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Regulating food risk management—a government–manufacturer game facing endogenous consumer demand

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Abstract

In the food industry, manufacturers may add some chemical additives to augment the appearance or taste of food. This may increase the food demand and sales profits, but may also cause health problems to consumers. The government could use a punishment policy to regulate and deter such risky behavior but could also benefit from economic prosperity and tax income based on their revenues. This generates a tradeoff for the government to balance tax income, punishment income, and health risks. Adapting to government regulations, the manufacturers choose the level of chemical additives, which impacts the consumer demand. To our knowledge, no prior work has studied the strategic interactions of regulating the government and the manufacturers, faced with strategic customers. This paper fills this gap by (a) building a government-manufacturer model and comparing the corresponding decentralized and centralized models; and (b) applying the 2008 Sanlu food contamination data to validate and illustrate the models.

Keywords: supply chain management; risk analysis; game theory; production

1. Introduction

There has been a significant growing literature focusing on health and safety in the food industry. Fearne and Hughes (1999) provide several success factors for the United Kingdom's fresh produce industry, including continuous investment, good staff, volume growth, improvement of measurement, control of costs, and innovation. Patil and Frey (2004) apply and compare different sensitivity analysis methods to assess food safety with complex models and recommend robust-independent methods. Roth et al. (2008) develop the "Six T's" (traceability, transparency, testability, time, trust, and

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training) of supply chain quality management, which are critical to preserve public welfare through a safe food supply. Food may contain a significant amount of chemical additives that could be added during the production, transportation, and storage stages throughout the food industry. On one hand, potential benefits of using food additives include preservation, provision of vitamins or minerals, and enhancement of the food texture, appearance, and flavors. Liu (2003) points out that additive and synergistic combinations of phytochemicals are good for health. On the other hand, Watt and Marcus (1980) point out that undegraded carrageenan as a food additive is harmful for users.

1.1. Food incidents and regulations

There have been several food contamination incidents in recent years. For example, in 2007, some dog food and cat food brands (including *Americas Choice*, *Preferred Pet,* and *Authority*) were recalled due to contamination of using a food additive called "wheat gluten" (US Food and Drug Administration, 2008), where veterinary organizations reported more than 100 pet deaths among nearly 500 cases of kidney failure (Associated Press, 2007). In 2008, the Chinese *Sanlu* company adulterated industrial chemical melamine into milk powder, which killed at least six infants due to kidney stones and damaged the kidneys of 300,000 infants (Branigan, 2008). In 2011, a chemical additive, 2-ethylhexyl phthalate (DEHP), was detected in the products of 47 Taiwan companies of food and drinks, which could cause some growth problems in children (Galarpe, 2011). In 2011, 150,000 tons of feed for chickens, turkey, and swine were contaminated with the cancer-causing additive called dioxin, which was added by the German company, *Harles and Jentzsch* (Spiegel Online, 2011).

The above-mentioned food incidents indicate potential problems on regulating the producers' and manufacturers' risky behaviors. These problems may include (a) lack of regulations and punishments in some developing countries, such as China (Ming, 2006); and (b) lack of resources for the government to enforce regulations (Ellis and Turner, 2010).

Researchers have suggested various forms of the government regulations, for better managing the (food) supply chain risks. These include (a) the imposition of liability for damages (Segerson, 1999); (b) the joint use of liability and safety regulation (Shavell, 1984); (c) fines and corrective taxes (Kambhu, 1990); (d) a higher inspection accuracy and stronger enforcement (Oh, 1995; Cheung and Zhuang, 2012); (e) transferring safety failure costs from the government to manufacturers (Chen, 2009); and (f) transferring costs and benefits from the government to manufacturers using penalty contracts (Hobbs and Kerr, 1999). This paper focuses on the government punishment strategies, while other types of regulation could be studied in future works.

1.2. Adding chemicals/additives in food industry

Figure 1 illustrates a general food industry process, where raw materials are initially raised by farmers. The food is then transported by the distributors to the manufacturers for processing, and are eventually sold to and used by the consumers. This paper focuses on the risky behavior of the manufacturers. During the process, chemical additives could be added by the farmers and manufacturers. For example, the farmers could use chemicals to irrigate crops, or add hormone in the fodder to foster animal growth. The manufacturers could use whitening/antistaling/dyeing agents to better preserve food and enhance appearance. Farmers and manufacturers may overuse

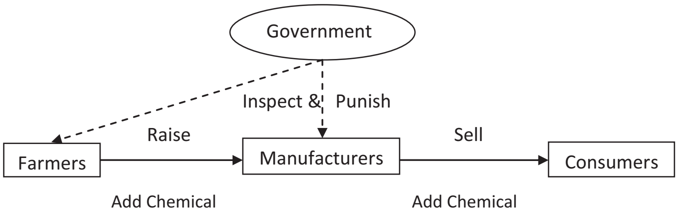


Fig. 1. Food industry with chemicals and regulating the government.

preservatives and antistaling agents to improve the product's appearance or delay the decomposition process. Finally, the consumers could get sick from consuming the contaminated food. At each stage of the food industry, the government could inspect (regulate) and punish (fine) each agent (e.g., farmers and manufacturers). Such government administrations include the US Food and Drug Administration, European Food Safety Authority, and Chinese Institute of Food Safety Control and Inspection.

1.3. *The manufacturer's motivation for using chemicals*

This paper considers that the chemicals are added by manufacturers. With the chemical additives, the food looks fresher and more beautiful, which increases sales profit and thus provides an incentive for the manufacturers to use food additives even though they could be risky (Harrington, 2011). Inspection and punishment could prevent the manufacturers from adding excessive or illegal chemical additives. Figure 2 shows an influence diagram of the manufacturers' decision making on how much chemical additives to be added. There are two chance nodes: one is potential sickness that directly affects the penalty cost, and another is the government's inspection and punishment that affects the manufacturers' decisions. The manufacturers' choices determine penalty cost, chemical cost, and sales profit; and these intermediate values eventually jointly determine the net profit values.

1.4. *The government's motivation for using punishment policy*

On one hand, the government prefers economic prosperity and more tax income (based on the manufacturer's sales revenue that may increase with chemical level). We acknowledge that the

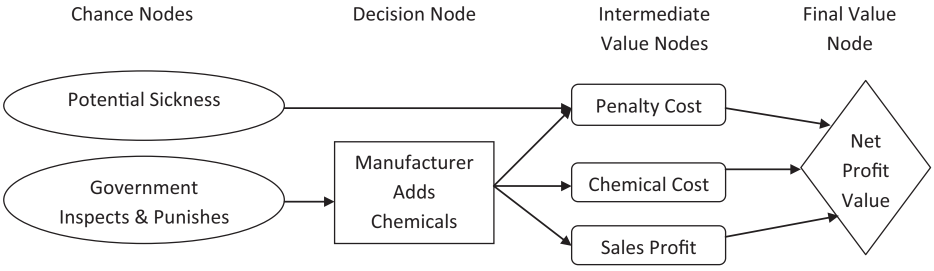


Fig. 2. Influence diagram for the manufacturer's decision on adding chemicals.

government may not directly maximize tax income; however, spending tax income is critical for the government to improve the welfare of the country, including health improvement for its citizens. On the other hand, once consumers fall sick after consuming the contaminated food, the government is liable to treat and compensate those victims. This generates a tradeoff for the government to determine how to punish the manufacturers' risky behavior of adding chemicals. Once the government punishment policy is set up, the manufacturers can observe it and respond by deciding the level of chemical additives. The government would like to consider such potential response strategies of the manufacturers while deciding its own punishment policy.

Figure 3 shows an influence diagram of the government's decision making on how to punish the manufacturers. There are two chance nodes of the manufacturer's chemical level and probability of sickness—both affecting the intermediate values including tax income, penalty income, and health cost. The government's decision impacts penalty income. Intermediate values jointly determine the government's net payoff.

1.5. Literature, contribution, and structure of this work

The study of strategic interactions between the companies and regulating government is not new in the literature. For example, Caswell and Johnson (1991) study firms' strategic responses to food safety and nutrition regulation. Henson and Caswell (1999) discover that the firms' compliance to the government regulation depends on the expected economic benefits and costs. Fares and Rouviere (2010) discover that the company's decision of using additives depends on its own costs (e.g., food spoilage and risks) and benefits (e.g., productivity enhancement), with or without facing government regulation. Caswell (1998) measures the companies' benefits and costs for improving food quality and safety in quality management systems. From the government's perspective, Frey et al. (2003) conduct sensitivity analyses for the government to identify the critical factors in food safety process. Bakshi and Gans (2010) analyze a strategic interaction between US Bureau of Customs and Border Protection, trading firms, and terrorists in a game theoretical model for containerized supply chain risk management.

Although there exist significant strategic interactions between players, to our knowledge, few studies consider endogenous consumer demand in a government–manufacturer game in the context of food safety. This paper fills the gap by analyzing how the government regulates and deters the manufacturers' risky behavior dealing with strategic customers and endogenous demand. In particular, we consider the scenario in which the government moves first by announcing punishment

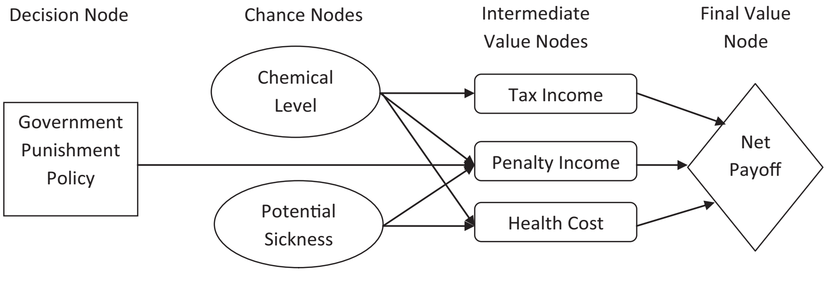


Fig. 3. Influence diagram for the government's decisions on setting punishment policies.

policies, balancing punishment, tax income, and health risk. In the first scenario, the manufacturer observes this punishment information and chooses the level of chemical additives, balancing the expected punishment cost, sales revenue, and chemical cost.

The remainder of this paper is organized as follows. Section 2 describes optimization problems for a government–manufacturer model, provides the best responses for the manufacturer and optimal solution for the government punishment policy with numerical illustration, and compares the equilibrium payoffs and strategies between the centralized and decentralized models. A decentralized government versus manufacturer (*GvM*) model and a centralized government/manufacturer (*GM*) model are introduced in Sections 2 and 2.5, respectively. Section 3 describes the Sanlu case and compares the results of two models. Section 4 summarizes this paper and provides some future research directions. Appendix provides the proofs for the propositions.

2. A *GvM* model

A decentralized GvM model is introduced in this section, where the government and manufacturer are modeled as two separate parties, and the strategic interaction between them is analyzed.

2.1. Notation, assumptions, and sequence of moves

Table 1 lists the notation that is used throughout this paper, including two decision variables (chemical level x and punishment level β), four functions (customer demand $Q(x)$, sickness probability $H(x)$, the government's utility $U_G(x, \beta)$, and the manufacturer's utility $U_M(x, \beta)$), and nine parameters (unit chemical cost p_m, coefficient of health cost c, tax rate γ, basic demand Q_0, slope for customer demand q, unit food price P, slope for probability of sickness λ, the protein amount required in milk powder x_p, and unit protein price p_p).

Table 1
Notation and explanation

Decision variables	$\beta \geq 0$	Level of punishment per sick customer set by the government
	x	Level of chemical additives
Functions	$Q(x) \geq 0$	Consumer demand
	$H(x) \in [0, 1]$	Probability of sickness
	$U_G(x, \beta)$	The government's utility function
	$U_M(x, \beta)$	The manufacturer's utility function
Parameters	$p_m \geq 0$	Unit chemical cost
	$[x^-, x^+]$	Chemical level lower bound x^- and upper bound x^+
	$c \geq 0$	Coefficient of health cost per number of sickness people
	$\gamma \in [0, 1]$	Tax rate
	$Q_0 > 0$	Baseline demand for $Q(X)$
	$q \geq 0$	Slope for $Q(X)$
	$P \geq 0$	Unit food price
	$\lambda \geq 0$	Slope for $H(x)$
	$x_p \geq 0$	The amount of raw material required for production
	$p_p \geq 0$	Unit raw material price

Stackelberg competition, an economics strategic game, is where a first, "leader" firm makes a decision and provides the first move of the game. A second, "follower" firm moves sequentially based on the leader firm's action. Figure 4 illustrates the sequence of moves between the government and manufacturer in a Stackelberg game setting. In particular, the government moves first by announcing the punishment level β and the amount of penalty in case that a sickness incident happens. The manufacturer observes β and then chooses the level of chemical additives x, which is between the bounds x^- and x^+ and affects the customer's sickness probability $H(x)$. We normalize the bounds of chemical additives to between 0 and 1 and apply this normalization throughout the remainder of this paper for analysis. Potential customers adapt to x by aggregately determining the food demand $Q(x)$. Both the government and manufacturer are assumed to be rational and maximize their expected payoffs U_G and U_M, respectively.

We assume that consumer demand $Q(x)$ as a function of the chemical level x in Equation (1) has the following properties:

$$Q(x) = Q_0 + qx, \ \forall x \in [x^-, x^+] \tag{1}$$

$$Q(0) = Q_0; \qquad Q'(x) \geq 0. \tag{2}$$

Figure 5a shows $Q(x)$ as a linear function $Q''(x) = 0$, where Q_0 is the basic sales demand without chemical and q is the slope for the additional sales amount with chemical; that is, the higher q is, the faster $Q(x)$ increases.

Similarly, we assume that the probability of sickness $H(x)$ as a function of chemical level x has the following properties:

$$H(x) \in [0, 1]; \qquad H'(x) \geq 0; \qquad H''(x) \leq 0, \tag{3}$$

where the higher the chemical level x, the higher is the probability of sickness. We use parameter λ to model the slope of $H(x)$. Figure 5b shows $H(x)$ as a linear function in Equation (4); the higher λ is, the faster $H(x)$ increases.

$$H(x) = \lambda x. \tag{4}$$

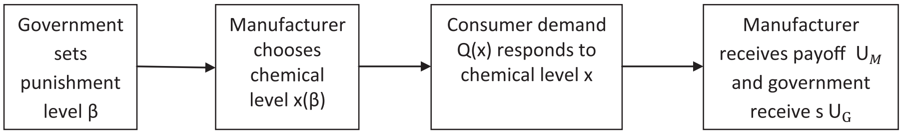
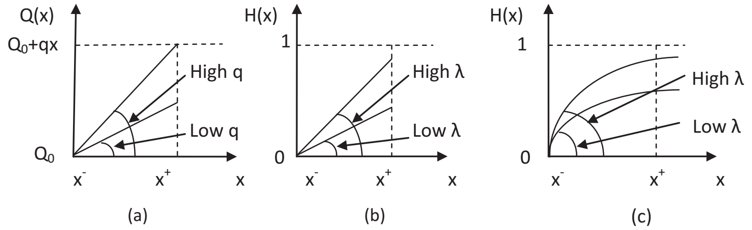


Fig. 4. Sequence of moves for the *GvM* model.



(a) (b) (c)

Fig. 5. Illustration of functions $Q(x)$ and $H(x)$.

2.2. The manufacturer's and government's optimization problems and definition of equilibrium

In this section, we assume that the chemical x provides productivity enhancement, where a manufacturer can substitute chemical x with lower cost p_m for part of the original production material x_p with higher cost p_p. Therefore, the chemical is the substitute for production raw material, where x_p has negative relationship with x. We assume that the manufacturer chooses the chemical additives level x to maximize his expected payoff shown in Equation (5) that consists of four items: (a) total sales revenue $PQ(x)$, (b) total production cost including chemical cost $p_m x Q_x$ and production cost $p_p x_p Q_x$, (c) expected punishment cost $\beta Q(x)H(x)$, and (d) tax cost $\gamma PQ(x)$.

$$\max_{x\in[x^-,x^+]} U_M(x,\beta) = \underbrace{PQ(x)}_{\text{Sales Revenue}} - \underbrace{p_m x Q(x)}_{\text{Chemical Cost}} - \underbrace{p_p x_p Q(x)}_{\text{Production Cost}} - \underbrace{\beta Q(x)H(x)}_{\text{Punishment Cost}} - \underbrace{\gamma PQ(x)}_{\text{Tax Cost}}. \tag{5}$$

One of the government's roles is to supervise and regulate the firms/manufacturers in case of any risky behavior in food industry by setting punishment policy for the sake of public health. Another role of the government is, in order to maintain a stable and healthy economic growth and employment rate, the government will not put too much economic burden to discourage firms'/manufacturers' development. On the other hand, tax income through the firms'/manufacturers' sales revenue and punishment income are the fiscal income used for fiscal expenditure such as social welfare expenditure–public medical service. Therefore, based on the tradeoff of the government, we assume that the government chooses the punishment level β to maximize his expected payoff shown in Equation (6) that consists of three items: (a) expected health cost (public health expenditure) $cQ(x)H(x)$, (b) punishment income $\beta Q(x)H(x)$, and (c) tax income $\gamma PQ(x)$.

$$\max_{\beta\geq 0} U_G(x,\beta) = -\underbrace{cQ(x)H(x)}_{\text{Health Cost}} + \underbrace{\beta Q(x)H(x)}_{\text{Punishment Income}} + \underbrace{\gamma PQ(x)}_{\text{Tax Income}}. \tag{6}$$

Definition 1. *We call a strategy pair (x^*, β^*) a subgame-perfect Nash equilibrium, or "equilibrium" for the GvM model, if and only if both Equations* (7) *and* (8) *are satisfied:*

$$x^* = \hat{x}(\beta^*) \tag{7}$$

$$\beta^* = \operatorname*{argmax}_{\beta\geq 0} U_G(\hat{x}(\beta), \beta), \tag{8}$$

where the manufacturer's best response is defined to be

$$\hat{x}(\beta) \equiv \operatorname*{argmax}_{x\in[x^-,x^+]} U_M(x,\beta),\ \forall\beta \geq 0. \tag{9}$$

2.3. Solution

In this section, we analyze the manufacturer's best response and the government's optimal regulating policy.

Proposition 1. *Under some technical second-order condition $Q(x)H''(x) + 2Q'(x)H'(x) \geq 0$, the solution to the manufacturer's optimization problem* (9) *is given by*

$$\hat{x}(\beta) = \begin{cases} x^- & \text{if } \left.\dfrac{\partial U_M(x,\beta)}{\partial x}\right|_{x=x^-} \leq 0 \\ x^+ & \text{if } \left.\dfrac{\partial U_M(x,\beta)}{\partial x}\right|_{x=x^+} \geq 0 \\ \left\{x : \dfrac{\partial U_M(x,\beta)}{\partial x} = 0\right\} & \text{if } \left.\dfrac{\partial U_M(x,\beta)}{\partial x}\right|_{x=x^-} > 0 > \left.\dfrac{\partial U_M(x,\beta)}{\partial x}\right|_{x=x^+} \end{cases}, \tag{10}$$

where $\frac{\partial U_M(x,\beta)}{\partial x} = (1-\gamma)PQ'(x) - \beta H'(x)Q(x) - \beta H(x)Q'(x) - p_m x Q'_x - p_m Q(x) - p_p x_p Q'(x)$ *is the marginal payoff for the manufacturer. We also have* $\frac{\mathrm{d}\hat{x}}{\mathrm{d}\beta} \leq 0$.

Remark. Proposition 1 shows that there exist three types of optimal chemical levels: (a) when the marginal payoff is negative at $x = x^-$, the manufacturer uses a lower chemical bound x^-; (b) the manufacturer sets the chemical additives at an intermediate level, such that the marginal benefit equals the marginal cost; and (c) when the marginal payoff is positive at $x = x^+$, the manufacturer takes the highest possible chemical level x^+. In addition, the manufacturer's chemical level decreases (weakly) with the government punishment level.

The government's optimal punishment policy is analyzed in Proposition 2.

Proposition 2. *The optimal strategy for the government is as follows:*

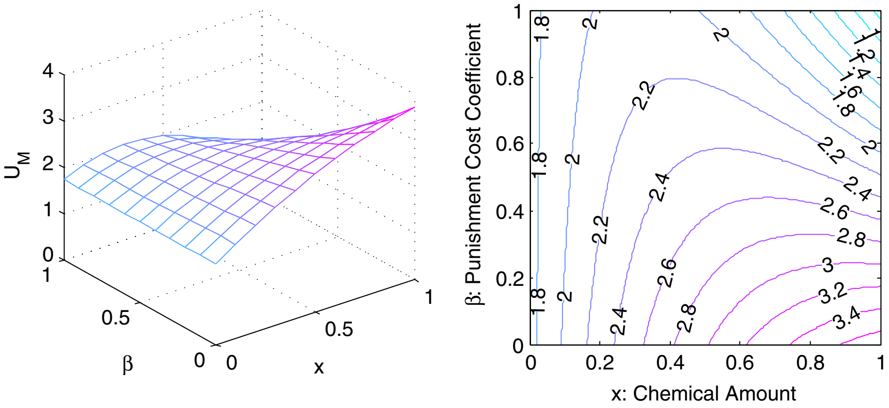
$$\beta = \begin{cases} 0 & \text{if } \left.\dfrac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta}\right|_{\beta=0} < 0 \\ \left\{\beta : \dfrac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta} = 0\right\} & \text{if } \left.\dfrac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta}\right|_{\beta=0} \geq 0, \end{cases} \tag{11}$$

where $\frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta} = \frac{\partial U_G}{\partial \beta} + \frac{\partial U_G}{\partial x}\frac{\mathrm{d}\hat{x}(\beta)}{\mathrm{d}\beta}$ *is the total marginal payoff for the government.*

Remark. Proposition 2 indicates that when the total marginal payoff for the government $\frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta}$ is positive at $\beta = 0$, the optimal punishment is such that the marginal payoff equals the marginal cost, otherwise the optimal punishment is 0.

2.4. Solution and illustration when $H(x) = \lambda x$ and $Q(x) = Q_0 + qx$

This section uses specific linear $Q(x)$ and $H(x)$ functions introduced in Equations (1) and (4) for studying and illustrating equilibrium solutions.



(a) Manufacturer Payoff (3D) (b) Manufacturer Payoff (Contour)

Fig. 6. The manufacturer's payoffs as functions of strategies x and β, using baseline values $\gamma = 0.1$, $P = 2$, $Q_0 = 1$, $q = 2$, $c = 1$, $p_m = 0.5$, $\lambda = 0.1$, $x_p = 0.1$, $p_p = 0.6$, $x^- = 0$, and $x^+ = 1$.

2.4.1. The manufacturer's best response

Inserting Equations (1) and (4) into Equation (5), the manufacturer's optimization problem becomes

$$\max_{x \in [x^-, x^+]} U_M(x, \beta) = (P(1-\gamma) - p_p x_p)Q_0 + ((1-\gamma)Pq - p_m Q_0 - \beta\lambda Q_0 - p_p x_p q)x - (\beta\lambda + p_m)qx^2. \tag{12}$$

Figure 6 illustrates how the combination of chemical and punishment levels affect the manufacturers' payoff, using the baseline values $\gamma = 0.1$, $P = 2$, $Q_0 = 1$, $q = 2$, $c = 1$, $p_m = 0.5$, $\lambda = 0.1$, $x_p = 0.1$, $p_p = 0.6$, $x^- = 0$, and $x^+ = 1$. We observe that the manufacturer's payoff increases in chemical amount x when punishment level β is low but decreases in x when β is high. The manufacturer's payoff also decreases in punishment level β, which means that the punishment level should not be too high in order to maintain the manufacturer's payoff.

Applying Proposition 1, with the bounds $x^- = 0$ and $x^+ = 1$, the solution to the manufacturer's optimization problem (12) becomes

$$\hat{x}(\beta) = \begin{cases} 0 & \text{if } \beta \geq \beta_A \\ \dfrac{Pq - \gamma Pq - p_m Q_0 - \beta\lambda Q_0 - p_p x_p q}{2\beta\lambda q + 2p_m q} & \text{if } \beta_C < \beta < \beta_A \\ 1 & \text{if } \beta \leq \beta_C, \end{cases} \tag{13}$$

where the two thresholds for β are defined as $\beta_A \equiv \frac{Pq - \gamma Pq - p_m Q_0 - p_p x_p q}{\lambda Q_0}$ and $\beta_C \equiv \frac{Pq - \gamma Pq - p_m Q_0 - p_p x_p q - 2p_m q}{\lambda Q_0 + 2\lambda q}$, and we have $\beta_A \geq \beta_C \geq 0$ if $Pq - \gamma Pq - p_m Q_0 - p_p x_p q \geq 0$ or $\beta_A \leq \beta_C \leq 0$ if $Pq - \gamma Pq - p_m Q_0 - p_p x_p q - 2p_m q \leq 0$. The second-order condition holds since $\frac{\partial^2 U_M(x,\beta)}{\partial x^2} = -2\beta\lambda q - 2p_m q \leq 0$. We also verify that the manufacturer's optimal chemical amount decreases in punishment because $\frac{\mathrm{d}\hat{x}}{\mathrm{d}\beta} = -\frac{\lambda Q_0(\beta\lambda q + p_m q) + \lambda q(Pq - \gamma Pq - p_m Q_0 - \beta\lambda Q_0 - p_p x_p q)}{2(\lambda c q + p_m q)^2} \leq 0$, when $\beta_C < \beta < \beta_A$ and $\frac{\mathrm{d}\hat{x}}{\mathrm{d}\beta} = 0$ otherwise.

This paper only concerns a company's risky behavior for short-term benefit in a nontransparent supply chain. With the increasing transparency in the food industry and the consumers' food safety concerns, the demand could decrease if the chemical level increases, which means $q < 0$. In this case, based on Equation (13), we have $\beta_A < 0$. Since the punishment level $\beta \geq 0 > \beta_A$, we always have $\hat{x} = 0$. This indicates that in the long run, as the consumer's health-related concern rises and the transparency in food industry increases, the company would not add chemicals with or without punishment policy.

Figure 7 shows how the government's punishment β affects the value of chemical level x, using the same baseline values as in Fig. 6. In particular, when the food price P is low ($P = 0.3$), Fig. 7a shows that the optimal chemical amount $x^* = 0$ for all punishment levels β, where $\beta_A = -0.8$ and $\beta_C = -3.92$. When the food price is intermediate ($P = 1$), Fig. 7b shows that as β increases, x^* decreases to zero at the point $\beta = \beta_A = 11.8$ (i.e., deterred by punishment), where $\beta_C = -1.4$. When the food price is $P = 2$, Fig. 7c shows that as β increases, x^* first remains 1 until the point $\beta = \beta_C = 2.2$, and then decreases to zero at the point $\beta = \beta_A = 29.8$ (i.e., deterred by punishment). Comparing Fig. 7a–c, we observe that there is no need to set high punishment levels to prevent risky behavior when the food price is low but when the food price is high, a higher punishment level is needed for deterrence.

2.4.2. The government's optimal strategies

Inserting Equations (1) and (4) into Equation (6), the government's optimization problem becomes

$$\max_{\beta \geq 0} U_G(\hat{x}(\beta), \beta) = \gamma P Q_0 + (\gamma P q + \lambda\beta Q_0 - c\lambda Q_0)\hat{x}(\beta) + (\beta - c)q\lambda\hat{x}^2(\beta). \tag{14}$$

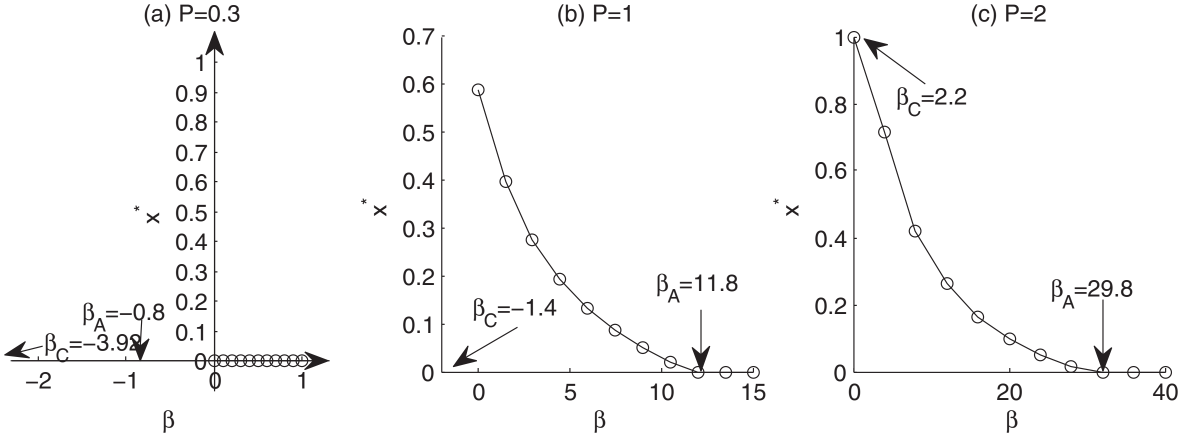


Fig. 7. Illustration of the manufacturer's best responses as functions of the government's punishment strategies β using baseline values $\gamma = 0.1$, $Q_0 = 1$, $q = 2$, $c = 1$, $p_m = 0.5$, $\lambda = 0.1$, $x_p = 0.1$, and $p_p = 0.6$.

Inserting Equation (13) into Equation (14), we get three possible forms of the government utility $U_G(\hat{x}(\beta), \beta) =$

$$\begin{cases} \gamma P Q_0 & \text{if } \beta \geq \beta_A \\ \gamma P Q_0 + (\gamma P q + \lambda \beta Q_0 - c\lambda Q_0) \dfrac{Pq - \gamma P q - p_m Q_0 - \beta\lambda Q_0}{2\beta\lambda q} & \text{if } \beta_C < \beta < \beta_A \\ +(\beta - c) q \lambda \left(\dfrac{Pq - \gamma P q - p_m Q_0 - \beta\lambda Q_0}{2\beta\lambda q} \right)^2 & \\ \gamma P Q_0 + \gamma P q + \lambda \beta Q_0 - c\lambda Q_0 + (\beta - c) q \lambda & \text{if } \beta \leq \beta_C \end{cases}$$

For the second case of $\beta_C < \beta < \beta_A$, applying Proposition 2, we get interior possible candidate β (denoted as β_B) by setting its first derivative to 0. Then we compare the government's utilities evaluated at those interior (β_B) and boundary points (β_A, β_C, c, 0) and get the final optimal solution β^*, corresponding to the highest level of the government payoff. The explicit solution for the optimal β^* is too complex to document in this paper but is available upon request.

We assume that if the government is indifferent between different punishment levels that lead to the same payoff, the lowest punishment level would be chosen. From a mathematical perspective, as open interval for punishment range, there does not exist a highest punishment level to maximize government payoff. Figure 8 shows that the government's payoff U_G changes in the punishment β, which affects the value of chemical x, using the same baseline value used in Fig. 6. When the food price P is low ($P = 0.3$), Fig. 8a shows that $U_G(\beta)$ remains constant for all punishment levels β, where $\beta^* = 0$. When the food price is intermediate ($P = 1$), Fig. 8b shows that $U_G(\beta)$ increases in β until the optimal strategy $\beta^* = 3.146$, and then decreases to the point $\beta = \beta_A = 11.8$. When the food price is high ($P = 2$), Fig. 8c shows that $U_G(\beta)$ increases in β until optimal strategy $\beta^* = 4.229$, and then decreases to the point $\beta = \beta_A = 29.8$. Figure 8a–c demonstrates that (a) there is no need to set high punishment when the food price is low, and (b) the higher food price is, the higher level of punishment is needed.

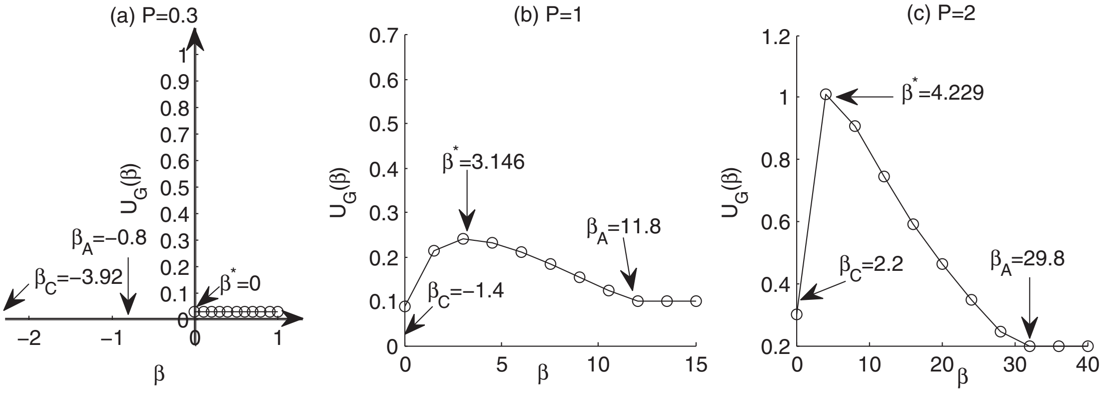


Fig. 8. Illustration of the government's payoff as functions of punishment strategies β using baseline values $\gamma = 0.1$, $Q_0 = 1$, $q = 2$, $c = 1$, $p_m = 0.5$, $\lambda = 0.1$, $x_p = 0.1$, and $p_p = 0.6$.

2.4.3. *Sensitivity analyses of equilibrium strategies and payoffs*

Figure 9 shows the dynamics of equilibrium levels of chemical additive x, punishment β, the manufacturer's payoff U_M, and government's payoff U_G as functions of parameters γ, P, Q_0, q, c, p_m, and λ. We vary one parameter at a time, while fixing the others at their baseline values as used in Fig. 6. The solid line in Fig. 9 represents each parameter's baseline value; the vertical dashed lines demarcate different cases. In principle, there are six cases listed as follows, five of which are observed in Fig. 9:

- Case #1: $\beta > 0$, $x = x^-$; positive punishment and low chemical level.
- Case #2: $\beta > 0$, $x \in (x^-, x^+)$; positive punishment and intermediate chemical level.
- Case #3: $\beta > 0$, $x = x^+$; positive punishment and high chemical level.
- Case #4: $\beta = 0$, $x = x^-$; no punishment and low chemical level.

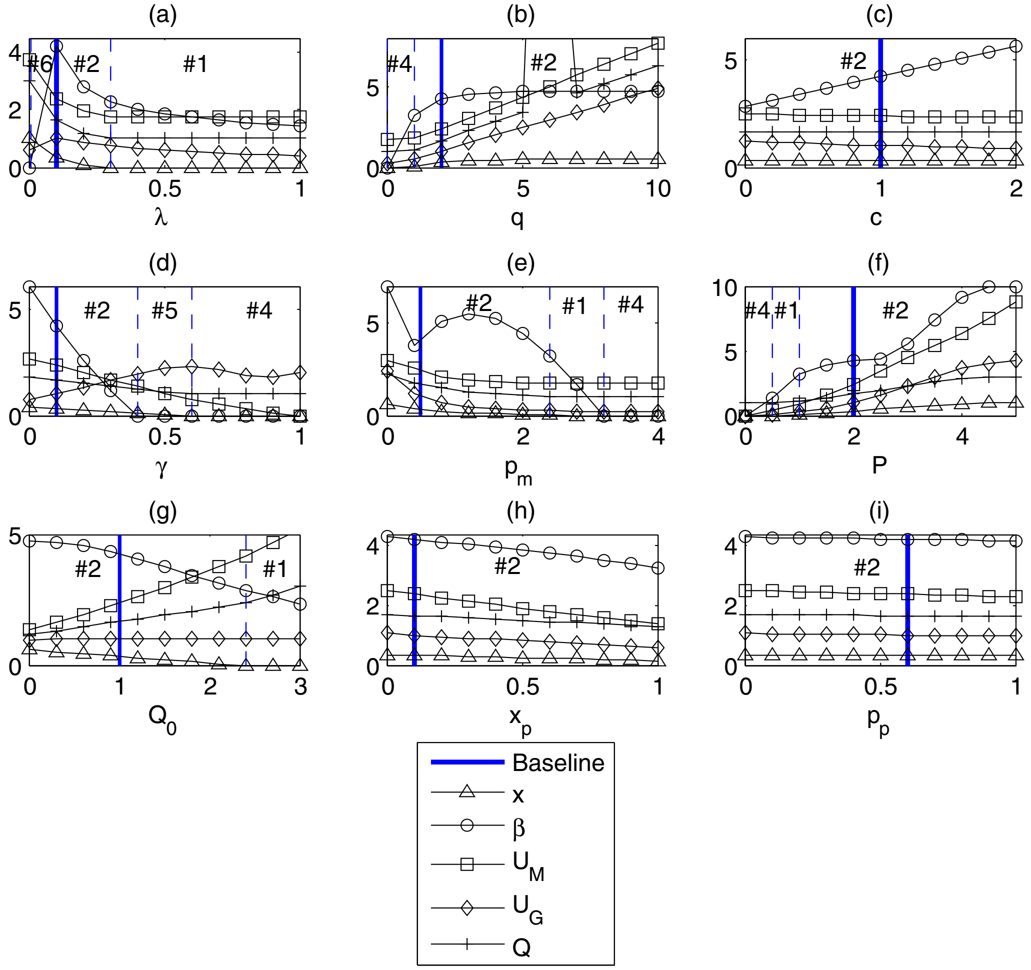


Fig. 9. Optimal level of chemical and utilities with decentralized decision making as a function of λ, q, c, γ, p_m, P, and Q_0 using baseline values $\gamma = 0.1$, $Q_0 = 1$, $q = 2$, $c = 1$, $p_m = 0.5$, $\lambda = 0.1$, $x_p = 0.1$, and $p_p = 0.6$.

- Case #5: $\beta = 0$, $x \in (x^-, x^+)$; no punishment and intermediate chemical level.
- Case #6: $\beta = 0$, $x = x^+$; no punishment and high chemical level.

In Fig. 9a, case #6 occurs when slope parameter of sickness $\lambda = 0$; that is, when there is no health risk, there is no need to set punishment β, and the manufacturer uses high chemical level x^+. When λ continues to increase, case #2 occurs, where we have intermediate levels of x and positive β. When λ continues to increase, case #1 occurs, where we have low level of x and positive β. We observe that as λ increases, the manufacturer could be punished more due to increasing sickness and thus chooses to decrease the chemical level; as a result, the government punishment level could decrease. In other words, it is noteworthy to see that punishment β and government's payoff first increases and then decreases in λ. For the whole area, the manufacturer's payoff and consumer demand decrease in λ.

In Fig. 9b, case #4 occurs when the potential additional sales amount satisfies $q \in [0, 1]$. In this region, the additional sales profit is too small for the manufacturer to take risks, thus the chemical level x remains at 0 and punishment level β keeps at 0. When $q \in (1, 10]$, case #1 occurs; that is, due to high profit incentives, chemical level x increases in q despite the increasing punishment β. For the whole area, both players' payoffs and the consumer demand increase in q.

In Fig. 9c, case #2 occurs. That is, when the health cost c increases, the punishment β increases, which deters the chemical level x. Both players' payoffs decrease in c.

In Fig. 9d, as tax rate γ increases cases #2, #5, and #4 occur. Due to the high tax rate, there is no incentive for the manufacturer in business, thus he/she gives up adding the chemical. We also observe that the punishment level decreases in the tax rate γ. The government utility and manufacturer utility increases and decreases, respectively, in γ.

In Fig. 9e, when the unit chemical cost p_m increases, we observe cases #2, #1, #4 in order. That is, as p_m increases, the manufacturer faces higher costs of using chemicals and then decreases x to zero; thus the government needs a lower level of punishment β to deter the manufacturer. For the whole area, both players' payoffs and consumer demand decrease in p_m. In Fig. 9f, we observe cases #4, #1, #2 in order as the food price P increases, for similar reasons to Fig. 9b.

In Fig. 9g, as the baseline sales amount Q_0 increases, the manufacturer gains more profits and thus does not have to take risky behavior of adding chemical additives, thus decreasing the chemical level. Therefore, the government does not have to maintain a high level of punishment. For the whole area, both players' payoffs and consumer demand increase in Q_0.

In Fig. 9h and i, case #2 occurs for similar reasons in Fig. 9c.

2.5. Centralized (GM) model, and the comparison with the decentralized (GvM) model

Sections 2.2–2.4 analyzed the manufacturer's and government's optimization problems. In this section, we combine the manufacturer's and government's payoffs as a social utility to study a centralized *GM*/social planner model. For example, the company could be state-owned, and there exists a social planner to decide on the chemical additive level. Adding Equations (5) and (6) together, punishment income/cost and tax income/cost are canceled out leaving

$$\max_{x^- \le x \le x^+} U_c(x) = U_M + U_G = \underbrace{PQ(x)}_{\text{Sales Revenue}} - \underbrace{p_m x Q(x)}_{\text{Chemical Cost}} - \underbrace{p_p x_p Q(x)}_{\text{Production Cost}} - \underbrace{cQ(x)H(x)}_{\text{Health Cost}}. \tag{15}$$

Note that in this societal problem (15), the government punishment level no longer matters and we only have one decision variable, the chemical level x.

Using function forms specified in Equations (1) and (4), Equation (15) becomes

$$U_c(x) = (P - p_p x_p)Q_0 + (Pq - p_m Q_0 - c\lambda Q_0 - p_p x_p q)x - (\lambda c q + p_m q)x^2. \tag{16}$$

Solving Equation (16), the optimal chemical level is attained when $x^- = 0$ and $x^+ = 1$.

$$x_c{}^* = \begin{cases} 0 & \text{if } \dfrac{Pq - p_m Q_0 - c\lambda Q_0 - p_p x_p q}{2qc\lambda + 2p_m q} \leq 0 \\ \dfrac{Pq - p_m Q_0 - c\lambda Q_0 - p_p x_p q}{2qc\lambda + 2p_m q} & \text{if } \dfrac{Pq - p_m Q_0 - c\lambda Q_0 - p_p x_p q}{2qc\lambda + 2p_m q} \in (0, 1) \\ 1 & \text{if } \dfrac{Pq - p_m Q_0 - c\lambda Q_0 - p_p x_p q}{2qc\lambda + 2p_m q} \geq 1. \end{cases} \tag{17}$$

Based on Equations (10) and (17), we have

$$x_c{}^* - \hat{x} = \frac{\gamma p_m P - (1-\gamma)\lambda c P - p_p x_p \lambda c + \beta\lambda(P - p_p x_p)}{2(\beta\lambda + p_m)(\lambda c + p_m)} \text{ if } \hat{x},\ x_c{}^* \in (0, 1). \tag{18}$$

As in Proof of Proposition 2, we have $x_c{}^* \geq \hat{x}$ when $\beta \geq \frac{(1-\gamma)\lambda c P - \gamma p_m P - p_p x_p c\gamma}{\lambda P - \lambda p_p x_p}$, which means that sufficiently high punishment could lead to less risky behavior under decentralized policy.

Figures 10 and 11 compare the equilibrium chemical amounts and societal utilities between the centralized (x_c and U_c, respectively) and decentralized (x_d and U_d, respectively) models, using the same baseline values as in Fig. 6. In Fig. 10, it is noteworthy that x_d is smaller than (or equals to) x_c, especially when the potential additional sales amount q and the unit chemical cost p_m (Fig. 10b and e) are low, or when the slope parameter of sickness λ and food price P (Fig. 10a and f) are at intermediate levels, or when the tax rate γ, baseline sales amount Q_0, required protein amount x_p, and unit protein price p_p (Fig. 10d and g–i) are high. In Fig. 11, we see that the social utility from the decentralized model U_d is always smaller than (or equals to) the society utility from the centralized model U_c, and the difference is significant especially when the unit chemical cost p_m (Fig. 11e) is low, or when the slope parameter of sickness λ and food price P (Fig. 11a and f) are at intermediate levels, or when the potential additional sales amount q and tax rate γ (Fig. 11b and d) are high.

Equation (19) summarizes the breakdown of the societal utility changes from the decentralized to centralized models, where the sales revenue increases but the chemical cost and health cost decrease. Although the centralized model leads to higher societal utility, it also leads to higher chemical level and lower production cost.

$$\underbrace{U_c}_{\text{Total Payoff}\nearrow} = \underbrace{PQ(x)}_{\text{Sales Rvenue}\nearrow} - \underbrace{p_m x Q(x)}_{\text{Chemical Cost}\nearrow} - \underbrace{p_p x_p Q(x)}_{\text{Production Cost}\swarrow} - \underbrace{cQ(x)H(x)}_{\text{Health Cost}\nearrow}. \tag{19}$$

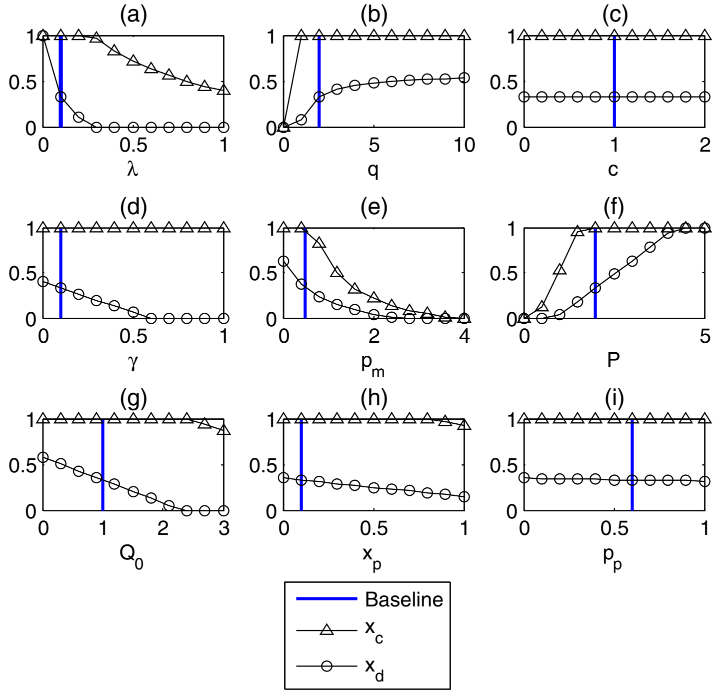


Fig. 10. Comparing equilibrium chemical amounts between the centralized (x_c) and decentralized (x_d) models using baseline values as used in Fig. 6.

3. Sanlu case study

3.1. Data sources

In 2008, the manufacturer Sanlu company produced tainted milk powder, leading to kidney damages to about three million infants (Branigan, 2008). The penalty set by the government to Sanlu company included a fine of 49.4 million Chinese RMB (about $7 million in 2008) (Xinhuanet, 2009) and compensation of 902 million RMB (Xinhua, 2009). In 2009, this company was pronounced bankrupt (Legal Education Network, 2009). In this section, we apply the real data from the Sanlu milk power contamination case to validate and illustrate the models in Section 2. The milk powder price set is $P = 25$ RMB/400 g $= 62.5$ RMB/kg (Bloomberg, 2008), the melamine cost is $p_m = 0.7$ RMB/kg (Wong, 2008), and the appropriation tax rate for milk powder is $\gamma = 0.17$ (State Administration of Taxation, 2011).

To estimate the sickness probability $H(x)$ using chemical melamine, we use six data points from the sickness probability of rats that were exposed to melamine (Hau et al., 2009): (0, 0), (750, 0.2), (1500, 0.5), (3000, 0.7), (6000, 0.9), (12000, 1), where the first number in the bracket is chemical level x in parts per million (ppm) and the second is the sickness probability $H(x)$. Based on the data and transferring the units to kilograms per kilograms, we exponentially regress the sickness probability function $H(x) = 1 - \exp^{-\lambda x}$, where the best estimate for λ equals 389.7. Figure 12a illustrates how

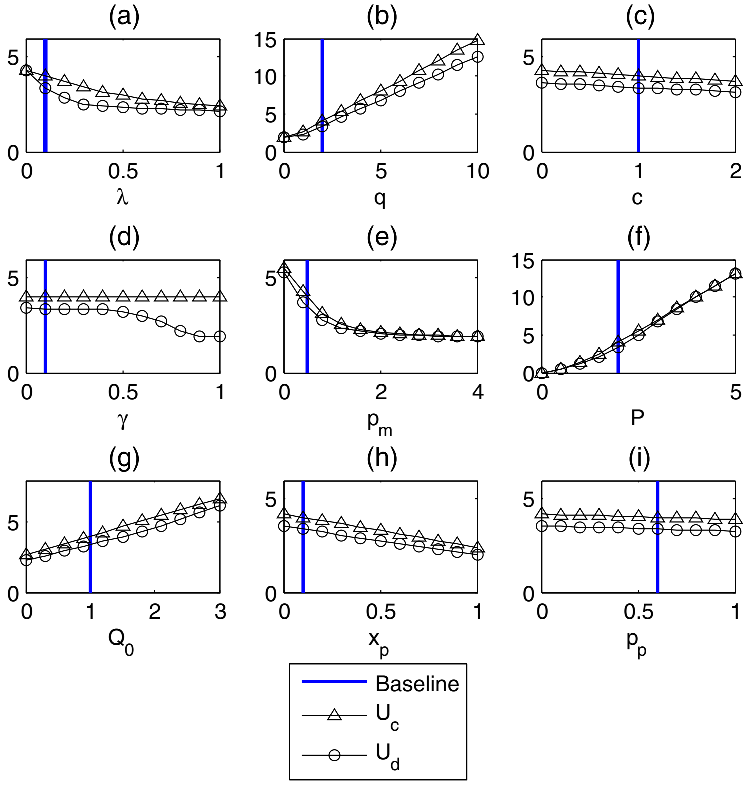


Fig. 11. Comparing equilibrium social utilities between the centralized (U_c) and decentralized (U_d) models using the baseline values as used in Fig. 6.

the sickness probability $H(x)$ depends on the chemical level x using the exponential function in Equation (3).

The total sales amount is roughly estimated at $Q(x) = 700,000$ kg (Southern Metropolis, 2008) as the chemical level $x = 2563$ ppm $= 2.563 \times 10^{-3}$ kg/kg (CCTV.com, 2009). For simplicity,

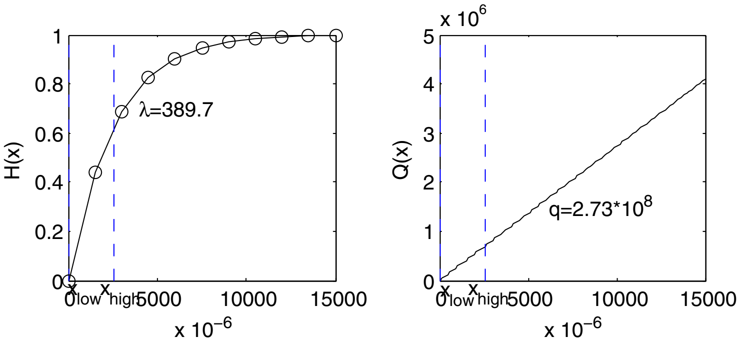


Fig. 12. Illustration of functions $H(x)$ and $Q(x)$.

we assume that $Q_0 = 0$. Thus, we derive the coefficient to be $q = \frac{Q(x)}{x} = 2.73 \times 10^8$. Figure 12b illustrates how the sales demand $Q(x)$ is affected by the chemical level x using the linear function in Equation (2).

Based on the medical treatment compensation fund prepared by the government, around 9.1×10^8 RMB (Henan Legal Daily, 2011), total sales amount $Q(x) = 700,000$ kg, and sickness probability $H(x) = 1 - \exp^{-389.7\times 2.563\times 10^{-3}} = 0.6317$, we have the coefficient of health cost per number of sickness people $c = \frac{9.1\times 10^8}{700,000\times 0.6317} = 2000$ RMB/person.

The remainder of the data used in this paper are from the Food Safety Rapid Detection of Network (2011): The protein amount required in milk powder is $x_p = 15$–20%, where we average it as 0.18, and the amount of nitrogen in protein is $n_p = 16\%$, thus the total amount of nitrogen in 1 kg milk powder is $N = 0.18 \times 0.16 = 0.0288$ kg. The melamine is added to the milk powder because it has higher nitrogen density, which is $n_m = 66.6\%$. Finally, in order to produce the same amount of protein, since the cost of melamine is one-fifth of the cost of protein, we get the protein price $p_p = \frac{16\%}{66.6\%} \times 5 \times p_m = 0.84$ RMB/kg. To satisfy the required protein amount (generally nitrogen amount is tested by Kjeldahl determination method to calculate the amount of protein in milk powder), we have $n_p x_p + n_m x \geq N$.

Before the Sanlu incident, the product quality law regulates that three times the value of the equivalent amount of illegal incomes should be fined (Xinhua News Agency, 2008), which means a lower bound for punishment $\beta_{low} = 3 \times 62.5 = 187.5$ RMB/person. In reality, the chemical level used for Sanlu Company is very high $x_{high} = 2563$ ppm. With the fine and the number of sick people as mentioned in Section 3, a higher bound for punishment is $\beta_{high} = (49.4 + 902) \times 10^6/(3 \times 10^6) = 3170$ RMB/person. After the incidents, the maximum amount of melamine that can be put into baby formula is $x_{low} = 1$ ppm (Beijing News, 2012).

3.2. The government–manufacturer model in Sanlu case

The manufacturer utility function in Equation (5) is slightly revised to Equation (20), where Q_0 is replaced by $Q(x)$.

$$\max_{x\in[x^-,x^+]} U_M(x,\beta) = \underbrace{PQ(x)}_{\text{Sales Revenue}} - \underbrace{(p_m x + p_p x_p)Q(x)}_{\text{Chemical \& Protein Cost}} - \underbrace{\beta Q(x)H(x)}_{\text{Punishment Cost}} - \underbrace{\gamma PQ(x)}_{\text{Tax Cost}}. \tag{20}$$

Inserting exponential sickness probability function into Equations (6) and (20), the government's and manufacturer's optimization problems become

$$\max_{\beta\geq 0} U_G(\hat{x}(\beta),\beta) = -(\beta - c)qxe^{-\lambda x} + (\beta - c + \gamma)Pqx \tag{21}$$

$$\max_{x\in[x^-,x^+]} U_M(x,\beta) = -\left(p_m - \frac{p_p n_m}{n_p}\right)qx^2 + \beta qxe^{-\lambda x} + \left[(1-\gamma)P - \left(p_m - \beta - \frac{p_p N}{n_p}\right)\right]qx. \tag{22}$$

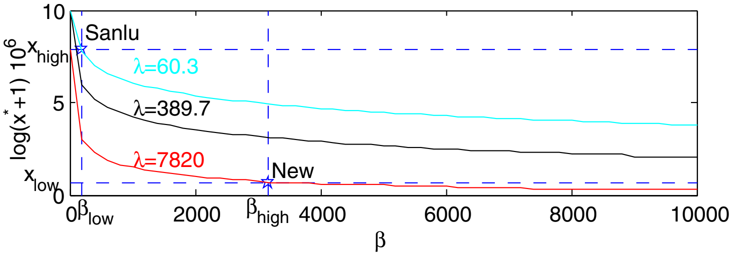
The total utility in Equation (15) for the centralized case becomes the summation of Equations (21) and (22) given by

$$\max_{x^- \le x \le x^+} U_c(x) = -q\Big(p_m - \frac{p_p n_m}{n_p}\Big)x^2 + cqxe^{-\lambda x} + q\Big(P - \frac{p_p N}{n_p} - c\Big)x. \tag{23}$$

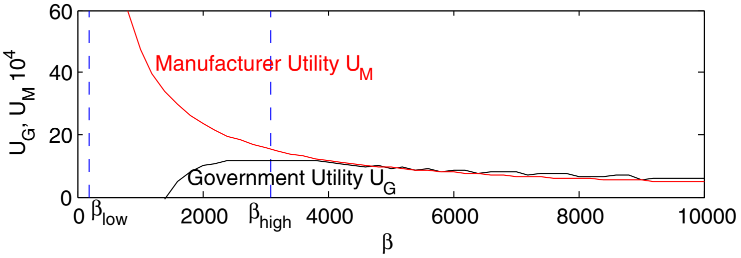
3.3. *Illustration of the manufacturer's best response based on punishment*

Figure 13 illustrates how the government punishment β affects the chemical level x and the government's and manufacturer's utilities U_G and U_M with real data. In Fig. 13a, the point (β_{low}, x_{high}) corresponds to Sanlu Company's behavior, and the point (β_{high}, x_{low}) corresponds to the new milk powder regulation. Corresponding these two points (β_{low}, x_{high}) and (β_{high}, x_{low}), we use regression model to estimate two new slopes of sickness probability $\lambda = 60.3$ and $\lambda = 7820$, respectively. Recall that we have $\lambda = 389.7$ corresponding to the data from Hau et al. (2009) as mentioned in

(a) $x^*(\beta)$



(b) $U_G(\beta, x^*(\beta))$, $U^*_M(\beta)$ when λ=389.7



(c) Parts of Government Utility when λ=389.7

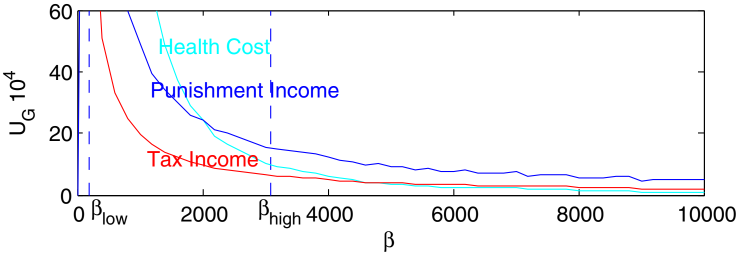


Fig. 13. Illustration of the manufacturer's best response based on punishment using Sanlu real data.

Section 3.1. Figure 13a shows that as the punishment β increases, the chemical level x decreases. In addition, as the sickness probability slope λ decreases, the chemical level x increases, which means that the manufacturer would take riskier behavior. Figure 13b demonstrates that as punishment β increases, the government's utility U_G increases and manufacturer's utility U_M decreases. Figure 13c further details how the government utility is affected by β in health cost, punishment income, and tax income, where all these decrease in β. The health cost decreases more than the others, which reflects that now the manufacturer is deterred from using chemicals by a high punishment level.

3.4. Sensitivity analysis of equilibrium strategies for Sanlu case study

The sensitivity analysis for the new parameter, the unit cost of protein p_p, is shown in Fig. 14. The results for other parameters are similar to the results in Section 2.4 and are not provided here. The results show that the punishment policy β and chemical level x decrease in the unit cost of protein p_p. It is noteworthy that the manufacturer would decrease the chemical level when the protein cost is sufficiently high, where the substitute chemical level needed to meet the nitrogen requirement could result in a high sickness probability. Balancing this tradeoff, the manufacturer would stop producing milk powder, thus it does not need a high government punishment policy.

3.5. Comparing centralized and decentralized models

Table 2 compares the chemical level x, total utility U_c, and government utility U_G, sale demand $Q(x)$, and sickness probability $H(x)$ between the GvM and GM models. It shows that the GvM model leads to lower chemical level x, sickness probability $H(x)$, and society cost $Q(x)H(x)$, while

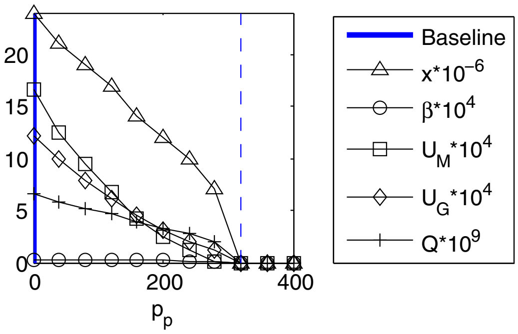


Fig. 14. Optimal levels of strategies, utilities, and quantity with decentralized decision making as a function of p_p for Sanlu case study.

Table 2
Comparison between the *GvM* and *GM* models for Sanlu case study

	x	U_c	U_G	$Q(x)$	$H(x)$	$Q(x)H(x)$
GvM	2.4×10^{-5}	286, 522	121,032	6552	0.009	58.968
GM	4×10^{-5}	343,047	*N/A*	10,920	0.015	163.8

the *GM* model leads to higher government utility U_G, social utility U_c, and sales amount $Q(x)$. All the results here are consistent with the results in Section 2.5. The results show that the chemical level, sickness probability, government utility, social utility, sales amount, and society cost in the decentralized model are lower than those in the centralized model.

4. Conclusion and future research directions

Regulating the manufacturer's risky behavior in food industry is an important and challenging task for the government, which could be complicated by factors such as economic prosperity, taxes, and consumer responses. In this paper, we first build up the government–manufacturer sequential game model, where the government is the first mover whose punishment strategy affects the corresponding manufacturer's decision on adding chemical additives. We consider that the chemicals with lower price can be substituted for the production materials with higher cost. The best response for the manufacturer and optimal punishment strategy for the government are analyzed and numerically illustrated. This indicates that the punishment level should not be too high in order to maintain the manufacturer's payoff. There is no need to set high punishment when the food price is low; and the higher food price is, the higher level of punishment is needed. This also indicates that in the long run, as the consumer's health-related concern rises and the transparency in food industry increases, the company would not add chemicals with or without punishment policy.

We acknowledge that in general, the demand function may not be linear. By considering nonlinear demand function, we would not be able to get closed-form analytical solutions. For concave demand function (e.g., the food sales amount may increases in the chemical level with diminishing marginal returns), we would expect that the manufacturer would have more likely to choose a lower chemical level and the government may set a lower level of punishment.

Note that in the Sanlu case study (Section 3) we considered a nonlinear (exponential) form for the sickness probability function, which fits into the data very well. However, we note that using nonlinear form, it is difficult to get closed-form analytical solution, as we did using a linear form (Section 2.4).

The chemical level in the decentralized model has been compared to the level in the centralized model. It shows that the difference is significant, especially when the potential additional sales amount and the unit chemical cost are low, or when the slope parameter of sickness and food price are at intermediate levels, or when the tax rate, baseline sales amount, required protein amount, and unit protein price are high. This also shows that when punishment is sufficiently high, risky behavior would happen less under the decentralized policy.

In addition, we apply the real data from the Sanlu milk powder contamination to the model. We show that a significant difference exists when the slope for health cost, coefficient for health cost, and protein price are low, and the chemical level in the centralized model is higher than in the decentralized model. It shows that the decentralized model has lower chemical level and sickness probability, and lower government utility, social utility, sales amount, and society cost when compared to the centralized model. These results provide novel policy insights to the government for food industry risk management.

Potential future research directions are as follows. First, analyzing the role of competition between multiple (heterogeneous or homogeneous) manufacturers, this paper focuses on one manufacturer while in practice, the competition between manufacturers may affect their incentives of adding chemical additives (Cheung and Zhuang, 2012). Second, modeling the preincident government checking, this paper focuses on postincident punishment while in practice, the government may use preincident checking to deter the manufacturers from using chemicals. Third, considering the effects of chemical additives on the food's perishing rate, some types of chemicals could better preserve food while the other types may shorten the shelf lives. Fourth, considering farmers as another decision maker in the food industry, this paper focuses on the manufacturer adding the chemical additives, while in practice, the farmers could also add them.

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A. Appendix

A.1. Proof of Proposition 1

First, we calculate the second derivative of Equation (5) as follows:

$$\frac{\partial^2 U_M(x,\beta)}{\partial x^2} = \underbrace{((1-\gamma)P - p_p x_p + p_m x)Q''(x)}_{0} \underbrace{-\beta Q(x)H''(x)}_{\geq 0} \underbrace{-2\beta Q'(x)H'(x)}_{\leq 0} \underbrace{-\beta Q''(x)H(x)}_{0} + \underbrace{2p_m Q'(x)}_{\geq 0}.$$

Under the condition $\beta Q(x)H''(x) + 2\beta Q'(x)H'(x) - 2p_m Q'(x) \geq 0$, we have $\frac{\partial^2 U_M(x,\beta)}{\partial x^2} \leq 0$, which implies that the marginal utility $\frac{\partial U_M(x,\beta)}{\partial x}$ decreases in x. Thus, (a) when $\frac{\partial U_M(x,\beta)}{\partial x}|_{x=x^-} \leq 0$, the optimal level of x must be its minimum level since a higher x will further decrease the utility; (b) when $\frac{\partial U_M(x,\beta)}{\partial x}|_{x=x^+} \geq 0$, the optimal level of x must be its maximum level; and (c) otherwise, we get the interior solution x such that the marginal utility equals zero.

Next, at optimality when $x = x^-$ or $x = x^+$, we have $\frac{\mathrm{d}\hat{x}}{\mathrm{d}\beta} = 0$; otherwise, when the optimal x is interior, based on the first-order condition (first derivative equals zero), we have

$$\frac{\partial U_M(x,\beta)}{\partial x} = \underbrace{(1-\gamma)PQ'(x)}_{\geq 0} - \underbrace{\beta Q(x)H'(x)}_{\leq 0} - \underbrace{\beta Q'(x)H(x)}_{\leq 0} - \underbrace{p_m Q(x)}_{\geq 0} - \underbrace{p_m x Q'(x)}_{\geq 0} - \underbrace{p_p x_p Q'(x)}_{\geq 0} = 0 \Rightarrow$$

$$\begin{aligned} &\frac{\mathrm{d}}{\mathrm{d}\beta}\Big(\beta Q(x)H'(x) + \beta Q'(x)H(x)\Big) \\ &\quad = \frac{\mathrm{d}}{\mathrm{d}\beta}\Big((1-\gamma)PQ'(x) - p_m Q(x) - p_m x Q'(x) - p_p x_p Q'(x)\Big) \Rightarrow \\ &\qquad H'(x)Q(x) + H(x)Q'(x) + \beta\Big(Q(x)H''(x) + 2Q'(x)H'(x) + Q''(x)H(x)\Big)\frac{\mathrm{d}\hat{x}}{\mathrm{d}\beta} \\ &\quad = \Big((1-\gamma)PQ''(x) - 2p_m Q'(x) - p_m x Q''(x) - p_p x_p Q''(x)\Big)\frac{\mathrm{d}\hat{x}}{\mathrm{d}\beta}. \end{aligned}$$

Rearranging this equation, we have $\frac{\mathrm{d}\hat{x}}{\mathrm{d}\beta} = \frac{Q(x)H(x)+Q'(x)H(x)}{-\beta(Q(x)H''(x)+2Q'(x)H'(x)-2p_m Q'(x))} \leq 0$.

A.2. Proof of Proposition 2

The first derivative of the government utility $\frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta}|_{\beta=0} \le 0$ means that the government utility function decreases in β. In this case, due to $\beta \ge 0$, $\frac{\mathrm{d}U_G(\hat{x}(\beta),0)}{\mathrm{d}\beta} \ge \frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta}$, the best strategy for the government is to let $\beta = 0$. Otherwise, when $\frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta}|_{\beta=0} \ge 0$, we need to check the second-order conditions of the government utility function in order to get the optimal strategy:

$$\frac{\partial U_G(x,\beta)}{\partial x} = \underbrace{\gamma P Q'(x)}_{\ge 0} + (\beta - c)\underbrace{\Big(Q'(x)H(x) + Q(x)H'(x)\Big)}_{\ge 0}.$$

We have a sufficient and necessary condition that $\gamma P Q'(x) + (\beta - c)(Q'(x)H(x) + Q(x)H'(x)) \le 0$, which makes $\frac{\partial U_G(x,\beta)}{\partial x} \le 0$, resulting in $\beta - c \le 0$. Furthermore, we have $\frac{\partial^2 U_G(x,\beta)}{\partial x^2} \le 0$ as follows:

$$\frac{\partial^2 U_G(x,\beta)}{\partial x^2} = \underbrace{\gamma P Q''(x)}_{0} + \underbrace{(\beta - c)}_{\le 0}\Big(\underbrace{Q''(x)H(x)}_{0} + \underbrace{2Q'(x)H'(x) + Q(x)H''(x)}_{\ge 0}\Big) \le 0.$$

The first and second derivatives of the government utility function are as follows:

$$\frac{\partial U_G(x,\beta)}{\partial \beta} = Q(x)H(x) \ge 0$$

$$\frac{\partial^2 U_G(x,\beta)}{\partial \beta \partial x} = Q'(x)H(x) + Q(x)H'(x) \ge 0$$

$$\frac{\partial^2 U_G(x,\beta)}{\partial \beta^2} = 0$$

$$\frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta} = \frac{\partial U_G}{\partial \beta} + \frac{\partial U_G}{\partial x}\frac{\mathrm{d}\hat{x}(\beta)}{\mathrm{d}\beta}$$

$$\frac{\mathrm{d}^2 U_G(\beta)}{\mathrm{d}\beta^2} = \underbrace{\frac{\partial^2 U_G(x,\beta)}{\partial \beta^2}}_{0} + \underbrace{\frac{2\partial^2 U_G(x,\beta)}{\partial \beta \partial x}}_{\ge 0}\underbrace{\frac{\mathrm{d}\hat{x}(\beta)}{\mathrm{d}\beta}}_{\le 0} + \underbrace{\frac{\partial U_G(x,\beta)}{\partial x}}_{\le 0}\underbrace{\frac{\mathrm{d}^2\hat{x}(\beta)}{\mathrm{d}\beta^2}}_{\ge 0} + \underbrace{\frac{\partial^2 U_G(x,\beta)}{\partial x^2}}_{\le 0}\underbrace{(\frac{\mathrm{d}\hat{x}(\beta)}{\mathrm{d}\beta})^2}_{\ge 0}$$
$$\le 0.$$

Based on $\frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta} \ge 0$ and $\frac{\mathrm{d}^2 U_G(\beta)}{\mathrm{d}\beta^2} \le 0$, which means that the government utility function initially increases in β with decreasing marginal returns, we get an interior solution by setting the first derivative $\frac{\mathrm{d}U_G(\hat{x}(\beta),\beta)}{\mathrm{d}\beta} = 0$.