Heliyon 9 (2023) e22719

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Government and dealer regulatory decisions on producer illegal production in China's food supply chain

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ARTICLE INFO

Keywords:
Food safety
Illegal production
Utility-cost ratio
Regulatory intensity
Optimal regulation

ABSTRACT

Illegal food production in China has proliferated in recent years, triggering serious public concerns on food safety. In this work, we model a regulatory event in a food supply chain comprising a local government, a dealer, and a producer involved in illegal food production, and get equilibrium regulatory decisions of the government and the dealer, and equilibrium production decisions of the producer. The results show that: 1) in a situation where the producer is likely to produce illegally, the government does not regulate, and implements insufficient or sufficient regulation according to the utility-cost ratio of regulating. 2) The regulatory decisions of the dealer depend not only on the regulatory decisions of the government but also on the utility-cost ratio of regulating. 3) Only when the joint regulatory intensity of the government and the dealer is not less than a certain threshold value, the producer will not produce illegally, and the threshold value is the optimal regulatory intensity jointly implemented by the government and the dealer. Otherwise it is ineffective, inadequate, or excessive regulation. Therefore, we suggest that the government and the dealer jointly make regulatory decisions to achieve optimal regulation at the lowest regulatory cost and evade illegal food production by the producer.

1. Introduction

On March 15, 2022, "China Central Television 3.15 Gala" (which plays an important role in China's food safety disclosure) exposed the appalling food safety issue of "producing pickled cabbage in soil pits" (I.e., the supplier produced pickled cabbage in soil pits, which is an unsanitary production mode.). Because the producer is the supplier of pickled cabbage used in the best-selling instant noodle, the exposure caused a huge social panic and raised public concerns about food safety. Before this event, a series of food safety incidents emerged one after another [1]. In 2020, China Quality News Network reported that 37,200 cases were administratively punished for food safety in China. Food safety has seriously threatened people's health and life safety. To effectively resolve the food safety problem in China has been listed in the government agenda to comprehensively promote high-quality development of food safety during the 14th Five-year Plan.

Food safety is the direct embodiment of illegal production by food producers. Illegal production by food producers mainly refers to the food production behavior where the producers purposely reduce production costs to seek profit gains by using non-compliant or fake raw materials, relaxing hygiene management, and using food additives in violation of regulations [2]. In practice, food producers

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https://doi.org/10.1016/j.heliyon.2023.e22719
Received 24 February 2023; Received in revised form 15 November 2023; Accepted 16 November 2023
Available online 22 November 2023

may use distribution, direct sales, and other ways to sell, with distribution by dealers being the most common. For instance, in the highly toxic ginger incident [3], ginger planted with highly toxic pesticides entered the market through dealers; in the toxic sea cucumber incident [4], sea cucumber cultured with highly toxic pesticides also entered the market through dealers; in the pickled cabbage in soil pits incident [5], the instant noodle producer is essentially the dealer of the pickled cabbage packet.

Because dealers may bear some responsibility for food safety and may suffer financial or reputational damage from food safety incidents [6], dealers often control the food quality through regulation. Therefore, illegal production by food producers may be subject to regulation not only by the government but also by dealers. In addition, food may also be monitored by consumers, news media, and other social forces, but it is difficult for consumers with limited screening ability to discover food safety problems. News media also publicize food problems after detection by the government, and the governance role of social forces is very limited. Therefore, profit-seeking by some food producers is the root cause of illegal food production, while the regulatory decisions of the government or dealers are important parties to curb their illegal production.

China has enforced laws and regulations to address the illegal food production problem, such as the *Food Safety Law*, the *Food Safety Implementation Regulations*, the *Food Service Food Safety Regulation and Management Measures.* Among them, the *Food Safety Law (revised 2021)* sets a high penalty intensity for illegal production, such as imposing a high fine on the violator according to the value of the food involved. The regulation enacted by local governments includes food safety risk monitoring and assessment, spot check and testing samples, and other means. Local governments are constrained by manpower resources and testing conditions as well as the high cost of regulation. As a result, the governance by local governments is often not strong enough to ensure all food producers operate legally. Despite that local governments continue to formulate and enforce food regulations, it remains a formidable mission to curb the occurrence of endless food safety incidents. After the central government sets the punishment standards, there are some practical issues to tackle which include: 1) how local governments' regulatory decisions affect dealers' regulatory decisions; 2) how joint regulatory intensity of local governments and dealers affects the production decisions of food producers; 3) how much regulatory intensity should local governments and dealers implement to prevent food producers from producing illegally.

Indeed, such illegal production issues by food producers are widely investigated by researchers in three streams, i.e., improving food quality through supply chain management (e.g., Chebolu-subramanian and Gaukler [7]; Li et al. [8]; Wang et al. [9]), implementing food traceability (e.g., Song et al. [10]; Casino et al. [11]; Srivastava and Dashora [12]), and government regulation of food safety (e.g., Zhang et al. [13]; Cao et al. [14]; Chu [15]). However, these studies pay no attention to the regulatory decisions and effectiveness of local governments or food dealers against illegal production by producers in the food supply chain.

We extract the common problem of illegal production by food producers from practice and mainly use game theory to study it by building models, solving equilibrium, and analysing equilibrium. In doing so, we model a game scenario involving a local government, a food dealer, and a food producer. Then, we examine the regulatory decisions of the government and the dealer, and the production decisions of the producer, to provide managerial insights to solve the illegal production by food producers under this situation.

The main contributions of our study are as follows: 1) different from the previous literature on government regulation of food enterprises, we consider from the supply chain perspective that illegal production of the food producer is not only regulated by the government but also by the food dealer. We creatively model the regulatory event involving illegal production in the food supply chain and obtain the equilibrium decisions of the game subject under this situation. 2) Through the model, the motivation for illegal production by food producers is depicted, and the regulatory conditions to evade illegal production by food producers are given, i.e., the joint regulatory intensity of the government and the dealer has to reach a certain threshold value. 3) Our study finds that the regulation may be ineffective or inadequate when the joint regulatory intensity by the government and the dealer is weak. The regulation may be excessive when the joint regulatory intensity is strong. However, there is optimal regulation under certain conditions, and we give the conditions of optimal regulation, ineffective, inadequate, or excessive regulation for the government and the dealer respectively. 4) Our study finds that the government and the food dealer should not blindly reduce the regulatory cost and improve the regulatory intensity, but to grasp the production cost and sales income of different products as far as possible, and implement the optimal regulation accordingly.

The following section summarizes relevant literature and gives our research perspective. The third section describes the illegal production by food producers in the food supply chain and makes basic assumptions for establishing the model. The fourth section analyzes the model of this kind of illegal production. The fifth section is an example analysis. The sixth section provides the conclusions and limitations of this study.

2. Literature review

Solving illegal food production or improving food quality has always been a popular topic for academic researchers. Relevant scholars have carried out in-depth research mainly from three streams: improving food quality through supply chain management; how implementing food traceability; and government regulation of food. We review the existing studies in each stream and point out the differences between the current work and previous works to highlight our contributions.

2.1. Improving food quality through supply chain management

Some scholars have studied how to improve food quality through supply chain management. For example, Chebolu-Subramanian and Gaukler [7] modeled a contamination event in a generic food supply chain comprising suppliers, processing centers, and retailers, and simulated a real-world tomato contamination case to generate further insights. Li et al. [8] developed a mixed-integer nonlinear programming model for analyzing the food supply chain configuration problem, with new building blocks to address the perishability issue in terms of both food loss and quality deterioration. Wang et al. [9,16] proposed a new technology integrating Graphic Evaluation and Review Technique and Bayesian approach, and used this technology in food quality management to explore the tradeoffs among three sustainable metrics which involve quality, time, and carbon emissions in perishable food production. Zheng et al. [17] used panel data to investigate the relationship and mechanism between industrial agglomeration and dairy product quality and safety, and found that industrial agglomeration can significantly improve the quality and safety level of dairy products in China. In Dora et al. [18], a conceptual framework based on Technology Organisation Environment Human theory was used to determine the critical success factors (CSFs) influencing AI adoption in the context of Indian Food Supply Chain (FSC). The results of the study indicated that technology readiness, security, privacy et al. are the most significant CSFs for adopting AI in FSC. To improve the quality of perishable products, Lejarza and Baldea [19] introduced a computationally efficient optimal production and distribution planning framework for perishable products having multiple quality attributes that evolve in time as a function of environmental conditions during shipment and storage. Zhan et al. [20] found the balance between quality improvement and cost consumption from the perspective of perishable food production process, and identified the key quality improvement links. De Oliveira et al. [21] found that reducing the cost of accessing and disseminating information could improve the quality of milk products.

This stream is based on the legal production by food producers, and studies how to improve food quality from the perspectives of optimizing supply chain configuration, improving production links, industrial agglomeration, and adopting new technologies. Yet, such studies provide limited management insights on how to evade illegal production by food producers.

2.2. How to implement food traceability

Food traceability is one effective means to solve food safety problems with growing research attention. For instance, to improve the quality of food safety information disclosure in traceability systems, Song et al. [10] examined the influence of related factors on their internal relations in the process of information disclosure. Casino et al. [11] developed and tested a distributed trustless and secure architecture for the food supply chain to enhance traceability, and presented a food traceability case study from a dairy company to evaluate the feasibility of the proposed approach. Srivastava and Dashora [12] used fuzzy ISM to analyze the key drivers of electronic traceability implementation in agri-food supply chains. The results showed that the key factors were technological level, competitive advantage, coordination, transparency, and management support for electronic traceability. Considering the problem that supplies from suppliers with high traceability can be unavailable for buyers due to information asymmetry, Sun and Wang [22] adopted authentication as a screening tool and found that when the probability of high type is low, buyers can perfectly separate the two types through an authenticated hybrid contract. Kayikci et al. [23] investigated the suitability of blockchain technology in resolving major challenges, such as traceability, trust, and accountability in the food industry. Wang et al. [24] developed an optimization model integrating traceability initiatives with operations factors to achieve desired product quality and minimum impact of product recall in an economic manner. Piramuthu et al. [25] used Radio Frequency Identification (RFID) to solve the traceability of contaminated product recall in perishable food supply networks. Epelbaum and Martinez [26] presented a theoretical framework grounded on the Resources-based view of the firm to determine the strategic impacts of the technological evolution of food traceability systems. They showed that firms gain sustainable competitive advantage by innovating food traceability systems. Feng et al. [27] reviewed the characteristics and functions of blockchain technology and proposed the design framework and application process of a food traceability system based on blockchain. Wu et al. [28] studied how traceability information affects consumers' purchase intention of organic food and found that traceability information positively affects consumers' purchase intention of organic food. Ma et al. [29] used the Stackelberg game to explore the interaction between traceability recall and product safety optimization in the food chain, and found the best food safety investment and product traceability recall strategy.

This stream studies the information disclosure and regulation of food safety from the perspective of food traceability, which can curb illegal production by food producers to a certain degree. However, due to the constraints of food producers' willingness and cost of traceability, the comprehensive implementation of food traceability still encounters great resistance, and the effect of solving illegal production by food producers is limited.

2.3. Government regulation of food

In addition, addressing food safety has always been an important task for the government, and how to improve the efficiency of regulation is also a prioritized research agenda. In studying government regulatory decisions, Zhang et al. [13] examined the factors shaping food firms' intentions to control quality safety in the context of government regulation in China. They found that government regulation has a positive moderating effect on corporate social responsibility and collaboration between organizations in a supply chain. Cao et al. [14] established a one-to-many symmetric game model between the government and food enterprises to discuss the failure of government regulation and the optimal government regulation strategy when the number of food enterprises increases. Chu [15] empirically analysed enforcement strategies that characterize food safety regulations in China. It demonstrated that the export food sector exhibits strong deterrent measures whereas regulation of domestic food markets is reactive and relies on persuasive approaches to enforcement. Song and Zhuang [30] examined a game model between the government and food manufacturers to study how the government balances tax revenue, penalty revenue, and consumer health risks, and verified and illustrated the model with actual data. Wang et al. [31] found that when the willingness of food enterprises or grassroots food regulatory agencies to change their strategies is low, the legal production by food enterprises and the strategies of grassroots food regulatory agencies to strictly regulate are in a pure strategic stable state. Zhang et al. [32] constructed a food safety regulation performance index and utilized an analytic network process-fuzzy comprehensive evaluation model to precisely quantify the performance of government regulation.

This stream of government regulatory decisions mainly focuses on the effect analysis of regulation mode and policy. Although Cao et al. [14], and Song and Zhuang [30] discussed the game between government and food enterprises from the perspective of game theory, they did not reveal the illegal production motivation by food producers, nor did they recommend actions on how the government and dealers should make regulatory decisions.

We establish a game model for typical problems of illegal production by the producer in the food supply chain. This work studies the regulatory decisions of the government and the dealer, which is quite different from the above research in terms of research questions and research methods. To the best of our knowledge, this is the first attempt to study the regulatory decisions of such typical illegal production in the food supply chain, which has certain innovation and practical value.

3. Problem description and basic assumptions

For instance, in the event of "producing pickled cabbage in soil pits" exposed by "China Central Television 3.15 Gala", the pickled cabbage packet, as the key ingredient of a well-known brand of instant noodles, was produced in open soil pits locally. The quality of the pickled cabbage and the sanitary conditions in the production process were extremely poor, and there were extremely serious food safety risks. Although the instant noodle maker is also a food producer, its relationship with the pickled cabbage packet producer is essentially a distribution relationship.

Based on the above facts, we consider that a food producer provides a unit batch of products for a food dealer within the jurisdiction of a local government, and the local government and the food dealer consider regulating the food producer. In practice, regulatory decisions are made by the local government's department of market regulation (GDR). Because our study does not involve other departments of the local government, hereafter, we write GDR as the government for narrative convenience. Similarly, we write the dealer's department of regulation (DDR) as the dealer. In the game between the government, the dealer, and the producer, how the government and the dealer make regulatory decisions and how the producer makes production decisions are the problems to be solved in this study.

If the producer produces legally, the production cost c of a unit batch of products is constant. However, the producer can reduce the cost to γc through illegal production, where $\gamma\left(\underline{\gamma} \leq \gamma \leq 1\right)$ represents the degree of illegal production, and the smaller parameter γ represents the more serious degree of illegal production (similar to the assumption about cutting corners in Chaturvedi [33]). In practice, the degree of illegal production is reflected in the amount of non-compliance or fake raw materials used, the degree of relaxation of hygiene management, the dose of food additives not used in accordance with the regulations, and so on, in a unit batch of products. In addition, there is a certain lower limit for cost reduction through illegal production, i.e., it can only be reduced to $\underline{\gamma} c$, otherwise, production cannot be completed.

As the producer to supply the dealer, the producer is not only regulated by the government but may be regulated by the dealer. The regulatory intensity of the government and the dealer on the producer is η_g and η_d respectively, indicating the scope of regulatory intensity available to the government and the dealer for decision-making within the capacity, $0 \leq \eta_g \leq 1$, $0 \leq \eta_d \leq 1$ (similar to environmental regulation in Li et al. [34]). For subsequent analysis, we assume that the government and the dealer have the same regulatory capacity and effect. In addition, the regulation here is mainly reflected in the frequency of inspection of the production process of a unit batch of products, and the proportion of sample inspection and testing degree of a unit batch of products. We consider that the interval time of inspection frequency in the production period of a unit batch of products tends to be average, and the proportion of sampling inspection and test degree of each inspection tend to be consistent. Notably, during the production period of a unit batch of products, there are situations in which the government does not inspect in a certain period time, but the government frequently announced or unannounced inspections in a certain period time, which makes it impossible to quantify the regulatory intensity. We do not consider such situations.

Based on the above facts, the sequence of illegal production under the regulation of the government and the dealer is shown in Fig. 1: 1) the central government sets punishment standards. For instance, Chinese central government stipulates that when illegal food production is detected, illegal income and the food involved will be confiscated, and the producer will be fined according to the value of the food involved. 2) The government (generally the market regulation department of the township, town, or street office in China) makes targeted decisions on the regulatory intensity of different products, and the regulatory intensity implemented by the government is usually common knowledge for the dealer and the producer. 3) The dealer decides the regulatory intensity according to the government's regulatory intensity. The producer can know the dealer's regulatory intensity, but the government cannot. 4) The producer produces legally before knowing the regulatory intensity of the government and the dealer, and decides whether to produce illegally after knowing. 5) If the illegal production is not detected by the government and the dealer, and the products are consumed by

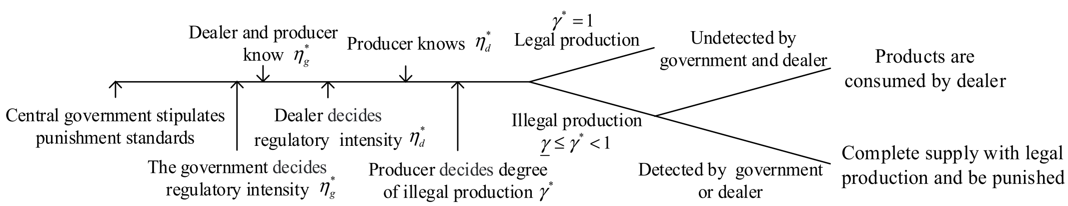

Fig. 1. Sequence of events.

the dealer, the event ends; if the illegal production is detected by the government or the dealer, the products will be confiscated and the producer will be fined by the government. Meanwhile, the producer must produce qualified products to complete the supply.

When illegal production is detected, according to the *Food Safety Law*: food safety regulation departments confiscate illegal income and illegally produced food, and penalize the producer with a fine according to the value of the food involved. Therefore, we assume that the producer has paid the cost $\underline{c}(0 < \underline{c} \leq \gamma c)$ to be detected by the government or the dealer for illegal production, which can indicate the quantity and value of a unit batch of products involved. The government will confiscate the illegal income and illegally produced food, and impose fines on the producer according to the value b of the food involved: ξb, ξ represents the intensity of punishment, according to the *Food Safety Law*, $\xi \geq 1$. ξ is determined by the central government, and it's a fixed constant in our model. Meanwhile, the cost $\underline{c}$ already paid by the producer is not recoverable. If the producer is not detected, this batch of products will be sold with income b.

In addition, we make the following important assumptions:

Assumption 1. The government's maximum regulatory intensity, i.e., $\eta_g = 1$, will ensure that the producer produces legally, i.e., $\gamma = 1$, and the dealer will not regulate, i.e., $\eta_d = 0$. (similar to Li et al. [34])

Assumption 1 is consistent with most situations in practice, but limited by regulatory cost, it is often difficult for the government to regulate all products to the maximum regulatory intensity. Therefore, the government needs to make targeted regulatory decisions. Assumption 1 also means that the joint regulatory intensity between the government and the dealer is: $0 \leq \eta_g + \eta_d \leq 1$, and writing $\eta = \eta_g + \eta_d$. For the convenience of description, we make the following definition:

Definition 1. If $\eta = 0$, it means that the government and the dealer do not regulate the producer; if $0 < \eta < 1$, it means that the joint regulation of the government and the dealer is insufficient regulation; if $\eta = 1$, it means that the joint regulation of the government and the dealer is sufficient regulation.

Sufficient regulation here means that the government (the dealer) can pay within the constraints of human resources, testing equipment, and other capabilities to the maximum regulatory intensity. That is, the government (the dealer) employs all regulatory personnel to implement the regulation of a unit batch of products using the most advanced testing equipment. It should be noted that sufficient regulation does not necessarily mean a full inspection of the batch, and does not guarantee that illegal production by the producer will be detected.

If at least one of the government and the dealer implements regulation (i.e., $\eta \neq 0$), and the producer produces illegally (i.e., $\gamma \neq 1$), the probability of the producer's illegal production being detected $\lambda(\gamma, \eta)$ increases with the degree of illegal production. Because a smaller parameter γ represents a higher degree of illegal production, we have: $\partial\lambda(\gamma,\eta)/\partial\gamma < 0$, $\partial^2\lambda(\gamma,\eta)/\partial\gamma^2 \geq 0$. The probability of being detected λ increases in regulatory intensity η, which satisfies: $\partial\lambda(\gamma,\eta)/\partial\eta > 0$. Therefore, similar to the probability of failure described in previous studies (i.e., Chaturvedi [33], and Mao et al. [35]), without loss of generality, we assume:

Assumption 2. The probability of the producer's illegal production being detected is $\lambda(\gamma, \eta) = 1 - \gamma^\eta$.

It should be pointed out that Assumption 2 has some limitations. Because of the different nature of different foods, the difficulty of regulating illegal production and the effect of regulation implemented by different local governments are different. Therefore, the probability of the producer's illegal production being detected is also different. It is difficult for us to use models to describe these differences. And the focus of this study is a local government's regulatory decisions on a food producer of unit batch products. Therefore, our model can ignore this difference, and such a design can reflect the facts we describe, which can support this study.

Assumption 3. The producer, the government, and the dealer seek to maximize the expected utility.

Assumption 3 means that the producer's illegal production and the degree of illegal production will affect the administrative

Table 1
Definitions of the main symbols involved.

Symbols	Definitions
η_g	The government's regulatory intensity of the producer's unit batch of products, $\eta_g \in [0, 1]$
η_d	The dealer's regulatory intensity of the producer's unit batch of products, $\eta_d \in [0, 1]$
η	The joint regulatory intensity of the government and the dealer, $\eta \in [0, 1]$
γ	The degree of illegal production, where a smaller value represents a higher degree of illegal production, $\gamma \in \left[\underline{\gamma}, 1\right]$
$\underline{\gamma}$	The maximum degree of illegal production, $\underline{\gamma} \in (0, 1)$
ξ	The intensity of punishment set by the central government, $\xi \geq 1$
b	The sales income of a unit batch of products
c	The cost of producing a unit batch of products
$\underline{c}$	The production cost paid by the producer when a unit batch of products produced illegally is detected, $\underline{c} \in (0, \gamma c)$
μ_g	The utility coefficient of a unit batch of products illegally produced by the producer to the government
μ_d	The utility coefficient of a unit batch of products illegally produced by the producer to the dealer
β_g	The government's regulatory cost coefficient of a unit batch of products
β_d	The dealer's regulatory cost coefficient of a unit batch of products

Note: Subscripts g, d and p represent the corresponding symbols of the government, the food dealer, and the food producer respectively.

efficiency of the government (i.e., GDR) and the work efficiency of the dealer (i.e., DDR). The government and the dealer do not take detection and punishment as the purpose of regulation. Constrained by the cost of regulation, they only expect to evade producers' illegal production activities or reduce the degree of illegal production as much as possible through regulation. In other words, the probability of the producer's illegal production being detected does not affect the expected utility of the government or the dealer.

Assumption 4. The dealer does not conspire with the producer for higher profits.

In practice, collusion can be possible if the dealer does not regulate. The dealer in our situation is considering whether to regulate not whether to conspire.

The main symbols and definitions involved in this study are shown in Table 1. The symbols not listed will be explained in the content.

4. Model analysis

As stated in the problem description, consistent with the practice, the government does not know the dealer's regulatory decision before making the decision, and the government will not rely on the regulation of the dealer. In line with the principle of high regulation, the government will make regulatory decisions based on the assumption that the dealer's regulatory intensity was 0. Different from the common dynamic game with incomplete information, this feature is the particularity of government decision-making. Since the asymmetry of this information is not considered in government decision-making in practice, this game is essentially a dynamic game with complete information, and backward induction is adopted to solve the equilibrium.

According to Assumption 3, constrained by the cost of regulation, the government expects to evade the illegal production activities of the producer or reduce the degree of illegal production as much as possible through regulation, which is an administrative responsibility unrelated to whether illegal production is detected or not.

In addition, the government will hand over the fines in accordance with the law, and the government will not carry out regulation for the purpose of fines, nor for the purpose of detection, whether or not the detection will affect the expected utility of decision-making. Therefore, suppose $-\mu_g(\mu_g \geq 0)$ is the utility coefficient of the unit batch of products illegally produced by the producer to the government, which is mainly the loss to the administrative efficiency of the government regulation department. At the same time, regulation will cost labor, testing, and other expenses. Assume that the cost of regulating η_g is $\beta_g\eta_g$, β_g is the unit regulatory cost of the government. Combining Assumption 3, similar to Li et al. [34] describing the expected utility of purchasers to reduce software system failures, the expected utility of the government is:

$$U_g(\eta_g) = -\mu_g(1 - \widetilde{\gamma}) - \beta_g\eta_g \tag{1}$$

Note that since the government does not know the dealer's regulatory intensity η_d, $\widetilde{\gamma}$ in expression (1) is the degree of illegal production by the producer when the government assumes $\eta_d = 0$. Such an assumption ensures that the degree of illegal production by the producer that the government thinks is no less than the true degree of illegal production by the producer, i.e., $\widetilde{\gamma} \leq \gamma$.

Similarly, the regulation department of the dealer also hopes to evade the illegal production activities of the producer or reduce the degree of illegal production as much as possible through regulation, which is also the work responsibility unrelated to whether illegal production is detected or not. $-\mu_d(\mu_d \geq 0)$ is the utility coefficient of the unit batch of products illegally produced by the producer to the dealer, which is mainly the loss to the work efficiency of the dealer regulation department. Similarly, β_d is the unit regulatory cost of the dealer. The expected utility of the dealer is:

$$U_d(\eta_d) = -\mu_d(1 - \gamma) - \beta_d\eta_d \tag{2}$$

Since the government's regulatory decisions are common knowledge, γ in Expression (2) is the true degree of illegal production by the producer.

In this case, if the producer's illegal production is detected by the government or the dealer, the producer not only cannot recover the cost $\underline{c}$ already paid but also needs to pay another cost c to complete the delivery as per the contract. In practice, producers may be removed from the supply relationship by dealers if they are found to be producing illegally, but it is also common to supply again after legal production, and we only consider such case. In addition, the producer will be fined ξb by the government. Therefore, the expected utility of the producer is:

$$E_p(\gamma) = \gamma^{\eta_g+\eta_d}(b - \gamma c) + (1 - \gamma^{\eta_g+\eta_d})(b - c - \underline{c} - \xi b) \tag{3}$$

The first term of expression (3) is the expected utility of the producer if the illegal production is not detected, and the second term is the expected utility of the producer if the illegal production is detected.

Next, we will find the equilibrium solution for the above decision problems. The decision-making sequence is as follows: the government first decides regulatory intensity, the dealer decides regulatory intensity after knowing the government's regulatory intensity, and the producer makes illegal production decisions according to the joint regulatory intensity of the government and the dealer. Since the government is unable to obtain the dealer's regulatory decisions, to better fulfill its regulatory responsibilities, the government will make regulatory decisions based on the assumption that the dealer's regulatory intensity was 0.

In addition, the government will have an in-depth understanding of the production and operations of food producers within the jurisdiction for regulation. So we assume that the government and the dealer have a full understanding of the producer, and c, $\underline{c}$, and b are common knowledge of the government, the dealer, and the producer.

Therefore, according to backward induction, the first-order condition of expression (3) for γ can be obtained:

$$E_p^{'}(\gamma) = -(\eta_g + \eta_d + 1)\gamma^{\eta_g+\eta_d}c + (\eta_g + \eta_d)\gamma^{\eta_g+\eta_d-1}c + (\eta_g + \eta_d)\gamma^{\eta_g+\eta_d-1}\underline{c} + (\eta_g + \eta_d)\gamma^{\eta_g+\eta_d-1}\xi b$$

When $E_p^{'}(\gamma) = 0$, we have:

$$\gamma = \frac{(\eta_g + \eta_d)(c + \underline{c} + \xi b)}{(\eta_g + \eta_d + 1)c} \tag{4}$$

Lemma 1 can be obtained from expression (4).

Lemma 1. In our model, if the government or the dealer implements sufficient regulation (i.e., $\eta_g^* = 1$ and $\eta_d^* = 0$, or $\eta_g^* = 0$ and $\eta_d^* = 1$), or the government and the dealer jointly implement sufficient regulation (i.e., $\eta^* = 1$), the producer will not produce illegally (i.e., $\gamma^* = 1$). At the same time, the government and the dealer jointly implement regulation to meet: $0 \le \eta^* \le 1$.

Lemma 1 verifies Assumption 1 and further explains the rationality of the basic Assumptions.

Although Lemma 1 indicates that if the government or the dealer implements sufficient regulation, or if the government and the dealer jointly implement sufficient regulation, the producer will not produce illegally, however, sufficient regulation can only be implemented under certain conditions. In practice, due to high regulatory cost, it is often difficult to achieve sufficient regulation.

Since the government makes decisions based on $\eta_d = 0$, the expected degree of illegal production by the producer on which the government makes decisions is:

$$\widetilde{\gamma} = \frac{\eta_g(c + \underline{c} + \xi b)}{(\eta_g + 1)c} \tag{5}$$

Substituting expression (5) into expression (1) to obtain:

$$U_g(\eta_g) = -\mu_g\left(1 - \frac{\eta_g(c + \underline{c} + \xi b)}{(\eta_g + 1)c}\right) - \beta_g\eta_g \tag{6}$$

The first-order condition of expression (6) for η_g can be obtained: $U_g^{'}(\eta_g) = \frac{\mu_g(c+\underline{c}+\xi b)}{(\eta_g+1)^2 c} - \beta_g$, let $U_g^{'}(\eta_g) = 0$, i.e., $\mu_g(c + \underline{c} + \xi b) = \beta_g c(\eta_g + 1)^2$, and based on constraint $0 \le \mu_g \le 1$, we have:

Proposition 1. The equilibrium regulatory decisions of the government are:

$$\eta_g^* = \begin{cases} 0, \text{if } \dfrac{\mu_g}{\beta_g} \le \dfrac{c}{c + \underline{c} + \xi b} \\ \sqrt{\dfrac{\mu_g(c + \underline{c} + \xi b)}{c\beta_g}} - 1, \text{if } \dfrac{4c}{c + \underline{c} + \xi b} > \dfrac{\mu_g}{\beta_g} > \dfrac{c}{c + \underline{c} + \xi b} \\ 1, \text{if } \dfrac{\mu_g}{\beta_g} \ge \dfrac{4c}{c + \underline{c} + \xi b} \end{cases} \tag{7}$$

According to Proposition 1, the government takes the utility-cost ratio as the basis for regulatory decisions. When the utility-cost ratio is not greater than a certain threshold value (i.e., $\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$), the government does not regulate. When the utility-cost ratio is not less than another threshold value (i.e., $\frac{\mu_g}{\beta_g} \ge \frac{4c}{c+\underline{c}+\xi b}$), the government implements sufficient regulation. When the utility-cost ratio is in a certain range (i.e., $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$), the government implements insufficient regulation, and the equilibrium regulatory intensity increases with the increase in the utility-cost ratio. Proposition 2 reflects the pertinence of regulation of different products by local governments. The threshold value at which the government implements insufficient or sufficient regulation ($\frac{c}{c+\underline{c}+\xi b}$ or $\frac{4c}{c+\underline{c}+\xi b}$) increases in the cost of producing unit batch of products c, and decreases in the sales revenue of unit batch of products b. Since we assume that c, $\underline{c}$, and b are common knowledge, but in practice c and $\underline{c}$ may be private information of the producer, Proposition 1 also illustrates the importance of the government and the dealer to fully understand the production and operations situation of the producer.

Since the dealer can know the regulatory decision of the government η_g^*, we can substitute η_g^* into expression (4) to obtain:

$$\gamma = \frac{(\eta_g^* + \eta_d)(c + \underline{c} + \xi b)}{(\eta_g^* + \eta_d + 1)c} \tag{8}$$

The dealer makes decisions based on the degree of illegal production by the producer, i.e., expression (8). Substituting expression (8) into expression (2) to obtain:

$$U_d(\eta_d) = -\mu_d\left(1 - \frac{\left(\eta_g^* + \eta_d\right)(c + \underline{c} + \xi b)}{\left(\eta_g^* + \eta_d + 1\right)c}\right) - \beta_d\eta_d \tag{9}$$

The first-order condition of expression (9) for η_d can be obtained: $U_d'(\eta_d) = \frac{\mu_d\left(c+\underline{c}+\xi b\right)}{(\eta_g^*+\eta_d+1)^2 c} - \beta_d$, if $U_d'(\eta_d) = 0$, $\mu_d(c + \underline{c} + \xi b) = \beta_d c(\eta_g^* + \eta_d + 1)^2$, and by the constraint conditions $0 \le \eta_d \le 1$, $0 \le \eta^* \le 1$, we have:

Proposition 2. The equilibrium regulatory decisions of the dealer are :

$$\eta_d^* = \begin{cases} 0, \text{ if } \frac{\mu_g}{\beta_g} \ge \frac{4c}{c+\underline{c}+\xi b}, \text{ or } \frac{\mu_d}{\beta_d} \le \frac{c}{c+\underline{c}+\xi b}, \text{ or } \frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b} \text{ and } \frac{\mu_d}{\beta_d} \le \frac{\mu_g}{\beta_g} \\ \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - 1, \text{ if } \frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b} \text{ and } \frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b} \\ \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - \sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}}, \text{ if } \frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b} \text{ and } \\ \frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b} \text{ and } 0 < \sqrt{\frac{\mu_d}{\beta_d}} - \sqrt{\frac{\mu_g}{\beta_g}} < \sqrt{\frac{c}{c+\underline{c}+\xi b}} \\ 1, \text{ if } \frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b} \text{ and } \frac{\mu_d}{\beta_d} \ge \frac{4c}{c+\underline{c}+\xi b} \end{cases} \tag{10}$$

According to Proposition 2, the regulatory decision of the dealer depends not only on the regulatory decision of the government but also on the utility-cost ratio of regulating. Specifically, when the government does not regulate, the dealer does not regulate, implements insufficient or sufficient regulation depending on the utility-cost ratio. When the government implements insufficient

Table 2
The equilibrium regulatory decisions of the government and the dealer.

(a) The equilibrium regulatory decisions η^*

η_g^* / η_d^*	0	$\sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}} - 1$	1
0	0 (I)	$\sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}} - 1$ (II)	1 (III)
$\sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - 1$	$\sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - 1$ (IV)	/	/
$\sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - \sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}}$	/	$\sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - 1$ (V)	/
1	1 (VI)	/	/

(b) Conditions corresponding to equilibrium regulatory decisions η^*

Cases	Conditions
I	$\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \le \frac{c}{c+\underline{c}+\xi b}$
II	$\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \le \frac{\mu_g}{\beta_g}$
III	$\frac{\mu_g}{\beta_g} \ge \frac{4c}{c+\underline{c}+\xi b}$
IV	$\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$ and $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b}$
V	$\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b}$ and $0 < \sqrt{\frac{\mu_d}{\beta_d}} - \sqrt{\frac{\mu_g}{\beta_g}} < \sqrt{\frac{c}{c+\underline{c}+\xi b}}$
VI	$\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \ge \frac{4c}{c+\underline{c}+\xi b}$

Note:
I: Both the government and the dealer do not regulate.
II: The government implements insufficient regulation, the dealer does not regulate.
III: The government implements sufficient regulation, the dealer does not regulate.
IV: The government does not regulate, the dealer implements insufficient regulation.
V: Both the government and the dealer implement insufficient regulation.
VI: The government does not regulate, the dealer implements sufficient regulation.

regulation, the dealer will implement insufficient regulation only when the dealer's utility-cost ratio is higher than the government's utility-cost ratio, otherwise, the dealer will not regulate. When the government implements sufficient regulation, the dealer does not regulate. Corollary 1 can be obtained from Propositions 1 and 2:

Corollary 1. The equilibrium regulatory decisions of the government and the dealer are shown in Table 2:

Corollary 1 shows that the government, as the leader in regulating illegal production, will make decisions on no regulation, insufficient or sufficient regulation depending on the utility-cost ratio. For the dealer, 1) when the government does not regulate, i.e., $\eta_g^* = 0$, the dealer's regulatory decisions depend on the utility-cost ratio, i.e., if $\frac{\mu_d}{\beta_d} \le \frac{c}{c+\underline{c}+\xi b}$, the dealer does not regulate, $\eta_d^* = 0$; if $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b}$, the dealer implements insufficient regulation, $\eta_d^* = \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - 1$; if $\frac{\mu_d}{\beta_d} \ge \frac{4c}{c+\underline{c}+\xi b}$, the dealer implements sufficient regulation, $\eta_d^* = 1$. 2) When the government implements insufficient regulation, i.e., $\eta_g^* = \sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}} - 1$, the dealer's regulatory decisions also depend on the utility-cost ratio, i.e., if $\frac{\mu_d}{\beta_d} \le \frac{\mu_g}{\beta_g}$, the dealer does not regulate, $\eta_d^* = 0$; if $0 < \sqrt{\frac{\mu_d}{\beta_d}} - \sqrt{\frac{\mu_g}{\beta_g}} < \sqrt{\frac{c}{c+\underline{c}+\xi b}}$, the dealer implements insufficient regulation, $\eta_d^* = \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - \sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}}$. 3) When the government implements sufficient regulation, i.e., $\eta_g^* = 1$, the dealer does not regulate whatever its utility-cost ratio is, $\eta_d^* = 0$.

Substituting expression (10) into expression (8), we have Proposition 3.

Proposition 3. 1) In the following four situations, the illegal production decision of the producer: $\gamma^* = \underline{\gamma}$.

(1) If $\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \le \frac{c}{c+\underline{c}+\xi b}$, the government and the dealer do not regulate.

(2) If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \le \frac{\mu_g}{\beta_g}$ and $\frac{\mu_g}{\beta_g} \le \frac{c(c+\underline{c}+\xi b)}{(c+\underline{c}+\xi b-c\underline{r})^2}$, only the government regulates, but its regulatory intensity is small.

(3) If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_g}{\beta_g} \le \frac{c(c+\underline{c}+\xi b)}{(c+\underline{c}+\xi b-c\underline{r})^2}$, only the dealer regulates, but its regulatory intensity is small.

(4) If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $0 < \sqrt{\frac{\mu_d}{\beta_d}} - \sqrt{\frac{\mu_g}{\beta_g}} < \sqrt{\frac{c}{c+\underline{c}+\xi b}}$ and $\frac{\mu_g}{\beta_g} \le \frac{c(c+\underline{c}+\xi b)}{(c+\underline{c}+\xi b-c\underline{r})^2}$, both the government and the dealer regulate but the joint regulatory intensity is small.

2) If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \le \frac{\mu_g}{\beta_g}$ and $\frac{c(c+\underline{c}+\xi b)}{(c+\underline{c}+\xi b-c\underline{r})^2} < \frac{\mu_g}{\beta_g} < \frac{c(c+\underline{c}+\xi b)}{(\underline{c}+\xi b)^2}$, only the government regulates and its regulatory intensity is in a certain range, the illegal production decision of the producer: $\gamma^* = \frac{c+\underline{c}+\xi b}{c} - \sqrt{\frac{\beta_g(c+\underline{c}+\xi b)}{\mu_g c}}$.

3) In the following two situations, the illegal production decision of the producer: $\gamma^* = \frac{c+\underline{c}+\xi b}{c} - \sqrt{\frac{\beta_d(c+\underline{c}+\xi b)}{\mu_d c}}$.

(1) If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$ and $\frac{c(c+\underline{c}+\xi b)}{(c+\underline{c}+\xi b-c\underline{r})^2} < \frac{\mu_d}{\beta_d} < \frac{c(c+\underline{c}+\xi b)}{(\underline{c}+\xi b)^2}$, only the dealer regulates and its regulatory intensity is in a certain range.

(2) If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $0 < \sqrt{\frac{\mu_d}{\beta_d}} - \sqrt{\frac{\mu_g}{\beta_g}} < \sqrt{\frac{c}{c+\underline{c}+\xi b}}$ and $\frac{c(c+\underline{c}+\xi b)}{(c+\underline{c}+\xi b-c\underline{r})^2} < \frac{\mu_d}{\beta_d} < \frac{c(c+\underline{c}+\xi b)}{(\underline{c}+\xi b)^2}$, both the government and the dealer regulate, and the joint regulatory intensity is in a certain range.

4) In the following three situations, the illegal production decision of the producer: $\gamma^* = 1$.

(1) If $\frac{\mu_g}{\beta_g} \ge \frac{4c}{c+\underline{c}+\xi b}$, the government implements sufficient regulation.

(2) If $\frac{\mu_d}{\beta_d} \ge \frac{4c}{c+\underline{c}+\xi b}$ and $\frac{\mu_g}{\beta_g} \le \frac{c}{c+\underline{c}+\xi b}$, the government does not regulate, but the dealer implements sufficient regulation.

(3) If $\frac{c}{c+\underline{c}+\xi b} < \frac{\mu_g}{\beta_g} < \frac{4c}{c+\underline{c}+\xi b}$ and $0 < \sqrt{\frac{\mu_d}{\beta_d}} - \sqrt{\frac{\mu_g}{\beta_g}} < \sqrt{\frac{c}{c+\underline{c}+\xi b}}$ and $\frac{\mu_d}{\beta_d} > \frac{c(c+\underline{c}+\xi b)}{(\underline{c}+\xi b)^2}$, both the government and the dealer regulate, and the joint regulatory intensity is large.

We know the intensity of punishment ξ is determined by the central government, and it's a fixed constant in our model. According to Proposition 3, under the regulation of the government, if ξ set by the central government is large enough (i.e., $\xi \ge \frac{4c\beta_g}{b\mu_g} - \frac{c}{b} - \frac{\underline{c}}{b}$), the government can always implement sufficient regulation and the producer can always produce legally. However, the central government needs to consider a variety of factors in determining the intensity of punishment. In addition, different local governments have different utility-cost ratios of regulation. It is often difficult for each local government to implement sufficient regulation by the uniform intensity of punishment, and it is not feasible to only increase the intensity of punishment.

Since then, to describe the regulation effect, we make the following definition:

Definition 2. The regulation cannot reduce the degree of illegal production by the producer, which is called ineffective regulation. The regulation can reduce the degree of illegal production by the producer but cannot evade illegal production, which is called inadequate regulation. The regulatory intensity is the minimum regulatory intensity that can make the producer produce legally, which is called optimal regulation. The regulatory intensity corresponding to optimal regulation is the optimal regulatory intensity.

The regulatory intensity is greater than the minimum regulatory intensity that can make the producer produce legally, i.e., greater than the optimal regulatory intensity, which is called excessive regulation.

When the joint equilibrium regulatory intensity is the optimal regulatory intensity, it is a perfect regulation state, i.e., the regulation can just make the producer produce legally. In other words, if the equilibrium regulatory intensity is less than the optimal regulatory intensity, the producer will still produce illegally. If the equilibrium regulatory intensity is greater than the optimal regulatory intensity, although the producer can produce legally, it will increase the regulatory cost. After that, we will give the expression of optimal regulatory intensity and corresponding conditions to provide theoretical support for the government and the dealer to make regulatory decisions.

Corollaries 2 and 3 follow from Proposition 3.

Corollary 2. If the joint regulatory intensity is $\eta^* \le \frac{\gamma c}{c+\underline{c}+\xi b-\underline{\gamma} c}$, the producer will produce illegally to the maximum degree possible, $\gamma^* = \underline{\gamma}$; If the joint regulatory intensity is in a certain range, $\frac{\gamma c}{c+\underline{c}+\xi b-\underline{\gamma} c} < \eta^* < \frac{c}{\underline{c}+\xi b}$, the degree of illegal production is $\underline{\gamma} < \gamma^* < 1$; If the joint regulatory intensity is $\eta^* \ge \frac{c}{\underline{c}+\xi b}$, the producer will not produce illegally, $\gamma^* = 1$.

According to Corollary 3, if the joint regulatory intensity is not greater than a certain threshold value, $\eta^* \le \frac{\gamma c}{c+\underline{c}+\xi b-\underline{\gamma} c}$, the producer will not reduce the level of illegal production because of regulation, $\gamma^* = \underline{\gamma}$, the regulation is ineffective regulation. With the increase of joint regulatory intensity, i.e., $\frac{\gamma c}{c+\underline{c}+\xi b-\underline{\gamma} c} < \eta^* < \frac{c}{\underline{c}+\xi b}$, the degree of illegal production decreases in joint regulatory intensity, $\underline{\gamma} < \gamma^* < 1$, the regulation is inadequate regulation. If the joint regulatory intensity is $\eta^* = \frac{c}{\underline{c}+\xi b}$, it just makes the producer produce legally, and the regulation is optimal regulation. If the joint regulatory intensity is $\eta^* > \frac{c}{\underline{c}+\xi b}$, the joint regulatory intensity allows the producer to produce legally, but the regulation is excessive, and the regulation is excessive regulation.

Corollary 3 can be obtained from the above analysis.

Corollary 3. The optimal regulatory intensity is $\eta^{**} = \frac{c}{\underline{c}+\xi b}$.

In practice, as a follower, the dealer's regulatory decisions depend on the government's regulatory decisions, so joint regulation may be ineffective, inadequate, or excessive, i.e., $\eta^* \le \frac{\gamma c}{c+\underline{c}+\xi b-\underline{\gamma} c}$, $\frac{\gamma c}{c+\underline{c}+\xi b-\underline{\gamma} c} < \eta^* < \frac{c}{\underline{c}+\xi b}$ and $\eta^* > \frac{c}{\underline{c}+\xi b}$, thus affecting the regulation efficiency. Only if the joint equilibrium regulatory intensity is $\eta^* = \frac{c}{\underline{c}+\xi b}$, is there optimal regulation. At this point, the regulation just makes the producer produce legally at the lowest regulatory cost. However, in practice, the government or the dealer is limited by regulatory cost, and the government cannot know the dealer's regulatory decisions, so it is difficult to achieve optimal regulation when the government and the dealer jointly implement regulation. In this case, it is necessary for the government and the dealer to share information and jointly make regulatory decisions, to evade ineffective, inadequate, or excessive regulation.

5. Example analysis

In this section, we will demonstrate relevant conclusions through numerical examples.

Similar to the example analysis of literature, without loss of generality, we set $b = 4$, $c = 3$, $\underline{c} = 0.5$, $\xi = 1$, $\underline{\gamma} = 0.4$ in Figs. 2–5. When $\mu_g = 1$, $0.5 \le \beta_g \le 2.6$, the effect of the government's utility-cost ratio of regulating on its regulatory intensity is simulated, as shown in Fig. 2.

As shown in Fig. 2, if the utility-cost ratio is small, i.e., $\mu_g/\beta_g \le 0.4$, the government does not regulate. If the utility-cost ratio is large, i.e., $\mu_g/\beta_g \ge 1.6$, the government implements sufficient regulation. If the utility-cost ratio is between the two threshold values, i.e.,

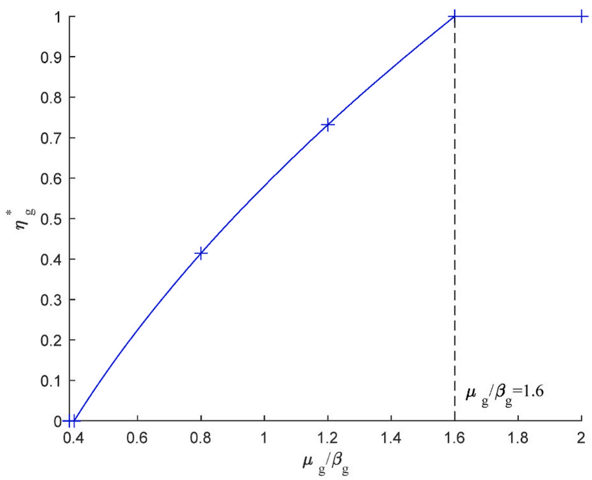

Fig. 2. The effect of the government's utility-cost ratio on its regulatory intensity.

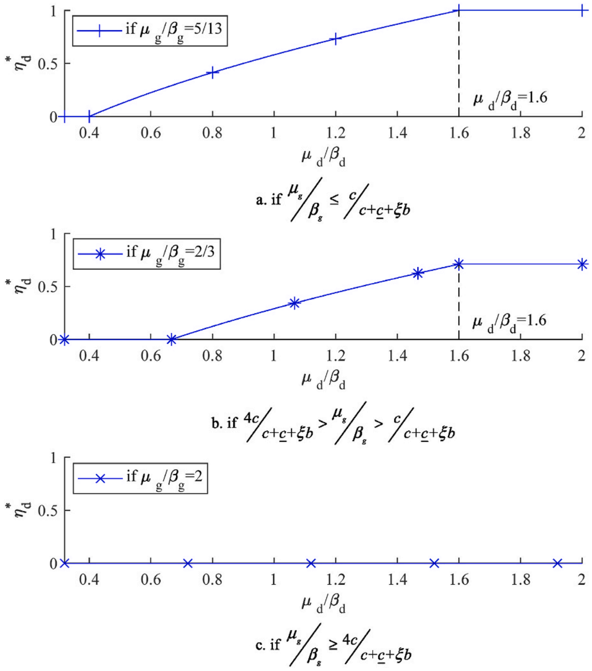

Fig. 3. The effect of the dealer's utility-cost ratio on its regulatory intensity.

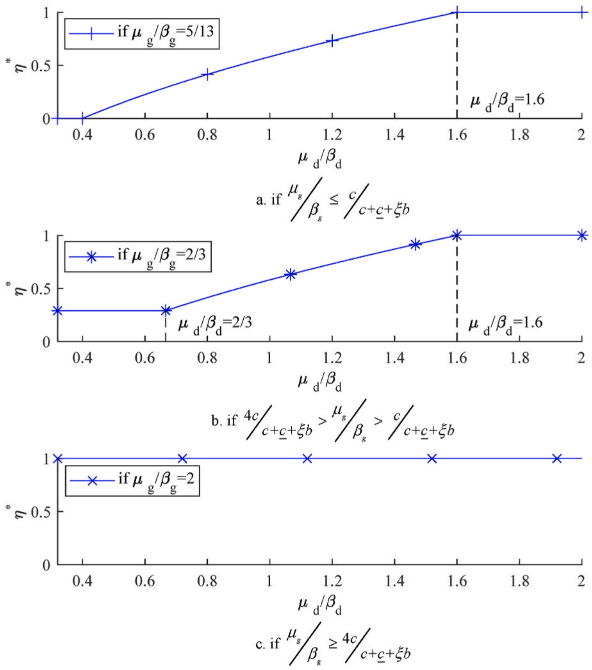

Fig. 4. The effects of the dealer's utility-cost ratio on joint regulatory intensity.

$0.4 < \mu_g/\beta_g < 1.6$, the government implements insufficient regulation, and equilibrium regulatory decisions increase in the utility-cost ratio.

When $\mu_g = 1$, $\beta_g = 0.5$ or 1.5 or 2.6, $\mu_d = 0.8$, $0.4 \leq \beta_d \leq 2.5$, the effects of the dealer's utility-cost ratio on its regulatory intensity, joint regulatory intensity, and the producer's illegal production decisions are respectively simulated, as shown in Figs. 3–5.

As shown in Figs. 3 and 1) when $\mu_g/\beta_g = 2$, $\eta_g^* = 1$, the government implements sufficient regulation, and the dealer does not regulate, $\eta_d^* = 0$. 2) When $\mu_g/\beta_g = 2/3$, $\eta_g^* = \sqrt{5/3} - 1$, the government implements sufficient regulation, whether or not the dealer

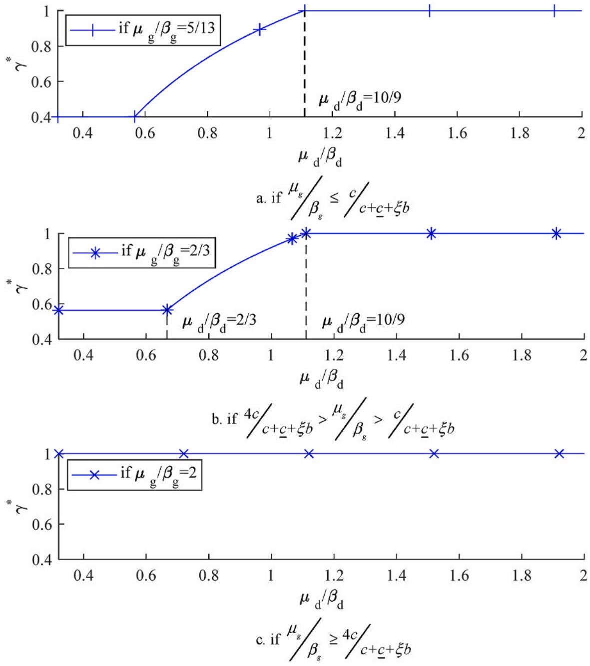

Fig. 5. The effects of the dealer's utility-cost ratio on the producer's illegal production decisions.

implements regulation depends on the utility-cost ratio: if $\mu_g/\beta_g \leq 2/3$, the dealer does not regulate, $\eta_d^* = 0$; if $2/3 < \mu_d/\beta_d < 1.6$, the dealer implements insufficient regulation, $0 < \eta_d^* < 2 - \sqrt{5/3}$, joint regulatory intensity $\sqrt{5/3} - 1 < \eta^* < 1$; if $\mu_d/\beta_d \geq 1.6$, the dealer also implements insufficient regulation, $\eta_d^* = 2 - \sqrt{5/3}$, but joint regulatory intensity $\eta^* = 1$, and the joint regulation is sufficient regulation. 3) When $\mu_g/\beta_g = 5/13$, $\eta_g^* = 0$, the government does not regulate, whether or not the dealer implements regulation depends on the utility-cost ratio: if $\mu_d/\beta_d \leq 0.4$, the dealer does not regulate, $\eta_d^* = 0$; if $0.4 < \mu_d/\beta_d < 1.6$, and the dealer implements insufficient regulation, $0 < \eta_p{}^* < 1$; if $\mu_d/\beta_d \geq 1.6$, the dealer implements sufficient regulation, $\eta_d^* = 1$. Fig. 3 intuitively shows that the equilibrium regulatory decision of the dealer depends not only on its cost-utility ratio but also on the regulatory decision of the government.

As shown in Figs. 4 and 1) when $\mu_g/\beta_g = 2$, $\eta_g^* = 1$, the government implements sufficient regulation, the dealer does not regulate, and joint regulatory intensity is $\eta^* = 1$. 2) When $\mu_g/\beta_g = 2/3$, $\eta_g^* = \sqrt{5/3} - 1$, the government implements insufficient regulation, whether or not the dealer implements regulation depends on the utility-cost ratio: if $\mu_d/\beta_d \leq 2/3$, the dealer does not regulate, $\eta^* = \sqrt{5/3} - 1$; if $2/3 < \mu_d/\beta_d < 1.6$, the dealer implements insufficient regulation, $\sqrt{5/3} - 1 < \eta^* < 1$; if $\mu_d/\beta_d \geq 1.6$, the dealer implements insufficient regulation, but joint regulatory intensity is $\eta^* = 1$. 3) When $\mu_g/\beta_g = 5/13$, $\eta_g^* = 0$, the government does not regulate, whether or not the dealer implements regulation depends on the utility-cost ratio: if $\mu_d/\beta_d \leq 0.4$, the dealer does not regulate, $\eta^* = 0$; if $0.4 < \mu_d/\beta_d < 1.6$, the dealer implements insufficient regulation, $0 < \eta^* < 1$; if $\mu_d/\beta_d \geq 1.6$, the dealer implements sufficient regulation, $\eta^* = 1$.

Combined with Corollary 3, we can know that the optimal regulatory intensity jointly implemented by the government and the dealer is: $\eta^{**} = 2/3$. As shown in Fig. 4, in the example we set, only when $\eta_g^* = \sqrt{5/3} - 1$ and $\eta_d^* = 5/3 - \sqrt{5/3}$, or $\eta_g^* = 0$ and $\eta_d^* = 2/3$, is the joint equilibrium regulatory intensity is the optimal regulatory intensity, i.e., the optimal regulation, otherwise, it is ineffective, inadequate, and excessive regulation.

As shown in Fig. 5, when $\mu_g/\beta_g = 0.5$, the government implements sufficient regulation, the dealer does not regulate, $\eta^* = 1$, the producer does not produce illegally, $\gamma^* = 1$. It is excessive regulation.

When $\mu_g/\beta_g = 2/3$, the government implements insufficient regulation, and whether or not the dealer implements regulation depends on the utility-cost ratio: if $2 \geq \mu_d/\beta_d \geq 1.6$, the dealer implements insufficient regulation, and the joint regulation of the government and the dealer is sufficient regulation, $\eta^* = 1$, the producer does not produce illegally, $\gamma^* = 1$, but it is excessive regulation. If $1.6 > \mu_d/\beta_d > 10/9$, both the government and the dealer implement insufficient regulation, but $\eta^* > 2/3$, the producer does not produce illegally, $\gamma^* = 1$, but it is also excessive regulation. If $\mu_d/\beta_d = 10/9$, both the government and the dealer implement insufficient regulation, but $\eta^* = 2/3$, the producer does not produce illegally, $\gamma^* = 1$, it is optimal regulation. If $10/9 > \mu_d/\beta_d > 2/3$, both the government and the dealer implement insufficient regulation, $2/3 > \eta^* > \sqrt{5/3} - 1$, the producer produces illegally, $1 > \gamma^* > 2.5 - \sqrt{15}/2$, it is inadequate regulation. If $2/3 > \mu_d/\beta_d \geq 0.32$, only the government implements insufficient regulation, $\eta^* = \sqrt{5/3} - 1$, the producer produces illegally, $\gamma^* = 2.5 - \sqrt{15}/2$, it is inadequate regulation.

When $\mu_g/\beta_g = 5/13$, the government does not regulate, and joint regulatory intensity depends on the dealer's utility-cost ratio: if

$2 \geq \mu_d/\beta_d \geq 1.6$, the dealer implements sufficient regulation, $\eta^* = 1$, the producer does not produce illegally, $\gamma^* = 1$, it is excessive regulation. If $1.6 > \mu_d/\beta_d > 10/9$, the dealer implements insufficient regulation, $\eta^* > 2/3$, the producer does not produce illegally, $\gamma^* = 1$, it is excessive regulation. If $\mu_d/\beta_d = 10/9$, the dealer implements insufficient regulation, $\eta^* = 2/3$, the producer does not produce illegally, $\gamma^* = 1$, it is optimal regulation. If $10/9 > \mu_d/\beta_d \geq 250/441$, the dealer implements insufficient regulation, but $2/3 > \eta^* > 0$, the producer produces illegally, $1 > {\gamma_s}^* > 0.4$, it is inadequate regulation. If $250/441 > \mu_d/\beta_d > 0.4$, the dealer implements insufficient regulation, $\eta^* = 0$, the producer produces illegally to the maximum degree, $\gamma^* = 0.4$, it is ineffective regulation. If $0.4 > \mu_d/\beta_d \geq 0.32$, the dealer does not regulate, $\eta^* = 0$, the producer produces illegally to the maximum degree, $\gamma^* = 0.4$.

We set $b = 3$,3.5 or 4, $c = 3 \in [1, 3]$, $\underline{c} = 0.5$, $\xi = 1$ in Fig. 6. When $b = 3$,3.5 or 4, the effects of production cost on optimal regulatory intensity at different sales income is simulated, as shown in Fig. 6.

As shown in Fig. 6, the optimal regulatory intensity increases with production cost and decreases with sales income. This reflects the fact that when implementing regulation, the government should target optimal regulation for food products with different production costs or sales incomes.

6. Conclusion and implications

6.1. Research conclusions

To solve the problem of illegal production by food producers in China, we model a game involving a local government, a food dealer and a food producer, and get the equilibrium regulatory decisions of the government and the dealer, and the equilibrium production decisions of the producer.

Illegal production by the producer is regulated not only by the government but also by the dealer. In our model, the government's regulatory decisions depend on its utility-cost ratio of regulation. When the utility-cost ratio is not greater than a certain threshold value, the government does not regulate. When the utility-cost ratio is not less than another certain threshold value, the government implements sufficient regulation. When the utility-cost ratio is in the two threshold value ranges, the government implements insufficient regulation, and the equilibrium regulatory intensity increases in its utility-cost ratio.

When the joint regulatory intensity of the government and the dealer is not higher than a certain threshold value, the producer will not reduce the degree of illegal production because of regulation, which is ineffective regulation. With the increase of joint regulatory intensity within a certain range, the degree of illegal production by the producer decreases with the joint regulatory intensity, which is inadequate regulation. When the joint regulatory intensity is not less than a certain threshold value, it just leads the producer to produce legally, which is optimal regulation, and the regulatory intensity corresponding to optimal regulation is the optimal regulatory intensity. Since then, when the joint regulation is greater than optimal regulatory intensity, the joint regulation can lead the producer to produce legally, but it is excessive regulation.

6.2. Research implications

Summarizing management insights, we give the expression of the optimal regulatory intensity. When the joint regulation implemented by the government and the dealer is optimal regulation, the producer can produce legally with the lowest regulatory cost. However, in practice, the government or the dealer is restrained by regulatory cost, and the government cannot know the dealer's regulatory decisions, so it is difficult to achieve optimal regulation when the government and the dealer jointly implement regulation. In this case, it is necessary for the government and the dealer to share information and jointly make regulatory decisions, to evade ineffective, inadequate, or excessive regulation. In addition, the government and the food dealer should not blindly reduce the

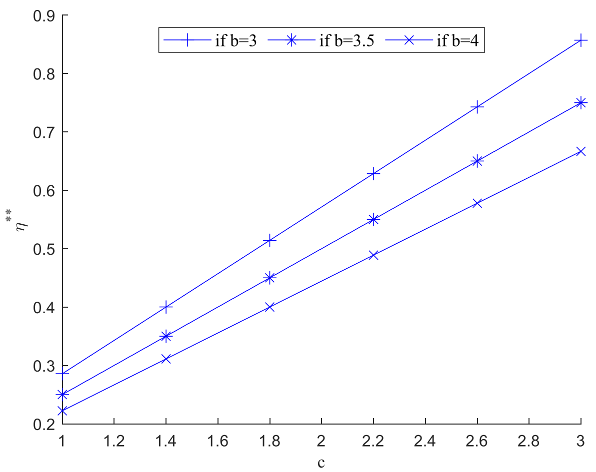

Fig. 6. The effects of production cost on optimal regulatory intensity at different sales income.

regulatory cost and improve the regulatory intensity, but to grasp the production cost and sales income of different products as far as possible, and implement the optimal regulation accordingly.

6.3. Limitations and future directions

Notably, our model does not reflect the difficulty of detection of different foods and the difference in the effects of different local governments' regulation when describing the probability of being detected, which suffers certain limitations to interpret the study results. Furthermore, we assume that the government and the dealer have a good understanding of the producer. The government and the dealer know the production cost and sales income of a unit batch of products, to decide the regulatory intensity. In practice, it is not difficult to obtain the sales income of a unit batch of products, but it may be difficult to accurately obtain the production cost of a unit batch of products, which is another limitation of the model. In addition, we do not consider situations where the regulatory intensity cannot be quantified during the production period of the unit batch of products. These limitations illustrate the complexity of regulating illegal production by food producers which are promising directions to extend this line of research.

Ethics statement

The authors of this article declare their commitment and adherence to all the provisions of the ethical statement Journal of Heliyon. We want to make it clear that we didn't use human or animal samples in our research, so we didn't have required a special permit. And the authors announced that the Journal of Heliyon has permission to publish this article.

Funding

This research is supported by the National Natural Science Foundation of China (71871150), Innovative Research Project of Sichuan University (2021CXC22), PolyU, Hong Kong, China Business School of The Hong Kong Polytechnic University, Hong Kong, China (P0040888).

Data availability statement

Data included in article/supp. Material/referenced in article.

CRediT authorship contribution statement

Dong Cai: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Kee-hung Lai:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Chun-xiang Guo:** Validation, Supervision, Software, Resources, Project administration, Conceptualization.

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.

Appendix

Proof of Lemma 1. :

If the constraint condition is not considered, when $\eta^* = 1$, $\gamma^* = \frac{c+\underline{c}+\xi b}{2c}$, and due to the constraint conditions $\xi \geq 1$, $\gamma \leq 1$, we have $\gamma^* = 1$, i.e., the producer will not produce illegally. Furthermore, as a follower, the dealer observes that if $\eta_g^* = 1$, then $\eta_d^* = 0$; if $0 \leq \eta_g^* < 1$, then $0 \leq \eta_d^* \leq 1 - \eta_g^*$. Therefore, the government and the dealer jointly implement regulation to meet: $0 \leq \eta^* \leq 1$.

Q.E.D.

Proof of Proposition 1. :

Based on the above analysis, it can be obtained from $\mu_g(c + \underline{c} + \xi b) = \beta_g c(\eta_g + 1)^2$:

$$\eta_g = \sqrt{\frac{\mu_g(c + \underline{c} + \xi b)}{c\beta_g}} - 1$$

According to the constraint conditions $0 \leq \eta_g \leq 1$, if $\frac{\mu_g}{\beta_g} \leq \frac{c}{c+\underline{c}+\xi b}$, $\eta_g^* = 0$; if $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$, $\eta_g^* = \sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}} - 1$; if $\frac{\mu_g}{\beta_g} \geq \frac{4c}{c+\underline{c}+\xi b}$, $\eta_g^* = 1$. So we have Proposition 1.

Q.E.D.

Proof of Proposition 2. :

We are divided into the following cases to discuss: 1) if $\frac{\mu_g}{\beta_g} \geq \frac{4c}{c+\underline{c}+\xi b}$, the government implements sufficient regulation, the dealer does not regulate. If $\frac{\mu_d}{\beta_d} \leq \frac{c}{c+\underline{c}+\xi b}$, whether the government regulates or not, the dealer does not. If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$, the government implements insufficient regulation, $\eta_g^* = \sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}} - 1$, and from $\mu_d(c+\underline{c}+\xi b) = \beta_d c(\eta_g^* + \eta_d+1)^2$, we have $\eta_g^* + \eta_d = \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{\beta_d c}} - 1$, and then we consider the constraint conditions $0 \leq \eta_d \leq 1$, $0 \leq \eta^* \leq 1$: if $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_g}{\beta_g} \geq \frac{\mu_p}{\beta_p}$, $\eta_d^* = 0$, i.e., the dealer does not regulate. In sum, if $\frac{\mu_g}{\beta_g} \geq \frac{4c}{c+\underline{c}+\xi b}$, or $\frac{\mu_d}{\beta_d} \leq \frac{c}{c+\underline{c}+\xi b}$, or $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \leq \frac{\mu_g}{\beta_g}$, so $\eta_d^* = 0$.

2) If $\frac{\mu_g}{\beta_g} \leq \frac{c}{c+\underline{c}+\xi b}$, the government does not regulate, when $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b}$, the dealer implements insufficient regulation, $\eta_d^* = \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - 1$. Therefore, $\frac{\mu_g}{\beta_g} \leq \frac{c}{c+\underline{c}+\xi b}$, $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b}$, so $\eta_d^* = \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}} - 1$.

3) If $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$, the government implements insufficient regulation, $\eta_g^* = \sqrt{\frac{\mu_g(c+\underline{c}+\xi b)}{c\beta_g}} - 1$, $\eta_d = \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{\beta_d c}} - \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}}$, and then we consider the constraint conditions $0 \leq \eta \leq 1$, $0 \leq \eta^* \leq 1$: if $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_g}{\beta_g} > \frac{c}{c+\underline{c}+\xi b}$ and $\frac{4c}{c+\underline{c}+\xi b} > \frac{\mu_d}{\beta_d} > \frac{c}{c+\underline{c}+\xi b}$ and $0 < \sqrt{\frac{\mu_d}{\beta_d}} - \sqrt{\frac{\mu_g}{\beta_g}} < \sqrt{\frac{c}{c+\underline{c}+\xi b}}$, so $\eta_d^* = \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{\beta_d c}} - \sqrt{\frac{\mu_d(c+\underline{c}+\xi b)}{c\beta_d}}$.

4) If $\frac{\mu_g}{\beta_g} \leq \frac{c}{c+\underline{c}+\xi b}$ and $\frac{\mu_d}{\beta_d} \geq \frac{4c}{c+\underline{c}+\xi b}$, the government does not regulate, the dealer implements sufficient regulation, $\boldsymbol{\eta}_d^* = 1$.

In sum, we have Proposition 2.
Q.E.D.

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