Journal of Management Science and Engineering 7 (2022) 453–472

Science Press

Contents lists available at ScienceDirect

Journal of Management Science and Engineering

journal homepage: www.keaipublishing.com/en/journals/journal-of-management-science-and-engineering/

Optimal strategies of automakers with demand and credit price disruptions under the dual-credit policy

Yongwei Cheng [a], Tijun Fan [a, *], Li Zhou [b]

[a] School of Business, East China University of Science and Technology, Shanghai, 200237, China
[b] Faculty of Business, University of Greenwich, London, SE10 9LS, UK

ARTICLE INFO

Article history:
Available online 4 January 2022

Keywords:
Decision analysis
Automakers
Demand disruption
Credit price disruption
Dual-credit policy

ABSTRACT

In this paper, a production and pricing decision model for automakers under the dual-credit policy is formulated. Then, with consideration of demand and credit price disruptions, a nonlinear programming model that maximizes automakers' profit and constrains the production of fuel vehicles (FVs) and new energy vehicles (NEVs) is investigated. Furthermore, four strategies that involve adjusting the production or price of FVs and NEVs are proposed, and four optimal solutions for each strategy are obtained. Finally, 16 scenarios are comprehensively analyzed, and a case study involving demand and credit price disruptions is conducted. The results show that the dual-credit policy has a positive impact on the development of NEVs, especially in early stages of NEV development. The FV credit coefficient has a significantly positive impact on the probability of automakers adopting adjustment strategies, while the NEV credit coefficient has almost no such impact. Moreover, automakers are inclined to adjust the prices of NEVs or the production of FVs to cope with demand and credit price disruptions.

1. Introduction

In recent years, the Chinese government has introduced subsidy policies to promote the NEV industry, which has resulted in the rapid development of China's NEV industry (Yuan et al., 2015; Li et al., 2016). In 2020, the annual sales of China's NEVs exceeded 1 million units, and the total holdings of NEVs in China reached 4.92 million units, ranking first in the world and making China one of the world's most important markets for NEVs (Naumanen et al., 2019). However, with the continuous growth of NEV consumption, the Chinese government is suffering from expenditures on subsidies for NEVs. By 2020, the subsidies for NEVs had surprisingly reached more than 100 billion RMB, leading to the introduction of the dual-credit policy called the “Measures for Passenger Cars CAFC and NEV Credit Regulation” (He et al., 2020).

The dual-credit policy is an industrial regulation policy designed to encourage automakers to simultaneously reduce the corporate average fuel consumption (CAFC) of their FVs and increase the production of NEVs. The total value of automakers' CAFC and NEV credits must be "nonnegative." If automakers have total surplus credits, they can sell these credits in the credit market for additional profits. If automakers have insufficient total credits, they need to buy credits from the credit market. The credit price is determined by the supply-demand relationship in the credit market and shows considerable volatility similar

* Corresponding author.
E-mail address: tjfan@ecust.edu.cn (T. Fan).

https://doi.org/10.1016/j.jmse.2021.12.006
2096-2320/

to carbon prices (Feng et al., 2011; Xu et al., 2016). The volatility of credit prices will have a significant impact on the production and pricing decisions of automakers under the dual-credit policy.

The volatility of credit prices will also aggravate production and pricing instability for FVs and NEVs (Singhal and Hendricks, 2005; Chen and Xiao, 2009). When the credit price increases, automakers will tend to produce more NEVs and reduce the production of FVs, which may lead to an excess production of NEVs and insufficient production of FVs. Excess or insufficient production will influence corresponding pricing. Additionally, the degree of production and pricing of FVs and NEVs depend on the actual demand of the vehicle market (Gong et al., 2014). Therefore, it is necessary for automakers to make production and pricing decisions while considering both demand and credit price disruptions under the dual-credit policy.

There have been a few studies on credit price disruptions. Different from traditional demand or cost disruption models that only consider a single product, disruption models under the dual-credit policy involve two products of FVs and NEVs. Moreover, these studies only focus on demand or credit price disruptions. This paper formulates a production and pricing decision model for automakers under the dual-credit policy and comprehensively analyzes automakers' optimal adjustment strategies under 16 scenarios with demand and credit price disruptions. These strategies will help automakers better cope with uncertainty under the dual-credit policy.

The remainder of this paper is organized as follows. Related literature is reviewed in Section 2. The studied problem is mathematically formulated and analyzed with respect to automakers' adjustment strategies under demand and credit price disruptions and initial decision optimization in Section 3. Numerical examples are given in Section 4. Section 5 concludes the paper with a discussion of possible directions for future research. All proofs are presented in the Appendix.

2. Literature review

2.1. Subsidy policy for NEVs

Many scholars have studied the NEV subsidy policy. Wang et al. (2017) discussed whether current subsidy policies reflect consumers' potential purchase demand. Zhang and Qin (2018) traced the evolution of NEV policies most beneficial to the future development of the NEV industry in China. Huang et al. (2013) analyzed an FV supply chain and an electric-and-fuel vehicle supply chain under a government's subsidy incentive scheme. Luo et al. (2014) investigated a vehicle supply chain serving heterogeneous consumers with electric vehicles under a government subsidy ceiling. These studies show that subsidy policies have played an important role in the development of China's NEV industry. However, few of these studies focus on the impact of NEV subsidy policies on automakers' decisions.

As a unique industrial policy adopted in China, the dual-credit policy is different from the NEV subsidy policy. The former is a production subsidy, and the latter is a consumption subsidy (Ma et al., 2017; Li et al., 2018). A few scholars have studied dual-credit policy efficiency. Ou et al. (2018) summarized the dual-credit policy and developed FV and NEV credit models to quantify the impacts of this policy on consumer choices and industry profits. Zhao et al. (2019) established a bottom-up framework to estimate the impacts of regulation on the technological trends of battery electric vehicles under the dual-credit policy adopted in China. Zhou et al. (2019) generalized the dual-credit policy and investigated its effects on green technology investments and pricing decisions in a two-echelon supply chain. Although Cheng and Fan (2021), Li et al. (2020), and Cheng and Mu (2018) investigated the impacts of subsidy and dual-credit policies on NEV and FV production decisions, these studies did not take into account credit price disruptions, nor did they consider competition between FVs and NEVs.

2.2. Disruption management

Many scholars have performed relevant research on disruption management (Tomlin, 2006; Schmitt et al., 2015). Giri and Bardhan (2015) analyzed the impact of uncertainty on optimal supply chain decisions made in centralized and decentralized decision-making models. Yang and Fan (2016) studied the impact of information management on closed-loop supply chain disruption. These studies show that the main disruptive factors in a supply chain are demand, cost and supply disruptions.

Demand disruptions have always greatly plagued the efficiency of supply chain operations (Baghalian et al., 2013; Feng et al., 2021). Qi et al. (2004) investigated a one-supplier–one-retailer supply chain that experiences a disruption in demand during the planning horizon. Asian and Nie (2014) studied the effectiveness of contract-based mitigation strategies with demand and supply disruptions. These studies generally focus on demand disruptions of a single product. However, under the dual-credit policy, demand disruptions involve two products of FVs and NEVs, which will complicate the problem.

A few related studies have examined credit price disruptions, but we can regard these as a special form of cost disruption (Snyder et al., 2016). Xiao and Qi (2008) studied the coordination of a supply chain after the production cost was disrupted. Sawik (2015) studied the cost and customer service level in the presence of supply chain disruption risks. These traditional cost disruption models cannot effectively explain credit price disruptions. The credit price not only increases the cost of FVs but also reduces the cost of NEVs or increases their unit profit (Kleindorfer and Saad, 2005). Therefore, these cost disruption models must be extended to joint decision models, including those for FVs and NEVs.

Credit price disruptions will also increase the uncertainty of demand for FVs and NEVs. Lei et al. (2012) investigated risk management strategies adopted in a supply chain with demand and cost disruptions, and a few studies show that joint decisions help reduce the negative impacts of demand disruptions (Petersen et al., 2005; Liu et al., 2016). Some scholars have developed programming models to derive the optimal adjustment strategies in a disruptive environment (Soleimani et al., 2016; Yang et al., 2021) and have introduced the revenue sharing contract (Linh and Hong, 2009; Zhang et al., 2012) and quantity discount contract (Corbett and Groote, 2000; Cai et al., 2017) as means to coordinate the supply chain. However, these studies do not consider multiproduct production decisions with demand and credit price disruptions.

3. Mathematical formulation and analysis

Under the dual-credit policy, automakers will produce both FVs and NEVs. Assume that these two types of vehicles have competitive demand, and their expected demand is as follows (Wang et al., 2013; Chen et al., 2012):

$$\overline{q}_m = a\overline{\varphi} - b_m\overline{p}_m + r\overline{p}_n \tag{1}$$

$$\overline{q}_n = (1-a)\overline{\varphi} - b_n\overline{p}_n + r\overline{p}_m \tag{2}$$

Where $\overline{\varphi}$ is the expected potential market scale. a and $(1-a)$ are the market shares of FVs and NEVs, respectively. When FVs are the main source of sales for automakers, such as Volkswagen and Great Wall Motors, then $a \geq 1/2$, while for automakers such as BAIC and BYD, their NEVs become the main source of sales, and then $0 < a < 1/2$. $\overline{p}_m$ and $\overline{p}_n$ are expected retail prices. b_m and b_n are their respective price sensitivity coefficients, and r is the substitution coefficient between these two vehicle types. The larger r is, the more mature the NEV market is and the more attractive it is to vehicle consumers. For ease of expression, subscript ″m″ refers to FVs, and subscript ″n″ refers to NEVs.

Regarding fuel consumption credits, we assume that automakers' initial fuel consumption level is e_0. By improving fuel consumption technology, automakers can reduce fuel consumption by an annual average rate of δ, and the actual fuel consumption level after energy saving is $e_0(1-\delta)$. If the government's prescribed target fuel consumption is $(e_0 - \Delta e)$, then we can calculate automakers' fuel consumption credits as $(\delta e_0 - \Delta e)\overline{q}_m$. When $\delta e_0 > \Delta e$, automakers will obtain positive fuel consumption credits; when $\delta e_0 \leq \Delta e$, automakers will obtain negative fuel consumption credits.

The dual-credit policy also forces automakers to produce a certain proportion of NEVs. Assuming that the proportion is $t(0 \leq t \leq 1)$, we can calculate automakers' demand for positive NEV credits based on their production of FVs as $[(\Delta e - \delta e_0)^+ + t]\overline{q}_m$. Let $\beta_m = (\Delta e - \delta e_0)^+ + t$ be the FV credit coefficient (including the fuel consumption credit) where $(\Delta e - \delta e_0)^+$ indicates that there will be no demand for positive NEV credits based on the production of FVs if automakers' fuel consumption credits are positive; if automakers' fuel consumption credits are negative, positive NEV credits will be required to offset them. However, regardless of whether fuel consumption points are positive or negative, t of NEV credits must be purchased for the production of FVs.

Regarding NEV credits, according to the dual-credit policy, automakers will obtain positive NEV credits β_n from the production of NEVs based on cruising distance. Let β_n be the NEV credit coefficient. The greater the cruising distance is, the more positive credits will be for each NEV. Automakers will obtain positive NEV credits $\beta_n\overline{q}_n$ by producing $\overline{q}_n$ NEVs.

From the above assumptions and analysis, we can determine that automakers' total credits (both FV credits and NEV credits) are $(\beta_n\overline{q}_n - \beta_m\overline{q}_m)$, assuming that the expected credit price is $\overline{p}_e$ and that the production costs of FVs and NEVs are c_m and c_n, $c_m \leq c_n$, respectively. Therefore, we formulate the automakers' decision problem as follows:

$$\max_{\overline{p}_m,\ \overline{p}_n} \overline{\pi}(\overline{p}_m, \overline{p}_n) = \overline{q}_m(\overline{p}_m - c_m) + \overline{q}_n(\overline{p}_n - c_n) + (\beta_n\overline{q}_n - \beta_m\overline{q}_m)\overline{p}_e \tag{3}$$

where $(\beta_n\overline{q}_n - \beta_m\overline{q}_m)\overline{p}_e$ indicates the profits or costs from credit trading. In addition, Eq. (3) can be rewritten as follows:

$$\max_{\overline{p}_m,\overline{p}_n} \overline{\pi}(\overline{p}_m, \overline{p}_n) = [a\overline{\varphi} - b_m\overline{p}_m + r\overline{p}_n](\overline{p}_m - c_m - \beta_m\overline{p}_e) + [(1-a)\overline{\varphi} - b_n\overline{p}_n + r\overline{p}_m](\overline{p}_n - c_n + \beta_n\overline{p}_e). \tag{4}$$

3.1. Optimal initial decisions made under the dual-credit policy

Because $\frac{\partial^2\overline{\pi}}{\partial^2\overline{p}_m}\frac{\partial^2\overline{\pi}}{\partial^2\overline{p}_n} - \frac{\partial^2\overline{\pi}}{\partial\overline{p}_m\partial\overline{p}_n} = 4(b_mb_n - r^2) > 0$ and $\frac{\partial^2\overline{\pi}}{\partial^2\overline{p}_m} = -2b_m < 0$, $\overline{\pi}(\overline{p}_m, \overline{p}_n)$ in Eq. (4) is jointly concave in $(\overline{p}_m, \overline{p}_n)$. Then, we can obtain the optimal solutions that maximize automakers' profits under the dual-credit policy are as follows.

$$\overline{p}_m^* = \frac{1}{2}\left[\frac{ab_n + (1-a)r}{b_mb_n - r^2}\overline{\varphi} + c_m + \beta_m\overline{p}_e\right]$$

$$\overline{p}_n^* = \frac{1}{2}\left[\frac{ar + (1-a)b_m}{b_mb_n - r^2}\overline{\varphi} + c_n - \beta_n\overline{p}_e\right]$$

$$\overline{q}_m^* = \frac{1}{2}[(a\overline{\varphi} - b_mc_m + rc_n) - (b_m\beta_m + r\beta_n)\overline{p}_e]$$

$$\overline{q}_n^* = \frac{1}{2}\left[((1-a)\overline{\varphi} - b_n c_n + r c_m) + (r\beta_m + b_n\beta_n)\overline{p}_e\right]$$

Furthermore, we can calculate automakers' optimal FV/NEV unit profit $\overline{y}_m^*$ ($\overline{y}_n^*$), total credits $\overline{\mu}^*$ and total profit $\overline{\pi}^*$ under the dual-credit policy as follows:

$$\overline{y}_m^* = \frac{1}{2}\left[\frac{ab_n + (1-a)r}{b_m b_n - r^2}\overline{\varphi} - c_m - \beta_m\overline{p}_e\right]\overline{y}_n^* = \frac{1}{2}\left[\frac{ar + (1-a)b_m}{b_m b_n - r^2}\overline{\varphi} - c_n + \beta_n\overline{p}_e\right]$$

$$\overline{\mu}^* = \beta_n\overline{q}_n^* - \beta_m\overline{q}_m^* = \frac{1}{2}\left\{-[a\beta_m - (1-a)\beta_n]\overline{\varphi} + (b_m\beta_m + r\beta_n)c_m - (r\beta_m + b_n\beta_n)c_n + \left(b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2\right)\overline{p}_e\right\} \quad (5)$$

$$\overline{\pi}^* = \frac{(1-a)^2 b_m + 2a(1-a)r + a^2 b_n}{4(b_m b_n - r^2)}\overline{\varphi}^2 - \frac{1}{2}[ac_m + (1-a)c_n]\overline{\varphi} + \frac{1}{4}\left[b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2\right]\overline{p}_e^2$$
$$+\frac{1}{2}[(b_m c_m - r c_n)\beta_m - (b_n c_n - r c_m)\beta_n]\overline{p}_e - \frac{1}{2}[a\beta_m - (1-a)\beta_n]\overline{\varphi}\overline{p}_e + \frac{1}{4}\left[b_m c_m^2 - 2r c_m c_n + b_n c_n^2\right]$$

From automakers' optimal initial decisions under the dual-credit policy, we address the following lemmas to investigate the effects of FV/NEV unit profit on automakers' optimal initial production and total credits.

Lemma 1. *Automakers' optimal initial production and unit profit satisfy the following relationships:* $\overline{q}_m^* = b_m\overline{y}_m^* - r\overline{y}_n^*$ *and* $\overline{q}_n^* = b_n\overline{y}_n^* - r\overline{y}_m^*$.

Lemma 1 *implies that the production of FVs and NEVs depends on the FV/NEV unit profit, i.e., the production of FVs (NEVs) is positively related to its own unit profit* $\overline{y}_m^*(\overline{y}_n^*)$ *but negatively related to the other party's unit profit* $\overline{y}_n^*(\overline{y}_m^*)$. *Taking the production of NEVs as an example, as the NEV unit profit increases due to credit price increases and battery costs decrease, automakers will be inclined to reduce the production of FVs and increase the production of NEVs. Moreover, the greater the substitution coefficient is, the greater the impact of the NEV unit profit on the production of FVs will be. Therefore, under the dual-credit policy, if a high credit price can be effectively raised and maintained, this will accelerate automakers' shift in production from FVs to NEVs.*

Lemma 2. *Automakers' initial total credits and unit profit satisfy the following relationships:*
$\overline{\mu}^* = (r\beta_m + b_n\beta_n)\overline{y}_n^* - (b_m\beta_m + r\beta_n)\overline{y}_m^*$. *Automakers' initial total credits will be in equilibrium or even positive when the following condition is met:* $\frac{\overline{y}_n^*}{\overline{y}_m^*} \geq \frac{b_m\beta_m + r\beta_n}{r\beta_m + b_n\beta_n}$.

Lemma 2 *implies that automakers' initial total credits are positively related to the NEV unit profit and negatively related to the FV unit profit. This conclusion is actually consistent with* Lemma 1. *When the NEV unit profit is relatively high and the FV unit profit is relatively low, automakers will be inclined to produce more NEVs and fewer FVs to obtain more positive NEV credits. Moreover, the higher the FV credit coefficient is, the higher the* $\frac{\overline{y}_n^*}{\overline{y}_m^*}$ *value becomes, and the more difficult it is for automakers to achieve credit equilibrium. The higher the NEV credit coefficient is, the lower the* $\frac{\overline{y}_n^*}{\overline{y}_m^*}$ *value becomes, and the easier it is for automakers to achieve credit equilibrium or even positive total credits. Therefore, increasing the cruising distance of NEVs and reducing the fuel consumption of FVs will help automakers achieve credit equilibrium.*

From the optimal initial decisions, we find that the expected demand and credit price have a substantial impact on automakers' optimal decisions. Therefore, automakers will adjust their optimal decisions to cope with demand and credit price disruptions. Let the actual demand and credit price be $\tilde{\varphi}$ *and* $\tilde{p}_e$, *respectively, and let their disruptions be* $\delta\varphi = \tilde{\varphi} - \overline{\varphi}$ *and* $\delta p_e = \tilde{p}_e - \overline{p}_e$, *respectively. If we do not consider decision adjustment costs, we can determine automakers' optimal decision adjustment strategies from the following proposition.*

The optimal adjustment strategies for automakers to cope with demand and credit price disruptions without considering adjustment costs are expressed as follows.

$$\Delta\overline{p}_m^* = \frac{ab_n + (1-a)r}{2(b_m b_n - r^2)}\delta\varphi + \frac{\beta_m}{2}\delta p_e, \Delta\overline{p}_n^* = \frac{ar + (1-a)b_m}{2(b_m b_n - r^2)}\delta\varphi - \frac{\beta_n}{2}\delta p_e$$

$$\Delta\overline{q}_m^* = \frac{a}{2}\delta\varphi - \frac{b_m\beta_m + r\beta_n}{2}\delta p_e, \Delta\overline{q}_n^* = \frac{1-a}{2}\delta\varphi + \frac{r\beta_m + b_n\beta_n}{2}\delta p_e$$

$$\Delta\overline{y}_m^* = \frac{ab_n + (1-a)r}{2(b_m b_n - r^2)}\delta\varphi - \frac{\beta_m}{2}\delta p_e, \Delta\overline{y}_n^* = \frac{ar + (1-a)b_m}{2(b_m b_n - r^2)}\delta\varphi + \frac{\beta_n}{2}\delta p_e$$

$$\Delta\overline{\mu}^* = \Delta\left(\beta_n\overline{q}_n^* - \beta_m\overline{q}_m^*\right) = -\frac{a\beta_m - (1-a)\beta_n}{2}\delta\varphi + \frac{b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2}{2}\delta p_e$$

$$\Delta\overline{\pi}^* = \frac{(1-a)^2 b_m + 2a(1-a)r + a^2 b_n}{4\left(b_m b_n - r^2\right)}\Delta\varphi^2 + \left[a\overline{y}_m^* + (1-a)\overline{y}_n^*\right]\delta\varphi$$
$$+\frac{1}{4}\left(b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2\right)\Delta p_e^2 + \left(\beta_n\overline{q}_n^* - \beta_m\overline{q}_m^*\right)\delta p_e - \frac{1}{2}\left[a\beta_m - (1-a)\beta_n\right]\delta p_e\delta\varphi$$

We investigate the effects of demand and credit price disruptions on automakers' optimal decision adjustment strategies without considering decision adjustment costs in the following proposition.

Proposition 1. *The optimal adjustment strategies without considering adjustment costs have the following properties:*

i) *The optimal adjustment strategies for FV/NEV prices, production and unit profit are positively related to demand disruption. The correlation between the optimal adjustment strategies of automakers' total credits and demand disruption depends on the relative market share of FVs and NEVs.*
ii) *The optimal adjustment strategies of FV prices, NEV production, NEV unit profit, and automakers' total credits are positively related to credit price disruption. The optimal adjustment strategies of NEV prices, FV production and FV unit profit are negatively related to credit price disruption.*
iii) *When demand and credit price disruptions exceed a certain level, the optimal adjustment profit of automakers is positively related to demand and credit price disruptions; when demand and credit price disruptions are lower than a certain level, the optimal decision adjustment profit of automakers is negatively related to demand and credit price disruptions.*

Proposition 1 *implies that the expansion of demand is beneficial to the development of both FVs and NEVs when one does not consider decision adjustment costs. Specifically, when the market share of NEVs reaches a certain proportion (i.e.,* $\frac{\beta_m}{\beta_m+\beta_n} < (1-a) \leq 1$*), the expansion of demand will further encourage automakers to produce more NEVs to obtain more positive NEV credits. The rise in the credit price will undoubtedly be more conducive to the development of NEVs and to curbing the development of FVs. Considering the total profits of automakers, neither expanding demand nor credit price growth will lead to an increase in total profit and may even lead to negative growth.*

From the above analysis, we know that the credit price has an important impact on automakers' credit equilibrium and total profit under the dual-credit policy. We solve for the credit price threshold for determining automakers' credit equilibrium according to Eq. (4) *given in the following lemma.*

Lemma 3. *The credit price threshold for determining automakers' credit equilibrium is* $\overline{p}_e^* = \frac{[a\beta_m-(1-a)\beta_n]\overline{\varphi}-(b_m\beta_m+r\beta_n)c_m+(r\beta_m+b_n\beta_n)c_n}{b_m\beta_m^2+2r\beta_m\beta_n+b_n\beta_n^2}$.

Lemma 3 *shows that when the expected credit price is equal to* $\overline{p}_e^*$*, automakers' total credits will be in equilibrium; when the expected credit price exceeds* $\overline{p}_e^*$*, automakers will obtain positive credits and excess profits; and when the expected credit price is lower than* $\overline{p}_e^*$*, automakers will obtain negative credits and lose profits. Therefore,* $\overline{p}_e^*$ *plays an important role in encouraging automakers to obtain positive credits by reducing fuel consumption and developing NEVs. From credit price threshold* $\overline{p}_e^*$*, we derive the following proposition.*

Proposition 2. *The higher the market share of NEVs is, the lower the credit price threshold for automakers' credit equilibrium is, and the easier it is for the dual-credit policy to encourage automakers to develop NEVs. Moreover, when the market share of NEVs reaches a certain proportion (i.e.,* $\frac{\beta_m\overline{\varphi}+(b_m\beta_m+r\beta_n)c_m-(r\beta_m+b_n\beta_n)c_n}{(\beta_m+\beta_n)\overline{\varphi}} < (1-a) \leq 1$*),* $\overline{p}_e^*$ *will be negative, meaning that automakers will actively produce and sell NEVs, and the dual-credit policy will no longer be necessary. In addition,* $\overline{p}_e^*$ *will increase in* β_m *and decrease in* β_n *when* $\overline{p}_e^* \geq 0$.

Proposition 2 *implies that the dual-credit policy is mainly applicable to the initial stage of the development of NEVs. At this stage, a higher credit price is required to force automakers to reduce FV production and fuel consumption. As the market share of NEVs increases, automakers will no longer have an insufficient number of positive credits, and the credit price will fall until it reaches* 0*, which indicates that the dual-credit policy will no longer have an impact. Therefore, the efficiency of the dual-credit policy has positive feedback effects on the maturity of the NEV market. At this stage, NEVs with more cruising distance will obtain more positive credits such that automakers can achieve credit equilibrium at a lower credit price. Conversely, FVs with higher fuel consumption will exacerbate the insufficient number of positive credits for automakers, which will lead to an increase in the credit price.*

3.2. Optimal disruption management strategies

In practice, automakers use a variety of data and methods to increase the accuracy of their demand and credit price forecasts. However, some prediction error is of course unavoidable. Once the actual demand and credit price fluctuate significantly, automakers' initial decisions will no longer be the "optimal decisions" and should be adjusted. In reality, whether from price adjustment, production adjustment, personnel adjustment or other changes, automakers will face corresponding decision adjustment costs. In the above sections, we analyze the optimal adjustment strategies without considering adjustment costs. Once we consider the adjustment costs of FVs and NEVs, what will automakers' optimal adjustment strategies be?

In the presence of demand and credit price disruptions, if the sales volume is higher than the expected value, automakers will bear emergency costs g_m and g_n from temporarily increasing the production of FVs and NEVs, respectively; if the sales volume is lower than the expected value, automakers will bear disposal costs s_m and s_n to temporarily reduce the production of FVs and NEVs, respectively. The optimal adjustments of the retail price and production of FVs and NEVs are (x_m, x_n) and $(\Delta q_m, \Delta q_n)$, respectively. $\tilde{\pi}$ represents automakers' actual total profits. Then, we can formulate the disruption management problem as follows:

$$\begin{aligned}\max_{x_m,x_n}\tilde{\pi}(x_m,x_n) &= \left[a(\overline{\varphi}+\Delta\varphi)-b_m(\overline{p}_m^*+x_m)+r(\overline{p}_n^*+x_n)\right]\left[(\overline{p}_m^*+x_m)-c_m-\beta_m(\overline{p}_e+\delta p_e)\right]\\&+\left[(1-a)(\overline{\varphi}+\Delta\varphi)-b_n(\overline{p}_n^*+x_n)+r(\overline{p}_m^*+x_m)\right]\left[(\overline{p}_n^*+x_n)-c_n+\beta_n(\overline{p}_e+\delta p_e)\right]-[\Delta q_m]^+g_m\\&-[-\Delta q_m]^+s_m-[\Delta q_n]^+g_n-[-\Delta q_m]^+s_n\end{aligned}$$

This equation can be rewritten as follows:

$$\begin{aligned}\max_{x_m,x_n}\tilde{\pi}(x_m,x_n) &= \left(\overline{q}_m^*+\Delta q_m\right)\left[\overline{y}_m^*+x_m-\beta_m\delta p_e\right]+\left(\overline{q}_n^*+\Delta q_n\right)\left[\overline{y}_n^*+x_n+\beta_n\delta p_e\right]\\&-[\Delta q_m]^+g_m-[-\Delta q_m]^+s_m-[\Delta q_n]^+g_n-[-\Delta q_n]^+s_n.\end{aligned} \tag{6}$$

In Eq. (6), $\Delta q_m = a\delta\varphi - b_m x_m + r x_n$, $\Delta q_n = (1-a)\delta\varphi + r x_m - b_n x_n$. $\overline{q}_m^*$, $\overline{q}_n^*$, $\overline{y}_m^*$, and $\overline{y}_n^*$ are automakers' optimal decisions in Section 3.1.

Since Δq_m and Δq_n may be positive or negative, Eq. (6) can be solved separately in four scenarios: Strategy A ($\Delta q_m \ge 0$, $\Delta q_n \ge 0$), Strategy B ($\Delta q_m \ge 0, \Delta q_n < 0$), Strategy C ($\Delta q_m < 0, \Delta q_n \ge 0$) and Strategy D ($\Delta q_m < 0, \Delta q_n < 0$), and we take the first scenario, "Strategy A," as an example to solve and analyze Eq. (6).

Under Strategy A ($\Delta q_m \ge 0, \Delta q_n \ge 0$), automakers will increase the production of both FVs and NEVs to cope with demand and credit price disruptions. In addition, Eq. (6) can be further rewritten as follows:

$$\begin{aligned}\max_{x_m,x_n}\tilde{\pi}(x_m,x_n) &= \left(\overline{q}_m^*+a\delta\varphi-b_m x_m+r x_n\right)\left(\overline{y}_m^*+x_m-\beta_m\delta p_e\right)\\&+\left[\overline{q}_n^*+(1-a)\delta\varphi+r x_m-b_n x_n\right]\left(\overline{y}_n^*+x_n+\beta_n\delta p_e\right)\\&-(a\delta\varphi-b_m x_m+r x_n)g_m-[(1-a)\delta\varphi+r x_m-b_n x_n]g_n,\end{aligned}$$

$$s.t.\begin{cases}a\Delta\varphi-b_m x_m+r x_n\ge 0,\\(1-a)\Delta\varphi+r x_m-b_n x_n\ge 0,\\x_m\in N, x_n\in N\end{cases} \tag{7}$$

Because $\frac{\partial^2\tilde{\pi}}{\partial^2 x_m}\frac{\partial^2\tilde{\pi}}{\partial^2 x_n}-\frac{\partial^2\tilde{\pi}}{\partial x_m\partial x_n}=4(b_m b_n-r^2)>0$ and $\frac{\partial^2\tilde{\pi}}{\partial^2 x_m}=-2b_m<0$, Eq. (7) includes nonlinear convex programming with inequality constraints. Then, we can solve this programming according to KKT (Karush-Kuhn-Tucker) conditions as follows.

$$\begin{cases}\partial(-\tilde{\pi})/\partial x_m=0,\\\partial(-\tilde{\pi})/\partial x_n=0,\\\lambda_m(a\delta\varphi-b_m x_m+r x_n)=0,\\\lambda_n[(1-a)\delta\varphi+r x_m-b_n x_n]=0,\\a\Delta\varphi-b_m x_m+r x_n\ge 0,\\(1-a)\Delta\varphi+r x_m-b_n x_n\ge 0,\\\lambda_m\ge 0,\lambda_n\ge 0,\ x_m\in N, x_n\in N\end{cases} \tag{8}$$

According to the different values of λ_m and λ_n, Eq. (8) can be solved in four scenarios: Strategy A1 ($\lambda_m = 0, \lambda_n = 0$), Strategy A2 ($\lambda_m = 0, \lambda_n > 0$), Strategy A3 ($\lambda_m > 0, \lambda_n = 0$) and Strategy A4 ($\lambda_m > 0, \lambda_n > 0$). The following are the optimal decision adjustment strategies for automakers in the four scenarios of Strategies A1-A4.

- Optimal adjustment strategies in Strategy A1 ($\lambda_m = 0, \lambda_n = 0$)

$$x_m^* = \frac{1}{2}\left[\frac{ab_n + (1-a)r}{b_m b_n - r^2}\delta\varphi + \beta_m \delta p_e + g_m\right], x_n^* = \frac{1}{2}\left[\frac{ar + (1-a)b_m}{b_m b_n - r^2}\delta\varphi - \beta_n \delta p_e + g_n\right]$$

$$\Delta q_m^* = \frac{1}{2}[a\delta\varphi - (b_m\beta_m + r\beta_n)\delta p_e - b_m g_m + r g_n]$$

$$\Delta q_n^* = \frac{1}{2}\{(1-a)\delta\varphi + (r\beta_m + b_n\beta_n)\delta p_e + r g_m - b_n g_n\}$$

According to constraints $\Delta q_m^* \geq 0$ and $\Delta q_n^* \geq 0$, the disruption range of δp_e and $\delta\varphi$ should satisfy the following relationship:

$$\frac{-(1-a)\delta\varphi - r g_m + b_n g_n}{r\beta_m + b_n\beta_n} \leq \delta p_e \leq \frac{a\delta\varphi - b_m g_m + r g_n}{b_m\beta_m + r\beta_n}. \tag{9}$$

Eq. (9) reveals that the disruption range of δp_e and $\delta\varphi$ belongs to an interval consisting of two straight lines. For analytical convenience, we let these two constraint lines be $\Delta p_e^{A-line1} = \frac{-(1-a)\delta\varphi - r g_m + b_n g_n}{r\beta_m + b_n\beta_n}$ and $\Delta p_e^{A-line2} = \frac{a\delta\varphi - b_m g_m + r g_n}{b_m\beta_m + r\beta_n}$. In addition, Eq. (9) can only be established when $\Delta p_{e1}^{line2} \geq \Delta p_{e1}^{line1}$; that is, $\delta\varphi \geq \frac{(b_m b_n - r^2)(\beta_n g_m + \beta_m g_n)}{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n} = \delta\varphi'$.

Similarly, we can obtain the optimal decision adjustment strategies for other scenarios and the corresponding conditions that need to be satisfied.

- Optimal adjustment strategies in Strategy A2 ($\lambda_m = 0, \lambda_n > 0$)

$$x_m^* = \frac{1}{2}\left[\frac{ab_n + (1-a)r}{b_m b_n - r^2}\delta\varphi + \beta_m \delta p_e + g_m\right], x_n^* = \frac{1}{2b_n}\left[\frac{arb_n + (1-a)(2b_m b_n - r^2)}{b_m b_n - r^2}\delta\varphi + r(\beta_m \delta p_e + g_m)\right]$$

$$\Delta q_m^* = \frac{1}{2b_n}\left\{[ab_n + (1-a)r]\delta\varphi - \left(b_m b_n - r^2\right)(\beta_m \delta p_e + g_m)\right\}, \Delta q_n^* = 0$$

$$\lambda_n^* = -\frac{1}{b_n}[(1-a)\delta\varphi + (r\beta_m + b_n\beta_n)\delta p_e + r g_m - b_n g_n]$$

According to constraints $\lambda_n^* > 0$ and $\Delta q_m^* \geq 0$, δp_e and $\delta\varphi$ should satisfy the following relationships:

$$\delta p_e < \frac{-(1-a)\delta\varphi - r g_m + b_n g_n}{r\beta_m + b_n\beta_n} = \Delta p_e^{A-line1}, \delta p_e \leq \frac{[ab_n + (1-a)r]\delta\varphi - \left(b_m b_n - r^2\right)g_m}{\left(b_m b_n - r^2\right)\beta_m} = \Delta p_e^{A-line3}$$

- Optimal adjustment strategies in Strategy A3 ($\lambda_m > 0, \lambda_n = 0$)

$$x_m^* = \frac{1}{2b_m}\left[\frac{a(2b_m b_n - r^2) + (1-a)rb_m}{b_m b_n - r^2}\delta\varphi + r(-\beta_n \delta p_e + g_n)\right], x_n^* = \frac{1}{2}\left[\frac{ar + (1-a)b_m}{b_m b_n - r^2}\delta\varphi - \beta_n \delta p_e + g_n\right]$$

$$\Delta q_m^* = 0, \Delta q_n^* = \frac{1}{2b_m}\left\{[ar + (1-a)b_m]\delta\varphi + \left(b_m b_n - r^2\right)(\beta_n \delta p_e - g_n)\right\}$$

$$\lambda_m^* = \frac{1}{b_m}[-a\delta\varphi + (b_m\beta_m + r\beta_n)\delta p_e + b_m g_m - r g_n]$$

According to constraints $\lambda_m^* > 0$ and $\Delta q_n^* \geq 0$, δp_e and $\delta\varphi$ should satisfy the following relationships:

$$\delta p_e > \frac{a\delta\varphi - b_m g_m + r g_n}{b_m\beta_m + r\beta_n} = \Delta p_e^{A-line2}, \delta p_e \geq \frac{-[ar + (1-a)b_m]\delta\varphi + \left(b_m b_n - r^2\right)g_n}{\left(b_m b_n - r^2\right)\beta_n} = \Delta p_e^{A-line4}$$

- Optimal adjustment strategies in Strategy A4 ($\lambda_m > 0, \lambda_n > 0$)

$$x_m^* = \frac{ab_n + (1-a)r}{b_m b_n - r^2}\delta\varphi, x_n^* = \frac{ar + (1-a)b_m}{b_m b_n - r^2}\delta\varphi, \Delta q_m^* = 0, \Delta q_n^* = 0$$

$$\lambda_m^* = -\frac{ab_n + (1-a)r}{b_m b_n - r^2}\delta\varphi + \beta_m \delta p_e + g_m, \lambda_n^* = -\frac{ar + (1-a)b_m}{b_m b_n - r^2}\delta\varphi - \beta_n \delta p_e + g_n$$

According to constraints $\lambda_m^* > 0$ and $\lambda_n^* > 0$, δp_e and $\delta\varphi$ should satisfy the following relationship:

$$\frac{[ab_n + (1-a)r]\delta\varphi - (b_m b_n - r^2)g_m}{(b_m b_n - r^2)\beta_m} < \delta p_e < \frac{-[ar + (1-a)b_m]\delta\varphi + (b_m b_n - r^2)g_n}{(b_m b_n - r^2)\beta_n} \tag{10}$$

The upper and lower limits in Eq. (10) are exactly the two straight lines $\Delta p_e^{A-line3}$ in Strategy A2 and $\Delta p_e^{A-line4}$ in Strategy A3. Moreover, we find that the five constraint lines, $\Delta p_e^{A-line1}$, $\Delta p_e^{A-line2}$, $\Delta p_e^{A-line3}$, $\Delta p_e^{A-line4}$ and $\delta\varphi'$, have a common intersection, which can lead to the following lemma.

Lemma 4. *For adjustment strategies A-D, there will be only one unique optimal adjustment strategy available for automakers to cope with demand and credit price disruptions.*

Lemma 4 *implies that for any demand and credit price disruptions, automakers can adopt corresponding optimal adjustment strategies to reduce losses.* Tables 1–4 *summarize the optimal adjustment strategies for Strategies A-B. Let* $M_1 = ab_n + (1-a)r$, $M_2 = ar + (1-a)b_m$, $M_3 = a\delta\varphi - (b_m\beta_m + r\beta_n)\delta p_e$, $M_4 = (1-a)\delta\varphi + (r\beta_m + b_n\beta_n)\delta p_e$, *and* $H = b_m b_n - r^2$.

Tables 1–4 *shows that when considering decision adjustment costs, automakers will have* 16 *strategies to adjust their decisions to cope with demand and credit price disruptions. Moreover, among these* 16 *strategies, optimal decision adjustment strategies A-D will be simultaneous obtained. These* 4 *optimal decision adjustment strategies may be the same or different, so automakers also*

Table 1
Optimal adjustment strategies considering adjustment costs: Strategy A ($\Delta q_m \geq 0, \Delta q_n \geq 0$).

Strategies	x_m^*	x_n^*	Δq_m^*	Δq_n^*	*Disruption range*
$A1\begin{pmatrix}\lambda_m = 0\\ \lambda_n = 0\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}\frac{M_1}{H}\Delta\varphi + \\ \beta_m \Delta p_e + g_m\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}\frac{M_2}{H}\Delta\varphi - \\ \beta_n \Delta p_e + g_n\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}M_3 - \\ b_m g_m + r g_n\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}M_4 + \\ r g_m - b_n g_n\end{pmatrix}$	$\delta p_e \geq \Delta p_e^{A-line1}$ $\delta p_e \leq \Delta p_e^{A-line2}$
$A2\begin{pmatrix}\lambda_m = 0\\ \lambda_n > 0\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}\frac{M_1}{H}\Delta\varphi + \\ \beta_m \Delta p_e + g_m\end{pmatrix}$	$\frac{1}{2b_n}\begin{bmatrix}\left(1 - a + \frac{b_n M_2}{H}\right)\Delta\varphi \\ +r(\beta_m \delta p_e + g_m)\end{bmatrix}$	$\frac{1}{2b_n}\begin{bmatrix}M_1\Delta\varphi - \\ (\beta_m \delta p_e + g_m)H\end{bmatrix}$	0	$\delta p_e < \Delta p_e^{A-line1}$ $\delta p_e \leq \Delta p_e^{A-line3}$
$A3\begin{pmatrix}\lambda_m > 0\\ \lambda_n = 0\end{pmatrix}$	$\frac{1}{2b_m}\begin{bmatrix}\left(a + \frac{b_m M_1}{H}\right)\Delta\varphi + \\ r(-\beta_n \delta p_e + g_n)\end{bmatrix}$	$\frac{1}{2}\begin{pmatrix}\frac{M_2}{H}\Delta\varphi - \\ \beta_n \Delta p_e + g_n\end{pmatrix}$	0	$\frac{1}{2b_m}\begin{bmatrix}M_2\Delta\varphi + \\ (\beta_n \delta p_e - g_n)H\end{bmatrix}$	$\delta p_e > \Delta p_e^{A-line2}$ $\delta p_e \geq \Delta p_e^{A-line4}$
$A4\begin{pmatrix}\lambda_m > 0\\ \lambda_n > 0\end{pmatrix}$	$\frac{M_1}{H}\delta\varphi$	$\frac{M_2}{H}\delta\varphi$	0	0	$\delta p_e > \Delta p_e^{A-line3}$ $\delta p_e < \Delta p_e^{A-line4}$

Table 2
Optimal adjustment strategies considering adjustment costs: Strategy B ($\Delta q_m \geq 0, \Delta q_n < 0$).

Strategies	x_m^*	x_n^*	Δq_m^*	Δq_n^*	*Disruption range*
$B1\begin{pmatrix}\lambda_m = 0\\ \lambda_n = 0\end{pmatrix}$	$\frac{1}{2}\begin{bmatrix}\frac{M_1}{H}\Delta\varphi + \\ \beta_m \Delta p_e + g_m\end{bmatrix}$	$\frac{1}{2}\begin{pmatrix}\frac{M_2}{H}\Delta\varphi - \\ \beta_n \Delta p_e - s_n\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}M_3 - \\ b_m g_m - r s_n\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}M_4 + \\ r g_m + b_n s_n\end{pmatrix}$	$\delta p_e \leq \Delta p_e^{B-line1}$ $\delta p_e \leq \Delta p_e^{B-line2}$
$B2\begin{pmatrix}\lambda_m = 0\\ \lambda_n > 0\end{pmatrix}$	$\frac{1}{2}\begin{bmatrix}\frac{M_1}{H}\Delta\varphi + \\ \beta_m \Delta p_e + g_m\end{bmatrix}$	$\frac{1}{2b_n}\begin{bmatrix}\left(1 - a + \frac{b_n M_2}{H}\right)\Delta\varphi \\ +r(\beta_m \delta p_e + g_m)\end{bmatrix}$	$\frac{1}{2b_n}\begin{bmatrix}M_1\Delta\varphi - \\ (\beta_m \delta p_e + g_m)H\end{bmatrix}$	0	$\delta p_e > \Delta p_e^{B-line1}$ $\delta p_e \leq \Delta p_e^{B-line3}$
$B3\begin{pmatrix}\lambda_m > 0\\ \lambda_n = 0\end{pmatrix}$	$\frac{1}{2b_m}\begin{bmatrix}\left(a + \frac{b_m M_1}{H}\right)\Delta\varphi \\ -r(\beta_n \delta p_e + s_n)\end{bmatrix}$	$\frac{1}{2}\begin{pmatrix}\frac{M_2}{H}\Delta\varphi - \\ \beta_n \Delta p_e - s_n\end{pmatrix}$	0	$\frac{1}{2b_m}\begin{bmatrix}M_2\Delta\varphi + \\ (\beta_n \Delta p_e + s_n)H\end{bmatrix}$	$\delta p_e > \Delta p_e^{B-line2}$ $\delta p_e \leq \Delta p_e^{B-line4}$
$B4\begin{pmatrix}\lambda_m > 0\\ \lambda_n > 0\end{pmatrix}$	$\frac{M_1}{H}\delta\varphi$	$\frac{M_2}{H}\delta\varphi$	0	0	$\delta p_e > \Delta p_e^{B-line3}$ $\delta p_e > \Delta p_e^{B-line4}$

Table 3
Optimal adjustment strategies considering adjustment costs: Strategy C ($\Delta q_m < 0, \Delta q_n \geq 0$).

Strategies	x_m^*	x_n^*	Δq_m^*	Δq_n^*	*Disruption range*
$C1 \begin{pmatrix} \lambda_m = 0 \\ \lambda_n = 0 \end{pmatrix}$	$\frac{1}{2}\left[\frac{M_1}{H}\Delta\varphi + \beta_m \Delta p_e - s_m\right]$	$\frac{1}{2}\left(\frac{M_2}{H}\Delta\varphi - \beta_n \Delta p_e + g_n\right)$	$\frac{1}{2}\left(M_3 + b_m s_m + r g_n\right)$	$\frac{1}{2}\left(M_4 - r s_m - b_n g_n\right)$	$\delta p_e \geq \Delta p_e^{C-line1}$ $\delta p_e \geq \Delta p_e^{C-line2}$
$C2 \begin{pmatrix} \lambda_m = 0 \\ \lambda_n > 0 \end{pmatrix}$	$\frac{1}{2}\left[\frac{M_1}{H}\Delta\varphi + \beta_m \Delta p_e - s_m\right]$	$\frac{1}{2b_n}\left[\left(1 - a + \frac{b_n M_2}{H}\right)\Delta\varphi + r(\beta_m \delta p_e - s_m)\right]$	$\frac{1}{2b_n}\left[M_1 \Delta\varphi - (\beta_m \Delta p_e - s_m)H\right]$	0	$\delta p_e \geq \Delta p_e^{C-line3}$ $\delta p_e < \Delta p_e^{C-line1}$
$C3 \begin{pmatrix} \lambda_m > 0 \\ \lambda_n = 0 \end{pmatrix}$	$\frac{1}{2b_m}\left[\left(a + \frac{b_m M_1}{H}\right)\Delta\varphi + r(-\beta_n \delta p_e + g_n)\right]$	$\frac{1}{2}\left(\frac{M_2}{H}\Delta\varphi - \beta_n \Delta p_e + g_n\right)$	0	$\frac{1}{2b_m}\left[M_2 \Delta\varphi + (\beta_n \delta p_e - g_n)H\right]$	$\delta p_e \geq \Delta p_e^{C-line4}$ $\delta p_e < \Delta p_e^{C-line2}$
$C4 \begin{pmatrix} \lambda_m > 0 \\ \lambda_n > 0 \end{pmatrix}\cdots$	$\frac{M_1}{H}\delta\varphi$	$\frac{M_2}{H}\delta\varphi$	0	0	$\delta p_e \leq \Delta p_e^{C-line3}$ $\delta p_e \leq \Delta p_e^{C-line4}$

Table 4
Optimal adjustment strategies considering adjustment costs: Strategy D ($\Delta q_m < 0, \Delta q_n < 0$).

Strategies	x_m^*	x_n^*	Δq_m^*	Δq_n^*	*Disruption range*
$D1 \begin{pmatrix} \lambda_m = 0 \\ \lambda_n = 0 \end{pmatrix}$	$\frac{1}{2}\left[\frac{M_1}{H}\Delta\varphi + \beta_m \Delta p_e - s_m\right]$	$\frac{1}{2}\left(\frac{M_2}{H}\Delta\varphi - \beta_n \Delta p_e - s_n\right)$	$\frac{1}{2}\left(M_3 + b_m s_m - r s_n\right)$	$\frac{1}{2}\left[M_4 - r s_m + b_n s_n\right]$	$\delta p_e \geq \Delta p_e^{D-line2}$ $\delta p_e \leq \Delta p_e^{D-line1}$
$D2 \begin{pmatrix} \lambda_m = 0 \\ \lambda_n > 0 \end{pmatrix}$	$\frac{1}{2}\left[\frac{M_1}{H}\Delta\varphi + \beta_m \Delta p_e - s_m\right]$	$\frac{1}{2b_n}\left[\left(1 - a + \frac{b_n M_2}{H}\right)\Delta\varphi + r(\beta_m \delta p_e - s_m)\right]$	$\frac{1}{2b_n}\left[M_1 \Delta\varphi - (\beta_m \Delta p_e - s_m)H\right]$	0	$\Delta p_e > \Delta p_e^{D-line1}$ $\delta p_e \geq \Delta p_e^{D-line3}$
$D3 \begin{pmatrix} \lambda_m > 0 \\ \lambda_n = 0 \end{pmatrix}$	$\frac{1}{2b_m}\left[\left(a + \frac{b_m M_1}{H}\right)\Delta\varphi - r(\beta_n \delta p_e + s_n)\right]$	$\frac{1}{2}\left(\frac{M_2}{H}\Delta\varphi - \beta_n \Delta p_e - s_n\right)$	0	$\frac{1}{2b_m}\left[M_2 \Delta\varphi + (\beta_n \Delta p_e + s_n)H\right]$	$\delta p_e < \Delta p_e^{D-line2}$ $\delta p_e \leq \Delta p_e^{D-line4}$
$D4 \begin{pmatrix} \lambda_m > 0 \\ \lambda_n > 0 \end{pmatrix}$	$\frac{M_1}{H}\delta\varphi$	$\frac{M_2}{H}\delta\varphi$	0	0	$\delta p_e > \Delta p_e^{D-line4}$ $\delta p_e < \Delta p_e^{D-line3}$

need to compare these 4 *optimal decision adjustment strategies and determine which one will bring the highest decision-adjusted profit, and this strategy will be the final optimal decision adjustment strategy for automakers.*

By comparing these 16 *optimal strategies in* Tables 1–4, *we find important relationships summarized in the following proposition.*

Proposition 3. *The 16 decision adjustment strategies of automakers have the following relationships:*

i) *Strategy A*2 = Strategy B2,
ii) *Strategy A*3 = Strategy C3,
iii) *Strategy A*4 = Strategy B4= *Strategy C*4= *Strategy D*4,
iv) *Strategy B*3= *Strategy D*3,
v) *Strategy C*2= *Strategy D*2.

Proposition 3 *shows that automakers can obtain consistent decision adjustment strategies in different scenarios of production or pricing adjustment. In other words, some strategies can be applied simultaneously in multiple disruption ranges of demand and credit price. To more intuitively understand how automakers obtain optimal decision adjustment strategies based on demand and credit price disruptions, we show these* 16 *strategies in* Fig. B1 *as shown in* Appendix B, *and we use four different colors to represent these different adjustment strategies.*

Since the sizes of the strategy intervals vary, the probability of automakers adopting different decision adjustment strategies also varies. Generally, automakers are more concerned about how they can maintain production stability under demand and credit price disruptions, which is also known as "production flexibility" (Moreno and Terwiesch, 2015). *The blue strategy interval* (*Strategies A4-D4*) *is simply the "production flexibility" interval in which automakers do not need to make any production adjustment, which we call the "robust interval"* (*Strategies A4-D4*).

Assuming that the probability of demand and credit price disruptions is evenly distributed, the size of each decision adjustment strategy's robust interval (*Strategies A4-D4*) *can reflect the probability that automakers will maintain production stability, which is vital for automakers to gain a competitive advantage under the dual-credit policy. We provide the following definition to calculate the probability of each decision adjustment strategy's robust interval* (*Strategies A4-D4*).

Definition 1. The probability of each decision adjustment strategy's robust interval (Strategies A4-D4) is $P(\theta) = \theta/\ 2\pi$ where $\theta = arctan\left(\left|\frac{k_1-k_2}{1+k_1k_2}\right|\right)$ or $\theta = \pi - arctan\left(\left|\frac{k_1-k_2}{1+k_1k_2}\right|\right)$ and $\theta \in [0,\pi]$ is the angle formed by the two constraint lines, the slopes of which are k_1 and k_2. The greater $P(\theta)(0 \le P(\theta) \le \frac{1}{2})$ is, the more likely automakers will maintain production stability under demand and credit price disruptions.

In the same way, we can use the angle formed by the constraint lines to calculate the probability of other strategy intervals. Consequently, we can acquire a better understanding of how automakers adopt optimal decision adjustment strategies to cope with demand and credit price disruptions under the dual-credit policy. Therefore, we make the following propositions.

Proposition 4. *The slopes of all of the constraint lines remain unchanged across all strategies* (Strategies A-D). The changes in the intercept and angle formed by these constraint lines indicate the variation in the probability of automakers adopting each decision adjustment strategy. Moreover, automakers have the same probability of adopting Strategies A and D and Strategies B and C, that is, $P(An) = P(Dn)$, $P(Bn) = P(Cn)$, *and* $n = 1,2,3,4$. The sum of the probabilities of adopting each adjustment strategy for automakers under Strategies A and B and Strategies C and D is fixed; that is, $P(An) + P(Bn) = \frac{1}{2}$, $P(Cn) + P(Dn) = \frac{1}{2}$, *and* $n = 1,2,3,4$.

Proposition 4 *shows that, considering decision adjustment costs, the probability of automakers simultaneously increasing or reducing the production of FVs and NEVs is the same and the sum of the probabilities for automakers separately increasing or reducing the production of FVs and NEVs is fixed. From a likelihood perspective, we address the following propositions on synchronous and individual decision adjustment strategies.*

Proposition 5. Under Strategies A and D, automakers are more inclined to separately adjust the production of FVs and NEVs. Under Strategies B and C, automakers are more inclined to simultaneously adjust or not adjust the production of both FVs and NEVs. Moreover, FV credit coefficient β_m has a significantly positive impact on the probabilities of the 16 decision adjustment strategies, while NEV credit coefficient β_n has almost no impact on the probabilities of the 16 decision adjustment strategies.

Proposition 5 *shows that automakers will prefer a major adjustment strategy with different disruption ranges of demand and credit price. Accordingly, the adoption of different decision adjustment strategies for automakers is mainly affected by FV credits and almost unaffected by NEV credits. Therefore, the management of FV credits is the key to optimizing automakers' decision adjustment strategies in coping with demand and credit price disruptions under the dual-credit policy.*

Proposition 6. Under Strategies A and D, as substitution coefficient *r* increases, automakers become more inclined to adjust NEV production to cope with demand and credit price disruptions. Under Strategies B and C, as substitution coefficient *r* increases, automakers become more inclined to adjust the production of both FVs and NEVs to cope with demand and credit price disruptions. The probability that automakers will separately adjust FV production or simultaneously not adjust both types of vehicle production is almost unaffected by substitution coefficient *r*.

Proposition 6 *shows that as FVs are replaced by NEVs, automakers will be more inclined to adjust NEV production to cope with demand and credit price disruptions. The benefits of adjusting FV production will decrease as substitution coefficient r increases. The replacement of FVs with NEVs will further strengthen the market competitive advantage of NEVs. Consequently, NEVs will become increasingly important for automakers to cope with demand and credit price disruptions under the dual-credit policy.*

3.3. Optimal initial decisions for automakers

The expected demand and credit price have a substantial impact on automakers' initial decisions and disruption management strategies; therefore, automakers need to identify the optimal expected demand and credit price to maximize expected profits (Yu et al., 2009). Suppose that the actual demand and credit price are continuous random variables subject to a probability distribution with expected mean values of μ_d and μ_p and standard deviations of σ_d and σ_p; the probability density functions are $f_d(\cdot)$ and $f_p(\cdot)$, and the distribution functions are $F_d(\cdot)$ and $F_p(\cdot)$. Therefore, from typical experience, should automakers consider expected mean values μ_d and μ_p as the optimal expected demand and credit price, respectively? In other words, can the expected mean value maximize automakers' expected profits?

In reality, the emergency and disposal costs of FVs and NEVs are often unequal; therefore, when emergency costs are relatively high, automakers will prefer to set higher levels of initial production to reduce emergency costs when actual demand exceeds expected demand. Similarly, when disposal costs are relatively high, automakers will prefer to set lower initial production levels to reduce disposal costs when the actual demand is lower than the expected demand. Since the probability of each actual demand and credit price is different, the expected mean value is often not the optimal value. Moreover, the optimal value that can maximize automakers' expected total profits should be another value that deviates from the expected mean value as the decision adjustment costs and probability distribution function change. We use a computational approach to derive the optimal expected demand and credit price that will maximize automakers' expected total profits.

4. Numerical study

We consider a Chinese automaker that produces both FVs and NEVs. The values of the parameters are as follows: $\overline{\varphi} = 2000000$, $a = 0.92$, $b_m = 12$, $b_n = 1$,$r = 0.01$, $c_m = 50000$, $c_n = 140000$, $e_0 = 6.9$, $\Delta e = 0.4$, $\delta = 0.1$, $t = 0.1$, $\beta_m = 0.1$, $\beta_n = 4.4$, $g_m = 5000$, $g_n = 8000$, $s_m = 20{,}000$, $s_n = 40{,}000$, $\overline{p}_e = 2000$, $p_e \sim N(2000, 500)$, and $\varphi \sim N(2,000,000, 50,000)$.

Table 5
The impact of $\overline{\varphi}$ and $\overline{p}_e$ on automakers' optimal initial decisions.

$(\overline{\varphi}, \overline{p}_e)$	$\overline{p}_m^*$	$\overline{p}_n^*$	$\overline{q}_m^*$	$\overline{q}_n^*$	$\overline{\mu}^*$	$\overline{\pi}^*$
(2500, 5)	119.10	184.94	822.59	66.25	209.25	60.87
(2000, 2)	100.18	166.35	599.46	34.65	92.52	31.18
(1500, 0.5)	81.34	144.46	375.39	6.35	−9.60	11.79

Note: the units of $\overline{\varphi}$, $\overline{q}_m^*$, $\overline{q}_n^*$ and $\overline{\mu}^*$ are in "thousands of units"; the units of $\overline{p}_m^*$ and $\overline{p}_n^*$ are in "thousands of RMB"; and the units of $\overline{\pi}^*$ are in "billions of RMB".

We analyze the impact of the expected demand and credit price on this automaker's optimal decisions in Table 5. When the expected demand and credit price are relatively high, the price, production and profit of FVs and NEVs will increase, and this automaker will obtain excess profits by selling positive total credits. When the expected demand and credit price are relatively low, the price, production and profit of FVs and NEVs will be lower, and this automaker will obtain negative total credits and need to buy positive NEV credits on the credit market. When the expected demand and credit price are at a normal level, the price, production, profit and total credits of FVs and NEVs will be at the levels found in the previous two situations. These results show that the expected demand and credit price have a positive correlation with automakers' optimal initial decisions.

We further find that only when the actual credit price reaches 1.74 (in thousands of RMB) can this automaker achieve total credit equilibrium. When the actual credit price is higher than this threshold credit price, this automaker will actively produce more NEVs to obtain positive credits. When the actual credit price is lower than the threshold credit price, this automaker will purchase credits on the credit market to offset the total negative credits. Moreover, when the market share of NEVs exceeds 8.38%, the threshold credit price for maintaining total credit equilibrium will be negative, meaning that there is no need for the dual-credit policy to encourage this automaker to produce NEVs.

Table 6 presents some cases for analyzing the optimal decision adjustment strategies of this automaker under demand and credit price disruptions. The first case shows that when the actual demand and credit price are higher than the expected value, this automaker will have four optimal decision adjustment strategies: Strategy A1, Strategy B2, Strategy C3 and Strategy D4. If Strategy A is adopted to increase the production of FVs and NEVs to cope with the increase in demand and credit price, the automaker will eventually increase the price and production of both FVs and NEVs (Strategy A1). On this premise, this automaker's total credits and profits will increase accordingly. If Strategy B is adopted to increase FV production and reduce NEV production to cope with the increase in demand and credit price, the automaker will eventually increase FV production but maintain NEV production (Strategy B2). Consequently, the price of NEVs will increase significantly, the automaker's total credits will decrease, and profits will also increase significantly. If Strategy C is adopted, the automaker will ultimately maintain FV production but significantly increase NEV production (Strategy C3), and the automaker's total credits and profit will also be improved. If Strategy D is adopted, the automaker will maintain the same level of FV and NEV production (Strategy D4) and increase both FV and NEV prices to cope with the increase in the demand and credit price, which will maintain total credit equilibrium and increase automakers' profit. When comparing these four optimal decision adjustment strategies, we

Table 6
Optimal adjustment strategies under demand and credit price disruptions.

$(\delta\varphi, \delta p_e)$	Strategies	x_m^*	x_n^*	Δq_m^*	Δq_n^*	$\Delta\mu^*$	$\Delta\pi^*$
(500, 2)	A1	21.37	24.79	193.80	25.43	92.49	28.03
	B2	21.37	50.21	194.05	0.00	−19.41	27.39
	C3	37.52	24.79	0.00	25.59	112.58	24.91
	D4	37.54	50.38	0.00	0.00	0.00	24.25
(500, −2)	A1	21.17	33.59	196.28	16.62	53.52	27.74
	B2	21.17	50.21	196.45	0.00	−19.65	27.47
	C3	37.53	33.59	0.00	16.79	73.87	24.53
	D4	37.54	50.38	0.00	0.00	0.00	24.25
(-500, 2)	A4	−37.54	−50.38	0.00	0.00	0.00	11.35
	B3	−37.54	−49.59	0.00	−0.79	−3.47	11.35
	C2	−28.67	−50.29	−106.45	0.00	10.65	12.29
	D1	−28.67	−49.59	−106.44	−0.70	7.57	12.29
(-500, −2)	A4	−37.54	−50.38	0.00	0.00	0.00	10.65
	B3	−37.53	−40.79	0.00	−9.59	−42.19	10.74
	C2	−28.87	−50.29	−104.05	0.00	10.41	11.55
	D1	−28.87	−40.79	−103.96	−9.50	−31.41	11.64

Note: the units of $\delta\varphi$, Δq_m^*, Δq_n^* and $\Delta\mu^*$ are in "thousands of units"; the units of x_m^* and x_n^* are in "thousands of RMB"; and the units of $\Delta\pi^*$ are in "billions of RMB".

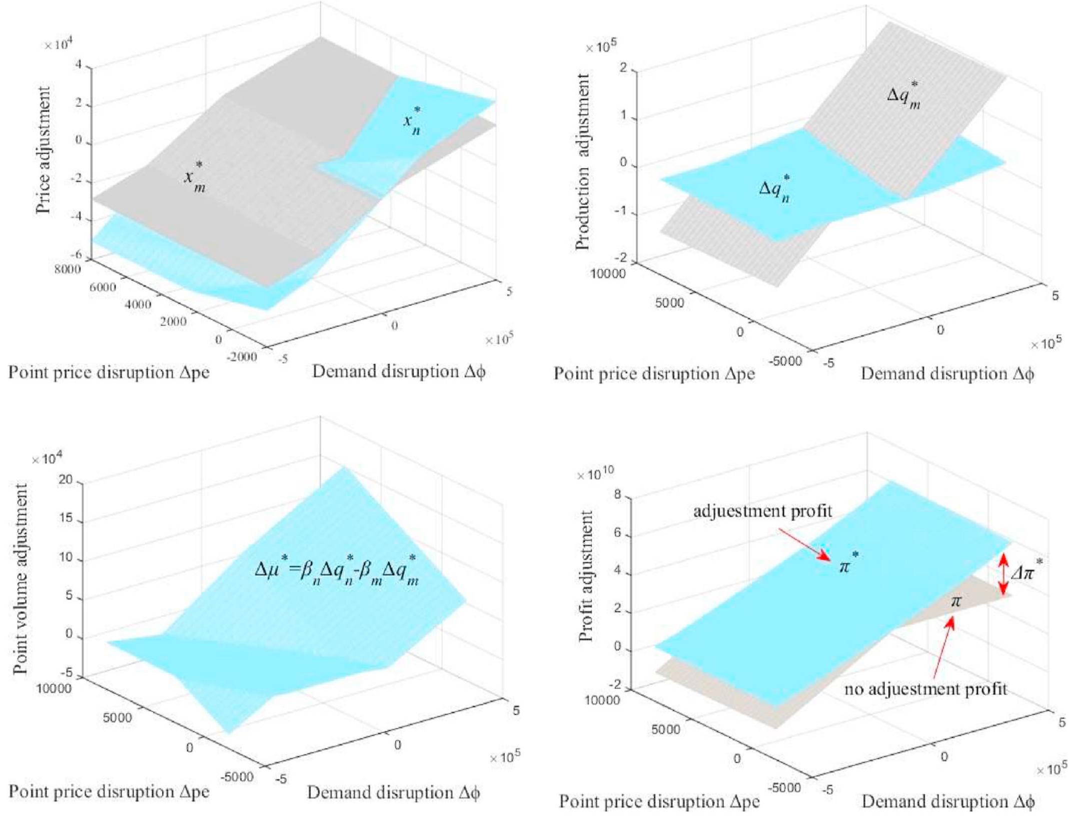

Fig. 1. Optimal adjustment strategies under demand and credit price disruptions.

find that the automaker adopting Strategy A1 will maximize its total profits and partially eliminate the negative effects of demand and credit price disruptions.

Similarly, when actual demand exceeds expected demand but the actual credit price is lower than the expected credit price, the automaker will also have four optimal decision adjustment strategies: Strategy A1, Strategy B2, Strategy C3 and Strategy D4. Strategy A1 will be the best of these decision adjustment strategies in terms of profit maximization. When actual demand is lower than expected demand and the actual credit price is higher than the expected credit price, the automaker will have four optimal decision adjustment strategies: Strategy A4, Strategy B3, Strategy C2 and Strategy D1. Strategies A4 and B3 will be the best of these four decision adjustment strategies in terms of profit maximization. When the actual value of demand and credit price are lower than the expected value, the automaker will also have four optimal decision adjustment strategies: Strategy A4, Strategy B3, Strategy C2 and Strategy D1. Strategy D1 will be the best of these four decision adjustment strategies in terms of profit maximization.

Fig. 1 provides other optimal adjustment strategies that can help the automaker cope with a larger disruption range of demand and credit prices. First, from the perspective of price adjustment, when actual demand exceeds expected demand and the disruption range of the credit price is relatively small, the automaker's price adjustment for NEVs will be greater than the price adjustment for FVs. When the actual demand and credit price are significantly higher than the expected value, the automaker's price adjustment for FVs will be greater than the price adjustment for NEVs. When actual demand is lower than expected demand, regardless of the disruption range of the credit price, the automaker's price adjustment for NEVs will be greater than the price adjustment for FVs. Therefore, under the dual-credit policy, price adjustment for NEVs is an important means for the automaker to cope with demand and credit price disruptions.

Second, from the perspective of production adjustment, when the disruption range of demand and the credit price is relatively small, the production of FVs and NEVs will remain consistent. When the disruption range of demand and the credit price is relatively large, especially when actual demand deviates significantly from expected demand, the automaker will adjust FV production accordingly. Therefore, under the dual-credit policy, FV production adjustment is a key means for the automaker to cope with demand and credit price disruptions.

Finally, in terms of total credits and profit adjustment, when the disruption range of demand and the credit price is relatively small, total credits will be in equilibrium. However, when the actual demand and credit price are significantly higher than their expected values, the automaker will obtain more positive credits. In contrast, when the actual demand and credit price are significantly lower than the expected values, the automaker will obtain more negative credits. Compared to adopting no decision adjustment, decision adjustment strategies will enable the automaker to partially eliminate the negative impacts of demand and credit price disruptions and increase total profits.

Fig. 2 shows the interval angle θ of the automaker's 16 adjustment strategies and the impact of FV credit coefficient β_m and NEV credit coefficient β_n on the automaker's probability of adopting optimal decision adjustment strategies. Fig. 2 demonstrates that the strategic probabilities $P(\theta)$ of the four strategies under Strategies A and D and Strategies B and C are consistent and the strategic probability between Strategy A/D and Strategy B/C is fixed. Taking Strategies A and B as examples, when $\beta_m = 0.1$ and $\beta_n = 4.4$, according to Definition 1, we can calculate the interval angles of Strategies A1-A4 as 9.37°, 170.54°, 170.62° and 9.47°, respectively, and their strategic probabilities are 2.60%, 47.37%, 47.40% and 2.63%, respectively. Similarly, the interval angles of Strategies B1−B4 are 170.63°, 9.46°, 9.38° and 170.53°, respectively, and their strategic probabilities are 47.40%, 2.63%, 2.60% and 47.37%, respectively. Of course, $P(An) + P(Bn) = \frac{1}{2}$, $n = 1, 2, 3, 4$.

Fig. 2 also demonstrates that FV credit coefficient β_m has a significant impact on the automaker's optimal decision adjustment strategies, but NEV credit coefficient β_n has almost no impact on these decision adjustment strategies. When this automaker adopts Strategy A or Strategy D, as the FV credit coefficient increases, this automaker prefers to adopt Strategies A2 and D2 or Strategies A3 and D3 and thus increase FV or NEV production alone to cope with demand and credit price disruptions. When the automaker adopts Strategy B or Strategy C, it will be more inclined to choose Strategies B1 and C1 or Strategies B4 and C4, which will increase or maintain the production of FVs and NEVs. Therefore, under the dual-credit policy, the FV credit coefficient is a key factor in determining automakers' selection of optimal decision adjustment strategies.

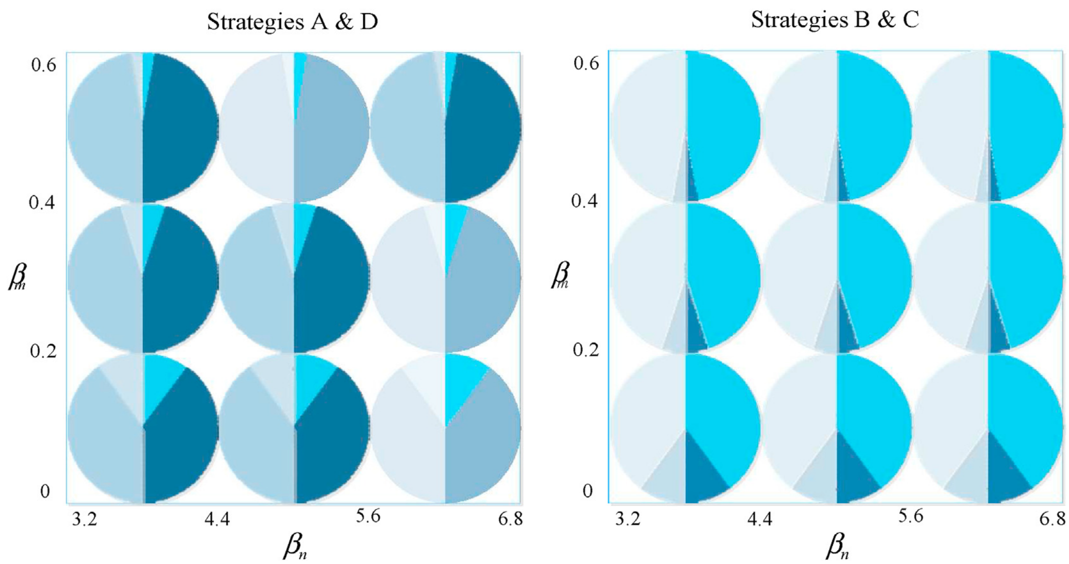

Fig. 2. Impact of β_m and β_n on the probabilities of optimal decision adjustment strategies.

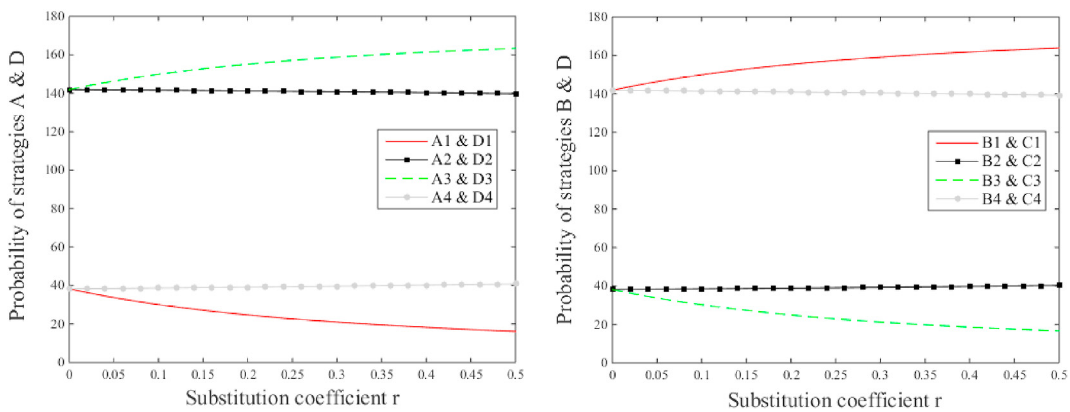

Fig. 3. Impact of demand substitution r on the probabilities of optimal adjustment strategies.

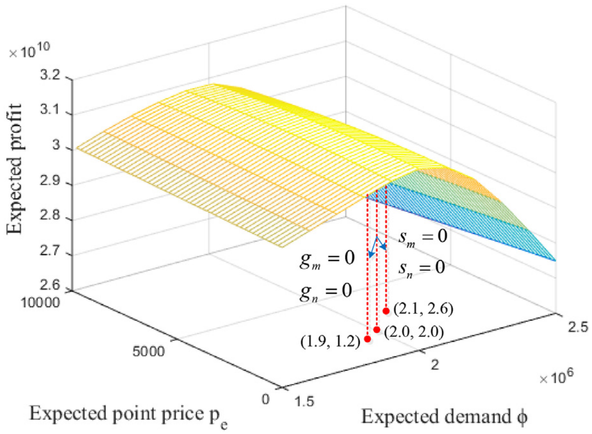

Fig. 4. Impact of optimal initial decisions $(\overline{\varphi}, \overline{p}_e)$ on the automaker's expected total profits.

Fig. 3 shows the impact of demand substitution coefficient r on the automaker's probability when adopting optimal decision adjustment strategies. As shown in Fig. 3, if the automaker chooses Strategy A or Strategy D, as the substitution coefficient increases, the automaker will be more inclined to increase NEV production alone to cope with demand and credit price disruptions. However, the strategic probability of increasing both FV and NEV production will decrease, and there will be no change in the strategic probability of increasing FV production alone or maintaining the same production for both of these vehicle types. If the automaker adopts Strategy B or Strategy C, as the substitution coefficient increases, the automaker will be more inclined to simultaneously adjust the production of FVs and NEVs. The strategic probability of reducing NEV production alone will decrease, and there will be no change in the strategic probability of adjusting FV production alone or maintaining the same production for both of these vehicle types.

Fig. 4 shows the impact of optimal initial decisions $(\overline{\varphi}, \overline{p}_e)$ on the automaker's expected total profits. When $g_m = 5000$, $g_n = 8000$, $s_m = 20{,}000$, and $s_n = 40{,}000$, the automaker will make initial decisions to adopt $\overline{\varphi} = 2.0$ (millions of units) and $\overline{p}_e = 2.0$ (thousands of RMB) to maximize the expected total profits. When $g_m = 0$, $g_n = 0$, $s_m = 20{,}000$, and $s_n = 40{,}000$, the automaker's optimal initial decisions will be $\overline{\varphi} = 1.9$ (millions of units) and $\overline{p}_e = 1.2$ (thousands of RMB). Finally, when $g_m = 5000$, $g_n = 8000$, $s_m = 0$, and $s_n = 0$, the automaker's optimal initial decisions will be $\overline{\varphi} = 2.1$ (millions of units) and $\overline{p}_e = 2.6$ (thousands of RMB). These results show that the automaker's optimal initial decisions are closely related to emergency and disposal costs for coping with demand and credit price disruptions. When emergency costs are relatively low, the automaker will make initial decisions at a lower expected demand and credit price. In contrast, when disposal costs are relatively low, the automaker will prefer to increase the expected demand and credit price to expand initial production.

5. Conclusions

This study investigated the decision optimization problem faced by automakers given demand and credit price disruptions under the dual-credit policy. The purpose of the dual-credit policy is to encourage automakers to reduce the fuel consumption of FVs and increase the market share of NEVs through credit trading, ultimately achieving a low-carbon Chinese automobile industry. We first formulated a production and pricing decision model that includes FV and NEV credits to solve for automakers' optimal initial decisions made under the dual-credit policy. Then, considering the emergency and disposal costs of FVs and NEVs, a nonlinear programming model with demand and credit price disruptions was established. In solving this nonlinear programming model using the KKT (Karush-Kuhn-Tucker) approach, we obtained 16 optimal adjustment strategies for automakers. We also analyzed the relationships between these adjustment strategies and the probability that automakers will adopt these adjustment strategies according to the disruption range of demand and credit price. Finally, based on the probability distribution function of demand and credit price, a computational approach was used to solve for the initial optimal decisions that can maximize automakers' expected total profits.

Through this research, we obtained some interesting management findings. (1) As the credit price rises, the profit of NEVs will increase, and the profit of FVs will decline. Therefore, the dual-credit policy has a positive incentive effect on the development of NEVs. (2) The dual-credit policy is best suited for the development of NEVs at an initial stage, and it requires a relatively high credit price to incentivize automakers to reduce the fuel consumption of FVs and increase the production of NEVs. As the market share of NEVs continues to increase, the credit price will reach a market equilibrium at a relatively low level. (3) In the presence of demand and credit price disruptions, the strategic probabilities of 16 decision adjustment strategies exhibit good symmetry and complementarity. For automakers, adjusting the price of NEVs and controlling the production of FVs is the most effective adjustment strategy. For the government, the development of reasonable fuel consumption standards for FVs and the production proportion of NEVs have a significant impact on automakers' optimal initial decisions and adjustment strategies. Automakers' emergency and disposal costs have important impacts on automakers' optimal initial decisions. When emergency costs are relatively low, automakers will tend to adopt less initial production. In contrast, when disposal costs are relatively low, automakers will tend to set higher levels of initial production.

This study has several limitations, and there are several opportunities to extend this research in the future. In our model, we assume that automakers make production decisions for these two vehicle types simultaneously. However, FVs and NEVs are often not produced by the same automakers, which means that the pricing and production decisions of these two vehicle types are relatively independent. This means that a decentralized decision model is needed to improve our model. Moreover, this study only considers the impact of the dual-credit policy on automakers and does not analyze the impact of the dual-credit policy on upstream automobile suppliers and the overall automobile supply chain. These shortcomings will be refined in our future research.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos. 71904018, 72032001, and 71972071); a project funded by the China Postdoctoral Science Foundation (No. 2020M681212); and the Fundamental Research Funds for the Central Universities.

Appendix A

Proof of Lemma 1

$$\begin{aligned} b_m\overline{y}_m^* - r\overline{y}_n^* &= b_m\cdot\frac{1}{2}\left[\frac{ab_n+(1-a)r}{b_mb_n-r^2}\overline{\varphi} - c_m - \beta_m\overline{p}_e\right] - r\cdot\frac{1}{2}\left[\frac{ar+(1-a)b_m}{b_mb_n-r^2}\overline{\varphi} - c_n + \beta_n\overline{p}_e\right] \\ &= \frac{1}{2}[(a\overline{\varphi} - b_mc_m + rc_n) - (b_m\beta_m + r\beta_n)\overline{p}_e] \\ &= \overline{q}_m^* \end{aligned}$$

$$\begin{aligned} b_n\overline{y}_n^* - r\overline{y}_m^* &= b_n\cdot\frac{1}{2}\left[\frac{ar+(1-a)b_m}{b_mb_n-r^2}\overline{\varphi} - c_n + \beta_n\overline{p}_e\right] - r\cdot\frac{1}{2}\left[\frac{ab_n+(1-a)r}{b_mb_n-r^2}\overline{\varphi} - c_m - \beta_m\overline{p}_e\right] \\ &= \frac{1}{2}[((1-a)\overline{\varphi} - b_nc_n + rc_m) + (r\beta_m + b_n\beta_n)\overline{p}_e] \\ &= \overline{q}_n^* \end{aligned}$$

$\frac{\partial\overline{q}_m^*}{\partial\overline{y}_m^*} = b_m > 0$, $\frac{\partial\overline{q}_m^*}{\partial\overline{y}_n^*} = -r < 0$; $\frac{\partial\overline{q}_n^*}{\partial\overline{y}_n^*} = b_n > 0$, $\frac{\partial\overline{q}_n^*}{\partial\overline{y}_m^*} = -r < 0$.

This lemma is proven.

Proof of Lemma 2.

According to Lemma 1, we can further obtain that, $\overline{\mu}^* = \beta_n\overline{q}_n^* - \beta_m\overline{q}_m^* = \beta_n(b_n\overline{y}_n^* - r\overline{y}_m^*) - \beta_m(b_m\overline{y}_m^* - r\overline{y}_n^*) = (r\beta_m + b_n\beta_n)\overline{y}_n^* - (b_m\beta_m + r\beta_n)\overline{y}_m^*$; Then, let $\overline{\mu}^* \geq 0$, $\frac{\overline{y}_n^*}{\overline{y}_m^*} \geq \frac{b_m\beta_m + r\beta_n}{r\beta_m + b_n\beta_n}$.

So, $\frac{\partial\left(\frac{\overline{y}_n^*}{\overline{y}_m^*}\right)}{\partial\beta_m} = \frac{(b_mb_n - r^2)\beta_n}{(r\beta_m + b_n\beta_n)^2} > 0$, $\frac{\partial\left(\frac{\overline{y}_n^*}{\overline{y}_m^*}\right)}{\partial\beta_m} = -\frac{(b_mb_n - r^2)\beta_m}{(r\beta_m + b_n\beta_n)^2} < 0$. The higher the β_m, the higher the $\frac{\overline{y}_n^*}{\overline{y}_m^*}$, and the more difficult it is for automakers to achieve credit equilibrium. Similarly, the higher the β_n, the lower the $\frac{\overline{y}_n^*}{\overline{y}_m^*}$, and the more easier it is for automakers to achieve credit equilibrium.

This lemma is proven.

Proof of Proposition 1.

i) $\frac{\partial\Delta\overline{p}_m^*}{\partial\Delta\varphi} = \frac{ab_n + (1-a)r}{2(b_mb_n - r^2)} > 0$, $\frac{\partial\Delta\overline{p}_n^*}{\partial\Delta\varphi} = \frac{ar + (1-a)b_m}{2(b_mb_n - r^2)} > 0$; $\frac{\partial\Delta\overline{q}_m^*}{\partial\Delta\varphi} = \frac{a}{2} > 0$, $\frac{\partial\Delta\overline{q}_n^*}{\partial\Delta\varphi} = \frac{1-a}{2} > 0$;

$\frac{\partial\Delta\overline{y}_m^*}{\partial\Delta\varphi} = \frac{ab_n + (1-a)r}{2(b_mb_n - r^2)} > 0$, $\frac{\partial\Delta\overline{y}_n^*}{\partial\Delta\varphi} = \frac{ar + (1-a)b_m}{2(b_mb_n - r^2)} > 0$;

$\frac{\partial\Delta\overline{\mu}^*}{\partial\Delta\varphi} = -\frac{a\beta_m - (1-a)\beta_n}{2}$, if $0 \leq a \leq \frac{\beta_n}{\beta_m + \beta_n}$, then $\frac{\partial\Delta\overline{\mu}^*}{\partial\Delta\varphi} \geq 0$; if $\frac{\beta_n}{\beta_m + \beta_n} < a \leq 1$, then $\frac{\partial\Delta\overline{\mu}^*}{\partial\Delta\varphi} < 0$.

ii) $\frac{\partial\Delta\overline{p}_m^*}{\partial\delta p_e} = \frac{\beta_m}{2} > 0$, $\frac{\partial\Delta\overline{p}_n^*}{\partial\delta p_e} = -\frac{\beta_n}{2} < 0$; $\frac{\partial\Delta\overline{q}_m^*}{\partial\delta p_e} = -\frac{b_m\beta_m + r\beta_n}{2} < 0$, $\frac{\partial\Delta\overline{q}_n^*}{\partial\delta p_e} = \frac{r\beta_m + b_n\beta_n}{2} > 0$;

$\frac{\partial\Delta\overline{y}_m^*}{\partial\delta p_e} = -\frac{\beta_m}{2} < 0$, $\frac{\partial\Delta\overline{y}_n^*}{\partial\delta p_e} = \frac{\beta_n}{2} > 0$; $\frac{\partial\Delta\overline{\mu}^*}{\partial\delta p_e} = \frac{b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2}{2} > 0$.

iii) $\frac{\partial\Delta\overline{\pi}^*}{\partial\Delta\varphi} = \frac{(1-a)^2 b_m + 2a(1-a)r + a^2 b_n}{2(b_m b_n - r^2)}\Delta\varphi + [a\overline{y}_m^* + (1-a)\overline{y}_n^*] - \frac{1}{2}[a\beta_m - (1-a)\beta_n]\delta p_e$,

if $\Delta\varphi \geq -\frac{2(b_m b_n - r^2)\left\{[a\overline{y}_m^* + (1-a)\overline{y}_n^*] - \frac{1}{2}[a\beta_m - (1-a)\beta_n]\delta p_e\right\}}{(1-a)^2 b_m + 2a(1-a)r + a^2 b_n}$, then $\frac{\partial\Delta\overline{\pi}^*}{\partial\Delta\varphi} \geq 0$;

if $\Delta\varphi < -\frac{2(b_m b_n - r^2)\left\{[a\overline{y}_m^* + (1-a)\overline{y}_n^*] - \frac{1}{2}[a\beta_m - (1-a)\beta_n]\delta p_e\right\}}{(1-a)^2 b_m + 2a(1-a)r + a^2 b_n}$, then $\frac{\partial\Delta\overline{\pi}^*}{\partial\Delta\varphi} < 0$.

$$\frac{\partial\Delta\overline{\pi}^*}{\partial\delta p_e} = \frac{1}{2}\left(b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2\right)\delta p_e + \left(\beta_n\overline{q}_n^* - \beta_m\overline{q}_m^*\right) - \frac{1}{2}[a\beta_m - (1-a)\beta_n]\delta\varphi$$

If $\delta p_e \geq -\frac{2\left\{(\beta_n\overline{q}_n^* - \beta_m\overline{q}_m^*) - \frac{1}{2}[a\beta_m - (1-a)\beta_n]\delta\varphi\right\}}{b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2}$, then $\frac{\partial\Delta\overline{\pi}^*}{\partial\delta p_e} \geq 0$.

If $\delta p_e < -\frac{2\left\{(\beta_n\overline{q}_n^* - \beta_m\overline{q}_m^*) - \frac{1}{2}[a\beta_m - (1-a)\beta_n]\delta\varphi\right\}}{b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2}$, then $\frac{\partial\Delta\overline{\pi}^*}{\partial\delta p_e} < 0$.

This proposition is proven.

Proof of Proposition 2.

$\frac{\partial\overline{p}_e^*}{\partial a} = \frac{(\beta_m + \beta_n)\overline{\varphi}}{b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2} > 0$, let $\overline{p}_e^* \geq 0$, we obtain that $a \geq \frac{\beta_n\overline{\varphi} + (b_m\beta_m + r\beta_n)c_m - (r\beta_m + b_n\beta_n)c_n}{(\beta_m + \beta_n)\overline{\varphi}}$.

$$\frac{\partial\overline{p}_e^*}{\partial\beta_m} = \frac{-b_m(a\varphi - b_m c_m + rc_n)\beta_m^2 + 2b_m[(1-a)\varphi + rc_m - b_n c_n]\beta_m\beta_n + +\left\{[ab_n + 2(1-a)r]\varphi - \left(b_m b_n - 2r^2\right)c_m - rb_n c_n\right\}\beta_n^2}{\left(b_m{\beta_m}^2 + \beta_n(2r\beta_m + b_n\beta_n)\right)^2}$$

$$\frac{\partial\overline{p}_e^*}{\partial\beta_n} = \frac{-b_n[-(1-a)\varphi + b_n c_n - rc_m]\beta_n^2 - 2b_n(a\varphi - b_m c_m + rc_n)\beta_m\beta_n - \left\{[(1-a)b_m + 2ar]\varphi - \left(b_m b_n - 2r^2\right)c_n - rb_m c_m\right\}\beta_m^2}{\left(b_m{\beta_m}^2 + \beta_n(2r\beta_m + b_n\beta_n)\right)^2}$$

because $a \geq \frac{\beta_n\overline{\varphi} + (b_m\beta_m + r\beta_n)c_m - (r\beta_m + b_n\beta_n)c_n}{(\beta_m + \beta_n)\overline{\varphi}}$ ($\overline{p}_e^* \geq 0$), we obtain:

$$\frac{\partial\overline{p}_e^*}{\partial\beta_m} = \frac{\beta_n[\overline{\varphi} - (b_m - r)c_m - (b_n - r)c_n]}{(\beta_m + \beta_n)\left(b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2\right)} > 0, \frac{\partial\overline{p}_e^*}{\partial\beta_n} = -\frac{\beta_m[\overline{\varphi} - (b_m - r)c_m - (b_n - r)c_n]}{(\beta_m + \beta_n)\left(b_m\beta_m^2 + 2r\beta_m\beta_n + b_n\beta_n^2\right)} < 0$$

This proposition is proven.

Proof of Proposition 4.

The angle θ formed by the constraint lines for calculating the probability of 16 optimal decision adjustment strategies is as follows:

$$\theta_{A1}/\theta_{D1} = arctan\left(\frac{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n}{(r\beta_m + b_n\beta_n)(b_m\beta_m + r\beta_n) - a(1-a)}\right)$$

$$\theta_{A2}/\theta_{D2} = \pi - arctan\left(\frac{b_n\{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n\}}{\beta_m\left(b_m b_n - r^2\right)(r\beta_m + b_n\beta_n) - (1-a)[ab_n + (1-a)r]}\right)$$

$$\theta_{A3}/\theta_{D3} = \pi - arctan\left(\frac{b_m\{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n\}}{\beta_n\left(b_m b_n - r^2\right)(b_m\beta_m + r\beta_n) - a[ar + (1-a)b_m]}\right)$$

$$\theta_{A4}/\theta_{D4} = arctan\left(\frac{\left(b_m b_n - r^2\right)\{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n\}}{\left(b_m b_n - r^2\right)^2\beta_m\beta_n - [ar + (1-a)b_m][ab_n + (1-a)r]}\right)$$

$$\theta_{B1}/\theta_{C1} = \pi - arctan\left(\frac{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n}{(r\beta_m + b_n\beta_n)(b_m\beta_m + r\beta_n) - a(1-a)}\right);$$

$$\theta_{B2}/\theta_{C2} = arctan\left(\frac{b_n\{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n\}}{\beta_m\left(b_m b_n - r^2\right)(r\beta_m + b_n\beta_n) - (1-a)[ab_n + (1-a)r]}\right)$$

$$\theta_{B3}/\theta_{C3} = arctan\left(\frac{b_m\{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n\}}{\beta_n\left(b_m b_n - r^2\right)(b_m\beta_m + r\beta_n) - a[ar + (1-a)b_m]}\right)$$

$$\theta_{B4}/\theta_{C4} = \pi - arctan\left(\frac{(b_m b_n - r^2)\{[ar + (1-a)b_m]\beta_m + [ab_n + (1-a)r]\beta_n\}}{(b_m b_n - r^2)^2\beta_m\beta_n - [ar + (1-a)b_m][ab_n + (1-a)r]}\right)$$

Then, we can obtain that $P(An) = P(Dn)$, $P(Bn) = P(Cn)$; $P(An) + P(Bn) = \frac{1}{2}$, $P(Cn) + P(Dn) = \frac{1}{2}$, $n = 1, 2, 3, 4$. The Proof is complete.

Proof of Proposition 5.

From the Proof of Proposition 4, we can easily find that the probability of $P(\theta_{A2}/\theta_{D2})$ and $P(\theta_{A3}/\theta_{D3})$ is higher than the probability of $P(\theta_{A1}/\theta_{D1})$ and $P(\theta_{A4}/\theta_{D4})$ and that the probability of $P(\theta_{B1}/\theta_{C1})$ and $P(\theta_{B4}/\theta_{C4})$ is higher than the probability of $P(\theta_{B2}/\theta_{C2})$ and $P(\theta_{B3}/\theta_{C3})$.

The impact of the NEV credit coefficient β_n and FV credit coefficient β_m on the probabilities of 16 optimal decision adjustment strategies can be compared based on the size of the derivative. Because the substitution coefficient r is a relatively small value, to simplify this Proof, let $r = 0$, and we find that all of the angles θ of 16 optimal decision adjustment strategies satisfy the following relationship (take the Strategy A1 as an example): $\frac{\partial\theta_{A1}}{\partial\beta_m} - \frac{\partial\theta_{A1}}{\partial\beta_n} = \frac{1}{1+\left(\frac{[ar+(1-a)b_m]\beta_m+[ab_n+(1-a)r]\beta_n}{(r\beta_m+b_n\beta_n)(b_m\beta_m+r\beta_n)-a(1-a)}\right)^2}\cdot\frac{(1-a)[b_n b_m^2\beta_m^2+a^2(b_m+b_n)-ab_m]+ab_m b_n^2\beta_n^2}{[b_m b_n\beta_m\beta_n-a(1-a)]^2} > 0$, the impact of β_m will be higher than the β_n on the probability of 16 optimal decision adjustment strategies. Meanwhile, because the market share of NEVs $(1-a)$ is a small value, $\frac{\partial\theta_{A1}}{\partial\beta_n} = -\frac{1}{1+\left(\frac{[ar+(1-a)b_m]\beta_m+[ab_n+(1-a)r]\beta_n}{(r\beta_m+b_n\beta_n)(b_m\beta_m+r\beta_n)-a(1-a)}\right)^2}\cdot\frac{(1-a)b_n(a^2+b_m^2\beta_m^2)}{[b_m b_n\beta_m\beta_n-a(1-a)]^2}\rightarrow 0$, meaning that the impact of β_n is negligible.

The Proof is complete.

Proof of Proposition 6.

Since the market share of NEVs $(1-a)$ is a small value, let $(1-a)\rightarrow 0$ to simplify the analysis, and we can obtain all the angle θ derivatives based on the Proof of Proposition 4 as follows:

$$\frac{\partial(\theta_{A1}/\theta_{D1})}{\partial r} = -\frac{\beta_n}{1+(b_m\beta_m+r\beta_n)^2} < 0; \frac{\partial(\theta_{A2}/\theta_{D2})}{\partial r} = -\frac{2b_n\beta_m r}{b_n^2+(b_m b_n - r^2)^2\beta_m^2} \approx 0$$

$$\frac{\partial(\theta_{A3}/\theta_{D3})}{\partial r} = \frac{b_m\beta_n\left[b_n(b_m b_n - r^3)\beta_n^2 - b_m\beta_m^2 r^2 - 2r(b_m b_n + r^2)\beta_m\beta_n - b_n - b_m^2 b_n\beta_m^2\right]}{\left(\beta_n^2 r^2 + 2b_m\beta_m\beta_n r + 1 + b_m^2\beta_m^2\right)\left[\beta_n^2 r^4 + \left(1 - 2b_m b_n\beta_n^2\right)r^2 + b_m^2 b_n^2\beta_n^2\right]} \rightarrow \frac{b_m b_n\beta_n^2 - b_m^2\beta_m^2 - 1}{b_m b_n\beta_n\left(b_m^2\beta_m^2+1\right)} > 0$$

$$\frac{\partial(\theta_{A4}/\theta_{D4})}{\partial r} = \frac{2b_n\beta_m r^3 + \beta_n(b_m b_n + r^2)\left[b_n^2 + (b_m b_n - r^2)^2\beta_m^2\right] + 2rb_n(b_m b_n - r^2)^2\beta_m\beta_n^2}{\left[\beta_m^2 r^4 - 2b_m b_n\beta_m^2 r^2 + b_n^2\left(1 + b_m^2\beta_m^2\right)\right]\left[\beta_n^2 r^4 + \left(1 - 2b_m b_n\beta_n^2\right)r^2 + b_m^2 b_n^2\beta_n^2\right]} \rightarrow \frac{1}{b_m b_n\beta_n} \approx 0$$

$$\frac{\partial(\theta_{B1}/\theta_{C1})}{\partial r} = \frac{\beta_n}{1+(b_m\beta_m+r\beta_n)^2} > 0, \frac{\partial(\theta_{B2}/\theta_{C2})}{\partial r} = \frac{2b_n\beta_m r}{b_n^2+(b_m b_n - r^2)^2\beta_m^2} \approx 0$$

$$\frac{\partial(\theta_{B3}/\theta_{C3})}{\partial r} = -\frac{b_m\beta_n\left[b_n(b_m b_n - r^3)\beta_n^2 - b_m\beta_m^2 r^2 - 2r(b_m b_n + r^2)\beta_m\beta_n - b_n - b_m^2 b_n\beta_m^2\right]}{\left(\beta_n^2 r^2 + 2b_m\beta_m\beta_n r + 1 + b_m^2\beta_m^2\right)\left[\beta_n^2 r^4 + \left(1 - 2b_m b_n\beta_n^2\right)r^2 + b_m^2 b_n^2\beta_n^2\right]} \rightarrow \frac{-b_m b_n\beta_n^2 + b_m^2\beta_m^2 + 1}{b_m b_n\beta_n\left(b_m^2\beta_m^2+1\right)} < 0$$

$$\frac{\partial(\theta_{B4}/\theta_{C4})}{\partial r} = -\frac{2b_n\beta_m r^3 + \beta_n(b_m b_n + r^2)\left[b_n^2 + (b_m b_n - r^2)^2\beta_m^2\right] + 2rb_n(b_m b_n - r^2)^2\beta_m\beta_n^2}{\left[\beta_m^2 r^4 - 2b_m b_n\beta_m^2 r^2 + b_n^2\left(1 + b_m^2\beta_m^2\right)\right]\left[\beta_n^2 r^4 + \left(1 - 2b_m b_n\beta_n^2\right)r^2 + b_m^2 b_n^2\beta_n^2\right]} \rightarrow -\frac{1}{b_m b_n\beta_n} \approx 0$$

The larger the derivative is, the greater the impact of r on the angle θ and the probability of the 16 optimal decision adjustment strategies. The Proof is complete.

Appendix B

Constraint lines and their slopes for 16 optimal adjustment strategies.

$$\Delta p_e^{A-line1} = \frac{-(1-a)\delta\varphi - rg_m + b_n g_n}{r\beta_m + b_n\beta_n}, k_{A1} = \frac{-(1-a)}{r\beta_m + b_n\beta_n}$$

$$\Delta p_e^{A-line2} = \frac{a\delta\varphi - b_m g_m + rg_n}{b_m\beta_m + r\beta_n}, k_{A2} = \frac{a}{b_m\beta_m + r\beta_n}$$

$$\Delta p_e^{A-line3} = \frac{[ab_n + (1-a)r]\delta\varphi - \left(b_m b_n - r^2\right)g_m}{\left(b_m b_n - r^2\right)\beta_m}, k_{A3} = \frac{ab_n + (1-a)r}{\left(b_m b_n - r^2\right)\beta_m}$$

$$\Delta p_e^{A-line4} = \frac{-[ar + (1-a)b_m]\delta\varphi + \left(b_m b_n - r^2\right)g_n}{\left(b_m b_n - r^2\right)\beta_n}, k_{A4} = \frac{-[ar + (1-a)b_m]}{\left(b_m b_n - r^2\right)\beta_n}$$

$$\Delta p_e^{B-line1} = \frac{-(1-a)\delta\varphi - rg_m - b_n s_n}{r\beta_m + b_n\beta_n}, k_{B1} = \frac{-(1-a)}{r\beta_m + b_n\beta_n}$$

$$\Delta p_e^{B-line2} = \frac{a\delta\varphi - b_m g_m - rs_n}{b_m\beta_m + r\beta_n}, k_{B2} = \frac{a}{b_m\beta_m + r\beta_n}$$

$$\Delta p_e^{B-line3} = \frac{[ab_n + (1-a)r]\delta\varphi - \left(b_m b_n - r^2\right)g_m}{\left(b_m b_n - r^2\right)\beta_m}, k_{B3} = \frac{ab_n + (1-a)r}{\left(b_m b_n - r^2\right)\beta_m}$$

$$\Delta p_e^{B-line4} = \frac{-[ar + (1-a)b_m]\delta\varphi - \left(b_m b_n - r^2\right)s_n}{\left(b_m b_n - r^2\right)\beta_n}, k_{B4} = \frac{-[ar + (1-a)b_m]}{\left(b_m b_n - r^2\right)\beta_n}$$

$$\Delta p_e^{C-line1} = \frac{-(1-a)\delta\varphi + rs_m + b_n g_n}{r\beta_m + b_n\beta_n}, k_{c1} = \frac{-(1-a)}{r\beta_m + b_n\beta_n}$$

$$\Delta p_e^{C-line2} = \frac{a\delta\varphi + b_m s_m + rg_n}{b_m\beta_m + r\beta_n}, k_{c2} = \frac{a}{b_m\beta_m + r\beta_n},$$

$$\Delta p_e^{C-line3} = \frac{[ab_n + (1-a)r]\delta\varphi + \left(b_m b_n - r^2\right)s_m}{\left(b_m b_n - r^2\right)\beta_m}, k_{c3} = \frac{ab_n + (1-a)r}{\left(b_m b_n - r^2\right)\beta_m}$$

$$\Delta p_e^{C-line4} = \frac{-[ar + (1-a)b_m]\delta\varphi + \left(b_m b_n - r^2\right)g_n}{\left(b_m b_n - r^2\right)\beta_n}, k_{c4} = \frac{-[ar + (1-a)b_m]}{\left(b_m b_n - r^2\right)\beta_n}$$

$$\Delta p_e^{D-line1} = \frac{-(1-a)\delta\varphi + rs_m - b_n s_n}{r\beta_m + b_n\beta_n}, k_{D1} = \frac{-(1-a)}{r\beta_m + b_n\beta_n}$$

$$\Delta p_e^{D-line2} = \frac{a\delta\varphi + b_m s_m - rs_n}{b_m\beta_m + r\beta_n}, k_{D2} = \frac{a}{b_m\beta_m + r\beta_n}$$

$$\Delta p_e^{D-line3} = \frac{[ab_n + (1-a)r]\delta\varphi + \left(b_m b_n - r^2\right)s_m}{\left(b_m b_n - r^2\right)\beta_m}, k_{D3} = \frac{ab_n + (1-a)r}{\left(b_m b_n - r^2\right)\beta_m}$$

$$\Delta p_e^{D-line4} = \frac{-[ar + (1-a)b_m]\delta\varphi - \left(b_m b_n - r^2\right)s_n}{\left(b_m b_n - r^2\right)\beta_n}, k_{D4} = \frac{-[ar + (1-a)b_m]}{\left(b_m b_n - r^2\right)\beta_n}$$

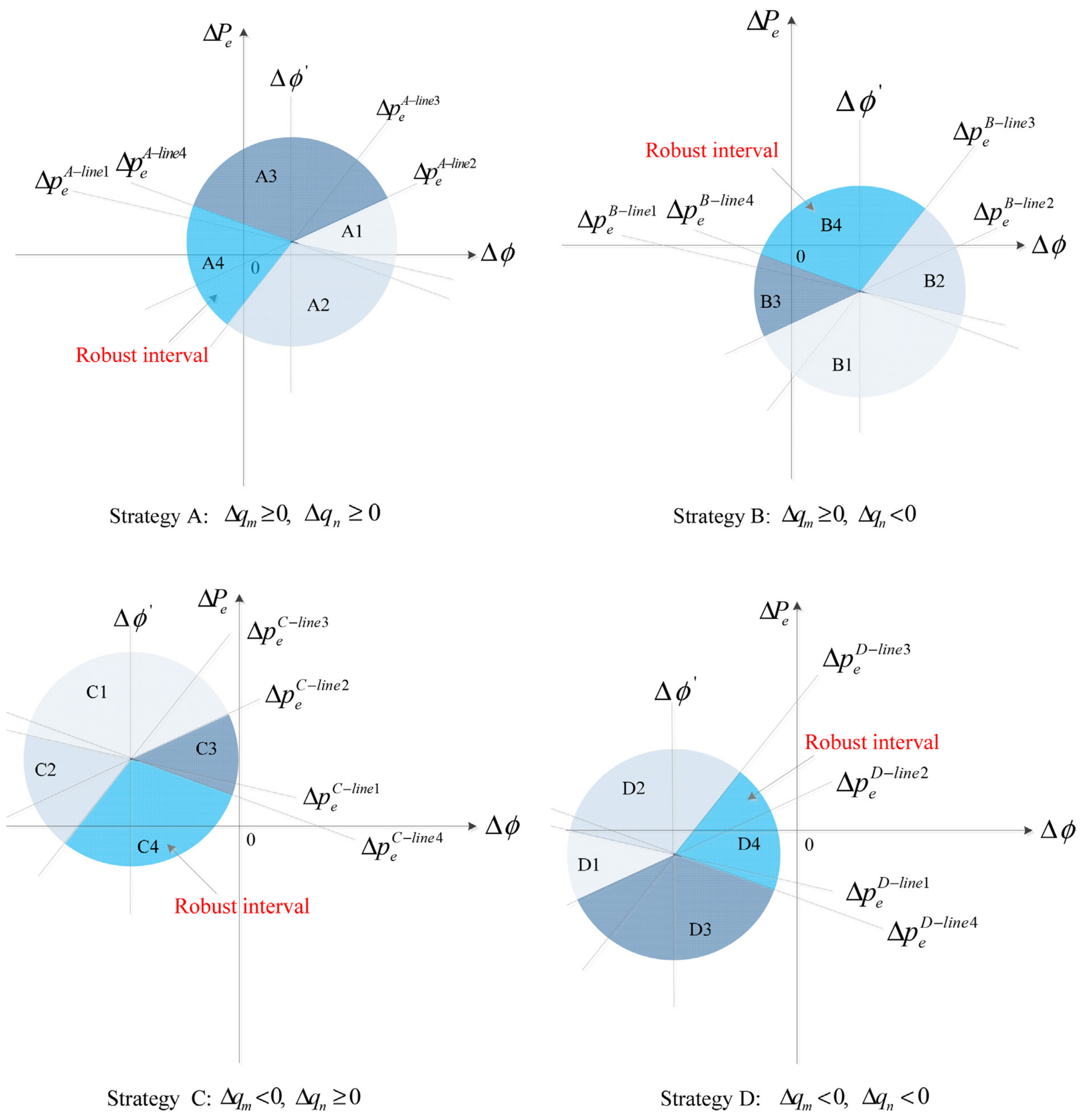

Fig. B1. Optimal adjustment strategies with 16 disruption ranges of demand and credit price.

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