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The impact of inspection on the sustainable production strategy: Environmental violation and abatement in emerging markets

Abstract

Environmental inspections help regulators ensure manufacturers compliance with environmental regulations and reduce pollution. However, the intensive inspections to ensure compliance are costly. This is especially problematic for emerging countries with limited resources for law enforcement. The liter-ature provides limited understandings for regulators to design a cost-effective inspection program. Our study enters this discourse by examining the relationship between governments environmental inspection frequency (effort) and manufacturers environmental performance (in terms of environmental incidents). First, by sampling Chinese-listed manufacturers, our empirical analysis reveals that higher inspection frequency improves a manufacturers environmental performance in the short but not the long term. We further develop a dynamic game model to explore the reasons behind this lack of effectiveness in the long term. The results show that effectiveness can be achieved through an integration between inspection frequency and penalties for noncompliance. Inspection leads to cosmetic improvements in a manufac-turer; frequent inspections accompanied with increased penalties substantially enhance a manufacturers abatement efforts, which is the most effective enforcement policy. Our study suggests that penalty can be the boundary condition between rational choice and behavioral shock on environmental enforcement. It urges manufacturers to make reasonable abatement efforts to reduce environmental penalties and improve environmental performance. Our study has important implications for policymakers in that it provides them a basis on which to review the current environmental law and enforcement process.

Keywords: sustainable operations management, environmental inspection, multimethod approach *History:* file version 1 February 2020

1 Introduction

Recurring industrial pollution incidents demonstrate the lack of manufacturer focus on minimizing environmental impacts as part of their corporate social responsibility (CSR). By making business decisions based on the most economically efficient criteria, market participants often deploy resources to pursue economically optimal goals. However, pursuing short-term productivity goals may compromise a manufacturer's non-financial outcomes, such as environmental performance (Orlitzky et al., 2003). Compromised environmental performance can directly deteriorate social welfare and increase social costs. Governments correct these market imperfections by imposing minimal regulation requirements for all manufacturers must follow. To ensure compliance, the regulators inspect environmental practices in product supplies and pursue the implementation of corrective measures in the case of noncompliance (Delmas and Toffel, 2008).

Environmental inspections can be viewed as games between the regulator and the inspected manufacturer. The regulator aims to motivate manufacturer pollution abatement efforts to reduce environmental effects, whereas manufacturers need to evaluate both cost and environmental performances in production. The divergent goals create an intrinsic obstacle to effective environmental protection.

Frequent inspection is a straightforward way to improve the enforcement effectiveness, because it increases the probability of identifying loopholes in manufacturers' environmental practices (Wiengarten et al., 2017). In the literature, (see El Ouardighi et al., 2021), intensive inspections are named as a contingent (i.e., the feedback) strategy while scattered inspections are deemed a commitment (i.e., the open-loop) strategy taken by a government. However, the monitoring tool of inspection is costly to implement (Kim, 2015). Enforcement with contingent strategy requires increased public budgets and resources, and may indirectly decrease employment, sales, worker wages, productivity, and survival rates in the inspected firms (Levine et al., 2012).

This problem is especially pertinent critical in developing countries, where the local regulators may have fewer resources and experiences to conduct effective inspections (Gray and Shimshack, 2011). In the developed countries, for example, the United States, Environmental Protection Agency (EPA) monitoring has been positively associated with firm environmental performance in terms of air pollution compliance (Deily and Gray, 2006), water pollution discharge (Glicksman and Earnhart, 2007), and hazardous waste-emission compliance (Stafford, 2003). However, these findings were based on the EPAs (2021) annual budget of USD 8.82 billion (EPA, 2021) which is 5.18 times higher than that of Chinas Ministry of Ecology and Environment (USD 1.70 billion) (MEE, 2019). This is a wide gap given China's manufacturing sector is 1.5 times larger than that of the US (secondary industry in gross domestic product [GDP]). The Chinese government is seeking to enhance the enforcement of environmental restoration practices by intensifying manufacturer inspections and imposing severe penalties, yet the efficiency and efficacy of an intensive inspection strategy remains indeterminate. Owing to a lack of understanding in this respect, emerging markets have limited reference to design environmental law, initiate enforcements, and predict effectiveness. This is critical given that environmental problems are by-products of economic development in many emerging markets (Cai and Choi, 2020).

It is essential to design an effective inspection strategy with reasonable inspection costs. Thus, this study thus aims to address this issue by examining the return of costly inspections with contingent strategy. Specifically, we first address an important question: how would a governmental inspection frequency affect manufacturers' subsequent environmental incidents? We empirically analyze the data collected from the Chinese manufacturing sector. The analysis result finds diminished marginal effects of such a contingent inspection strategy over time. Although higher government inspection frequency in a year (i.e., year t) reduced the number of corporate environmental incidents in the subsequent year (e.g., year $t+1$), its effect did not span for a longer period.

Our empirical results suggest that simply increasing inspection frequency is not cost-effective. The findings serve as a starting point of our heuristic approach to understand environmental inspections in emerging markets. This study also relates to the stream of operations management (OM) literature applying multiple methods. As Tong et al. (2016) indicated, the findings from empirics are limited to linear relations that draw from significant/non-significant results. The in-depth issues of how firms react to government inspection and how to design a more cost-effective inspection program cannot be well understood through empirical analysis. Thus, we adopt an analytical model to further understand the empirical analysis results.

We then extend the understanding by investigating the second and third research questions: why is the contingent inspection strategy not effective? How can the inspection strategy be improved to increase its cost-effectiveness? Previous literature has used game theory to discuss the strategic alternatives of government inspections because regulator and manufacturer can be conceptualized as the two parties in a Stackelberg game model (e.g., Kim, 2015). Thus, we develop a Stackelberg game model to capture interaction behaviors between the two parties, considering the restriction of environmental regulations. Considering a dynamic environment, we investigate how the interaction between a regulator's inspection strategy (contingent or commitment) and a manufacturer's pollution affect abatement efforts. The results reveal the cosmetic nature of the abatement efforts that a manufacturer undertakes in response to governmental inspections. Such efforts are easily abandoned by manufacturers in favor of economic benefit. Given that government inspections are costly, it is undesirable to recommend that the government maintain an intensive level of inspection for a long period. In addition, we draw on the public enforcement of law literature and examine the role of penalties in maintaining the deterrence effects of enforcement.

Last, we explore whether penalties can be incorporated into governmental inspection strategy to increase effectiveness. Our analytical results indicate that penalties are a successful means to increase the effectiveness of government inspection. To avoid noncompliance activity, manufacturers must undertake abatement actions and disclose improvement outcomes to the public and regulator. Therefore, the regulator may maintain a certain level of inspection and an effective environmental penalty. Both the open-loop and feedback equilibria are derived for the manufacturer and regulator, respectively, dynamically adjusting their strategic decisions. Based on the equilibrium outcomes, inspections can effectively be used to control and eliminate environmental pollution. The thresholds of pollution penalties are also identified to help a regulator to effectively monitor a manufacturers abatement efforts.

This study offers significant policy implications that aim to answer the recent call for research at the intersection of OM and government regulations (e.g., Tokar and Swink, 2019). To uncover noncompliance activities and ensure public environmental welfare, a regulator must design an appropriate inspection plan with effective regulation penalties. This approach will help the regulator to supervise a manufacturer's abatement efforts and to improve public social welfare. We not only focus on identifying the optimal inspection level in a dynamic scenario, but also analyze the function of pollution penalties in the regulator's strategic decisions. Intuitively, both the regulator and the manufacturer achieve a balance by complying with environmental regulations. However, contrary to common belief, we find that manufacturers make mere *cosmetic improvements*, so they can benefit from this behavior by avoiding penalties. We find that a manufacturer's cosmetic improvements can be aggravated when the regulator levies lesser penalties; thus, the regulator's inspection and penalty may act as complementary approaches to simultaneously restrict compliance violations and improve social responsibility.

The remainder of this paper is organized as follows. In Section 2, the related literature is reviewed from three perspectives. In Section 3, we present an empirical analysis to examine the relationships between governmental inspection frequency and a manufacturer's environmental incidents. In Section 4, the dynamic game-theoretical model is formulated to analyze scenarios with and without inspection in order to capture the interaction behaviors between the manufacturer and regulator. In Section 5 and 6, both the open-loop and feedback equilibria of two sub-games are characterized for the manufacturer and the regulator, respectively. We also analyze the influence of pollution penalty on efficient inspections. Finally, Section 7 summarizes and discusses the key results and managerial implications of our findings for various stakeholders, including scholars, the regulator, and manufacturers. All proofs are provided in Appendix A.

2 Literature Review

Scholars have studied the topic of inspections in a buyer-supplier context. Inspection from the buyer was expected to improve product quality and deter product adulteration. Recent literature has illustrated the difficulty in making such inspections effective. Babich and Tang (2012) find that inspection mechanisms cannot completely deter product adulteration, though the deferred payment mechanism performs well in the scenario. Chen and Lee (2017) find that, although audit instruments can directly lower responsibility risks, they are not as effective as supplier certification instruments in screening suppliers. To improve supplier reliability, Lee and Li (2018) propose three structures of buyer strategy - investment, inspection, and incentives. Given that both the buyer and its supplier may exert lesser efforts, stringent inspection is designed to control product quality, which is necessary to induce the suppliers' effort. The aforementioned research analyzes the problem of buyers designing effective inspection mechanisms to induce suppliers to invest greater effort in coordinating buyers' sourcing decisions. However, the supplier audit problem follows different model assumptions; in other words, the supplier implements risk aversion by disclosing full or partial information. In contrast, in our study, the manufacturer is required to abide by environmental laws or regulations to avoid serious pollution penalties. In the context of government inspection, the coercive pressure may be more salient than that between buyers and manufacturers. Thus, using environmental violation and abatement as the context, we focus on interactions between the regulator and manufacturer in a dynamic environment. In this section, we reviewed the literature to discuss the mechanism and effect of government inspection.

2.1 The deterrence effect of inspection

A series of studies has examined the deterrence effects of government enforcement. Overall, the literature on the EPA's environmental enforcement consistently concludes that enforcement is positively associated with firms' environmental performance (Gray & Shimshack, 2011). However, there have been mixed findings from studies on occupational health and safety inspections. Some studies have reported that the inspections can reduce workplace injuries (e.g., Ruser & Smith, 1991), while others have found no significant effects (e.g., Levine et al., 2012; Mendeloff & Gray, 2005).

These studies portray the deterrence effects from two perspectives. The first is the rational choice perspective, which considers noncompliance a rational decision resulting from cost-benefit analysis (Greve et al., 2010). Abatement efforts of manufacturers are affected by the inspection costs, including the expected probability of detection of violation and the expected magnitude of the potential penalty (Gray & Shimshack, 2011). Manufacturers will evaluate the cost of abatement efforts against the cost of being caught (or penalized). Thus, the effectiveness of enforcement is closely related to the following two aspects: (i) the frequency of inspection, owing to its effect on the likelihood of detecting noncompliance, and (ii) the penalty, owing to its effect on the magnitude of loss from violations. In a stringent enforcement context, manufacturing firms should increase the abatement level to avoid the potentially large penalties for violations (Mendeloff & Gray, 2005), thereby reducing the number of environmental incidents. However, from this perspective, manufacturers may not sustain the improvement in environmental performance given that their goal is to pursue an optimal control in the trade-off between abatement and investment costs (Feng et al., 2020).

The second perspective is based on the behavioral theory of the firm; under this premise, inspection can be considered a behavioral shock that alerts managers of latent operational failures (Mendeloff and Gray, 2005). In other words, an inspection identifies noncompliant manufacturers and alerts them of their poor environmental performance; this drives such manufacturers to seek corrective measures to improve their scenario (Madsen & Desai, 2010). Learning motivated by failure is also known as a problemistic search, in which organizations challenge old assumptions, take corrective actions, and innovate (Sitkin, 1992). In addition, failure experiences can provide organizations with explicit road maps describing which knowledge to seek and how to make the necessary changes and improvements. Therefore, the behavioral shock perspective considers that the problems exposed during inspections increase managers' attention to environmental issues, which likely stimulates a continuous improvement in the environmental practices.

In summary, both rational choice and behavioral shock perspectives indicate that a more stringent inspection can increase the abatement efforts of manufacturers and, consequently, reduce environmental incidents. However, the behavioral shock perspective shows that abatement efforts are continuous, and hence they can achieve continuous improvement in environmental performance. In contrast, the rational choice perspective shows that the abatement efforts will decline after inspections. Section 3 examines these two perspectives in the context of the Chinese government's environmental inspection initiatives.

2.2 Inspection mechanisms and effectiveness

The second stream of relevant studies focuses on the self-inspection/improvement work under environmental regulations; the examples of such studies are Biais et al. (2010), Kalkanci et al. (2012), Kim (2015), Wang et al. (2016), Alizamir and Kim (2017), Niu et al. (2017), and Xiao et al. (2019). These studies aim to design optimal inspection mechanisms, such as random and periodic inspections, to identify noncompliance in manufacturers. Biais et al. (2010) analyze a continuous-time moral hazard problem, without considering the influence of inspections. The study considers an insurance company and characterizes optimal investment and compensation policies to induce a manufacturer to invest effort in mitigating environmental risks. Evan et al. (2011) examine the effect of environmental auditing on the probability of regulatory inspection. They find that environmental auditing is more likely to be conducted in larger facilities subject to more stringent regulations. Kalkanci et al. (2012) investigate the effects of manufacturers disclosing social and environmental information in their supply chains, and find that voluntary disclosure boosts a manufacturer's market share. Kim (2015) develops a novel analytical framework by combining law enforcement economics with the reliability theory. In regard to mitigating the effects of environmental violations, the study finds that periodic inspections are more cost-effective than random inspections. Xiao et al. (2019) discuss the potential of two operational capabilities - the production-cost efficiency and the effectiveness of environmental process improvement - in assisting the manufacturer to lower its environmental impact at the terminal time.

Concerning the periodic inspection, our study discusses a manufacturer's reaction to environmental enforcements and its decision to improve social and environmental responsibility through enhanced abatement efforts. Plambeck and Taylor (2016) analyze how to encourage suppliers to exert greater efforts to pass the buyer's audit and prevent harm. Considering a dynamic environment, Alizamir and Kim (2017) discuss the role of self-inspections between a regulator and a manufacturer. They find that, in cases warranting a permanent restoration, a manufacturer amplifies self-inspection without reporting to the regulator. In contrast,in cases warranting a temporary restoration, a manufacturer's self-inspections can bring a net benefit to the regulator. Unlike these studies, we aim to analyze the trade-off faced by the manufacturer when conducting the self-improvement in compliance with the regulator's inspection scheme, which is a prerequisite for a manufacturer to implement an effective abatement effort.

In summary, this study lies at the intersection between the three aforementioned streams of literature. We empirically examine the effectiveness of inspection in the context of Chinese environmental inspections from the theoretical lenses of rational choice and behavioral shock. We also develop the dynamic game-theoretical model to capture the interaction behaviors between the manufacturer and regulator. The open-loop and feedback equilibria are characterized for both the manufacturer and the regulator, over an infinite time horizon. By investigating the equilibrium outcomes, we further examine how the periodic inspections and penalties simultaneously affect a manufacturer's environmental decisions.

3 Empirical Analysis: Chinese Manufacturing Sector

3.1 Samples

To answer the first question, we sample Chinese public manufacturers[1] and collect their environmental inspection and incident data in the following steps. First, we obtain the stock codes of all public firms in the manufacturing sector (i.e., industry code C13 to C43 based on the classification of the China Securities Regulatory Commission) listed on the Shanghai and Shenzhen Stock Exchange in China. We find 1,636 manufacturers.

Second, we use the stock codes of these 1,636 manufacturing firms to search for environmental announcements from the Green Stocks Database of the Institute of Public and Environmental (IPE)[2]. IPE collects all environmental announcements of government inspection and environmental violations from various government offices located in different cities, different provinces, or central government (i.e., Beijing). After we enter a firm's stock code in the search bar of IPE's Green Stock database, it shows all environmental inspections and incidents for the firm's factories and affiliates. We then collect all the information from the result page; the 1,573 environmental announcements include inspection and incident data.

Third, we categorize the announcements into inspection reports and environmental violations. IPE indicates if an announcement is a government inspection report in the source of the announcement. So, we manually check the content and source of each announcement that collected in the second step and find 399 environmental announcements of government inspection (out of 1,573 environmental announcements). In each source of the 399 inspection announcements, IPE indicates the inspection frequency for a firm in an observation year. There are four inspection frequencies: monthly (i.e., 12 times per year), quarterly (i.e., 4 times per year), semiannually (i.e., 2 times per year), and yearly (i.e., 1 time per year) inspection. Then, we calculate the total number of inspections for the firm in the year according to frequency: a total of 710 inspections. The remaining 1,174 announcements are firms environmental violations. Table 1 and Table 2 show yearly distribution, and industry distribution of inspection and incident data, respectively. We also provide two examples of the inspection and incident announcements in Appendix B.

Based on the data collected in the aforementioned steps, we match these 710 inspections and 1,174 environmental incidents to a firm in a specific year to create a panel dataset of 4,023 firm-year observations from 2004 to 2013. We search each manufacturing firm's accounting data from the China Stock Market

Table 1: Yearly distribution of inspections and violations

Year	No. of inspections	No. of violations
2004	7	27
2005	29	50
2006	38	92
2007	76	116
2008	132	123
2009	90	102
2010	96	147
2011	122	210
2012	98	173
2013	22	134
Total	710	1174

& Accounting Research (CSMAR) database. Table 3 shows the descriptive statistics of sample firms.

3.2 Measures

The examination of research question 1 requires assessing the long-term impacts of environmental inspection. Thus, we define year t as the year a regulator inspected a manufacturer. Subsequently, we test the impact of inspection on environmental incidents in the following three years (i.e., year $t+1$, $t+2$, and $t+3$). We use three-year period to examine the impact of inspection because firms may need a certain time period to improve their environmental performance and the "three-year period" is a commonly used long-term examination period in the previous literature (e.g., Kroes et al., 2012; Lo et al., 2012; Eccles et al., 2014).

Our dependent variable is the annual number of environmental violations committed by a firm, which directly reflects the firm's environmental performance (Clarkson & Richardson, 2004). The independent variable is the frequency of governmental inspection for the firm in year t, measured by the number of frequent inspections in each year. The IPE data indicate that the Chinese government inspects firm's environmental performance at four frequencies, such as monthly (i.e., 12 times per year), quarterly (i.e., 4 times per year), semiannually (i.e., 2 times per year), and yearly (i.e., 1 time per year) inspection.

Table 2: Industry distribution of inspections and violations

Industry category	Industry	No. of inspections	No. of violations	
	C17	Textile	32	53
	C18	Textiles, Garments and Apparel industry	11	7
Textiles and paper products	C20	Timber Processing, Timber, Bamboo, Cane, Palm Fiber and Straw Products	0	2
	C22	Papermaking and Paper Products	18	73
Total			61	135
	C26	Raw Chemical Materials and Chemical Products	120	231
Chemical products	C28	Chemical Fibre Manufacturing	19	30
	C29	Rubber and plastic product industry	19	12
Total			158	273
Pharmaceutical manufacturing	C27	Pharmaceutical manufacturing	54	96
Total			54	96
	C30	Non-metallic Mineral Products	59	109
Metal and non-metallic mineral products	C31	Smelting and Pressing of Ferrous Metals	28	85
	C32	Smelting and Pressing of Nonferrous Metals	61	82
	C33	Metal Products	31	21
Total			179	297
	C34	General Equipment Manufacturing	12	31
	C35	Special Equipment Manufacturing	32	14
	C36	Automobile Manufacturing	31	41
General equipment manufacturing	C37	Railway, shipbuilding, aerospace and other transportation equipment manufacturing	19	29
	C38	Electric Machines and Apparatuses Manufacturing	51	44
	C39	Computer, communication and other electronical device manufacturing	28	39
	C41	Other Manufacturing	0	2
Total			173	200
	C13	Farm Products Processing	16	36
	C14	Food Manufacturing	28	32
	C15	Wine, drinks and refined tea manufacturing	23	66
Others (all other not included)	C19	Leather, fur, feathers, and related products and shoe-making	0	2
	C23	Printing and Reproduction of Recorded Media	0	2
	C25	Petroleum Processing, Coking and Nuclear Fuel Processing	16	25
	C42	Comprehensive utilization industry of waste resources	2	10
Total			85	173
Grand Total			710	1174

Table 3: Descriptive statistics of the sample firms in the 4023 firm-year observations

	Total assets (RMB 000,000)	Sales (RMB 000,000)	Net income (RMB 000,000)	Number of employees (000)	ROA	Debt ratio	Financial leverage
Mean	7,664.51	6,656.27	464.48	6.47	0.05	0.52	1.60
Median	2,640.73	1,764.56	106.79	3.00	0.05	0.52	1.08
Std. error	300.21	306.47	29.35	0.18	0.00	0.00	0.33
Maximum	318,633.18	480,979.67	42,028.16	177.62	0.52	4.46	1,281.06
Minimum	0.00	0.00	-9,092.06	0.02	-0.96	0.03	-177.62

Note: The values are calculated based on the fiscal year ending prior to the observation year.
Debt ratio = Total liability / Total assets
Financial leverage = Operating income / Net income

We include control variables to increase the validity of the results of our analysis. Specifically, we control for firm size and performance because larger and more profitable firms may have greater resources to cope with environmental problems (Lo et al., 2018). Firm size is measured as the natural logarithm[3] of total assets. Firm performance is measured in terms of the industry-adjusted return-on-assets (ROA), which equals to the firms ROA minus the industry average ROA. All these factors are measured based on the year $t-1$. We control for firm age because older firms may have accumulated more experience to implement environmental practices. We also include the dummy variables for year and industry code (i.e., C13 to C43) to control for the confounding factors related to time (e.g., regulation change) and industry (e.g., competition and the economic conditions).

3.3 Estimation method

The ordinal and discrete nature of our dependent variable (the annual number of counts of environmental violations) violates the normality assumption of using the ordinary least squares (OLS) estimator. Therefore, we apply the panel Poisson regression to test the relationship between the inspection frequency (at year t) and manufacturing firms' environmental performance (at year $t+1$ to year $t+3$).

The endogeneity concerns hinder our examination of the relationships between inspections and incidents. Concerns may be raised because of reversed causality. To mitigate this concern, we apply a year lag for the independent variables to the dependent variables. The endogeneity concern may also emerge because of the confounding factors that simultaneously affect both independent and dependent variables. For example, managerial skills can potentially relate to both the likelihood of being targeted (inspection) and having environmental incidents. We include several control variables and fixed effects to mitigate concerns related to observable confounding factors (Ketokivi and McIntosh, 2017). However, some unobserved confounding factors may bias our analysis results. Thus, the Heckman two-stage analysis is applied to include the inverse Mill's ratio (IMR) in our model to minimize the possibility of endogeneity (Heckman, 1979).

In the first stage, we generate the IMR by probit regression. For the dependent variable, the firms are coded "1" if the violations are disclosed in a year; otherwise, the firms are coded "0". To fulfill the exclusion restriction requirement of the Heckman two-stage analysis, we include industrial independent variables, such as the industry sales growth (industry munificence), the Herfindahl-Hirschman index (HHI) (industry concentration), and the industry violation history (industry environmental performance), to fulfill the exclusion restriction requirement of the Heckman two-stage analysis. The first two variables represent economic conditions and industry competitiveness, which are commonly used in the econometric and operations literature (e.g., Wiengarten et al., 2019). Industry violation history represents the overall industrial environmental performance. These variables are selected as exogenous variables because they are exogenous to the firm; however, they are related to firms' relative performance. We also include firms' total assets (natural logarithm), industry-adjusted ROA, and industry- and year-dummies as independent variables to increase the model's explanatory power. We present the Stage 1 result in Appendix B. In the Stage 2, we incorporate the calculated IMR to our Poisson regression model to mitigate the endogeneity concern raising as a result of unobservable confounding factors.

3.4 Analysis results

Table 4 shows the correlations of the variables, and Table 5 presents the results of the fixed effect Poisson regression. The coefficient of inspection frequency in year $t+1$ is significantly negative (0.437, $p < 0.01$). This indicates that higher government inspection frequency in the year reduced the manufacturing firm's subsequent environmental incidents in the following year. The coefficients of inspection frequency in year $t+2$ and $t+3$ are insignificantly positive ($p > 0.05$), and this indicates that a higher inspection frequency in the year does not reduce or increase the firm's subsequent environmental incidents in the second and third years. To maintain the robustness of the analysis, using the random effects model, we repeat the aforementioned procedures and attain similar results.

Table 4: Correlation Table

	N	Mean	Std. deviation	Firm age	Total assets+	ROA+	IMR	Inspection frequency in year -1	Inspection frequency in year -2
Firm age	4,023	12.18	4.75						
Total assets+	4,023	21.82	1.27	0.155**					
ROA+	4,021	-0.01	0.07	-0.178**	0.172**				
IMR	3,545	1.54	0.63	0.145**	-0.282**	-0.111**			
Inspection frequency in year -1	4,023	0.12	0.82	0.047**	0.086**	0.013	0.009		
Inspection frequency in year -2	4,023	0.11	0.77	0.044**	0.101**	0.027	0.002	0.146**	
Inspection frequency in year -3	4,023	0.09	0.63	0.044**	0.096**	0.019	0.001	0.107**	0.188**

**: Correlation is significant at the 0.01 level (2-tailed).
+: Total assets are natural log value, ROA is industry adjusted value

Table 5: Poisson Regression Model of Environmental Violations

Parameter	Model Year $t+1$	Model Year $t+2$	Model Year $t+3$
Intercept	-30.976^{**} (9.86)	-30.981^{**} (9.81)	-30.899^{**} (9.82)
Year dummies	-	-	-
Industry dummies	-	-	-
Firm age	0.013 (0.01)	0.012 (0.01)	0.012 (0.01)
Total assets	0.330^{**} (0.06)	0.315^{**} (0.06)	0.311^{**} (0.06)
Industry-adjusted ROA	-1.417^{**} (0.5)	-1.423^{**} (0.5)	-1.400^{**} (0.5)
IMR	-0.193 (0.22)	-0.183 (0.22)	-0.188 (0.22)
Inspection frequency in Year t	-0.437^{**} (0.11)	0.027 (0.03)	0.060^{+} (0.03)
N	3,543	3,543	3,065
Log Likelihood	-2,485.30	-2,480.78	-2,243.99

Notes: Standard errors are in parentheses. Year and Industry dummies are included. $^{+}p < 0.10$; $^{**}p < 0.01$.

We also obtain the incidence rate ratios (IRR) from the exponents of coefficients in the Poisson regression model. The IRRs represent the relative risk compared with the baseline value (i.e., 1), which displays the marginal effects of frequent inspections on the violation propensity. In year $t+1$, IRR $= 0.646$ meant that one additional frequent inspection in the year decreased a firms likelihood of experiencing an environmental violation by a factor of 0.646 or 35.4% ($= 1 - 64.6\%$) one year after the inspections. IRRs in year $t + 2$ and $t + 3$ were 1.027 and 1.062, respectively, which are insignificantly positive ($p > 0.05$).

Overall, the results of the empirical analysis indicate that a higher inspection frequency improved the manufacturing firm's environmental performance in the short, but not in the long term. Thus, a game theory model is developed in the following sections to further investigate the firm's reaction to the enforcement of environmental regulations in terms of the frequency of the environmental monitoring. The complementary mechanism, that is, the violation penalty, is also analyzed; these penalties can be imposed in an effective manner to relieve the limited inspection budgets and public resources. Given the established environmental regulations, we first aim to capture intersection behaviors between the regulator and firm, and identify the effective operational strategies that can be adopted by the regulator and firm, respectively. Subsequently, we focus on characterizing a valid environmental penalty that would maintain the manufacturer's abatement efforts when the regulator's inspection frequency is low.

4 The Model

We consider a regulator (denoted by the subscript r and referred to as 'he') that aims to discover the violation behavior of a manufacturer (denoted by the subscript m and referred to as 'she') (i.e., the environmental pollution emerging as a result of a non-compliant behavior). The regulator and manufacturer independently set the inspection level and exert abatement efforts, respectively. To achieve her production target, the profit-driven manufacturer may neglect the constraints of environmental regulations, which can cause severe pollution. We formulate this problem as a Stackelberg game, in which a regulator is the leader and a manufacturer is the follower. This model setting is reasonable in practice; for example, following the European Restriction of Hazardous Substances (RoHS) Directive, Apple has implemented a series of projects/investments to reduce the over all pollution from three key aspects - climate change, resources, and materials;[4] Apple's annual environmental responsibility report has disclosed the improvement outcomes to the public and regulator. In this model setting, the manufacturer determines her abatement action in reducing the pollution generated during manufacturing processes. To avoid violation and enhance social responsibility, the manufacturer would disclose outcomes of abatement action to the public and the regulator. Meanwhile, to minimize the loss of social environmental welfare, the regulator sets the inspection level, conducts the inspection, and works with the manufacturer simultaneously to control pollution by setting the inspection level. The summary of notation is shown in Table 6.

Table 6: Summary of Notation

Notation	Description
t	The index of each period, $t \in [0, \infty]$
ρ	The continuous discount rate
c_e	The unit cost of a manufacturer's abatement effort
k	The pollution penalty for the non-compliance activity of a manufacturer
w	The loss of social welfare
c_p	The unit inspection cost of a regulator
$p(t)$	The realized environmental pollution/damage of a manufacturer in period t
$\theta(t)$	The abatement effort of a manufacturer in period t
$\tau(t)$	The inspection level of a regulator in period t
α	The ratio of leftover pollution stock considering the environmental absorption rate
β	The marginal effectiveness of manufacturer's abatement effort
γ	The marginal effectiveness of regulator's inspection

4.1 Accountability for reducing pollution

The manufacturer operates on a continuous infinite time horizon and is subject to the environmental regulations, such as the Resources Conservation and Recovery Act[5]. In practice, the regulator focuses on mitigating the environmental pollution through the inspections; however, the regulator imposes a penalty as a result of manufacturer's non-compliance. In response, the manufacturer exerts abatement efforts to reduce environmental damage. Specifically, the manufacturer incurs an abatement cost to comply with the regulations and reduce pollution of the environment simultaneously. In general, the regulator's strategic inspection and the abatement actions of the manufacturer minimize the loss of public environmental welfare. Thus, we model the realized pollution stock with the following kinematic equation.

$$\dot{p}(t) = \alpha p(t) - \beta\theta(t) - \gamma\tau(t), \tag{1}$$

where $p(0) = p_0$; that is, the initial pollution stock is p_0, which is a constant. We support the formulation of the pollution stock in three aspects. First, parameter α measures the environmental absorption rate. This setting is in line with the literature on environmental management and has been applied by the extant literature in the field of sustainable OM, such as Bertinelli et al. (2014), El Ouardighi et al. (2016), and Ma et al. (2018). Second, the manufacturer also can invest in abatement efforts, e.g., improving energy efficiency and using a green technology (Drake et al., 2016; Wang et al., 2021). For example, El Ouardighi et al. (2021) address that the pollution stock decreases with the manufacturer's abatement effort. The abatement effort can also be viewed as implementing an advanced technology, e.g., carbon capture and storage technology which can cut pollutions (Bertinelli et al., 2014). Further, the results of our empirical study support this assumption as well. The empirical result implies that the higher inspection frequency can reduce a manufacturer's subsequent environmental incidents and pollutions over time (IRR=0.646, see Section 3.4). Third, a higher inspection level (or frequent inspections) can help to reduce pollution and remedy noncompliance activities. For example, da Silva Rocha and Salomao (2019) show that stricter inspection (i.e., a higher inspection level) can increase the average degree of compliance, which further decreases pollution. In addition, 88% of 39,585 pollution problems are discovered by the inspectors in China, and 88% of problems are managed; this improves results in reducing pollutions (China Daily 2017).

4.2 The manufacturer's decision

Given the constraints of the environmental regulations, the manufacturer is under pressure to adjust its abatement effort. Thus, the investment cost of the abatement effort is the vital component of the manufacturer's total cost. In addition, the penalty is charged over time based on the pollution stock, which is in turn affected by the abatement efforts and inspection levels. This description is in line with the meaning of Equation (3). For Equation (4), the regulator aims to minimize the loss of public environmental welfare incurred by the environmental pollution. Notation w is the loss of social and environmental welfare. The model setting in Equation (4) also indicates that the regulator spends effort in inspection. Thus, there are two types of operational costs, i.e., the welfare loss and the inspection cost. Regarding the economic aspect, welfare loss is often used by regulators or governments to estimate the costs of environmental regulations (The World Bank, 2016). Based on this dynamic process described above, the objective of a manufacturer is to minimize the operations costs over an infinite time horizon with discount factor $e^{-\rho t}$; ρ is the continuous discount rate, which is an exogenous variable. The payoff function of manufacturer is developed as follows:

$$\Pi_m = \int_0^\infty e^{-\rho t} \left[kp(t)^2 + c_e\theta(t)^2 \right] dt. \tag{2}$$

On the right hand-side of Equation (2), the first term in the bracket denotes penalty, and the second term represents abatement cost. A verification of the manufacturer's abatement efforts can be effectively controlled/reduced by the strategic inspection and abatement actions of the regulator and manufacturer, respectively. However, if a manufacturer's abatement effort is identified as fraudulent or insufficient (inadequate as confirmed), it would seriously damage to the public environmental welfare and invite penalty. For example, a Chinese glass-making manufacturer, that is, Zhenhua Ltd, was fined USD 2.55 million (RMB 22 million) by the local government for breaching the environmental regulations since the company failed to limit its emissions of polluted air and dust into the atmosphere and harmed several local families.[7] Based on the above analysis, the manufacturer aims to minimize her long-term total discounted payoff over an infinite time horizon, subject to the pollution stock incurred by herself in any period. Therefore, Problem M (Manufacturer's subgame) can be formulated as follows:

$$\begin{aligned} &\min \Pi_m = \min_{\theta(t)} \int_0^\infty e^{-\rho t} \left[kp(t)^2 + c_e\theta(t)^2 \right] dt \\ &s.t.\ \dot{p}(t) = \alpha p(t) - \beta\theta(t) - \gamma\tau(t), \end{aligned} \tag{3}$$

where the decision variable in Problem F is the abatement effort $\theta(t)$. Both the penalty and the abatement cost are commonly modeled using the quadratic function in the literature, e.g., Bollen et al. (2010), Karp and Zhang (2012), Du et al. (2015), El Ouardighi et al. (2016).

4.3 The regulator's decision

To detect a manufacturer's noncompliance activity and to reduce the environmental damage, the regulator strictly enforces inspection by aligning its goals with those of the manufacturer. Thus, the objective of regulator is to minimize the loss of public environmental welfare by performing inspections over an infinite time horizon. The discounting of regulator's operational cost is discounted through the discount factor $e^{-\rho t}$, where ρ is the discount rate (an exogenous variable). For simplicity, we assume that the regulator uses the same discount rate, ρ, as the manufacturer. The optimization problem of the regulator can be formulated as follows, that is, Problem R,

$$\begin{aligned} &\min \Pi_r = \min_{\tau(t)} \int_0^\infty e^{-\rho t} \left[wp(t)^2 + c_p \tau(t)^2 \right] dt, \\ &s.t.\ \dot{p}(t) = \alpha p(t) - \beta \theta(t) - \gamma \tau(t), \end{aligned} \tag{4}$$

where the decision variable in this model is the regulator's inspection level $\tau(t)$. On the right hand-side of Equation (4), the first term in the bracket denotes the loss of public environmental welfare incurred by the environmental damage; the second term denotes the inspection cost of the regulator. Regarding the economic theory, the lack of a market for clean air provides the impetus for government intervention in markets involving polluting industries (EPA, 2010). Thus, it is the regulator's responsibility to protect human health and the environment. For example, air pollution caused serious health-related damages in Europe, which recorded an annual loss in consumption of about EUR 220 billion in 2000 prices (Nam et al., 2010). Conversely, the loss of public environmental welfare incurred by the environmental damage can be measured by the quadratic function. This setting is in line with the literature, for example, Ouchida and Gota (2014), Bian et al. (2018), Tsai et al. (2019). The loss of public environmental welfare also can be explained as the economic cost to society, which is also referred to as social cost, welfare cost, and loss in social welfare (WHO 2015). For example, the evidence indicates that air pollution is responsible for several million premature deaths per year; a global of 7 million premature deaths in 2012 (WHO, 2014).

5 Benchmark: No inspection

A benchmark model is developed to analyze the problem of manufacturer's self-disclosure without regulator's inspection. In other words, the manufacturer's action is not supervised by the regulator and the pollution stock can be only reduced by manufacturer abatement efforts. We aim to identify the manufacturer's behavior and possible outcomes of this scenario; thus, the problem becomes a standard optimal control problem that aims to minimize the pollution stock. The manufacturer's optimal control problem is formulated as follows:

$$\begin{aligned} &\min \Pi_m = \min_{\theta(t)} \int_0^\infty e^{-\rho t} \left[c_e \theta(t)^2 \right] dt \\ &s.t.\ \dot{p}(t) = \alpha p(t) - \beta \theta(t), \end{aligned} \tag{5}$$

Proposition 1. *Without the regulator's inspection, the manufacturer has no incentive to make abatement efforts.*

Proposition 1 shows that, without the regulator's inspection, the manufacturer is unlikely to invest in the abatement effort. This is an intuitive result because the manufacturer only aims to minimize its operations costs. In addition, pollution stock changes in the natural absorption rate. For example, air pollution has various malignant health effects and poses a major threat to climate; 91% of the world's population live in places where air quality exceeds WHO guideline limits (WHO 2020). Therefore, it is necessary to involve the pollution penalty for the manufacturers non-compliance activity. On the other hand, it is also worth to analyzing the manufacturers reaction when facing the punitive burden.

In the following section, we analyze two sub-games through backward induction. Two separate games are studied to characterize the interactions of strategic inspection and abatement actions over time, including the open-loop and the feedback games. First, we solve the optimal decision problem characterizing the solution when the manufacturer chooses the abatement strategy, which minimizes the overall discounted operational cost. Subsequently, we then focus on solving the regulator's problem. For both sub-games, we investigate the existence of a dynamic abatement effort, which is the best response; then, the equilibria are identified. Numerical examples are presented to validate the analytical outcomes.

6 Model Analysis

In this section, we analyze the Stackelberg game with the regulator as leader and manufacturer as follower. The regulator and manufacturer aim to minimize their payoffs, that is, the discounted value of operational costs, by adopting appropriate strategies over an infinite time horizon. Both the open-loop and feedback equilibria represent the solutions of the game assuming specific conditions. The open-loop equilibrium depends only on time, and the feedback equilibrium is based on the state variable at that particular time (Chiang, 2012).

6.1 Open-Loop equilibrium

Based on the open-loop concept, both the regulator and the manufacturer are forward-looking to make their ex ante decisions, by depending on time. Following the model setting described in previous section, the regulator announces an inspection plan before the manufacturer invests in her abatement effort for each time period. We analyze the game through backward induction. First, we focus on solving the manufacturer's problem; then the regulator's problem is solved recursively based on the manufacturer's best response. The open-loop equilibrium is presented in the following proposition.

Proposition 2. *When the regulator and manufacturer are both forward looking, the open-loop abatement effort and regulator's expectation, respectively, are given by*

$$\theta^{OL}(t) = \frac{k\beta p_0}{c_e(h_0+h)}e^{-ht} \quad \textit{and} \quad \tau^{OL}(t) = \frac{w\gamma p_0}{c_p(h_0+h)}e^{-ht}; \tag{6}$$

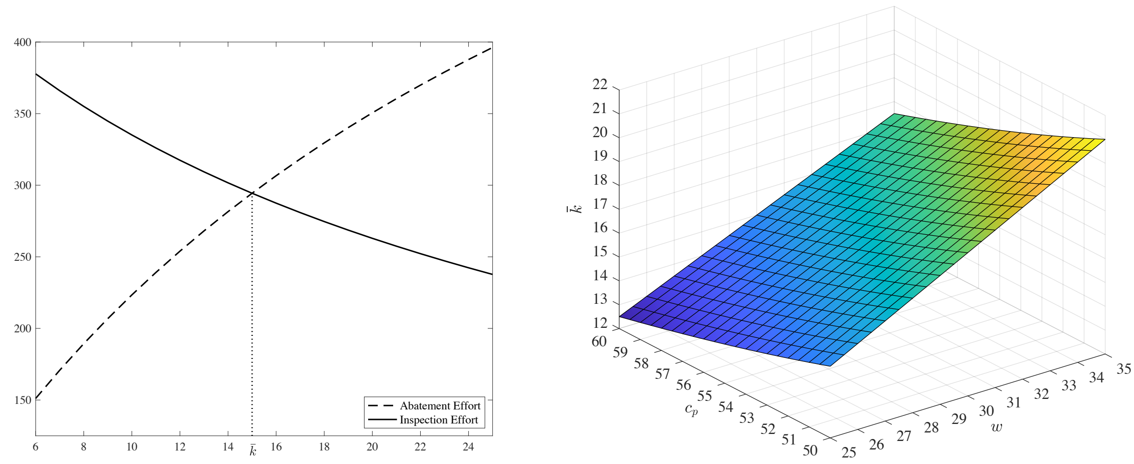
moreover, the cumulative pollution stock over time is characterized by $p^{OL}(t) = p_0 e^{-ht}$*, where* $h_0 = \rho - \alpha$*,* $h = (\sqrt{(\rho-2\alpha)^2 + C} - \rho)/2$*, and* $C = 4(k\beta^2/c_e + w\gamma^2/c_p)$*.*

A reasonable outcome can be observed based on this proposition; that is, the cumulative pollution stock shows a monotonically decreasing trend over time. This occurs because that a higher level of inspection increases the abatement effort and reduces the pollution stock. Another way to explain this outcome is that the manufacturer must adhere to the preannounced inspection level to avoid violation. Specifically, if the manufacturer learns the variance trend of inspection level, facing a smaller β, a low abatement effort would lower the mitigation speed; thus, a higher penalty should be paid by the manufacturer in early periods. This compels the manufacturer to improve/enhance the abatement effort, even when it is costly to invest in abatement activity. However, when pollution stock is decreasing, both the inspection level and abatement effort also show a monotonically decreasing trend over time. Meanwhile, we find another interesting result for the effective threshold of penalties. In other words, this reasonable threshold can be used to establish an alarm rejection effect, as shown in the following corollary.

Corollary 1. *Given the open-loop equilibrium,*

(i) the violation can be avoided if the penalty is no less than the threshold, i.e., $\bar{k} = \frac{\gamma w c_e}{\beta c_p}$*;*

(ii) the threshold $\bar{k}$ *is submodular in* (w, c_p)*.*

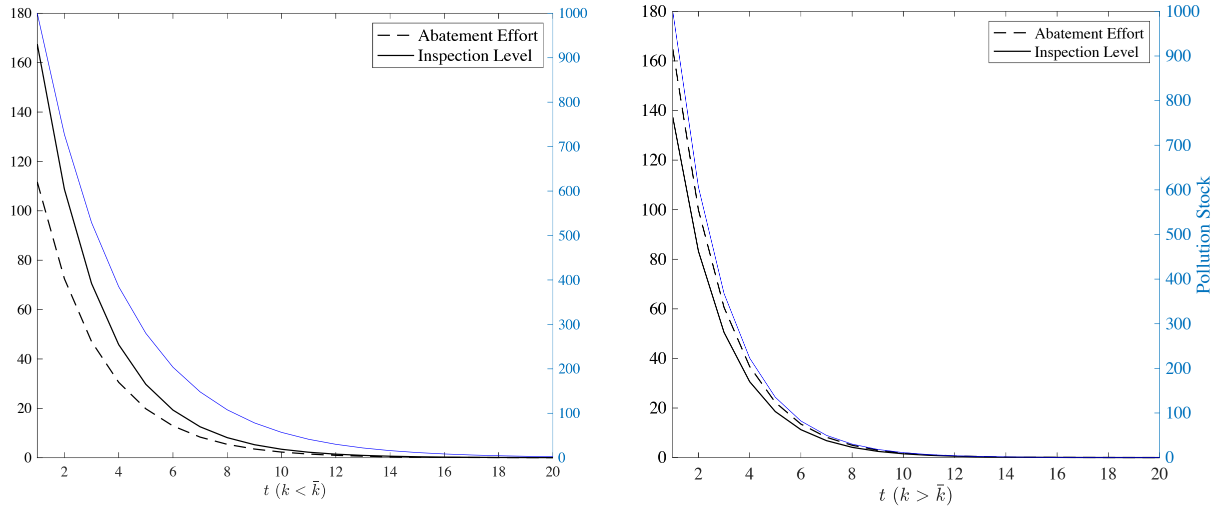


(i) (ii)

Figure 1: The Effects of Penalty

Corollary 1(i) shows that the regulator can identify an effective threshold, that is, $\bar{k}$. This can be used to force the manufacturer to enhance its efforts. This is because the incremental penalty cost increases with the pollution stock, thereby decreasing with her abatement efforts. This result is validated in a numerical example, and we set $w = 25$, $c_e = 30$, $c_p = 50$, $\beta = 0.5$, $\gamma = 0.5$, and we also vary k from 6 to 25 in increments of 1. As we can see from Figure 1(i), with an increasing in the pollution penalty, the regulator's inspection effort shows the decreasing trend. In other words, the regulator prefers a higher pollution penalty to reduce inspection costs. Meanwhile, to avoid excessive penalties, the manufacturer must improve production efficiency and reduce pollution. In such a scenario, we observe that a manufacturer can improve itself and upgrade from noncompliant to compliant. The submodularity of $\bar{k}$ shows that, to cut the inspection cost (c_p), the regulator should increase the pollution penalty (k)

when facing a higher social welfare loss (w), see Figure 1(ii). In addition, Figures 2 and 4 show that, when the regulator faces a higher pollution penalty (larger than $\bar{k}$), greater abatement effort is required to reduce pollution stock, while the regulator would benefit from a lower inspection level. In contrast, when $k < \bar{k}$, even with a higher inspection level, the manufacturer world invest only in passive efforts and the pollution stock would decline much more slowly than in the scenario with a larger penalty.



(i) (ii)

Figure 2: Open-Loop Abatement Effort, Inspection Level, and Pollution Stock

It is noteworthy that the open-loop equilibrium is time inconsistent and a static concept. In other words, the original best decisions based on the open-loop equilibrium cannot reflect the variance regarding the state variable (Dockner et al., 2000). This also implies that the irreversible pre-commitment decisions can be made by both the manufacturer and the regulator at the beginning (Gallego and Hu, 2014). In practice, this result can be implemented by designing a series of abatement targets for the manufacturer. However, periodically revisiting the inspection level could effectively induce the manufacturer's abatement efforts, while updating the initial inspection level would effectively control the cost of inspection and to mitigate the pollution. This leads to the following question: would the regulator achieve mutually beneficial results (i.e., minimize optional costs and mitigate the pollution) by adjusting the inspection level over time? Thus, it is worth investigating the feedback equilibrium in order to design a more flexible inspection plan. According to the state equation, the pollution stock is influenced by the interaction between the regulator's inspection level and the manufacturer's abatement efforts. Given such a scenario, both the manufacturer and the regulator could design/adjust their actions/decisions associated with the state of the pollution stock; that is, timely adjustment based on the variance in the states of pollution stock could to minimize the overall discounted operational costs for both the manufacturer and regulator.

6.2 Feedback equilibrium

In this subsection, we investigate the feedback equilibrium, which is more flexible and time consistent than the open-loop equilibrium. Feedback equilibrium specifies the abatement effort and inspection level for any time period, and jointly, the pollution stock in each period. Conversely, the open-loop equilibrium only focuses on the variance in the abatement efforts and the inspection levels as a function of time (i.e., a time dependent control path). According to the dynamic concept, the strategic inspection level and abatement effort at each time period is determined by the pollution stock in the each period.

Proposition 3. *When the regulator and manufacturer are both forward looking, the feedback abatement effort and regulator's expectation, respectively, are characterized by*

$$\theta^{FB}(t) = \frac{-\beta}{2c_e}(A_f p^{FB}(t) + B_f) \quad and \quad \tau^{FB}(t) = \frac{-\gamma}{2c_p}(A_r p^{FB}(t) + B_r); \tag{7}$$

and the corresponding pollution stock over time is given by $p^{FB}(t) = p_0 e^{Mt} - \frac{N}{M}(1 - e^{Mt})$*, where* $M = \frac{1}{2}\left(2\alpha + \frac{A_f\beta^2}{c_e} + \frac{A_r\gamma^2}{c_p}\right)$ *and* $N = \frac{1}{2}\left(\frac{B_f\beta^2}{c_e} + \frac{B_r\gamma^2}{c_p}\right)$.

Unlike the static outcomes in the open-loop equilibrium, Proposition 3 characterizes the trajectory of strategic decisions in regard to the variance in the pollution stock. With the fixed abatement effort and inspection level, regardless of the pollution stock, both the feedback equilibrium of the manufacturer's effort and the regulator's inspection level are linear and increase with pollution stock. That is, this proposition indicates more reasonable solutions are characterized in this proposition that are dependent on the amount of pollution stock and vary over time. Following the same parameter's setting, as we can see from Figure 3, the pollution stock shows a decreasing trend; given the status of pollution stock, both the regulator and the manufacturer could dynamically adjust their actions. The feedback inspection level decreases over time with a relatively higher initial setting and converges to a fixed constant. Accordingly, the manufacturer's abatement effort level also shows a decreasing trend. This is because that the feedback equilibrium fully considers the interaction among the inspection level, the abatement effort, and the pollution stock over the time horizon. Both the feedback inspection level and abatement effort are decrease with respect to the reduced pollution stock.

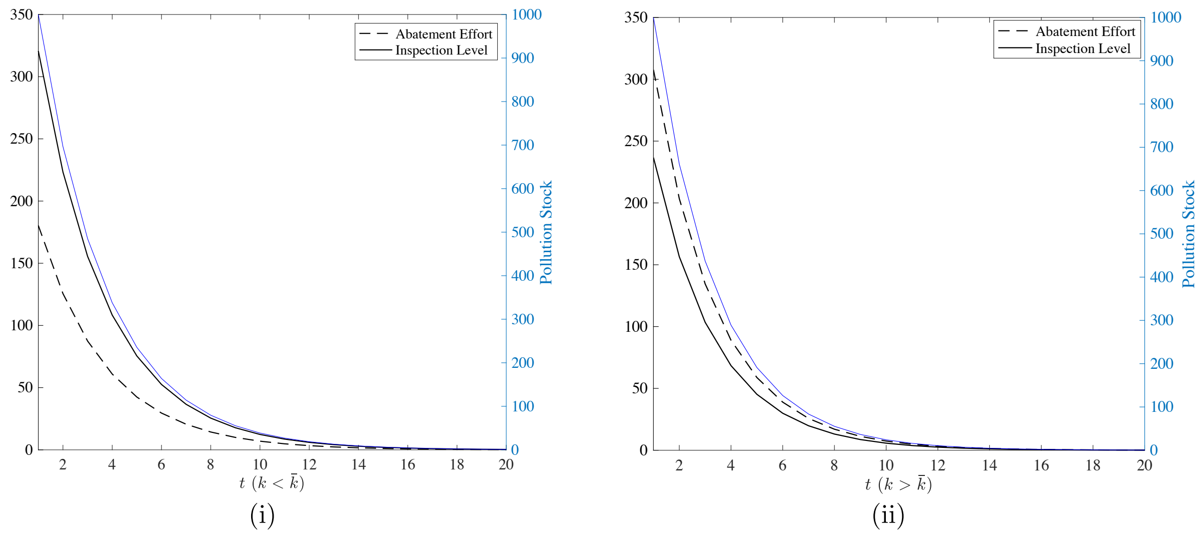


Figure 3: Feedback Abatement Effort, Inspection Level, and Pollution Stock

6.3 Efficient control through penalty

In this section, we investigate the impacts of penalty on the manufacturer's abatement effort, the regulator's inspection decision, and their operational costs. The existence of an efficient penalty threshold can generate a profound effect on the design of the reasonable environmental inspection scheme. When such a scheme exists, there is an incentive for the manufacturer to improve her abatement efforts, while the regulator only requires involving a lower inspection level. In line with the equilibrium outcomes in Propositions 2 and 3, and the parameter's setting in previous sections, the observations are summarized as follows based on the simulation results.

Observation 1. *Compared with the benchmark without inspection, the regulator always benefits from the periodic inspection to improve social and environmental responsiveness.*

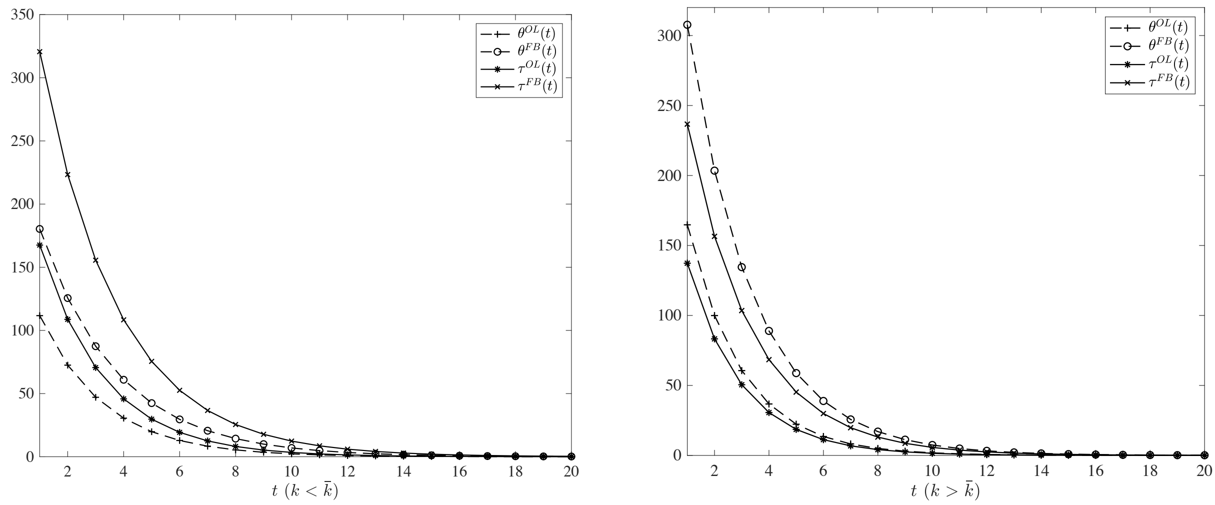
Observation 2. *Given the results of theoretical analysis,*

(i) the feedback abatement effort and inspection level are greater than those obtained using the open-loop equilibrium;

(ii) the pollution can be effectively controlled through adjusting penalty by the regulator

- *when $k \leqslant \bar{k}$, the regulator's inspection input is greater and the manufacturer may behave the cosmetic improvement;*
- *when $k > \bar{k}$, the manufacturer has to make more abatement effort, which can lower the regulator's inspection input.*

The observations provide interesting results. The feedback equilibrium incurs an intensified response. The open-loop equilibrium generates the static policy in regard to the manufacturer's abatement effort and the regulator's inspection level to minimize their operations costs. This policy ignores the impacts of pollution penalties and the loss of social welfare, which perform like a myopic solution. In contrast, the strategic interaction between inspection and improvement becomes inevitable when using the feedback equilibrium, that is, a dynamic policy. This motivates the use of the dynamic policy to induce the manufacturer to enhance abatement efforts, which would effectively control pollution and benefit both manufacturer and regulator.



(i) (ii)

Figure 4: The Comparison of Open-Loop and Feedback Equilibrium

With a higher inspection input and a smaller penalty, the manufacturer would be induced to consider self-improvement and avoid excess penalties. In reality, this can generate the positive results for the society. Abatement efforts will significantly reduce a manufacturer's noncompliance; conversely, greater inspection input will effectively control and minimize the environmental pollution. In addition, it is noteworthy that, as we can see from Figure 4, the regulator's inspection input is always greater than the manufacturer's abatement effort. This result implies that the regulators inspection plays a decisive role; that is, environmental governance mainly depends on a higher inspection input. In such a scenario, we find an interesting result; that is, the manufacturer may make a merely *cosmetic improvement* to avoid excess penalties. Therefore, to avoid the manufacturer's cosmetic behavior, a more effective scheme can be proposed by increasing the pollution penalties. Given the threshold identified above, the simulations are conducted for a larger and a smaller penalties, respectively; this illustrates the aforementioned analytical outcomes, as shown in Figure 4. The regulator can effectively design a more efficient inspection scheme based on both the feedback equilibrium and the threshold of penalty.

7 Conclusions and Implications

This study sheds new light on alleviating environmental incidents of the suppliers or manufacturers, from empirical and theoretical perspectives, in the emerging markets, e.g., China. This is a significant factor that reflects the environmental reputation of the buyer (Kumar et al., 2019). Based on the collected data on China's manufacturing sector, the empirical study analyzes the relationship between inspection frequency and a manufacturer's environmental performances (i.e., the number of environmental violations). We find that a higher level of inspection frequency could reduce the manufacturer's subsequent environmental incidents (at the year after the inspection, or in the first year). However, this result would not last in the long term (i.e., year 2-3). These results suggest that the current environmental inspections have not been effective in China.

We enhance the empirical results by developing an analytical model to understand the limited effectiveness of environmental inspection. Specifically, we formulate the game-theoretical model to analyze the intersection behaviors between the regulator and manufacturer, in a dynamic environment. The analytical results indicate that the inspection aims to improve the public environmental welfare by reducing the environmental pollution and enhancing the manufacturer's abatement efforts, that is, the environmental performance. Counter-intuitively, the inspected manufacturer may perform a mere cosmetic improvement to avoid pollution penalties and control the abatement costs. This analytical outcome also justifies the result of the empirical study. Based on the structured analysis above, we identify the thresholds of pollution penalty that can be used to increase the effectiveness of governmental inspection. In addition, we find that both repeated inspection and increased penalties can motivate manufacturer abatement efforts, and thereby, reduce pollution.

To summarize, we examine the effective inspection policies, including inspection frequency, abatement efforts, and environmental penalty, to guide regulators and manufacturers to make appropriate decisions that can promote sustainable operations. We also discuss the implications for scholars, government, and manufacturers, respectively.

7.1 Implications for scholars

Regarding environmental and safety enforcements and noncompliance, the sustainable operations literature has focused on firm-level antecedences, such as the OHS management system (Lo et al., 2014), operational coupling (Wiengarten et al., 2017), changes in debt (Pagell et al., 2019), and manufacturing firm performance feedback (Wiengarten et al., 2019). These studies mainly investigate violation behavior from an intra-organizational perspective. However, the occurrences of violations depend on inspections initiated by the government (an external stakeholder). The government should be considered as the initiator and manufacturer the responder in the inspection process. The lack of an interaction between the two actors leads to an incomplete understanding of the effectiveness of governmental enforcements. In addition, the literature has assumed that inspection is random and independent (Levine et al., 2012). However, given the status of a manufacturer's pollution stock, both the regulator and the manufacturer could dynamically adjust their decisions. For example, governments may pay extra visits to manufacturing firms heavily polluting the environment. Therefore, this study contributes the literature by taking inter-organizational and dynamic perspectives to investigate the manufacturer's reaction to the environmental enforcement. This study advances the sustainable operations literature by expanding the existing focus on noncompliance to understand the interaction between operational decisions and the pressures from external stakeholders. Specifically, we highlight the validity and limitation of governmental enforcement on manufacturer's decision to invest in environmental practices. Future research may investigate whether other external stakeholders (e.g., customers, non-government organizations, and professional institutions) can influence a manufacturer's noncompliant behaviors.

Second, we contribute to the supply chain literature by developing a multimethod approach (i.e., empirical and theoretical models) to investigate the supply-side environmental violation and abatement. In addition, the existing government inspection literature focuses on the enforcement effectiveness in developed countries, where the law and enforcement are more stringent (e.g., Glicksman and Earnhart, 2007; Levine et al., 2012). However, the developing countries suffering from severe pollution issues have less stringent environmental law enforcement (Gray and Shimshack, 2011), rendering enforcement effectiveness questionable in these contexts. Thus, this study advances the knowledge on environmental law enforcement by utilizing the Chinese context. Specifically, it studies the relationships between environmental enforcement (of government) and environmental performance (of manufacturers) in China. We find that the inspections can reduce a manufacturer's subsequent violation in the near future (one year), which is in line with the findings derived from the developed countries (e.g., Levine et al., 2012). However, we capture a pattern that such improvement in environmental performance is short term in nature. The number of environmental incidents bound back in the second and third years from the inspection. Our analytical analysis results show that manufacturers exert abatement efforts in response to the inspection, while these abatement efforts are adaptive and cosmetic in nature. Thus, the current inspection regime fails to provide an incentive to encourage continuous improvement in manufacturer's environmental practices.

The captured manufacturer's adaptive responses to environmental inspection supports the rational choice perspective. This perspective considers that the manufacturer will pursue a balance between abatement costs and violation (punishment) costs to determine the level of abatement efforts (Greve et al., 2010). Affected by this cost consideration, manufacturers may restrict their abatement efforts after meeting the governmental requirements. In addition, exploring potential loopholes in environmental practices is costly because it requires recruiting experts and purchasing detection equipment. Thus, the manufacturer may rely on government inspections, which will hinder the manufacturer's to conduct proactive improvement practices for a greener operation. As discussed in Section 2.1, the ideal circumstance is that the manufacturer can view inspection as a "behavioral shock" that can motivate a proactive and long-term improvement in environmental practices (Mendeloff & Gray, 2005). Our analytical analysis results suggest that the increased penalties can make such a shock more appealing to the managers. Further, the penalty can be taken as the boundary condition between rational choice and behavioral shock perspectives on the environmental enforcement.

Last, our study also contributes to the stream of OM literature using the multimethod approach. Previous studies address have applied the approach differently depending on whether the study is an inductive or deductive in nature. An inductive study may use a method to exploratorily build theory, then use another method for verification. For example, Chandrasekaran et al. (2016), Barratt et al. (2018), and Sting et al. (2019) all used case study as the first step to explore the focused issues. Then the case study findings were verified through simulation techniques. Similarly, Chen et al.'s (2016) case study findings were verified by a scenario-based experiment. In deductive studies, theories were first tested by empirical data. The empirical analysis findings were then further understood through another research method, such as the mechanism and boundary condition of the empirical findings. For example, Venkatesh et al. (2010) first used survey data to test the impacts of information and communication technology on employee's job performance. Contextual factors were further explored through case studies. Tong et al. (2016) first used a survey with a clustering analysis approach to confirm the classification of CSR implementation in China as leader, follower, and laggard. Then, an agent-based simulation approach was adopted to deeply understand the factors contributing to the choice to implement CSR. This research demonstrates a way to execute the cooperation between empirical and analytical modelling methods.

7.2 Implications for governments

This study provides significant policy implications for governments to enforce environmental law. Our study can guide regulators on how to adjust inspection frequency (effort) to minimize the loss of public environmental welfare and the inspection costs. The regulator can also benefit from our finding by adopting the flexible strategies in the long term; that is, they can learn how to design a reasonable penalty, given the expensive inspection process and limited budgets.

Public environmental welfare is the primary objective of regulators. However, our findings show that, during the examined period, the enforcements in China had limited effect on pushing manufacturers to reduce pollutions. Specifically, the effect was significant only in the first year after the inspection. This result indicates that, during this period, manufacturers may perform a cosmetic improvement. Thus, these results provide the Chinese government with a basis to evaluate and review the current environmental law and enforcement processes.

Our results provide implications for the regulator to design reasonable inspection frequency and manufacturer violation penalties. Based on the rational choice perspective, the increased likelihood of an exposure and the amount of penalty levels affect the perceived costs of environmental violation, which motivates manufacturers to increase their abatement efforts. Our analytical results (see Section 5.3) further confirm this proposition by showing that the increased penalties and inspection frequency are associated with the increased abatement efforts of manufacturers. The marginal effect of penalties is larger than that of the frequency of inspection. However, the integration of the two factors can be the most effectiveness. Based on these results, we summarize the effectiveness of different enforcement policies in Table 7.

	One-time inspection (Open-loop policy)	Frequent inspection (Feedback policy)
Low penalty level	The least effective enforcement policy: Low abatement efforts of inspected firms	The 3^{rd} effective enforcement policy: Low to moderate abatement efforts of inspected firms
High penalty level	The 2^{nd} effective enforcement policy: Moderate to high abatement efforts of inspected firms	The most effective enforcement policy: High abatement efforts of inspected firms.

Table 7: The effectiveness of enforcement policies for the manufacturing firms

The regulator must focus on conducting periodic inspections with a higher inspection frequency in a short time gap. That is, based on the proposed enforcement strategies in Table 7, an iterative modification of existing environmental regulations accompanied by a short-term, effective inspection, and communication, are more likely to protect the environment. The most effective enforcement policy with a high penalty level is also reasonable because firms tend to flout legislation if environmental regulations are not adequately enforced. This approach works in a scenario in which the government has sufficient inspection resources and budget or a key regulatory target. We note that administration costs of frequent inspection are high. Thus, the governments with limited administrative resources are recommended to adopt an open-loop policy accompanied by a high violation penalty level. Such a policy can also motivate the manufacturing firms to improve the environmental practices proactively. However, the regulator using this policy should ensure that the firm makes a cosmetic improvement to avoid environmental penalty in the long term.

7.3 Implications for manufacturers

Considering the sustainable OM perspective, we empirically and theoretically analyze the impacts of regulator's inspection on environmental incidents and the manufacturer's abatement behavior. The manufacturer can gain a deeper understanding of controlling its environmental abatement efforts by considering the regulations enforced through an inspection. Specifically, our finding shows that manufacturers tend to take an adaptive response to environmental inspection, which is not ideal for the continuous improvement in environmental practices. Nowadays, green operations provide sustainable competitive advantages, such as offering eco-friendly products and obtaining financial support to firms; further, any environmental incidents can seriously undermine the firm value (Lo et al., 2018). The buyer's environmental reputation is negatively influenced by the manufacturer's noncompliance activity (Kumar et al., 2019). Therefore, we urge the managers to view inspections as a valuable intellectual capital to learn from and proactively improve environmental performance, and reduce future environmental incidents. This will not only can reduce penalties but will also generate positive results for protecting the environment and enhancing the manufacturer's CSR.

7.4 Limitations

Despite its rigorous multimethod approach to answer the research questions, several limitations need to be addressed in future research. First, our empirical samples only focus on listed manufacturers that have more organizational resources. Private manufacturing firms may have limited financing channels to obtain resources to improve environmental practices. Therefore, future research may sample small and medium enterprises and explore their reaction to the environmental enforcements. Second, this study only focuses on the environmental inspection, while safety inspection is not included. The consequence of violating laws pertaining to occupational health and safety law may be more serious because the accidents can directly disrupt production processes and hurt workers. Future research may explore the interaction between safety enforcement and a manufacturer's improvement in safety practices. Third, the environmental incidents in our samples are reported by the government. It is worthwhile to study the impact of social media disclosure of environmental incidents because such negative publicity can be disseminated in a faster and broader manner. Manufacturers may increase the abatement efforts to mitigate the negative impacts. Fourth, future research may investigate how the key factors (e.g., consumers' willingness to pay for the eco-friendly products) affect the production technology choices of a manufacturer and its abatement efforts.

Endnotes

1. We focus on manufacturing firms because manufacturing operations constitute a major source of pollution in China.

2. IPE is a Beijing-based non-governmental organization (NGO) that identifies environmentally non-compliant Chinese manufacturing firms and reports their non-compliance on its website (IPE, 2010).

3. The natural logarithm was to correct for the skewness of total assets.

4. Apple Environmental Responsibility Report, 2018: https://www.apple.com/environment /pdf/Apple Environmental Responsibility Report 2018.pdf

5. Resource Conservation and Recovery Act (RCRA) Laws and Regulations: https://www. epa.gov/rcra

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