further explore how observing learning and word of mouth might differ from (such as their impacts on product sales) each other. However, in the context of supply chain disruption management, existing research mainly focuses on processing/disclosing information about supply risk (such as the likelihood of disruption) or demand distribution among echelons (Deng et al., 2014; Guan et al., 2019). For example, based on a supply chain with one buyer and two suppliers who are subject to disruptions and whose disruption information is private, Yang and Babich (2015) investigate whether or not the buyer benefit from engaging the services of a better-informed procurement service provider compared to procuring directly from the suppliers.

To the best of our knowledge, there has been no study on disclosing the information of customers' behavior in the process of designing an incentive stock-out compensation policy. In this paper, in the context of managing a greening production disruption, we will address this important research gap.

3. Model formulation

In this paper, we consider a manufacturer's make-to-order production system with a common setting: a firm produces and sells a single kind of green product directly to customers via an online channel. The notations used in this paper are defined in Table 1.

Customers purchase online with price p, yielding a demand function as

$$d^0 = a - \sigma p + \mu g. \tag{1}$$

where a is the primary market potential for the green product, σ and μ represent customers' sensitivities to price p and green level g.

Without production interruption, the price is defined by the manufacturer maximizing the profit π_0, that is, $p \in \max \pi_0$.

$$\pi_0 = \left(p - c - hg^2\right)(a + \mu g - \sigma p). \tag{2}$$

the item $p - c - hg^2$ represents the unit profit of manufacturing one green product. The parameter c symbolizes the regular unit production cost, and the second-order function of green degree, i.e. hg^2, stands for the extra unit cost related to greening production

Table 1
The notations.

Notations	Description
T	the length of disruption duration
p	the unit selling price of a green product
Δp	the markdown price during disruption
c	the unit cost of manufacturing a non-green product
θ	customer sensitivity to waiting time
a	the market potential for the green products,
σ	the price sensitivity of customers.
μ	the green sensitivity of customers
g	the green level of the green products
h	the greening cost coefficient
k	the observational learning (OL) intensity of customers under the policy of quantity disclosure
r	the expected backordering demand under the policy of quantity disclosure, namely, backorder reference in this paper
$d^j(t)$	the demand for the green products under the implementation of policy j, where j = "NC" and "DC".
NC	the compensation policy that does not disclose quantity information
DC	the compensation policy that discloses quantity information
$Q^j(t)$	the total backlogged demand quantity under the implementation of policy j
$\pi^j(t)$	the profit of the manufacturer under the implementation of policy j
π_0	the profit function of the manufacturer before disruption

Table 2
The optimal compensation Δp^{DC} under quantity information disclosure.

Conditions			The optimal compensation Δp^{DC}
$\frac{\theta}{k} \geq r$	$T \leq M/\theta$		P_2
	$M/\theta < T < 2M/\theta$	$\frac{\theta}{k} \geq r + R_1$	P_{min1}
		$\frac{\theta}{k} < r + R_1$	P_2
$\frac{\theta}{k} < r$	$T \leq F^{-1}(2M)$	$\frac{\theta}{k} > r - R_1$	P_2
		$\frac{\theta}{k} \leq r - R_1$	M/σ

and operations. This cost function is commonly used in relative literature regarding the green level (Liu et al., 2012; Rahmani and Yavari, 2019) or quality level (Shi et al., 2013; Liu et al., 2018) of a product.

Based on Eq. (2), the price that maximizes profit for the manufacturer can be directly derived as

$$p = \frac{c + hg^2}{2} + \frac{a + \mu g}{2\sigma}. \tag{3}$$

considering that both demand and profit are non-negative, the price is limited to $c + hg^2 < p < \frac{a+\mu g}{\sigma}$. That is, the following constraint is required.

$$c + hg^2 < \frac{a + \mu g}{\sigma}. \tag{4}$$

The production stops at time "0" due to supply or machine failures, and a stock-out with a deterministic length "T" occurs. Facing the stock-out, customers react in two ways: to leave (lost sales) or to stay (backorders), depending on the factors related to the disruption length, the countermeasures provided by the manufacturer, their patience to waiting time, and their preference towards green. The model based on such a basic setting could be a baseline for the models with multi-echelon, multi-disruption, and random demand.

To reduce the customers' dissatisfaction and avoid profit losses (lost sales), the manufacturer considers two policies during disruption: (a) compensating customers via a markdown Δp in price; (b) disclosing the information about how the previous customers respond to the compensation on the sales website. As a reaction, some customers who arrive at time t choose to accept the compensation and remain in the market. Each customer who places backorders will receive the green product at price $p - \Delta p$ after the production resumes at time T. We investigate the optimal markdown in price and the decision whether or not to disclose the quantity information, for the manufacturer.

Next, we discuss the dynamics of customers' reaction to the policies "NC" and "DC". Unless otherwise noted, in this study, customers' behavior/reaction refers to how many customers are willing to place a backorder during disruption, quantified as the remaining demand $d^j(t)$.

3.1. Dynamics of post-disruption demand without disclosing quantity information

After the occurrence of disruption, the manufacturer provides a compensation price Δp to customers who arrive at time t, here $\Delta p \geq 0$. Without any countermeasures employed, the customers' willingness to wait decreases over time, depending on their patience to waiting time. Denote the remaining demand under the strategy "NC" as $d^{NC}(t)$. Together with the demand in the absence of disruption (see (1)), we thus model $d^{NC}(t)$ as

$$d^{NC}(t) = a - \sigma(p - \Delta p) + \mu g - \theta(T - t). \tag{5}$$

where $T - t$ is the waiting time of the customers who arrive at time t, and the parameter θ represents the customers' sensitivity to waiting time, $\theta \geq 0$. In particular, when $\theta = 0$, customers have infinite tolerance for delayed deliveries. To guarantee that the demand is non-negative at any point in time under compensation, an additional constraint $a - \sigma(p - \Delta p) + \mu g - \theta T \geq 0$ is required. Note that $t \in (0, T)$. Substituting p into it, the lower bound for a positive Δp is derived as

$$\Delta p \geq P_{min1} = \frac{\theta T - M}{\sigma}, \tag{6}$$

where $M = \frac{a+\mu g}{2} - \frac{c+hg^2}{2}\sigma$.

If $\Delta p = P_{min1}$, no customer chooses to postpone his/her purchase at the initial time of the disruption, even the manufacturer reduces the price. Nonetheless, as the disruption goes on, the required waiting time of the customers who arrive in late periods becomes shorter. As a result, the backordering demand grows.

3.2. Dynamics of post-disruption demand with disclosing quantity information

Under the strategy "*DC*", the manufacturer takes two options to hedge against the negative impact of disruption: (a) providing the compensation Δp; (b) disclosing the quantity information $Q^{DC}(t)$, i.e., how many customers have accepted the compensation at time point t. Due to the OL effect facilitated by information, the decision of each customer is not only affected by waiting time and compensation, but also depends on his/her observation of previous customers' behavior. Thus, based on Eq. (5), we then model the demand under the strategy "*DC*" as

$$d^{DC}(t) = a - \sigma(p - \Delta p) + \mu g - \theta(T-t) + k\left[Q^{DC}(t) - rt\right]. \tag{7}$$

where, $Q^{DC}(t) = \int_0^t d^{DC}(\tau)d\tau$. The parameter r captures the expected backordering demand (similar to the well-utilized concept "reference price" in dynamic pricing, see Winer (1986)), $r \geq 0$. The difference $Q^{DC}(t) - rt$ represents the excess between the observed accumulated backordering demand and the expected backordering demand at time t. When $Q^{DC}(t) - rt > 0$, the information shows a positive impact on customers' willingness to wait. The parameter k represents the OL intensity, reflecting the tendency that the customers' consumption is driven by the information generated from previous periods, $k \geq 0$. In particular, if $k = 0$, information disclosure does not affect customers' reaction. Therefore, the term $k[Q^{DC}(t) - rt]$ characterizes the OL effect generated from the exposed information at time t.

Solving Eq. (7), the demand under the strategy "*DC*" can be determined as

$$d^{DC}(t) = (M_1 + \sigma\Delta p)e^{kt} - \frac{\theta}{k} + r. \tag{8}$$

where $M_1 = a + \mu g + \frac{\theta}{k} - \sigma p - \theta T - r$. To ensure the non-negativity of demand, the price reduction under information disclosure satisfies the following constraint:

$$\Delta p \geq P_{min1} \text{ if } \frac{\theta}{k} \geq r\text{, and } \Delta p \geq P_{min2} \text{ if } \frac{\theta}{k} < r. \tag{9}$$

$$P_{min2} = \frac{\left(\frac{\theta}{k} - r\right)\left(e^{-kT} - 1\right)}{\sigma} + P_{min1}. \tag{10}$$

P_{min1} is given in Eq. (6). The detail of achieving Eqs. 8–10 is presented in the Appendix.

According to Eq. (9), the lower bound of the price reduction falls into two cases, dependent on whether the inequality $\frac{\theta}{k} < r$ is satisfied. Under $\frac{\theta}{k} < r$, customers might exhibit two characteristics. First, they have a significant propensity to exploit previous customers' decisions when they purchase. Second, they expect a large backorder reference, that is, customers can only be encouraged by the quantity information to postpone their purchase when a large number of predecessors accept the compensation policy. Thus, a negative OL effect can be easily facilitated during the process of information disclosure. In other words, the inequality $\frac{\theta}{k} < r$ refers to the customers who have a certain degree of negative bias towards quantity information. They perceive negative information to be more persuasive than positive ones (Chen and Lurie, 2013; Zhang et al., 2010). As a consequence, the lower bound of the price reduction is required to be larger for this type of customers (namely, customers with a negative bias in this study), i.e., $P_{min2} > P_{min1}$. On the contrary, under $\frac{\theta}{k} \geq r$, a positive OL effect can be easily facilitated. However, this type of customers might not rely much on the observed information when they purchase. Therefore, the lower bound of the price reduction remains unchanged (i.e., P_{min1}) in the case of information disclosure.

Further analyzing the derivative of demand $d^{DC}(t)$ with respect to the time variable t, we present the dynamic of customers' reactions under the disclosure of quantity information in Lemma1.

Lemma 1. (***the customers' reaction to the quantity information***). *Under the disclosure of quantity information, the backordering demand $d^{DC}(t)$ increases with time during disruption if $\Delta p > -M_1$, and decreases otherwise.*

As stated in Lemma 1, if the compensation price Δp is lower than $-M_1$, the likelihood of placing backorders might decrease over time. The intuition behind this finding is stated below. At the beginning of the disruption, some customers are willing to postpone their orders because of their high patience on waiting, the preference for the green of the product, or the price reduction offered by the manufacturer. Nonetheless, as the disruption goes on, by observing the predecessors' purchasing behavior (i.e., the accumulated demand quantity), the subsequent customers perceive that the compensation is not good enough (i.e., with a low deal value). A negative OL effect is formed and magnified in the process of disclosing information. Impacted by the negative OL effect, the subsequent customers' tendency of remaining in the market drops, despite that their waiting time is shortened. The result is consistent with the findings in relative literatures. For example, Cui et al. (2019) point out that a lower discount (price compensation) could amply a deal's OL momentum when customers learns about deal value from inventory information.

4. The optimal reactive strategies

In this section, we propose the optimal compensation policies "*NC*" and "*DC*", and further generate insights into the important role of information disclosure.

4.1. The optimal compensation without disclosing quantity information

Based on the profit function without disruption (see Eq. (2)), we describe the profit under the implementation of the strategy "*NC*" during the disruption period $[0, T]$ as:

$$\pi^{NC} = \left(p - \Delta p - c - hg^2\right)\int_0^T d^{NC}(t)dt. \tag{11}$$

the item $p - \Delta p - c - hg^2$ gives the unit profit of compensating each customer during disruption. Based on the demand function Eq. (5), the total backlogged demand that chooses to stay during disruption and to be met after the end of disruption is derived as

$$Q^{NC}(T) = \int_0^T d^{NC}(t)dt = [a + \mu g - \sigma(p - \Delta p) - \theta T]T + \frac{1}{2}\theta T^2. \quad (12)$$

To guarantee $\pi^{NC} \geq 0$, the upper bound is determined for the markdown price:

$$\Delta p \leq p - c - hg^2. \quad (13)$$

in particular, if $\Delta p = p - c - hg^2$, there is no economic value for providing compensation. Other alternative countermeasures should be taken into consideration for mitigation, such as order transfer, rerouting to secondary sourcing if the production halt is triggered by supply failures, etc.

The optimization problem that decides the optimal price reduction of the green product to maximize his/her profit π^{NC}, is then formulated as

$$\Delta p^{NC} = \Delta p^* \in \arg\max \pi^{NC}. \quad (14)$$

Combining the lower and upper bounds of Δp given in Eq. (6) and Eq. (13), solving Model (14), the optimal compensation price without disclosing quantity information is presented in Proposition 1.

Proposition 1. *Without disclosing quantity information, the compensation policy tends to be effective if $\theta T < 2M$. The optimal compensation price is determined as*

$$\Delta p^{NC} = \begin{cases} P_1 = \dfrac{1}{4\sigma}\theta T, & \text{if } \theta T < \dfrac{4}{3}M; \\ P_{min1}, & \text{if } \dfrac{4}{3}M < \theta T < 2M. \end{cases} \quad (15)$$

where P_{min1} and M are given in Eq. (6).
Proof. *See the Appendix.*

As indicated in Proposition 1, without information disclosure, the compensation policy ("*NC*") can only be an option to cope with the disruptions shorter than $2M/\theta$. The optimal compensation price falls into two values: P_1 and P_{min1}, depending on whether the disruption length T exceeds the critical value $4M/(3\theta)$. It is worth noting that $P_{min1} > P_1$. The results suggest that the manufacturer utilizes a deeper compensation if the disruption becomes longer or customers exhibit more impatience. Furthermore, P_1 is defined by the customers' sensitivities to time and price, and the disruption length. In other words, as for short disruptions, there is no need to change the compensation price with respect to the green level.

Corollary 1 is also observed directly from the item M, explaining how the conditions of utilizing compensation change with relative factors.

Corollary 1. *M decreases with σ, and increases with the green level g if $\mu > 2h\sigma g$.*

Corollary 1 reveals two facts. First, the critical value linked to Mdecreases with the customers' sensitivity to price. In other words, without disclosing quantity information, the likelihood of utilizing compensation drops if the customers in the market are sensitive to price. Second, if the green level bellows $\mu/(2h\sigma)$, a rise of the green level leads to an increase in the advantage of compensation. This result indicates an interesting managerial insight. When the green level is low, by increasing the green of the product, a pure compensation strategy can suffice to cope with longer production disruptions. That is, greening can be a complementary on mitigating disruption.

4.2. The optimal compensation with disclosing quantity information

Like Eq. (11), the profit function π^{DC} under the disclosure of quantity information is formulated for the manufacturer as

$$\pi^{DC} = \left(p - \Delta p - c - hg^2\right) \int_0^T d^{DC}(t)dt. \quad (16)$$

the demand functions $d^{DC}(t)$ is given in Eq. (8). In order to guarantee $\pi^{DC} \geq 0$, the compensation price is also required to satisfy the constraints Eq. (9) and Eq. (13).

The optimization problem of the manufacturer is then formulated as

$$\Delta p^{DC} = \Delta p^* \in \arg\max \pi^{DC}. \quad (17)$$

combing the upper and lower bounds of the compensation price, solving Model (17), the optimal compensation price under quantity information disclosure is presented in Table 2. The calculation of Table 2 is shown in the Appendix.

In Table 2, M and P_{min1} are given in Eqs. (6)–(9).

$$P_2 = \frac{1}{2\sigma}\theta T - \frac{\frac{\theta}{k} - r}{2\sigma}\left(1 - \frac{e^{-kT}kT}{1 - e^{-kT}}\right). \quad (18)$$

$$R_1 = \frac{2M - \theta T}{1 - \frac{e^{-kT}kT}{1-e^{-kT}}} > 0. \quad (19)$$

$$F(T) = \theta T + \left(\frac{\theta}{k} - r\right)\left(e^{-kT} - 1\right). \quad (20)$$

As indicated in Table 2, the optimal compensation price can be one of the following values: P_2, M/σ, and P_{min1}, mainly depending on the disruption length and the customers' expected backordering demand. In particular, when $\Delta p^{DC} = M/\sigma$, there is no economic value for the manufacturer to utilize the compensation policy. Therefore, the results in Table 2 first shed light on the conditions under which the price reduction policy is ineffective to mitigate the negative disruption impact while the quantity information is disclosed, as stated in Proposition 2.

Proposition 2. *Under quantity information disclosure, the compensation policy tends to be ineffective in the following scenarios:*

(i) *if $\frac{\theta}{k} \geq r$: $T \geq 2M/\theta$;*
(ii) *if $\frac{\theta}{k} < r$: $T \geq F^{-1}(2M)$ or $\frac{\theta}{k} \leq r - R_1$.*

Where $F(T)$ and R_1 are given in (19)-(20), and $F^{-1}(2M) < 2M/\theta$.

Proof. *The results are directly deduced from Table 2.*

Two important managerial insights are revealed for the manufacturer. First, when $\frac{\theta}{k} \geq r$, the compensation under information disclosure ("*DC*") can only suffice to cope with the disruptions shorter than $2M/\theta$. Comparing the results with Proposition 1, we find that the threshold of the disruption length remains unchanged after the manufacturer discloses information. In other words, if customers do not show a negative bias when they evaluate the quantity information, the service of information disclosure will not affect the effectiveness of compensation.

Second, when $\frac{\theta}{k} < r$, customers exhibit a negative bias, and a negative OL effect appears. As a result, the compensation policy becomes ineffective to hedge against shorter disruptions, i.e., the upper bound of the disruption length is $F^{-1}(2M)$. Furthermore, when $\frac{\theta}{k} \le r - R_1$, customers expect a significant large reference backorder. In other words, they are with an extremely negative bias. The reduction in customers' dissatisfaction due to compensation can be easily offset by the significantly negative OL effect of information. Consequently, the compensation policy is ineffective to mitigate any disruption.

On the other hand, we also observe from Table 2 that P_2 increases with r. The result suggests that the manufacturer provides a higher compensation with a larger reference backorder r. On the other hand, similar to the optimal compensation price P_1 proposed for the cases without disclosing information, P_2 is also independent with the green level. Together with the conditions for P_{min1} being optimal, an interesting managerial insight is generated. Under information disclosure, the manufacturer only needs to adjust the compensation price to the green level if $\frac{\theta}{k} \ge r + R_1$ and $M/\theta < T$. This intuitive result is also reasonable. In this situation, the disruption will last relatively long and the customers do not primarily attribute the quantity information into their purchase. That is, the quality (the green level in this study) and price dedicate the customers' behavior. Correspondingly, the price compensation should be adjusted in accordance with the green level.

5. The numerical analysis

Due to the complex scenarios of optimal compensation price under strategies *″DC″* and *″NC″* (as given in Proposition 1 and Table 2), the advantage between these two strategies cannot be analytically examined. Thus, in this section, we conduct a numerical analysis to visually present the profit differences under different strategies. In addition to the afore proposed optimal strategies *″DC″* and *″NC″*, i.e., "information disclosure & compensation" and "compensation", we extend the comparison considering two commonly utilized strategies: "passive acceptance" (doing nothing but waiting for production restoration, denoted as *″N″*) and "pure information disclosure" (denoted as *″D″*). The profits under these two policies are respectively denoted as π^N and π^D in figures.

By doing so, we present the value of quantity information disclosure and price compensation, and generate further insights into the roles of the following factors: the green level g, the customers' sensitivities θ and μ to waiting time and green level, the disruption length T, and the factors related to customers' attitude for information. To this end, in view of the constraint Eq. (4), we establish the basic parameter values representing a given market condition, as follows: $a = 10$, $\sigma = 0.1$, $h = 0.5$, and $c = 10$. Note that, together with these four factors, the selling price of a green product before the occurrence of disruption is already optimized according to the green level (see Eq. (3)). The basic value of these four factors won't change our main findings in the following.

5.1. The profit difference of the strategies without information disclosure

In Fig. 1, the y-axis gives the profit differences for the green manufacturer implementing the policies "compensation" and "passive acceptance", under different green levels. The x-axis represents the maximum duration of the disruptions which can be alleviated by price compensation. The vertical line $T = M/\theta$ shows the length threshold of the disruptions that can be managed through the "passive acceptance" policy *″N″*. The results indicate that, comparing with the policy *″N″*, the manufacturer can cope with longer disruptions via price compensation. Nonetheless, the advantage of compensation drops when the disruption becomes longer. On the other hand, if customers are sensitive to the green level g (e.g., $\mu = 2$), the advantage of providing compensation increases with g. Without price reduction, the manufacturer could suffer huge losses while sells products with a high green level. Conversely, if customers are insensitive to g (e.g., $\mu = 0.1$), the results exhibit an opposite trend.

5.2. The profit difference of the strategies with information disclosure

The following figures are based on $\mu = 2$, that is, we take the case that the customers are sensitive to the green level for instance. Four types of profit differences are depicted in Figs. 2–5, standing for the superior comparison between the following policies: (a) "information disclosure & compensation" and "pure information disclosure"; (b) "information disclosure & compensation" and "compensation; (c) "pure information disclosure" and "compensation"; (d) "pure information disclosure" and "passive acceptance".

In the following, unless otherwise stated, the vertical imaginary lines stand for the length thresholds of the disruptions that can be alleviated by the countermeasure "pure information disclosure", and the x-axis gives the length thresholds of the disruptions that can be dealt with by other strategies. The y-axis represents the profit differences.

Fig. 2 shows the four profit differences under $k = 0.01$, $\theta = 0.1$, as well as their variation trends with respect to the customers' backorder reference r. Fig. 2(a) reveals three findings. First, the "pure information disclosure" strategy only suffices to cope with the disruptions shorter than 105 (see the vertical imaginary line). In other words, the "compensation & information disclosure" policy is effective to hedge against longer disruptions than "pure

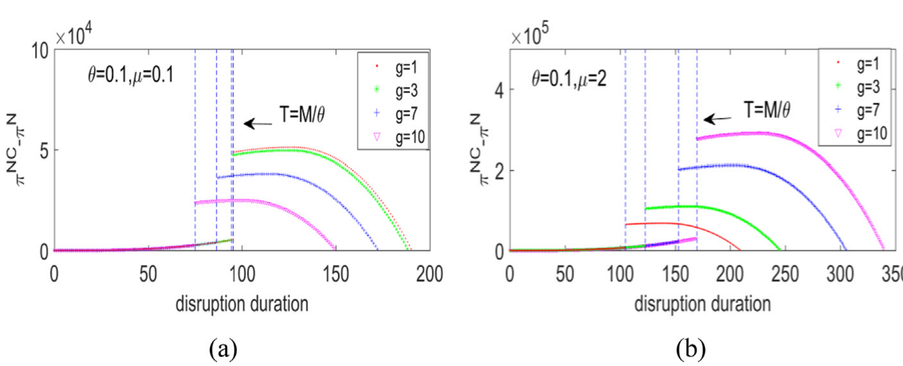

Fig. 1. The profit differences $\pi^{NC} - \pi^N$ under different green levels, while $\theta = 0.1$ and (a) $\mu = 0.1$; (b) $\mu = 2$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

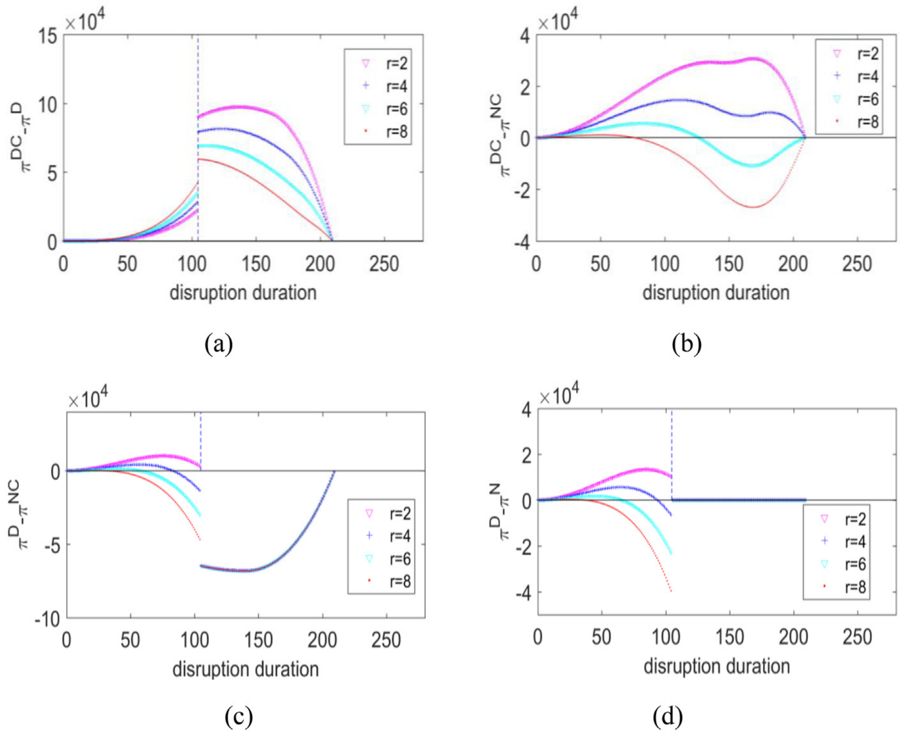

Fig. 2. The profit differences under different r, while $k = 0.01$, $\theta = 0.1$.

information disclosure". Second, the profit difference between these two decisions, i.e., the value of providing price compensation under information disclosure (when $T \leq 105$), increases with r. In other words, if customers expect a high backorder reference, the manufacturer should provide compensation while disclosing information. Third, the effectiveness of utilizing "compensation & information disclosure" drops with r. In order to visually evaluate the OL effect, i.e., the values of information disclosure, Fig. 2(b) and (d) present the profit differences facilitated from disclosing information, in the cases with and without price reduction. The results indicate that information disclosure leads to an increase in manufacturer's profit, if the disruption will not last long and customers do not expect a huge reference backorder. Due to the positive effect generated from information, Fig. 2(c) further confirms that the "pure information disclosure" policy could be superior to the "compensation" policy under some circumstances.

Fig. 3 extends the analysis of Fig. 2 to $k = 0.05$. Fig. 3(a) and (b) are partially zoomed, as shown in Fig. 3(e) and (f). Comparing the results of Figs. 2 and 3, we observe an important finding. Unlike the cases where k is small (e.g., Fig. 2), the effectiveness of implementing a combined compensation policy significantly drops with r. For instance, when $r = 8$, this strategy fails to mitigate the disruptions longer than 50 (Fig. 3(a)). The reason for this observation is intuitive. As k grows, the influence of information disclosure or compensation on profit is considerably magnified. Note that, we have run abundant analysis on increasing the value of k. Such main findings still hold.

Letting $\theta = 0.6$, Fig. 4 illustrates how does the customers' sensitivity to waiting time play roles in the manufacturer's strategic decision. First, both compensation and information disclosure become ineffective for shorter disruptions. The reason is also intuitive. Customers who are significantly impatient to time could quit the purchase quickly. Consequently, the manufacturer could lose the entire market in a short delay, despite providing compensation or information disclosure. In such cases, the manufacture should consider other alternative countermeasures to satisfy demand. Second, as for the short disruptions, information disclosure can still bring forward an extra profit increase for the manufacturer if r is small. However, as shown in Fig. 4(c), the "pure information disclosure" policy is inferior to the "compensation" policy. The result is consistent with reality in the market. In the face of impatient customers, if no countermeasure is adopted to decelerate lost sales, there will not be a large amount of backordering demand accumulated at any time point. As a result, no matter how customers evaluate information, the fact that a small number of previous customers choose to leave can hardly enhance their willingness to stay.

Fig. 5 illustrates how the green level influences the value of information disclosure and compensation. We take the case with $r = 5$ for example, which means that a previous backordering rate exceeding 50% could lead to a rise in the willingness of succeeding customers to accept a delayed delivery. Two interesting findings are observed. First, as shown in Fig. 5(a), the profit differences $\pi^{DC} - \pi^{D}$ remain unchanged for different green levels. The reason behind this observation is in two manifolds. On the first hand, as illustrated by the aforementioned analytical results, the optimal compensation price does not change with the green level in the process of hedging against some short disruptions. On the other hand, the role of compensation is to decelerate lose sales, which is significantly influenced by the customers' sensitivities and time-related factors such as disruption length. Second, the information disclosure exhibits an increasing value as the green level increases. The products with a high green level gain more advantages due to the OL effect. For short disruptions, the manufacturer could gain more profit from purely disclosing quantity information than providing price compensation. Note that, this trend is critically linked to the customers' sensitivity to the green level. By analyzing the cases with small μ, we find the opposite result: the value of information decreases to the green level. Therefore, it is essential to consider customers' preference towards the green level in managing disruptions for greening production.

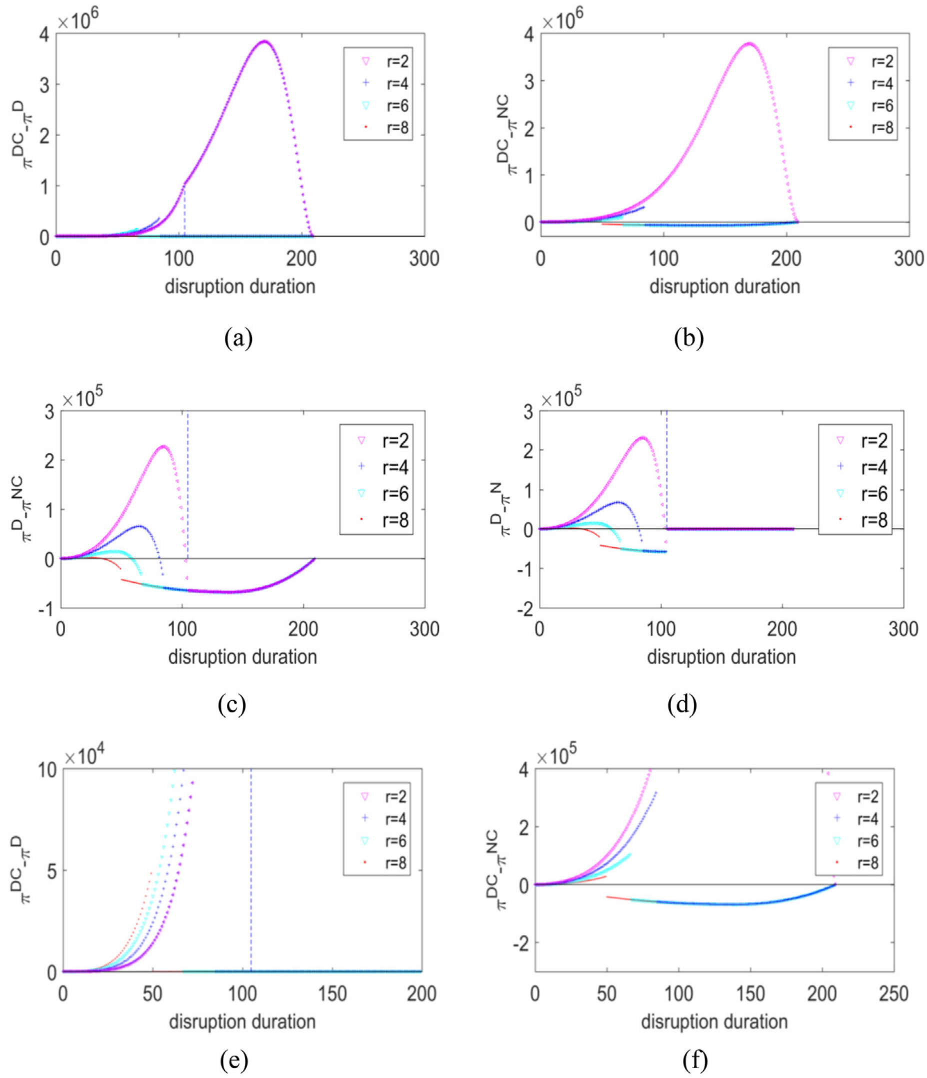

Fig. 3. The profit differences under different r, while $k = 0.05$, $\theta = 0.1$.

6. Conclusion

In this study, we consider a manufacturer produces and sells green products to customers via an online channel. The production might halt due to unexpected events. Customers are sensitive to the waiting time of the delivery, the price and the green level of the product, and the information that they browse from the sales website. Based on sales quantity information disclosure and price reduction, this paper explores optimal reactive strategies for the green manufacturer to mitigate disruption impacts.

Firstly, taking into consideration that customers' sensitivities to time, price, and green level, and customers' observational learning interaction for sales quantity information, we analytically present the dynamics of post-disruption demand under the services of disclosing information and reducing the price. Then, the optimal compensation price is analytically identified to maximize the profit of the green product during the disruption period, with and without information disclosure. Two types of optimal compensation strategies are proposed with closed forms: the pure compensation ("NC") and the compensation on top of quantity information disclosure ("DC").

Our results offer the following useful insights for the green manufacturer. We provide analytical guidance on how to strategically disclose information on the sales website and provide price compensation in the cases with and without disclosing information. The results present the conditions under which these two strategies are in-effective to cope with disruptions, mainly linked to disruption length, customers' sensitivities (to time, price, and green level), green level of the product, and customers' attitude towards information. In general, both the pure price compensation and the combined compensation in conjunction with information disclosure fail to hedge against long disruptions. Furthermore, the disruption length is required to be shorter if one of the following three occasions occurs: customers exhibit a higher sensitivity to time and price; the green level of the product becomes lower while customers are sensitive to green level; the quantity information is exposed when both the customers' learning intensity towards information and the backorder reference are large (customers are with a negative bias). On the other hand, our results indicate that increasing green can be considerably supportive for mitigating disruption when the green level of the product is low, and the compensation should change with the green level under some circumstances.

To visually examine the value of disclosing information and reducing price during disruption, numerical analyses are then conducted to compare the profitability of four policies: the pure

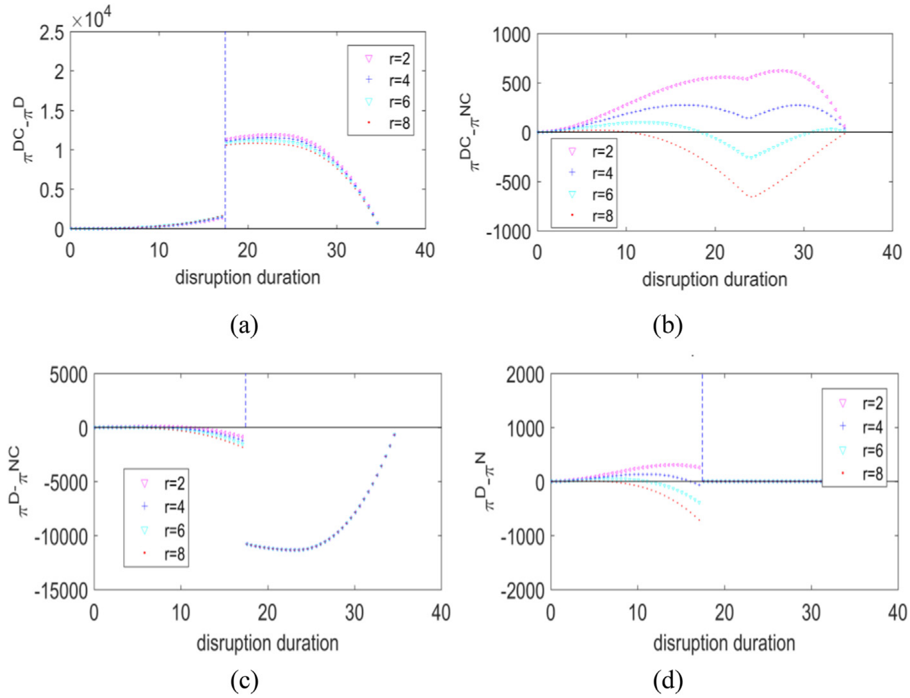

Fig. 4. The profit differences under different r, while $k = 0.01$, $\theta = 0.6$.

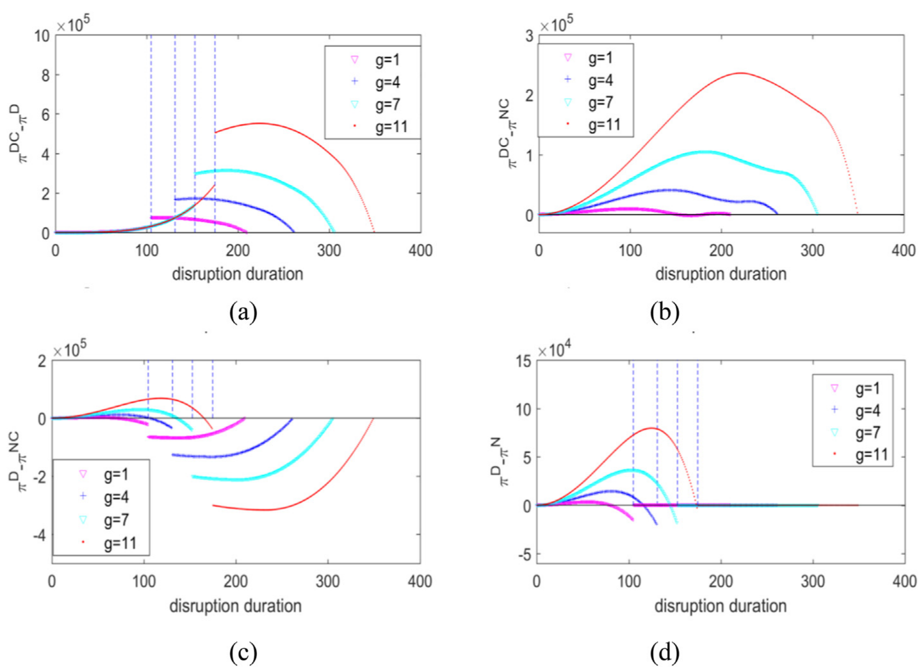

Fig. 5. The profit differences under different green levels while $r = 5$, $k = 0.01$, $\theta = 0.1$, and $\mu = 2$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

compensation (“NC”), the combine compensation (“DC”), the pure information disclosure, and the passive acceptance. In addition to the above analytic results, we also find that pure information disclosure might be favorable over pure compensation to alleviate short disruptions under some circumstances. The factors such as customers’ sensitivities, green level of the product, and customers’ attitude towards information, play different roles in affecting the value of disclosing information and implementing price compensation.

This study raises several directions for future research work. For example, in this paper, we consider providing static compensation during the entire out-of-stock period. A future study could extend by considering a continuously dynamic or periodical compensation. Another area worthy of exploration is to extend the question regarding information disclosure into a multi-echelon supply chain.

CRediT authorship contribution statement

Shanshan Li: Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft. **Yong He:** Conceptualization, Supervision, Validation, Resources, Project administration, Funding acquisition, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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