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Essays on Supply Chain Optimization: Operational Decisions With Corporate Social Responsibility Implementation and Live-streaming Channel Introduction

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ABSTRACT

In this dissertation, we study a supplier's operational decisions for supply chain optimization considering corporate social responsibility implementation and live-streaming channel introduction. Both essays start from analytical models that are inspired by observations, and we explore how different parameters affect the supplier's decisions through extensive numerical studies. In the first essay, we notice that cost auditing is becoming an increasingly important tool to improve supply chain efficiency and mitigate the influence of information asymmetry. We study how cost auditing indirectly influences retailer and supplier's behavior in social responsibility. We also discuss the potential negative social responsibility externalities of conducting an audit and the managerial insights. Finally, we find that customers' attitude towards different products changes retailer and supplier's social responsibility preference. In the second essay, we are interested in a new trend where suppliers today adopt live-streaming channels for online shopping. We analyze the trade-off between potential market demand and channel competition by introducing live-streaming channel and discuss the impact of live-streaming channel on supply chain optimization. As a result, both essays shed light on how suppliers respond to downstream companies' operational decisions.

ESSAYS ON SUPPLY CHAIN OPTIMIZATION: OPERATIONAL DECISIONS WITH CORPORATE SOCIAL RESPONSIBILITY IMPLEMENTATION AND LIVE-STREAMING CHANNEL INTRODUCTION

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Introduction

1.1. Overview of Essay 1

Firms increasingly recognize the importance of their upstream suppliers' social responsibility. However, they may fail to heed the unintended negative consequences of their own common practices on the suppliers' social responsibility decision. We consider a setting where both the customer demand and the production cost depend on the supplier's social responsibility level. The supplier has private information about his unit production cost, and the retailer uses an incentive contract, coupled with an audit, to induce truthful reporting of the supplier's cost type. We focus on the impact of cost auditing on the supplier's social responsibility decision. We find that the impact hinges on consumers' response to social responsibility. When demand takes the additive form as a result of the consumer response, the cost of information asymmetry does not change the supplier's social responsibility decision, whereas an audit intended to counteract the information asymmetry may cause the supplier to either increase, decrease, or maintain his social responsibility, depending on model parameters. When demand takes the multiplicative form, we find that the information asymmetry causes the supplier to deviate from his first-best solution, but the deviation is limited. The supplier always adjusts his social responsibility level in response to the audit. In cases of upward adjustments, the magnitude is typically insignificant. In cases of downward adjustments, however, the reduction is typically more noticeable. Our findings suggest that a downstream firm's seemingly unrelated common practices may often inadvertently undermine the supplier's social responsibility choice, which sheds light on the reluctance of many suppliers to commit to social responsibility programs.

1.2. Overview of Essay 2

Live-streaming shopping has become a significant and powerful sales force nowadays. It allows viewers to watch and shop through real-time interactions over the phone. More and more companies start to launch their live-streaming shopping to consumers. We investigate how a supplier responds to the fast-growing live-streaming commerce and if a supplier should collaborate with key opinion leaders (KOLs). We first examine multiple centralized settings when a supplier builds his own live-streaming teams and hosts live sessions. Our analysis shows that the supplier faces a trade-off between the potential market demand increase and the channel competition. The supplier should only use the traditional channel if the live-streaming channel cannot attract many consumers. Otherwise, despite the channel competition, the supplier should use a dual-channel supply chain or a single live-streaming channel for profit maximization. Note that when the channel substitution is low, the dual-channel supply chain can dominate the single-channel options. We also design a two-stage game to formulate one decentralized case that the supplier offers a revenue-sharing contract and sells products through a KOL's stream. Our results show that the supplier and the KOL will be discouraged in media investment compared with the centralized models, which might decrease the supplier's expected profit eventually.

Chapter2

The Impact of Cost Auditing on Supply Chain Social Responsibility

2.1. Introduction

Corporate social responsibility (CSR), broadly speaking, is a self-regulating business model that helps a company be socially accountable—to itself, its stakeholders, and the public. By practicing corporate social responsibility, companies can be conscious of the kind of impact they are having on all aspects of society, including economic, social, and environmental (Investopedia, 2021). CSR, along with a closely related concept ESG (environment, social, governance), which sets measurable goals for CSR, has become an increasingly higher priority for companies, driven by pressure from key stakeholders including consumers, regulators, and investors.

A growing body of academic research and consumer surveys have shown that CSR is now woven into the very fabric of how consumers lead their lives. They reveal that global consumers view CSR as a personal responsibility to be integrated and championed. For instance, Lee and Shin (2010) find a significant positive relationship between a company's CSR activities and consumers' purchase intention scales. Huang et al. (2017) report that CSR perceived by customers has a strong effect on fostering long-term loyalty. A survey in 2019 shows that 47% of internet users had switched to a different brand because the company violated their personal values (Insider Intelligence, 2019).

In an attempt to promote ESG awareness and transparency, the U.S. Securities and Exchange Commission (SEC) has issued a flurry of notices that ESG disclosures will be priorities in 2021 (The New York Times, 2021). Investors are expecting companies to more clearly explain how they are addressing ESG matters, as they realize that companies with a convincing ESG strategy can positively influence their future growth and reduce risks. According to a proxy season study in 2019, more than 50% of investors surveyed consider ESG to be the top management priorities. 77% European institutions and 65% U.S. institutions claim that they have an explicit ESG policy in their own organization (Ernst & Young LLP, 2020). Morningstar (2020) reports that the U.S. sustainable funds available to investors reached 10.5 billion in the first quarter of 2020, which is around 1.5 billion more than the record in the fourth quarter of 2019.

It is well-known that a supplier's social responsibility violation scandals have a ripple effect throughout the entire supply chain. For instance, a series of suicides of Foxconn's assembly line workers, due to immense stress, long workdays, unfair fines, unkept promises of benefits, and harsh managers who were prone to humiliate workers for mistakes, caused a media sensation – suicides and sweatshop conditions in the House of iPhone, as the tragedies took place at Foxconn's enormous plant in Shenzhen, China, which is a major manufacturer of Apple products (The Wall Street Journal 2011; CNN 2012). As a result, various rights groups demonstrated outside Apple stores in multiple cities around the world. Failure to correctly act on ESG policies also caused a building collapse in Bangladesh in 2013 with more than a thousand deaths (The New York Times 2013; The Guardian 2013). The building housed a number of separate garment factories that manufactured apparel for brands including Walmart, Benetton, Prada, Gucci, Versace, and Mango. As the public outcry grew, a group of seventeen major North American retailers, including Walmart, Gap, Target, and Macy's, announced a plan to improve factory safety in Bangladesh later that year. McDonald's was forced to cut ties with one of its chicken suppliers in 2015 after gruesome video footage made public appeared to show the supplier clubbing small and sickly birds to death (USA Today, 2015). The company reported in 2020 to have made substantial efforts to achieve every one of its responsible sourcing goals related to sustainably sourcing its priority commodities, including beef, chicken, coffee, palm oil, fish, and fiber-based guest packaging (McDonald's, 2020).

All the aforementioned examples point to the critical influence of a supplier's social responsibility level on downstream firms. Evidently, it is in the downstream firms' interest to provide incentives to bolster the supplier's social responsibility. Less evident is the peril that certain operations of the downstream firms, albeit well justified apparently, may *inadvertently* lead their suppliers to a lower social responsibility level. Cost auditing we study in this paper may be such a perilous practice that can cause unintended negative consequences.

Accounting research has documented that cost is a function of factors such as asset intensity, demand uncertainty, financial risk, supplier and labor relations (Hongren et al., 2012). A supplier's production cost is usually guarded as a top trade secret, as failure to protect cost information could expose him to significant risks and jeopardize his bargaining power in negotiating contracts with his business clients. In the presence of cost information asymmetry, the retailer can design an incentive contract to induce the supplier to truthfully reveal his private cost information. This, however, requires the retailer to pay a premium as the information rent to the supplier and distort her decisions, thus causing the so-called agency loss.

A cost audit comes in handy in such a situation, as it can further deter the supplier from misreporting his cost information and mitigate the agency loss. Cost audits have been reported to be widely used in supply chain management. Professional organizations such as the International Associations of Commerce and Contract Management (Contract Standards, 2018) recommend that cost audits be included as part of the standard supply chain contract clauses of "financial audit." Such audit clauses state that a buyer has the legal right to audit its suppliers' cost if the cost affects the execution of the contract. In practice, many specialized third-party audit services, such as Dryden Group (https://drydengroup.com/procurement-audit/), are readily available. Cost auditing is also common across the world. For instance, Indian companies in certain industries, such as manufacturing, mining, and services, are required to undergo a cost audit under the Companies Act, 2013. The Institute of Cost Accountants of India provides detailed guidelines on audit procedures of material, labor, and other costs.

To better understand the implications of cost auditing, we consider a two-tier supply chain consisting of a supplier (him) and a retailer (her). In the presence of private production cost information possessed by the supplier, the retailer designs an incentive contract with a potential cost audit. We concentrate on two major research questions: first, how does the retailer's audit mechanism affect the supplier's social responsibility decision? Second, to what extent does the impact of the audit mechanism hinge on market parameters and consumers' response to social responsibility? To answer these questions, we formulate a two-stage problem where the supplier chooses his social responsibility level in the first stage, in anticipation of the retailer's rational response. In the second stage, we adopt the principal-agent framework to model the optimal audit mechanism designed by the retailer (the principal), given the supplier's social responsibility decision in the first stage.

Needless to say, a high social responsibility boosts customer demand. But different consumer responses to the social responsibility could result in demand being amplified in different ways – termed additive and multiplicative demand models in our paper. It turns out that the different consumer responses play a pivotal role and the two corresponding demand models lead to distinct findings. In the additive demand model, we find that while the information asymmetry does not alter the supplier's social responsibility decision, an audit, which is meant to counteract the information asymmetry, may cause the supplier to increase, decrease, or maintain his decision, depending on parametric conditions. In the multiplicative model, the information asymmetry always causes the supplier's social responsibility level to deviate from its first-best solution, but the deviation is limited. The threat of an audit prompts the supplier to adjust his social responsibility level. In cases where the social responsibility level is decreased, the reduction is typically significant. Our results suggest that, from a managerial point of view, downstream firms should be mindful of noticeable unintended negative consequences of cost auditing. In addition, it is crucial for them to have a thorough understanding of the market parameters and the way consumers react to the supply chain's social responsibility level when considering a cost audit.

To the best of our knowledge, we are among the first to examine the potential negative impact of a downstream firm's common practice on the upstream supplier's social responsibility decision. Our findings caution practitioners to take a more complete view of their operations in order to avoid undermining the supply chain's social responsibility. Evidence in recent years suggests that despite the critical importance of CSR, many firms still lack commitment to CSR programs. Institutional Investor (2019), for instance, finds that many of the companies identified on Fortune magazine's annual Change the World list do not achieve the top ESG rankings in their industries, nor do they have any significant presence of socially responsibly investment (SRI) funds in their share registry. An Alfac survey also brings to light that 57% executives find it difficult to get their CSR programs funded, and investors estimate that, on average, only 45% of the companies they have invested in are socially responsible (Aflac, 2016). Moussu and Ohana (2016) provide a financial leverage interpretation of the underinvestment in CSR. Our paper offers a different angle through the lens of supply chain management to understand companies' insufficient commitment.

2.2. Literature Review

There has been increasing research interest in socially and environmentally responsible supply chain management in recent years (Deshpande and Swaminathan 2020; Feng et al. 2017), and the scale and scope of research are expected to keep growing in the near future (Atasu et al., 2020). Lee and Tang (2018) and Lee (2021) discuss new research opportunities in this area and describe sample research works based on real-life practices. We briefly review papers closely related to our work in this rapidly expanding research area.

Many researchers have studied various ways to induce, improve, or implement socially and environmentally responsible supply chains. Porteous et al. (2015) use empirical data to test the relationship between the buyer's supplier incentives and penalties for the supplier's social and environmental compliance, and the outcomes in terms of reduction in supplier social and environmental violations as well as the buyer's own operating costs. Letizia and Hendrikse (2016) study the impact of supply chain structures on the adoption of CSR activities. They show that incentives for CSR investments can be provided through the supply chain structure and that the structure that best incentivizes CSR investments depends on the interaction between CSR vertical synergy, free-riding, and countervailing power. In a similar spirit, Orsdemir et al. (2019) study vertical integration as a mechanism to address corporate social and environmental responsibility (CSER). They also investigate conditions under which CSER concerns will drive vertical integration. Wang et al. (2017) and Chuang et al. (2014) study the relationship between channel dynamics and sustainability. Guo et al. (2016) analyze the sourcing decision of a buyer choosing between responsible suppliers who adhere to strict social and environmental responsibility standards and risky suppliers who may experience responsibility violations. They show that efforts to improve supply chain responsibility that focus on consumers or increasing supply chain transparency may lead to unintended consequences, such as an increase in risky sourcing. Agrawal and Lee (2019) examine how a buyer can use sourcing policies to influence their suppliers to adopt sustainable processes. Feng et al. (2021) apply a bargaining framework to study the implementation of environmental and social responsibility programs in a general supply network.

Several papers study the role of information disclosure in addressing CSR. Cho et al. (2019) consider a setting where a manufacturer may or may not disclose to the public its amount of effort to inspect the supplier's employment of child labor. They find that information disclosure can reduce the use of child labor under certain conditions. Kalkanci and Plambeck (2020a) explore conditions under which a buying firm can increase supplier responsibility by committing to publish a list of its suppliers and/or the identities and violations of terminated suppliers. Kalkanci and Plambeck (2020b) consider the scenario where a buying firm might in the future incur costs associated with a supplier's social or environmental impacts. They investigate whether the buying firm should learn about the supplier's impacts, how much cost to incur to reduce the supplier's impacts, and whether to disclose the supplier's impacts to investors. They find that mandatory disclosure deters learning and thus, under plausible conditions, results in higher expected supplier impacts.

The majority of the responsible supply chain literature focuses on auditing as a mechanism to motivate supplier CSR or mitigate supplier responsibility risk. Plambeck and Taylor (2016) study a range of ways (increasing auditing, publicizing negative audit reports, providing loans to suppliers) to induce higher supplier social and environmental responsibility, and characterize a backfiring condition under which the supplier will evade audits and exert less effort to prevent harm. Chen and Lee (2017) compare common supplier responsibility risk mitigation instruments, including supplier certification, process audits, and contingency payments, and evaluate their effectiveness. They find that these instruments are all complementary to each other and that when used jointly, they deliver better supplier risk mitigation results. Caro et al. (2018) assess the benefits of joint audits (buyers conduct audits jointly) and shared audits (easy buyer conducts audits independently but share audit reports with each other), and find that they outperform independent audits. Chen et al. (2020a) consider a supply network with multiple buyers and suppliers, and analyze the impact of supplier centrality on the firms' auditing priority. Chen et al. (2020b) study the effect of supplier-auditor collusion on the buyer's auditing and contracting strategy and develop collusion-reduction measures. In a recent paper, Zhang et al. (2021) study how to best conduct audits in supply chain networks with multiple tiers of suppliers.

All the above-mentioned papers examine incentives and mechanisms directly designed to address CSR. Our model differs in that cost auditing, which is a common practice to mitigate the downstream firm's asymmetric cost information disadvantage, is not directly related to supplier CSR but could seriously undermine the supplier's CSR commitment.

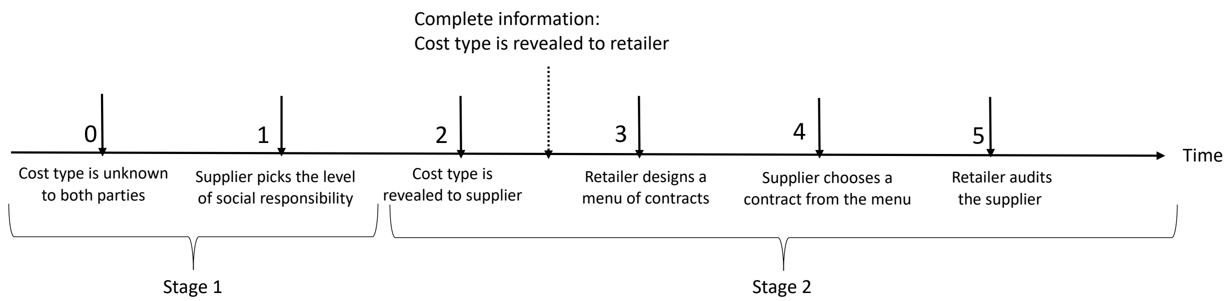
Our work is reminiscent of the literature on quality management in the sense that quality and social responsibility shape customer demand and production cost in a similar fashion (Kaya and Özer 2009; Banker et al. 1998). However, a key difference sets them apart: the social responsibility decision in our model is interlaced with the risk of supplier responsibility violations, which are usually much publicized through various channels (e.g., media, third party organizations) and receive a lot of attention, but supplier quality problems (in parts they supply) often do not manifest themselves until quality failure of the downstream buyer's final product.

2.3. Model Framework

2.3.1 Sequence of Events

Consider a two-tier supply chain consisting of a supplier and a retailer. The supplier's unit product cost could be either low (c_l) with probability w_l or high (c_h) with probability w_h, where $c_l < c_h$, and $w_l + w_h = 1$. To investigate the supplier's social responsibility level decision in anticipation of a possible audit by the retailer, we formulate a two-stage problem. The sequence of events, shown in Figure 2.1, is as follows:

Figure 2.1: Timeline of Events



Stage 1: At the beginning of the game (time 0), neither the supplier nor the retailer knows the cost type. At time 1, the supplier determines his level of social responsibility, θ, before knowing his cost type. It is worth mentioning that following prior literature (Caro et al. 2018; Kalkanci and Plambeck 2020a; Lu and Tomlin 2021), we use a single variable $\theta \in [0, 1]$ to denote the supplier's social responsibility level, which can be thought of as an aggregate measure of the supplier's degree of compliance to set industry standards. Such a modeling feature is supported by real life practices. Starbucks, for instance, has developed its Coffee and Farm Equity (C.A.F.E) program, which sets a series of ethical sourcing standards by using a published scoreboard. There are as many as 185 indicators to evaluate a supplier's behavior in economic transparency, social responsibility, environment leadership and quality. Only suppliers with an aggregate score of 80% or more would be awarded "strategic supplier" status (Daily Coffee News 2015; Starbucks Corporation 2020).

Similarly, IKEA has developed its own code of conduct, called IWAY, to evaluate its suppliers for responsibly procuring products, services, materials, and components (IKEA, 2019).

Stage 2: At time 2, the supplier learns his own cost type, which is still unknown to the retailer. At time 3, the retailer designs an audit mechanism, that is, a menu of contracts $\{p_i, t_i, x_i\},\ i \in \{l, h\}$, which consists of three elements: the unit retail price p_i, the transfer payment to the supplier t_i for goods acquired, and the audit probability x_i. At time 4, the supplier reports his cost type by choosing a contract from the menu, and finally, at time 5, the retailer audits the supplier's cost according to the audit mechanism designed at time 3 and charges the supplier a penalty o_i if the supplier misreports his cost type at time 4.

2.3.2 Model Setup

To ensure tractability and focus on the main research questions, we adopt a parsimonious demand model. The base demand is the classic downward sloping demand function $a - bp_i$, which is then augmented by supplier's social responsibility level. Conceivably, customers are more willing to purchase the product if it is sourced from a more socially responsible supplier. We consider two possible cases where customers are influenced by the supplier's social responsibility level θ. In the first case, termed additive case, an increase in θ attracts more customers to purchase the product, which effectively expands the market base from a to $a+g(\theta)$. Therefore, the demand function is given as follows:

$$q_i(\theta) = a + g(\theta) - bp_i,\ i \in \{l, h\}. \tag{2.1}$$

It is worth noting that $g(\theta)$ is assumed to be concave increasing, which reflects the fact that the pace of demand gain as a result of improved θ is typically decelerating.

In the second case, an increase in $g(\theta)$ prompts all existing customers who are willing to buy the product at the current price to increase their consumption. This is modelled as the multiplicative case as follows:

$$q_i(\theta) = (a - bp_i)g(\theta),\ i \in \{l, h\}. \tag{2.2}$$

The supplier's unit production cost consists of two parts. The first part is the base cost c_i, which has two types (low or high, i.e., $i \in \{l, h\}$), as explained earlier. The second part is $r(\theta)$, which captures the additional unit cost incurred corresponding to the social responsibility efforts. Note that $r(\theta)$ is assumed to be convex increasing, as it usually demands progressively more investments to improve the social responsibility level θ. Combined together, the supplier's unit production cost is $c_l+r(\theta)$ with probability w_l, and $c_h+r(\theta)$ with probability w_h.

2.4. Additive Demand Model

This section examines the additive demand model captured in Equation (2.1). To solve the two-stage problem, we employ the standard backward induction approach. That is, we begin with stage 2 to determine the retailer's optimal audit mechanism for a given supplier social responsibility level θ, then we go back to stage 1 to determine the supplier's optimal θ.

In stage 2, given the supplier's choice of θ, the retailer designs a menu of contracts $\{p_i, t_i, x_i\}$ to maximize her expected profit Π_r as follows.

$$\max_{\{p_i,t_i,x_i\}} \Pi_r = \sum_{i=l,h} w_i[p_i q_i - t_i - K x_i^2], \quad i \in \{l, h\}. \tag{2.3}$$

In the above formulation, for each cost type, $p_i q_i$ is the retailer's revenue, t_i is her payment to the supplier for the acquisition of q_i units of the products, and $K x_i^2$ is her cost to conduct an audit. Expectation is then taken over the two possible cost types.

In stage 1, in anticipation of the retailer's rational response, the supplier determines his optimal level of social responsibility θ, before his production cost type is revealed by nature, to maximize his expected profit Π_s as follows.

$$\max_{\theta} \Pi_s = \sum_{i=l,h} w_i[t_i - (c_i + r(\theta))q_i], \quad i \in \{l, h\}, \tag{2.4}$$

where t_i is the transfer payment received from the retailer, and $(c_i + r(\theta))q_i$ is the total cost of producing q_i units of the product. Again, expectation is taken over the two possible cost types, as the supplier has to make the θ decision before learning his true cost type.

2.4.1 First-Best Case: Complete Information

We first analyze the first-best case to establish a benchmark. In this case, the retailer has complete information about the supplier's cost type before designing the optimal audit mechanism, as illustrated by the dashed arrow in the timeline (see Figure 2.1). Given the knowledge of the true cost type, the retailer will clearly extract all surplus from the supplier, leaving him nothing. In other words, the retailer will set the transfer payment to $t_i = (c_i + r(\theta))q_i$ to just cover the supplier's production cost. In addition, audit is unnecessary, so the retailer's optimal audit probability $x_l = x_h = 0$. For the same reason, the cost of audit Kx_i^2 plays no role in this first-best case. As a result, the retailer's problem in stage 2 reduces from Equation (2.3) to the following:

$$\max_{\{p_i,t_i\}} \Pi_r = \sum_{i=l,h} w_i[p_i - c_i - r(\theta)][a - bp_i + g(\theta)]. \tag{2.5}$$

The optimal solutions are summarized in the following lemma. All proofs are collected in Appendix B.

Lemma 2.1. *In the first-best case, the retailer's optimal menu of contracts is as follows: for* $i \in \{l, h\}$, *the optimal price is* $p_i^F = \frac{1}{2b}[a + g(\theta) + b(c_i + r(\theta))]$, *the optimal transfer payment is* $t_i^F = [c_i + r(\theta)]q_i^F$, *and the corresponding* *demand is* $q_i^F = \frac{1}{2}[a + g(\theta) - b(c_i + r(\theta))]$, *where the superscript* F *denotes the optimal solution in the first-best case.*

Substituting the optimal decisions into Equation (2.5) yields the following optimal expected profit for the retailer, which is also the optimal expected profit for the entire supply chain:

$$\Pi_r^F = \sum_{i=l,h} \frac{1}{4b} w_i [a + g(\theta) - b(c_i + r(\theta))]^2 \tag{2.6}$$

As noted above, in the first-best case, the retailer will design the menu of contracts in such a way that the supplier makes no profit. As a result, the supplier's optimization problem in Equation (2.4) is trivial – the supplier is totally indifferent to θ. For the convenience of exposition, let us select the supply chain profit maximizing θ as the optimal choice in the first-best case. This result is formalized in the following proposition.

Proposition 2.1. *In the first-best case, the supplier's expected profit is always* 0*. The optimal social responsibility level, denoted by* θ^F*, can be characterized by*

$$br'(\theta^F) = g'(\theta^F). \tag{2.7}$$

From a marginal analysis point of view, the right-hand side of the above equation $g'(\theta^F)$ is the marginal benefit of increasing θ, as demand increases at the rate $g'(\theta^F)$. The left-hand side is the marginal cost, which is rate of the unit cost increase $r'(\theta^F)$ times the slope of the demand b. The optimal θ is set in such a way that these two sides are balanced. It is worth noting that there is at most one solution to the above equation, because by assumption, the convexity of $r(\theta)$ implies $br'(\theta^F)$ is strictly increasing and the concavity of $g(\theta)$ implies $g'(\theta^F)$ is strictly decreasing. As a result, the two curves can meet at most once. To avoid the trivial case of non-existence of any solution, we assume the following regularity condition: $a+g(\theta^F)-bp_i^F > 0$, which ensures a positive demand at θ^F, as can be seen from Equation (2.1). Further, we assume the parametric conditions are such that $\theta^F < 1$ to avoid the trivial case of boundary solutions.

2.4.2 Second-Best Case: Asymmetric Information without an Audit

We now turn our attention to the second-best case where there is asymmetric information about the supplier's unit production cost c_i for $i \in \{l, h\}$. More specifically, this cost is the supplier's private information not known to the retailer. This subsection examines the no-audit case, i.e., in stage 2 of the problem, the retailer's audit probability x_i is set to 0, and his decisions reduce to the price p_i and the transfer payment t_i.

As is standard in the mechanism design literature (Fudenberg and Tirole, 1991, Chapter 7), we invoke the revelation principle, which says that truth-telling direct revelation mechanisms can generally be used to achieve the Bayesian Nash equilibrium outcome of other mechanisms. In other words, we can restrict our attention to incentive compatible contracts where it is optimal for the supplier to reveal his true cost type.

The complete mechanism design problem for the retailer in stage 2 is as follows:

$$\max_{\{p_i,t_i\}} \Pi_r = \sum_{i=l,h} w_i(p_i q_i - t_i)$$

$s.t.$

$$(IR_l) \quad t_l - (c_l + r(\theta))q_l \geq 0,$$

$$(IR_h) \quad t_h - (c_h + r(\theta))q_h \geq 0,$$

$$(IC_l) \quad t_l - (c_l + r(\theta))q_l \geq t_h - (c_l + r(\theta))q_h,$$

$$(IC_h) \quad t_h - (c_h + r(\theta))q_h \geq t_l - (c_h + r(\theta))q_l.$$

In the above formulation, the objective function follows directly from Equation (2.3). The first two constraints are the so-called individual rationality (IR) constraints, which guarantee that the supplier's profit is nonnegative by truthfully reporting his cost type. The two incentive compatibility (IC) constraints ensure that he is (weakly) better off reporting his true cost type.

To facilitate further discussion, let us define the difference between the two cost types as $\Delta = c_h - c_l$. In addition, we introduce the concept of virtual cost below for convenience of notation.

Definition 1. The virtual cost for the high type (type h) is $v_n \equiv c_h + \frac{w_l}{w_h}\Delta$, where the subscript n refers to the no-audit case.

Proposition 2.2. *In the no-audit case, the retailer's optimal menu of contracts is as follows:*

$$\begin{bmatrix} p_l^N \\ t_l^N \end{bmatrix} = \begin{bmatrix} \frac{1}{2b}[a + b(c_l + r(\theta)) + g(\theta)] \\ (c_l + r(\theta))q_l^N + \Delta q_h^N \end{bmatrix},$$

$$\begin{bmatrix} p_h^N \\ t_h^N \end{bmatrix} = \begin{bmatrix} \frac{1}{2b}[a + b(v_n + r(\theta)) + g(\theta)] \\ (c_h + r(\theta))q_h^N \end{bmatrix},$$

where a decision with the superscript N denotes its optimal solution in the no-audit case, and q_i^N*, the demand corresponding to the optimal price* p_i^N*, can be determined from Equation (2.1) as follows:* $q_l^N = \frac{1}{2}[a + g(\theta) - b(c_l + r(\theta))]$*, and* $q_h^N = \frac{1}{2}[a + g(\theta) - b(v_n + r(\theta))]$*.*

Proposition 2.2 is consistent with standard results in the mechanism design literature. For the low type (efficient) supplier, we have $p_l^N = p_l^F$, which mirrors the "no distortion at the top" property (Fudenberg and Tirole, 1991), i.e., the first-best decision p_l^F is not distorted in the presence of information asymmetry. However, the optimal transfer payment t_l^N differs from its counterpart t_l^F in the first-best case. This is because the retailer has to pay the so-called information rent Δq_h^N to the low type supplier to prevent him from lying. For the high type supplier, the optimal price p_h^N deviates from its counterpart p_h^F in the first-best case, but they are similar structurally in the sense that they take the same functional form, with the only difference being that the virtual cost v_n is now in place of c_h. The reason for this change is that the retailer has to distort the price for the high type supplier to curtail the information rent paid to the low type supplier. As for the transfer payment t_h^N, it is just enough to for the high type supplier to cover his total production cost. This is because the high type supplier does not gain from pretending to be the low type (the constraint IC_h shows that given the optimal menu of contracts, the high type supplier is worse-off if he misreports). In other words, the high type supplier does not have any incentive to lie. As a result, the retailer can extract all his surplus.

Now we go back to stage 1 of the problem to solve for the supplier's optimal social responsibility level decision θ. To that end, we substitute the optimal results in Proposition 2.2 into the supplier's expected profit function in Equation (2.4), which becomes a function of the only unknown θ:

$$\begin{aligned} \max_\theta \Pi_s &= \sum_{i=l,h} w_i \left[t_i - (c_i + r(\theta))q_i\right] \\ &= w_l \Delta q_h = \frac{1}{2} w_l \Delta \left[a + g(\theta) - b(v_n + r(\theta))\right]. \end{aligned} \tag{2.8}$$

Proposition 2.3. *In the no-audit case, the supplier's optimal level of social responsibility is characterized by*

$$br'(\theta^N) = g'(\theta^N). \tag{2.9}$$

It is interesting to note that Equation (2.9) is identical to Equation (2.7), that is, the supplier's optimal social responsibility level decision is the same in the first-best and no-audit cases. This suggests that information asymmetry does not alter the supplier's optimal social responsibility level. Technically, this is because that the objectives functions in Equations (2.8) and (2.6) are structurally very similar, leading to the same optimization results. Intuitively, $g(\theta)$ only shifts the demand up or down, and the profit function inherits the shifting effect. The maximum profit may shift up or down, but the optimal θ stays the same.

2.4.3 Audit Case: Asymmetric Information with an Audit

As discussed in the no-audit case, possessing private information about the unit production cost c_i allows the low type supplier to have a net surplus, which is his information rent Δq_h^N. Information asymmetry also forces the retailer to distort the price for the high type supplier (p_h^N) from the first-best solution, thus causing agency loss for the entire supply chain. One tool is to address the adverse effects of information asymmetry is audit. As we will see shortly, threatening the supplier with a possible audit allows the retailer to squeeze some information rent out of the supplier. It can also partially restore the distortion in the price for the high type supplier p_h^N, thus mitigating the agency loss.

This section investigates the audit case, where the retailer's complete menu of contracts is $\{p_i, t_i, x_i\}$, and $x_i \in [0, 1]$ is the probability for the retailer to audit the supplier. Such a modeling approach draws on the vast economics literature, e.g., Mookherjee and Png (1989), Dunne and Loewenstein (1995), Khalil (1997), Laffont and Martimort (2002). In the supply chain management literature, Chen and Lee (2017) essentially employ the same approach, although they interpret the audit probability as the audit effort level. Audits are costly and we assume the retailer incurs an audit cost Kx_i^2, which is convex increasing in x_i for $K > 0$.

The retailer levies a penalty on the supplier if he is caught lying about his type in an audit. Let $o_i, i \in \{l, h\}$, denote type i supplier's penalty for misreporting. For example, if the low type supplier reports high cost c_h and the lie is detected in an audit, then the low type supplier has to pay a penalty o_l. Following Laffont and Martimort (2002), we adopt endogenous punishments and assume that the penalty is capped at the supplier's maximum gain from a false announcement. For instance, if a low type supplier pretends to be the high type, then his gain is $t_h - (c_l + r(\theta))q_h$, which is the highest possible penalty for o_l. More formally, we have the following two constraints:

$$t_h - (c_l + r(\theta))q_h \geq o_l, \tag{2.10}$$

$$t_l - (c_h + r(\theta)q_l \geq o_h. \tag{2.11}$$

Stage 2: Retailer's Mechanism Design

In the audit case, the retailer's mechanism design problem parallels the one in the no-audit case. The complete formulation is as follows.

$$\max_{\{p_i,t_i,x_i\}} \Pi_r = \sum_{i=l,h} w_i \left(p_i q_i - t_i - K x_i^2\right) \tag{2.12}$$

s.t.

$$(IR_l) \qquad t_l - (c_l + r(\theta))q_l \geq 0,$$

$$(IR_h) \qquad t_h - (c_h + r(\theta))q_h \geq 0,$$

$$(IC_l) \qquad t_l - (c_l + r(\theta))q_l \geq t_h - (c_l + r(\theta))q_h - x_h o_l,$$

$$(IC_h) \qquad t_h - (c_h + r(\theta))q_h \geq t_l - (c_h + r(\theta))q_l.$$

It is worth noting that the misreport penalty o_i does not enter the retailer's profit function, as the IC constraints ensure that the supplier will report his type truthfully, and thus no penalty will be levied in any event. The IC constraints also reveal potential benefits of an audit. Compared to their counterparts in the no-audit case, the right-hand side of the IC constraints is reduced by $x_i o_j$, where $i \neq j$, which effectively expands the feasible region of the optimal solutions, possibly leading to a higher objective function value. The downside of an audit is of course the expected cost of the audit, which is part of the profit function.

Before proceeding to the optimal solutions, we define the following virtual cost for the high type supplier in the audit case for ease of notation, similar to the no-audit case.

Definition 2. The virtual cost for the high type supplier in the audit case is $v_a = c_h + \frac{w_l}{w_h}(1 - x_h)\Delta$.

As we can see, v_a basically extends its counterpart v_n in the no-audit case by incorporating the audit probability x_h. Clearly, $v_a \leq v_n$, and the equality holds if and only if $x_h = 0$.

Proposition 2.4. *Assume $4Kw_h^2 - b\Delta^2 w_l^2 > 0$, then the retailer's optimal menu of contracts in the audit case is as follows:*

$$\begin{bmatrix} p_l^A \\ x_l^A \\ t_l^A \end{bmatrix} = \begin{bmatrix} \frac{a+g(\theta)+b(c_l+r(\theta))}{2b} \\ 0 \\ [c_l + r(\theta)]q_l^A + (1 - x_h)\Delta q_h^A \end{bmatrix},$$

$$\begin{bmatrix} p_h^A \\ x_h^A \\ t_h^A \end{bmatrix} = \begin{bmatrix} \frac{a+g(\theta)+b(v_a^A+r(\theta))}{2b} \\ \frac{w_l w_h \Delta}{4Kw_h^2 - b\Delta^2 w_l^2}[a + g(\theta) - b(v_n + r(\theta))] \\ [c_h + r(\theta)]q_h^A \end{bmatrix},$$

where a decision with the superscript A denotes its optimal solution in the audit case, $v_a^A \equiv c_h + \frac{w_l}{w_h}(1 - x_h^A)\Delta$, and q_i^A, the demand corresponding to the optimal price p_i^A, can be determined from Equation (2.1) as follows: $q_l^A = \frac{1}{2}[a + g(\theta) - b(c_l + r(\theta))]$, and $q_h^A = \frac{1}{2}[a + g(\theta) - b(v_a^A + r(\theta))]$.

This proposition merits a couple of remarks. First, the technical condition $4Kw_h^2 - b\Delta^2 w_l^2 > 0$ is sufficient to guarantee that the optimal solution x_h is positive. Otherwise and audit case will simply reduce to the no-audit case.

Coincidentally, it also ensures that the objective function is jointly concave in the decision variables. Note that K is a parameter pertaining to the *total* cost of all product units, while Δ is the price difference of *each* product unit. Therefore, they are typically two quantities of different magnitude, making the condition $4Kw_h^2 - b\Delta^2 w_l^2 > 0$ easy to satisfy. In fact, this condition is met in our extensive numerical experiments under all circumstances where k is reasonable large. Second, a comparison between the audit and no-audit cases reveals the role of the audit. For the low type supplier, the corresponding optimal price p_l^A is still the first-best solution, and the optimal audit probability $x_l^A = 0$, because the high type supplier has no incentive to lie at all (see proof of this proposition for more detailed explanations). Therefore, any supplier reporting to be the low type must be telling the truth, and it is optimal not to audit the reported low type. The information rent of the low type supplier, however, is reduced from Δq_h^N to $(1 - x_h)\Delta q_h^A$. This is exactly the potential benefit of the audit for the retailer. For the high type supplier, he still earns no surplus, but the audit probability x_h is positive. This is because a low type supplier may pretend to be the high type, so it is necessary for the retailer to use an audit to prevent misreporting. Further, the audit brings the optimal price p_h^A closer to the first-best solution (because a positive x_h brings v_a closer to c_h), thus mitigating the agency loss caused by information asymmetry.

Stage 1: Supplier's Social Responsibility Level Choice

We now go back to stage 1 to optimize the supplier's optimal social responsibility level θ. Substituting optimal stage 2 decisions in Proposition 2.4 into the supplier's expected profit function Π_r in Equation (2.4) yields

$$\begin{aligned}\max_{\theta} \Pi_s &= w_l \left[t_l^A - (c_l + r(\theta))q_l^A\right] + w_h \left[t_h^A - (c_h + r(\theta))q_h^A\right] \\ &= w_l \Delta q_h^A (1 - x_h^A).\end{aligned}$$

Note that x_h^A is a function of θ, and q_h^A is a function of both θ and x_h^A. Therefore, theoretically speaking, Π_r is a univariate function of the single decision variable θ. However, the complexity of the expressions for x_h^A and q_h^A makes the above profit function less amenable to further analysis. To address the tractability challenge, we make a variable transformation and express Π_r as a univariate function of x_h instead.

The transformation begins with the fact that we have shown in the proof of Proposition 2.4 that the retailer's expected profit is jointly concave in her decisions. In addition, the first order derivative with respect to x_h is $\partial \Pi_r / \partial x_h = w_l q_h \Delta - 2K w_h x_h$. Setting it to zero yields $w_l q_h^A \Delta = 2K w_h x_h^A$, which can then be used to transform the supplier's expected profit Π_r as follows:

$$\max_{\theta} \Pi_s = 2K w_h x_h^A (1 - x_h^A). \tag{2.13}$$

Using the chain rule, we can differentiate Π_s as follows:

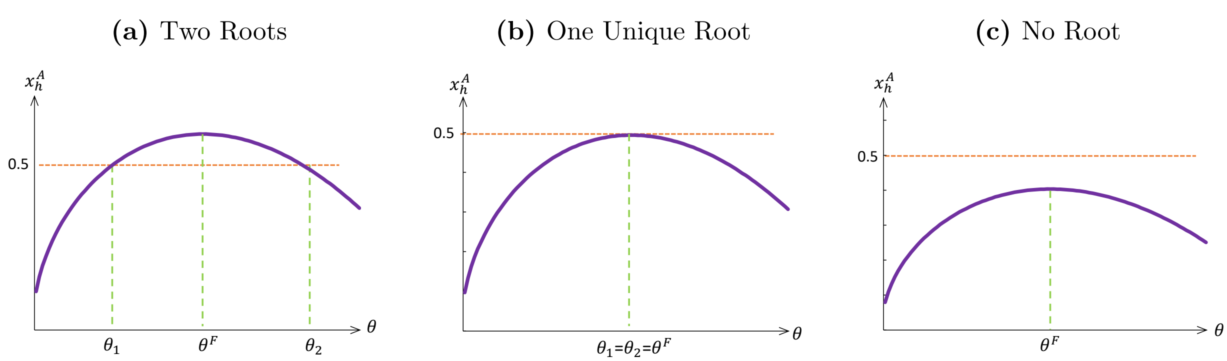
$$\frac{d\Pi_s}{d\theta} = \frac{\partial \Pi_s}{\partial x_h^A}\frac{\partial x_h^A}{\partial \theta} = 2Kw_h(1-2x_h^A)\frac{\partial x_h^A}{\partial \theta}. \tag{2.14}$$

Clearly, the stationary points of Π_s are characterized by $\frac{\partial x_h^A}{\partial \theta} = 0$ or $(1 - 2x_h^A) = 0$. Note from Proposition 2.4 that $\frac{\partial x_h^A}{\partial \theta} = 0$ reduces to $h^{'}(\theta) - br^{'}(\theta) = 0$. Also, from Proposition 2.1, we have $br'(\theta^F) = g'(\theta^F)$. Therefore, θ^F is a stationary point of Π_s. The other stationary points come from $(1-2x_h^A) = 0$. Substituting x_h^A from Proposition 2.4, we get

$$\frac{w_l w_h \Delta}{4Kw_h^2 - b\Delta^2 w_l^2}\left[a + g(\theta) - b(v_n + r(\theta))\right] = \frac{1}{2}. \tag{2.15}$$

It is straightforward to verify that x_h^A is concave in θ, which implies that Equation (2.15) has at most two roots, denoted by θ_1 and θ_2, where $\theta_1 \leq \theta_2$. See Figure 2.2a for an illustration. Note that parametric conditions may also lead to the case where Equation (2.15) has only one or even no root, as shown in the other two panels of Figure 2.2.

Figure 2.2: Solutions to Equation (2.15)



In sum, θ^F is always a stationary point of the supplier's expected profit function Π_s. In addition, there might be up to two other stationary points (θ_1 and θ_2), depending on the parametric conditions. The following proposition summarizes the supplier's optimal social responsibility level θ^A in three possible scenarios.

Proposition 2.5. *In the audit case, the supplier's optimal social responsibility level θ^A is as follows:*

(a) Scenario A: Equation (2.15) has two roots and $\theta_2 \leq 1$. In this scenario, $\theta_1 < \theta^F < \theta_2$, and the supplier's expected profit attains the same maximum value at both θ_1 and θ_2, so θ^A could be either θ_1 or θ_2. Further, the retailer is indifferent to the supplier's choice.

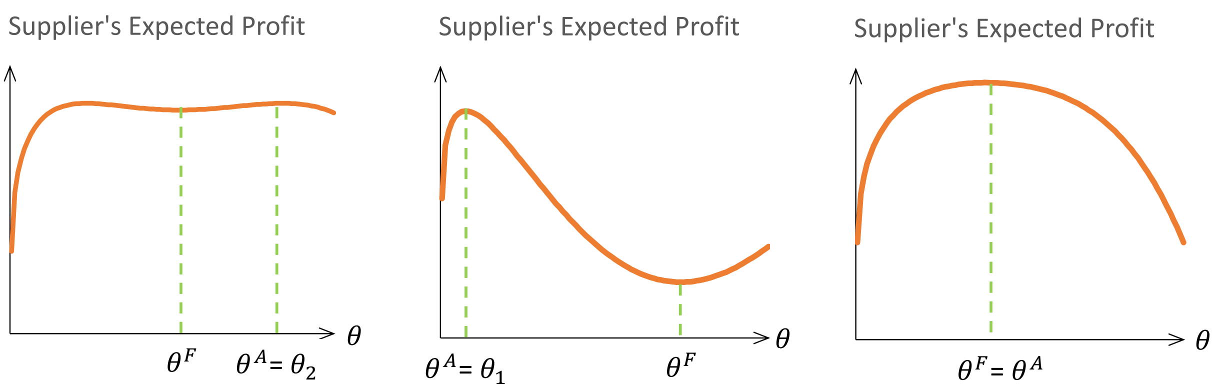
(b) Scenario B: Equation (2.15) has two roots and $\theta_2 > 1$. In this scenario, we have $\theta^A = \theta_1 < \theta^F$.

(c) Scenario C: Equation (2.15) has at most one root. In this scenario, $\theta^A = \theta^F$.

Figure 2.3 plots the supplier's expected profit Π_s as a function of his decision θ for us to visualize the three different scenarios described in the proposition above. In scenario A (Figure 2.3a), Π_s is bimodal. The stationary point θ^F is a local minimizer and falls between the two maximizers θ_1 and θ_2. Further, Π_s attains the same value at both maximizers. Therefore, the supplier is indifferent in regard to which one to choose. Interestingly, the retailer is indifferent too, as her expected profit remains constant at θ_1 and θ_2. Since both players are indifferent, we assume θ_2 is chosen as the optimal solution, i.e., $\theta^A = \theta_2$, for the good of the public.

Figure 2.3: The Supplier's Expected Profit Π_s as a Function of θ

(a) Scenario A **(b)** Scenario B **(c)** Scenario C



Scenario B in Figure 2.3b depicts the truncated version of scenario A, which occurs when θ_2, the larger root to Equation (2.15), falls beyond the feasible region $[0, 1]$. Since θ_1 becomes the only maximizer in this scenario, and clearly it is the supplier's optimal choice. In scenario C (Figure 2.3c), Π_s is unimodal and attains its maximum at the only stationary point θ^F, which is obvioiusly the supplier's best decision.

Through previous analyses, we have found that information asymmetry has no impact on the supplier's optimal social responsibility choice. Proposition 2.5, however, reveals that an audit to counteract the adverse effects of information asymmetry may induce the supplier's optimal social responsibility level to shift. In the presence of an audit, the supplier may increase (as in scenario A), decrease (scenario B), or maintain (scenario C) his social responsibility level, depending on parametric conditions. We explore how different parameters affect the supplier's decision through extensive numerical studies in Section 2.6.

2.5. Multiplicative Demand Model

In Section 2.3.2, we have discussed that different consumer reactions to the social responsibility level of a supply chain may lead to additive or multiplicative demand functions. This section examines the latter case, i.e., the multiplicative demand model, as described in Equation 2.2. We begin with the complete information case, which can serve as a benchmark, before proceeding to the no-audit case (asymmetric information case without an audit) and the audit case. Much of the formulation and analysis in this section parallel those in the additive demand model, so we will not repeat all the details whenever confusion is not caused by such omissions.

2.5.1 First-Best Case: Complete Information

If the retailer has complete information about the supplier's unit production cost c_i when designing the contracts, she will apparently extract all surplus of the supplier by setting the transfer payment exactly equals to the supplier's total production cost, i.e., $t_i = (c_i + r(\theta))q_i$.

The retailer's expected profit, which is the same as the supply chain profit, is as follows:

$$\max_{p_i} \Pi_r = \sum_{i=l,h} w_i[p_i - c_i - r(\theta)](a - bp_i)g(\theta). \tag{2.16}$$

The following lemma provides the optimal first-best solutions.

Lemma 2.2. *In the first-best case, the retailer's optimal menu of contracts is as follows: for* $i \in \{l, h\}$, *the optimal price is* $p_i^F = \frac{1}{2b}[a + b(c_i + r(\theta))]$, *the optimal transfer payment is* $t_i^F = [c_i + r(\theta)]q_i^F$, *and the corresponding demand is* $q_i^F = \frac{1}{2}[a - b(c_i + r(\theta))]g(\theta)$.

Next, we substitute the optimal decisions into Equation (2.16) to get the following retailer's optimal expected profit, which is also the optimal expected profit for the supply chain.

$$\Pi_r^F = \sum_{i=l,h} \frac{g(\theta)}{4b} w_i[a - b(c_i + r(\theta)]^2. \tag{2.17}$$

Since the supplier always earns zero profit and thus is indifferent to the choice of θ, we assume that his optimal decision θ^F, characterized in the following proposition, maximizes the supply chain profit.

Proposition 2.6. *In the first-best case, the supplier's expected profit is always* 0. *Under a mild sufficient condition* $\frac{g''(\theta)}{g'(\theta)}[a - b(w_l c_l + w_h c_h + r(\theta))] + br'(\theta) < 0$, *the supplier's optimal social responsibility level, denoted by* θ^F, *can be characterized by the following equation:*

$$\frac{g'(\theta^F)}{g(\theta^F)} = \frac{2br'(\theta^F)\left[a - b\left(w_l c_l + w_h c_h + r(\theta^F)\right)\right]}{w_l\left[a - b\left(c_l + r(\theta^F)\right)\right]^2 + w_h\left[a - b\left(c_h + r(\theta^F)\right)\right]^2}. \tag{2.18}$$

It is worth noting that the condition $\frac{g''(\theta)}{g'(\theta)}\left[a - b(w_l c_l + w_h c_h + r(\theta))\right] + br'(\theta) < 0$ is sufficient, but not necessary, to guarantee the unimodality of the supplier's expected profit function. Our extensive numerical experiments show that this condition is easily satisfied.

2.5.2 Second-Best Case: Asymmetric Information without an Audit

The retailer's optimal contract design problem in stage 2 can be formulated in exactly the same way as in the no-audit case in Section 2.4.2, except that now the demand function is given in Equation (2.2). Therefore, we omit the formulation to avoid repetition. Also, following exactly the same solution procedure (as in the proof of Proposition 2.2), we can simplify the retailer's expected profit as follows:

$$\begin{aligned} \max_{\{p_i,t_i\}} \Pi_r &= \sum_{i=l,h} w_i(p_i q_i - t_i) \\ &= w_l\left[p_l - c_l - r(\theta)\right] q_l + w_h\left[p_h - v_n - r(\theta)\right] q_h. \end{aligned} \tag{2.19}$$

The optimal solutions are presented in the following proposition, which parallels Proposition 2.2. As we can see, all results closely mimic those in the additive model.

Proposition 2.7. *In the no-audit case , the retailer's optimal menu of con-*

tracts is as follows:

$$\begin{bmatrix} p_l^N \\ t_l^N \end{bmatrix} = \begin{bmatrix} \frac{1}{2b}[a + b(c_l + r(\theta))] \\ (c_l + r(\theta))q_l^N + \Delta q_h^N \end{bmatrix}, \begin{bmatrix} p_h^N \\ t_h^N \end{bmatrix} = \begin{bmatrix} \frac{1}{2b}[a + b(v_n + r(\theta))] \\ (c_h + r(\theta))q_h^N \end{bmatrix},$$

and the corresponding demand is $q_l^N = \frac{1}{2}[a - b(c_l + r(\theta))]g(\theta)$ *and* $q_h^N = \frac{1}{2}[a - b(v_n + r(\theta))]g(\theta)$.

In the stage 1 problem, the supplier chooses the optimal social responsibility level to maximize his own expected profit Π_s. We substitute results in the above proposition to simplify Π_s as follows:

$$\begin{aligned} \max_{\theta} \Pi_s &= w_l \left[t_l^N - (c_l + r(\theta))q_l^N\right] + w_h \left[t_h^N - (c_h + r(\theta))q_h^N\right], \\ &= w_l \Delta q_h^N \;=\; \frac{1}{2} w_l \Delta \left[a - b(v_n + r(\theta)\right] g(\theta). \end{aligned} \tag{2.20}$$

Proposition 2.8. *In the no-audit case, the optimal decision* θ^N *can be characterized by:*

$$\frac{g'(\theta^N)}{g(\theta^N)} = \frac{br'(\theta^N)}{a - b(v_n + r(\theta^N))}. \tag{2.21}$$

A comparison between Propositions 2.8 and 2.6 shows that in stark contrast to the additive demand model, information asymmetry plays a more active role and does change the supplier's optimal social responsibility level in the multiplicative demand case. Compared with the additive demand model, the demand is scaled by $g(\theta)$ in multiplicative demand model. Thus, the profit functions in the first-best and the second-best are scaled differently, which leads a change in the optimal social responsibility level.

2.5.3 Audit Case: Asymmetric Information with an Audit

Again, the retailer's mechanism design problem in stage 2 mimics its counterpart in the additive demand model studied in Section 2.4.3, with the only exception that the demand function is now given in Equation (2.2). Following similar steps to those outlined in the proof of Proposition 2.4, we simplify the retailer's expected profit as follows:

$$\begin{aligned}\max_{\{p_l,p_h,x_h\}} \Pi_r &= w_l g(\theta)(a-bp_l)\left[p_l-(c_l+r(\theta))\right] \\ &\quad + w_h g(\theta)(a-bp_h)\left[p_h-v_a-r(\theta)\right]-w_hKx_h^2. \qquad (2.22)\end{aligned}$$

Proposition 2.9. *Assume $4Kw_h^2 - bg(1)\Delta^2 w_l^2 > 0$ in the audit case, then the retailer's optimal menu of contracts is:*

$$\begin{bmatrix} p_l^A \\ x_l^A \\ t_l^A \end{bmatrix} = \begin{bmatrix} \frac{a+b(c_l+r(\theta))}{2b} \\ 0 \\ [c_l+r(\theta)]q_l^A + (1-x_h^A)\Delta q_h^A \end{bmatrix},$$

$$\begin{bmatrix} p_h^A \\ x_h^A \\ t_h^A \end{bmatrix} = \begin{bmatrix} \frac{a+b(v_a^A+r(\theta))}{2b} \\ \frac{g(\theta)w_lw_h\Delta}{4Kw_h^2-bg(\theta)\Delta^2w_l^2}\left[a-b(v_n+r(\theta))\right] \\ [c_h+r(\theta)]q_h^A \end{bmatrix},$$

and the corresponding demand is $q_l^A = \frac{1}{2}[a-b(c_l+r(\theta))]g(\theta)$ and $q_h^A = \frac{1}{2}[a-b(v_a^A+r(\theta))]g(\theta)$.

We observe that all results in this proposition are structurally identical to those in the additive demand model counterpart Proposition 2.4. Since $g(\theta)$ is an increasing function, the technical condition $4Kw_h^2 - bg(1)\Delta^2 w_l^2 > 0$ ensures the positivity of x_h^A.

To solve for the supplier's optimal social responsibility level in stage 1, we substitute results in Proposition 2.9, along with the fact that $w_l \Delta q_h^A = 2Kw_h x_h^A$ (which is straightforward to verify based on results in Proposition 2.9 by noting that v_a^A is a function of x_h^A), to simplify the supplier's expected profit as follows:

$$\max_\theta \Pi_s \;=\; w_l(1 - x_h^A)\Delta q_h^A \;=\; 2Kw_h x_h^A(1 - x_h^A), \tag{2.23}$$

which turns out to be structurally identical to Equation (2.13) in the additive case. As a result, the analysis of the stationary points is the same as before, that is, the stationary points of the supplier's expected profit Π_s, as a function of θ, are characterized by $\frac{\partial x_h^A}{\partial \theta} = 0$ or $(1 - 2x_h^A) = 0$. The only difference is that now the solution to $\frac{\partial x_h^A}{\partial \theta} = 0$, denoted by θ_s, does not correspond to the first-best solution θ^F, and the roots to $(1 - 2x_h^A) = 0$ have different values than in the additive demand model.

The following proposition, which parallels its counterpart Proposition 2.5 in the additive demand model, summarizes the optimal solutions in the multiplicative demand model.

Proposition 2.10. *In the audit case, the supplier's optimal social responsi-*

bility level θ^A is as follows:

(a) *Scenario A: Equation (2.15) has two roots and $\theta_2 \leq 1$. In this scenario, $\theta_1 < \theta_s < \theta_2$, and the supplier's expected profit attains the same maximum value at both θ_1 and θ_2, so θ^A could be either θ_1 or θ_2.*

(b) *Scenario B: Equation (2.15) has two roots and $\theta_2 > 1$. In this scenario, we have $\theta^A = \theta_1 < \theta_s$.*

(c) *Scenario C: Equation (2.15) has at most one root. In this scenario, $\theta^A = \theta_s$.*

This proposition is identical to Proposition 2.5, except one difference in scenario A. Recall that in the additive demand model, both the supplier and the retailer are indifferent to the two maximizers θ_1 and θ_2. In the multiplicative demand model, the supplier is still indifferent. It is, however, no longer the case for the retailer. As a result, let us designate the retailer's preferred choice as the optimal solution θ^A. The following proposition examines the retailer's preference.

Proposition 2.11. *In scenario A, the retailer prefers θ_1 if*

$$4Kw_h^2 > b\Delta^2\sqrt{g(\theta_1)g(\theta_2)w_l}(1+w_h)w_l.$$

Otherwise, her preference is θ_2.

It is worth mentioning that based on numerical experience, more often than not, θ_1 is the better choice for the retailer. This is because the condition $4Kw_h^2 > b\Delta^2\sqrt{g(\theta_1)g(\theta_2)w_l}(1+w_h)w_l$ bears a resemblance to the technical condition $4Kw_h^2 - bg(1)\Delta^2 w_l^2 > 0$, which is required for results in Proposition 2.9 to be positive. Figure 2.4 illustrates the case where θ_1 outperforms θ_2 from the retailer's perspective. As can be seen from the figure, the supplier's expected profit, represented by the solid line, is bimodal with the same maximum value at both θ_1 and θ_2. However, the retailer's expected profit, represented by the dashed line, indicates that she can garner a higher profit at θ_1.

Figure 2.4: Scenario A in the Multiplicative Demand Model

Note that the optimal decision in scenario B is always $\theta^A = \theta_1$. Therefore, the above discussion suggests that there is a good chance for the supplier to choose θ_1 as his optimal decision in the presence of an audit. If θ_1 happens to be less than the second-best decision θ^N, then the audit is well likely to have an unintended negative consequence — it may lead the supplier to a lower level of social responsibility.

2.5.4 Summary of Managerial Insights

Before concluding this section, we summarize managerial insights provided by our modeling results. As we have discussed earlier, different consumer reactions to a supply chain's social responsibility level result in different demand functions. Our analyses in Sections 2.4 and 2.5 show that the different demand functions, in turn, may lead to different impact of the audit on the supplier's social responsibility choice.

In the additive demand model, the information asymmetry plays no role in the supplier's decision, namely, it does not change the supplier's social responsibility level at all. As an audit is intended to counteract the adverse effects of the information asymmetry, one might intuit that the audit would not shift the supplier's decision. However, this turns out not to be the case. We find that the audit may actually alter the supplier's choice. Specifically, the supplier may increase, decrease, or maintain his social responsibility level in the presence of an audit, depending on different parametric conditions. The next section investigates numerically how different parameters prompt the supplier to modify his behavior.

The multiplicative demand model uncovers a different set of insights. In this case, the supplier, in response to his information advantage under information asymmetry, always chooses a different social responsibility level than the first-best solution. We use numerical examples in the next section to explore the direction and magnitude of the change caused by the information asymmetry. Under the threat of an audit, the supplier may increase, decrease, or maintain his social responsibility level, compared with the no-audit case. Our theoretical analysis predicts that he is more likely to lower his social responsibility, which is confirmed by our extensive numerical experiments.

In sum, a key takeaway from our modeling analysis is that while cost auditing could be an effective tool for the retailer to mitigate the adverse effects of the asymmetric information possessed by the supplier, she should be mindful of the potential unintended consequence — the supplier may respond to the audit with a lower social responsibility level, which is not in the interest of the public. Further, it is important for us to understand consumers' attitude toward corporate social responsibility, as it drives how the supplier reacts to the audit.

2.6. Numerical Analysis

So far, we have analytically characterized the supplier's optimal social responsibility decisions with and without an audit. The complexity of the optimal solutions, however, still leaves open our key research question: how does the supplier vary his decision in response to an audit? In particular, what is the directional change from the complete information case to the no-audit case and then to the audit case, especially in the multiplicative demand model? Further, how does each parameter affect the supplier's reaction? This section employs a comprehensive numerical study to address these questions.

Recall that the trade-offs involved in the social responsibility level are reflected in the concave increasing function $g(\theta)$ and convex increasing function $r(\theta)$. We find that the qualitative insights remain intact regardless of the various functional forms we tried for the two functions. Therefore, we report our results based on the following: $g(\theta) = G\sqrt{\theta}$ and $r(\theta) = R\theta^2$, which can be used to simplify some analytical results obtained earlier, as detailed in the following corollary.

Corollary 1. *Given the functions $g(\theta) = G\sqrt{\theta}$ and $r(\theta) = R\theta^2$, the following results hold:*

(a) In the additive demand model, $\theta^F = \theta^N = \left(\frac{G}{4bR}\right)^{\frac{2}{3}}$. They are increasing in G, decreasing in b and R, and independent of other parameters (a, c_h, c_l, w_l and K).

(b) In the multiplicative demand model, the first-best solution θ^F is decreasing in R and independent of G and K. The second-best solution θ^N solves $5R\theta^2 = \frac{a}{b} - \left[c_h + \frac{w_l}{w_h}(c_h - c_l)\right]$. It is increasing in a, c_l, w_h, decreasing in b, R, c_h, w_l, and independent of G, K.

Table 2.1: Parameters in the Numerical Experiment

Parameters	Additive Demand			Multiplicative Demand		
	Base Value	Range	Step Size	Base Value	Range	Step Size
a	200	[150, 300]	1	200	[100, 300]	1
b	2	[0.8, 3]	0.02	2	[0.5, 3.5]	0.02
G	180	[100, 250]	1	10	[5, 30]	0.1
R	60	[25, 150]	1	60	[30, 300]	2
c_h	20	[17, 23]	0.05	20	[16, 23]	0.05
c_l	14	[11, 19]	0.05	14	[10, 19]	0.05
w_l	0.75	[0.5, 0.8]	0.002	0.75	[0.5, 0.8]	0.002
K	2000	[1750, 2500]	10	5000	[1800,10000]	50

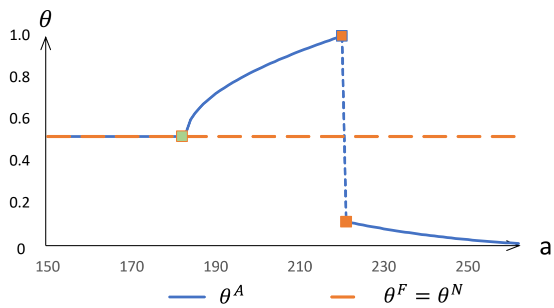
* Note that the parameter w_h is omitted for brevity, due to the fixed relationship $w_h = 1 - w_l$.

Table 2.1 describes parameters used in our experiment design. Note that the base values of certain parameters differ in the additive and multiplicative demand models to meet different regularity conditions (to ensure positive demand and decisions) across the two models.

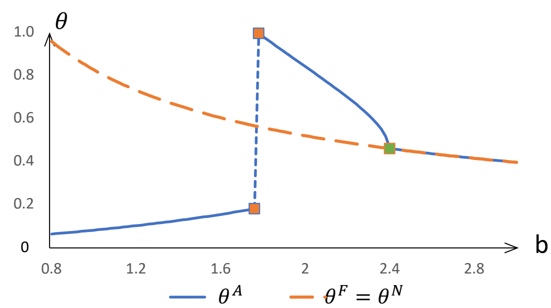
Figure 2.5 plots the supplier's optimal social responsibility levels θ^F (in the complete information case), θ^N (in the no-audit case), and θ^A (in the audit case) under the additive demand model. It also shows how each parameter affects these optimal solutions. As we can see, the impact of parameters on θ^A falls into two distinct patterns. In all sub-figures on the left-hand side, the first segment of θ^A overlaps with θ^F and θ^N, corresponding to scenario C described in Proposition 2.5. The second segment of θ^A corresponds to scenario

Figure 2.5: The Supplier's Optimal Social Responsibility Level in the Additive Demand Model

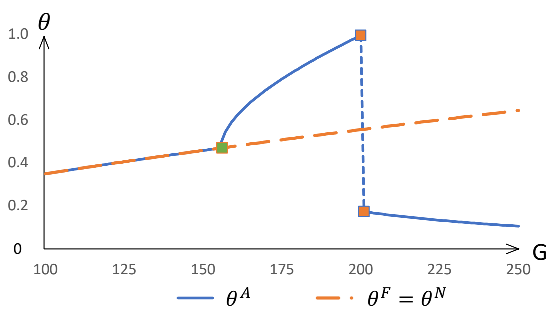
(a) The Impact of the Parameter a



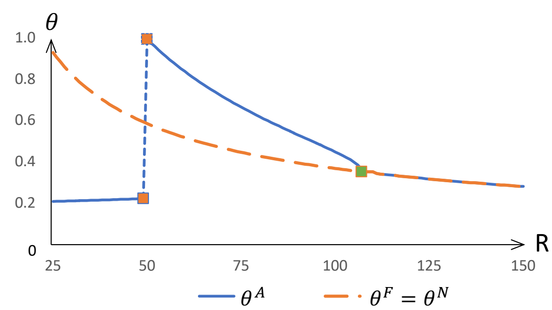
(b) The Impact of the Parameter b



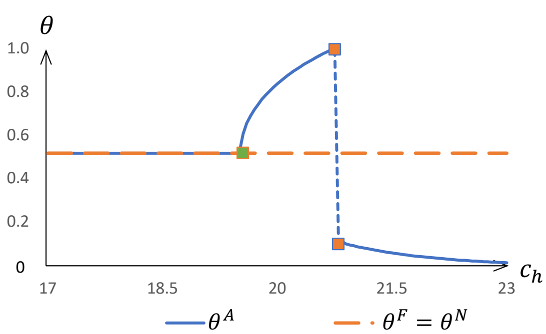
(c) The Impact of the Parameter G



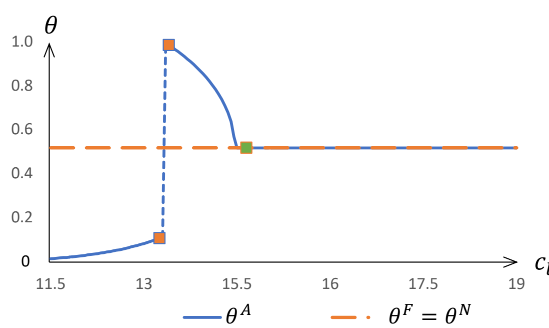
(d) The Impact of the Parameter R



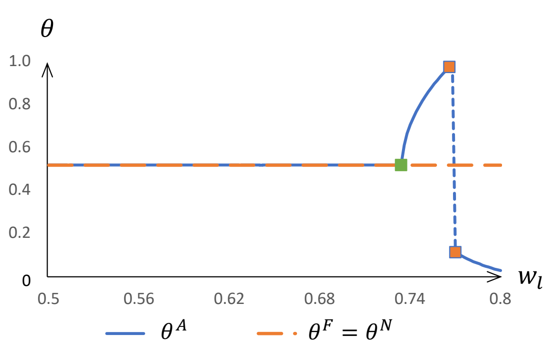
(e) The Impact of the Parameter c_h



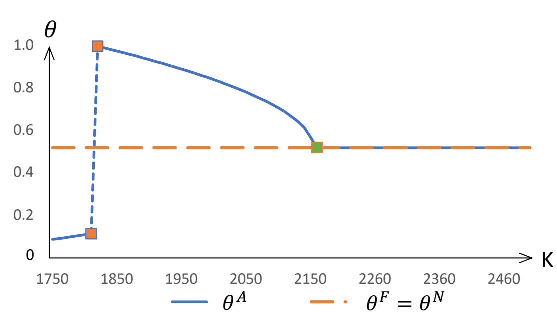
(f) The Impact of the Parameter c_l



(g) The Impact of the Parameter w_l



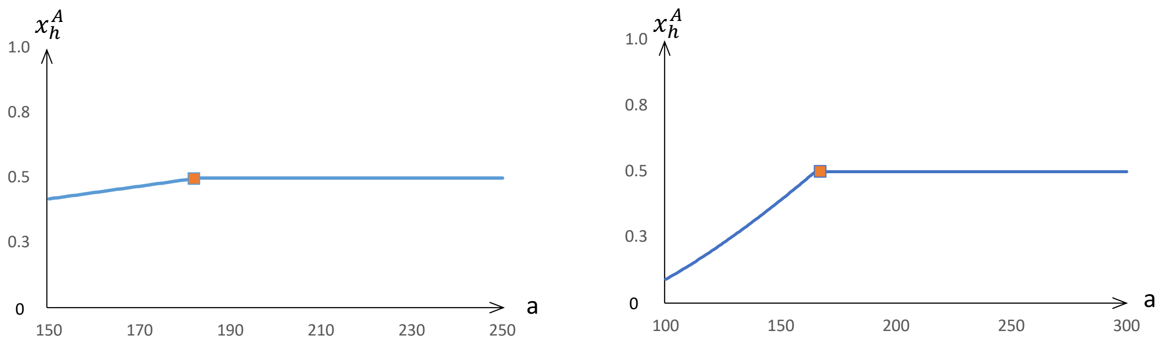
(h) The Impact of the Parameter K



A in Proposition 2.5, and is equal to θ_2. Once θ_2 exceeds its upper support 1, we enter the last segment of θ^A, which is now equal to θ_1, corresponding to scenario B in Proposition 2.5. To understand why θ^A varies in such a way, let us take the parameter a for example. Technically, the first segment is the same as θ^F, which is invariant to a. The last two segments are obtained when Equation (2.15) has two roots $\theta_1 < \theta_2$, as depicted in Figure 2.2a. When a increases, the left-hand side of Equation (2.15) also increases, which means the curve in Figure 2.2a will shift up. As a result, the smaller root θ_1 will move to the left, and the larger root θ_2 will move to the right. This explains why the second segment is increasing while the last segment is decreasing in Figure 2.5a. Intuitively, the audit probability, as depicted in Figure 2.6a, is relatively small in the low range of a, so the supplier is not incentivized enough to deviate from θ^F or θ^N. When a reaches a certain threshold, the threat of an audit is higher and the supplier is pressured to react. To gauge the supplier's reaction, it is useful to note from Equation (2.13) that his expected profit is proportional to $a + g(\theta) - b(v_n + r(\theta))$. In the intermediate range of a, the market potential $a + g(\theta)$ is more sensitive to changes in $g(\theta)$, as $g(\theta)$ accounts for a relatively big chunk of the total market potential. An increase in θ can boost the market potential relatively significantly, which outpaces the negative impact of the production cost increase. Therefore, the supplier is inclined to increase θ in this range. If a is already large enough, then the market potential is less sensitive to changes in $g(\theta)$. In such a case, the supplier turns out to be better off if he reduces θ, as the demand decrease is more than offset by the cost savings.

Figure 2.6: The Optimal Audit Probability for the High Type as a Function of the Parameter a

(a) Additive Demand Model **(b)** Multiplicative Demand Model

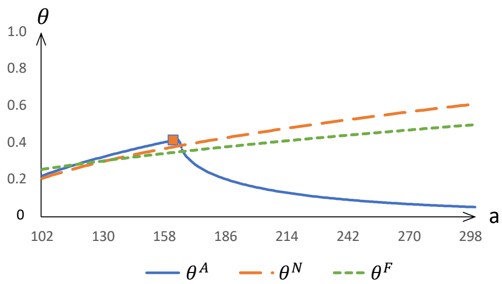


In all sub-figures on the right-hand side, the pattern is flipped — the three segments of θ^A correspond to scenarios B, A, and C, respectively. We omit details of further discussion as the underlying logic is similar.

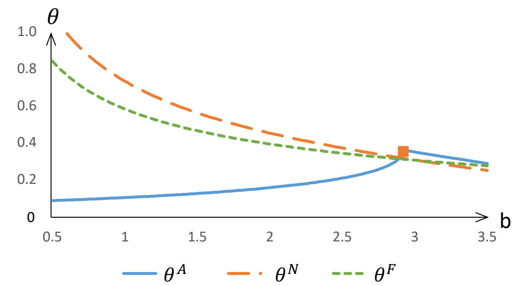
In the multiplicative demand model, the supplier's optimal social responsibility levels θ^F, θ^N, and θ^A are plotted in Figure 2.7. Similar to the additive demand case, the impact of parameters on θ^A exhibits two different patterns. In all sub-figures on the left-hand side, the first segment of θ^A corresponds to scenario C in Proposition 2.10, and the second segment corresponds to scenarios A and B. It is worth mentioning that in all examples, the retailer prefers θ_1 to θ_2 in scenario A, which means that scenario A effectively turns into scenario B. This explains why, unlike in the additive demand model, there is no third segment. The interpretation of why θ^A varies in such a fashion with parameters, say a, is also similar to before. The pattern is flipped

Figure 2.7: The Supplier's Optimal Social Responsibility Level in the Multiplicative Demand Model

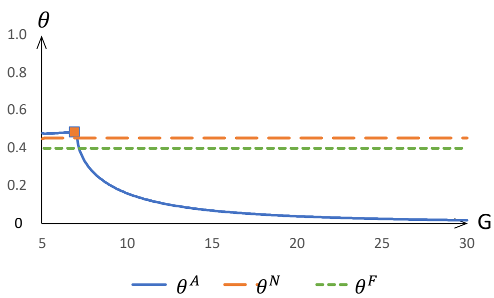
(a) The Impact of the Parameter a



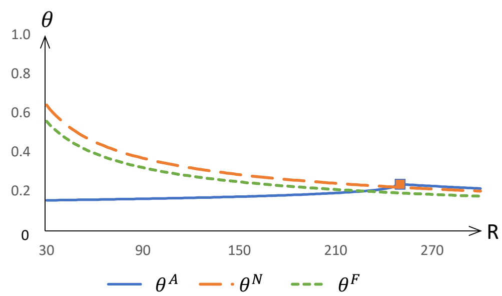
(b) The Impact of the Parameter b



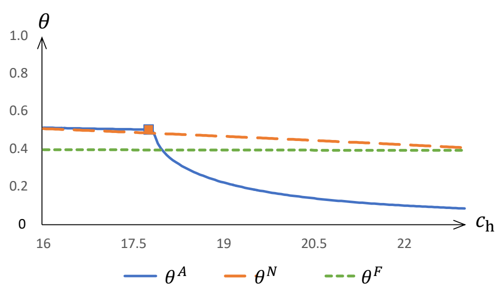
(c) The Impact of the Parameter G



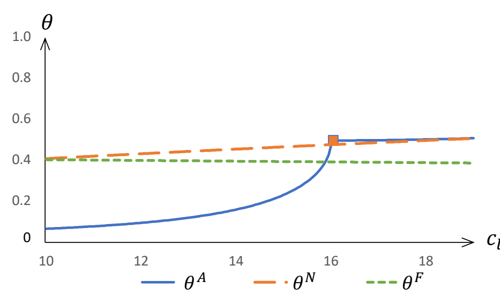
(d) The Impact of the Parameter R



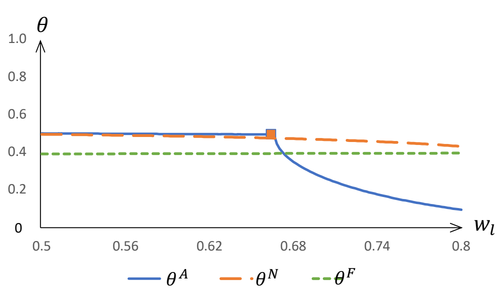
(e) The Impact of the Parameter c_h



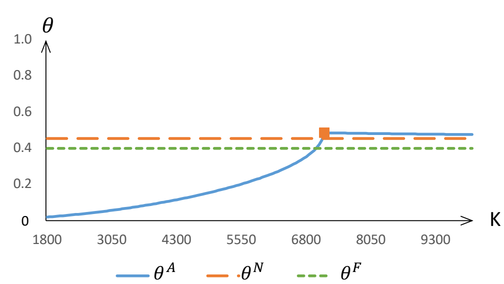
(f) The Impact of the Parameter c_l



(g) The Impact of the Parameter w_l



(h) The Impact of the Parameter K



in sub-figures on the right-hand side.

Note that the results in the multiplicative demand model depart from those in the additive demand model in a few dimensions. First, either θ^F or θ^N could dominate each other (e.g., Figure 2.7a), which means the information asymmetry can cause the supplier to either increase or decrease his social responsibility level. However, the change is typically not significant, as can be seen from the relatively narrow gap between θ^F and θ^N. Second, we observe that θ^A is always different from θ^F and θ^N. In other words, under the threat of an audit, the supplier would always adjust his social responsibility level. Third, and more important, in cases where the supplier increases his social responsibility level in response to the audit (i.e., $\theta^A > \theta^N$), the increase is usually limited. However, if the supplier is to decrease his social responsibility level, the reduction could be much more noticeable (e.g., towards the upper support of the parameter a in Figure 2.7a). This presents a unique risk in the multiplicative demand setting.

To summarize, cost auditing could be very beneficial. In some cases, it could not only mitigate the adverse effects of the information asymmetry, but also induce the supplier to adopt a higher social responsibility level. Under certain parametric conditions, however, it may decrease the supplier's social responsibility level, and the reduction could be substantial. Therefore, it is crucial for practitioners to take the business environment into account when considering a cost audit.

2.7. Conclusion and Future Research

Despite rapidly growing recognition of the importance of CSR, many firms are still found to under-invest in their CSR initiatives. Motivated by this perplexing observation, we study the impact of cost auditing on the supplier's social responsibility level in this paper. We consider a two-tier supply chain consisting of a supplier, whose production cost is his private information, and a retailer, who uses an incentive contract coupled with an audit to induce the supplier to truthfully report his cost type. In our model framework, we formulate a two-stage game where the supplier determines his social responsibility level in the first stage, followed by the retailer's optimal audit mechanism design in the second stage.

Both the customer demand and the production cost depend on the supplier's social responsibility decision. To capture different consumer responses to the supplier's social responsibility, we examine both the additive and the multiplicative demand models. In each demand model, we analyze three cases, including the complete information (first-best), no-audit (second-best), and audit cases. We characterize the optimal solutions and compare the supplier's optimal decisions to understand how his decision is driven by the information asymmetry and cost auditing. In addition, we conduct extensive numerical studies to evaluate the effects of various model parameters on the supplier's decision.

Our findings suggest that a downstream firm's seemingly unrelated common practices may often inadvertently undermine the supplier's social responsibility choice, which sheds light on the reluctance of many suppliers to commit to social responsibility programs.

As a first step towards understanding how common practices in supply chains may deter the upstream supplier's social responsibility effort, we adopt a stylized model in a simplified supply chain network. Future research directions might include adding a demand noise and expanding the bilateral monopoly to incorporate horizontal competition. In addition, the consideration of audit evasion by the supplier could also provide more insights.

2.8. Appendix

2.8.1 Appendix A: Summary of Notation

The notation we use is summarized below.

Decision of the supplier (agent):

θ	supplier's level of social responsibility, $\theta \in [0, 1]$

Decisions of the retailer (principal):

p_i	unit selling price for the product $p_i \equiv p(c_i)$, $i \in \{l, h\}$
t_i	transfer payments from the retailer $t_i \equiv t(c_i)$, $i \in \{l, h\}$
x_i	the probability with which the retailer audits the supplier

Parameters:

$r(\theta)$	the supplier's social responsibility level related unit production cost
$g(\theta)$	additional customer demand boosted by supplier's social responsibility level
$q_i(\theta)$	customer demand of the product, $q_i = a + g(\theta) - bp_i, i \in \{l, h\} \quad a, b > 0$
c_i	type i supplier's unit production cost, $i \in \{l, h\}$
w_i	the probability of supplier's cost type c_i, $i \in \{l, h\}$
o_i	the penalty for the supplier if the audit reveals that he misreports

his cost type

K the coefficient of the cost the retailer incurs (Kx_i^2) to conduct the audit, $K > o$

2.8.2 Appendix B: Technical Proofs

Proof of Lemma 2.1

Evidently, the optimization problem is separable in the two decisions p_l and p_h. Taking the first order derivative of the retailer's expected profit in Equation (2.5) with respect to p_l yields

$$\frac{\partial \Pi_r}{\partial p_l} = w_l[a + g(\theta) - 2bp_l + b(c_l + r(\theta))].$$

It is straightforward to verify that the second order derivative with respect to p_l is $-2bw_l < 0$, which established the concavity of the objective function in p_l. The optimal solution then directly follows from the first order condition (i.e., setting the first order derivative to 0). Similar steps are followed to derive the optimal price p_h^F corresponding to the high type. ■

Proof of Proposition 2.1

Taking the first order derivative of the optimal supply chain expected profit in Equation (2.6) with respect to θ yields

$$\frac{\partial \Pi_r^F}{\partial \theta} = \sum_{i=l,h} \frac{w_i}{2b}[a + g(\theta) - b(c_i + r(\theta))][g'(\theta) - br'(\theta)], \tag{2.24}$$

which is the product of two factors. Note that the first factor $a + g(\theta) - b(c_i + r(\theta))$ is the customer demand when price is set to cost, which clearly should be positive. This implies that the stationary points should satisfy $g'(\theta) - br'(\theta) = 0$.

Next, we take the second order derivative as follows:

$$\frac{\partial^2 \Pi_r^F}{\partial \theta^2} = \sum_{i=l,h} \frac{w_i}{2b} \left\{ [g'(\theta) - br'(\theta)]^2 + [a + g(\theta) - b(c_i + r(\theta))][g''(\theta) - br''(\theta)] \right\}. \tag{2.25}$$

Evaluating the second order derivative at stationary points yields

$$\left. \frac{\partial^2 \Pi_r^F}{\partial \theta^2} \right|_{\frac{\partial \Pi_r^F}{\partial \theta}=0} = \sum_{i=l,h} \frac{w_i}{2b} \{ [g''(\theta) - br''(\theta)][a + g(\theta) - b(c_i + r(\theta))] \} < 0,$$

where the last inequality follows from our assumptions that $g(\theta)$ is concave increasing and $r(\theta)$ is convex increasing in θ. Since the second order derivative is negative at all stationary points, this implies that Π_r^F is unimodal in θ, and the first order condition characterizes the optimal solution θ^F, as stated in the proposition. ■

Proof of Proposition 2.2

We take the following 4 steps to prove this proposition. The first three steps explore basic properties of the constraints, which enables us to eliminate the transfer payments t_h and t_l from the objective function in the last step, thus reducing the dimensionality of the optimization problem.

- Step 1: we first show that the constraint IR_l is redundant.

  If IR_h and IC_l are satisfied, by adding IR_h and IC_l, we have $t_l - [c_l + r(\theta)]q_l \geq \Delta q_h \geq 0$.

Thus, as long as IC_l and IR_h are satisfied, IR_l is always satisfied, which means the low cost type supplier always generates a nonnegative surplus. Further, IR_l is not binding unless the supplier's production quantity for the high cost type is 0 (i.e., $q_h = 0$).

- Step 2: we prove that the constraint IR_h must be binding, i.e., $t_h = (c_h + r(\theta))q_h$.

  If IR_h is not binding, i.e., if $t_h > (c_h + r(\theta))q_h$, the retailer can always decrease the transfer payments t_h and t_l by the same amount to increase her profit, because such a change keeps IC_l and IC_h satisfied. Thus, IR_h must be binding, i.e., $t_h = (c_h + r(\theta))q_h$.

- Step 3: we prove that the constraint IC_l must be binding.

  Substituting $t_h = (c_h + r(\theta)) * q_h$ from the previous step into the constraint IC_l yields

$$t_l - (c_l + r(\theta))q_l \geq \Delta q_h.$$

  In other words, $t_l \geq (c_l + r(\theta))q_l + \Delta q_h$. If IC_l is not binding, i.e., if $t_l > (c_l + r(\theta))q_l + \Delta q_h$, the retailer would decrease the transfer payment t_l until it equals to $(c_l + r(\theta))q_l + \Delta q_h$ to increase her profit without violating other constraints. Therefore, IC_l must be binding, which implies that $t_l = (c_l + r(\theta))q_l + \Delta q_h$.

- Step 4: objective function simplification and optimization.

Substituting the expressions for the transfer payments t_h and t_l from previous steps, we can simplify the retailer's expected profit as follows:

$$\begin{aligned}
\max_{\{p_l,p_h\}} \Pi_r &= w_l(p_l q_l - t_l) + w_h(p_h q_h - t_h) \\
&= w_l\left[p_l q_l - (c_l + r(\theta))q_l - \Delta q_h\right] + w_h\left[p_h q_h - (c_h + r(\theta))q_h\right] \\
&= w_l\left[p_l - c_l - r(\theta)\right] q_l + w_h\left[p_h - \left(c_h + \frac{w_l}{w_h}\Delta\right) - r(\theta)\right] q_h \\
&= w_l\left[p_l - c_l - r(\theta)\right] q_l + w_h\left[p_h - v_n - r(\theta)\right] q_h \\
&= w_l\left[p_l - c_l - r(\theta)\right]\left[a + g(\theta) - bp_l\right] \\
&\quad + w_h\left[p_h - v_n - r(\theta)\right]\left[a + g(\theta) - bp_h\right].
\end{aligned}$$

Taking the first order derivative of the expected profit with respect to p_l yields

$$\frac{\partial \Pi_r}{\partial p_l} = w_l[a + g(\theta) - 2bp_l + b(c_l + r(\theta))].$$

It is straightforward to verify that the second order derivative with respect to p_l is $-2bw_l < 0$, which establishes the concavity of the objective function in p_l and the optimal solution then directly follows from the first order condition. Similar steps are followed to derive the optimal price p_h^N corresponding to the high type. ■

Proof of Proposition 2.3

Taking the first order derivative of the supplier expected profit in Equation (2.8) with respect to θ yields

$$\frac{\partial \Pi_s}{\partial \theta} = \frac{1}{2} w_l \Delta[-br'(\theta) + g'(\theta)].$$

Next, we take the second order derivative as follows:

$$\frac{\partial^2 \Pi_s}{\partial \theta^2} = \frac{1}{2} w_l \Delta[-br''(\theta) + g''(\theta)].$$

Since $r(\theta)$ is convex increasing in θ and $g(\theta)$ is concave increasing in θ, we have $r'(\theta) > 0, g'(\theta) > 0$ and $r''(\theta) > 0, g''(\theta) < 0$. As a result, the second order derivative is negative and the optimal decision θ^N follows from the first order condition. ■

Proof of Proposition 2.4

We make a claim upfront to facilitate our further discussion. The claim is the retailer does not need to audit a supplier claiming that he is efficient type, c_l (i.e.,$x_l = 0$). Because the supplier with inefficient type, c_h, does not have incentive to pretend to be a supplier with efficient type, c_l. Thus, if a supplier claims that he produces with a cost type, c_l, he must tell the truth.

We take the following 5 steps to prove this proposition. The first four steps explore basic properties of the constraints, which enables us to eliminate the transfer payments t_h and t_l from the objective function in the last step, thus reducing the dimensionality of the optimization problem.

- Step 1: we first prove that the constraint IR_h must be binding, i.e., $t_h = (c_h + r(\theta))q_h$.

If IR_h is not binding, i.e., if $t_h > (c_h + r(\theta))q_h$, the retailer can always decrease the transfer payments t_h and t_l by the same amount to increase her profit, because such a change keeps IC_l and IC_h satisfied. Thus, IR_h must be binding, i.e., $t_h = (c_h + r(\theta))q_h$.

- Step 2: we show that the constraint IR_l is redundant.

  The *The Maximal Punishment Principle* (Border and Sobel, 1987) implies that Equation (2.10) must be binding, i.e., $t_h - (c_l + r(\theta))q_h = o_l$. Substituting $t_h = c_h + r(\theta))q_h$ from the previous step yields $o_l = t_h - (c_l + r(\theta))q_h = \Delta q_h$.

  If IR_h and IC_l are satisfied, by adding IR_h and IC_l, we have $t_l - [c_l + r(\theta)]q_l \geq \Delta q_h - x_h o_l = (1 - x_h)\Delta q_h \geq 0$. Thus, as long as IC_l and IR_h are satisfied, IR_l is always satisfied, which means the low cost type supplier always generates a nonnegative surplus. Further, IR_l is not binding unless the supplier's production quantity for the high cost type is 0 (i.e., $q_h = 0$).

- Step 3: we prove that the constraint IC_l must be binding.

  Substituting $t_h = (c_h + r(\theta))q_h$ from step 1 into the constraint IC_l yields

  $$t_l - (c_l + r(\theta))q_l \geq (1 - x_h)\Delta q_h.$$

  In other words, $t_l \geq (c_l + r(\theta))q_l + (1 - x_h)\Delta q_h$. If IC_l is not binding, i.e., if t_l is strictly greater than $(c_l + r(\theta))q_l + (1 - x_h)\Delta q_h$, the retailer would decrease the transfer payment t_l until it equals to $(c_l + r(\theta))q_l + (1 - x_h)\Delta q_h$ to increase her profit without violating other constraints. Therefore, IC_l must be binding, which implies that $t_l = (c_l + r(\theta))q_l + (1 - x_h)\Delta q_h$.

- Step 4: we prove that the audit probability for the low type supplier is $x_l = 0$.

  To prove this result, let us revisit the no-audit case studied in Section 2.4.2. Using results in Proposition 2.2, we can simplify the constraint IC_h to $0 \geq \Delta(q_h^N - q_l^N)$, which can be easily verified to hold with strict inequality. In other words, the high type supplier is strictly better-off reporting his true type. Since there is no incentive for the high type supplier to lie, any supplier reporting to be the low type must be telling the truth. Therefore, an audit of the (reported) low type should be avoided as the audit is costly and does not add any value. In conclusion, $x_l = 0$.

- Step 5: objective function simplification and optimization.

  Substituting $x_l = 0$ and the expressions for the transfer payments t_h and t_l from previous steps, we can simplify the retailer's expected profit in Equation (2.13) to an optimization problem with three remaining decisions p_l, p_h, and x_h as follows:

$$\begin{aligned}
\max_{\{p_l,p_h,x_h\}} \Pi_r &= w_l(p_l q_l - t_l) + w_h(p_h q_h - t_h - K x_h^2) \\
&= w_l \left[p_l q_l - (c_l + r(\theta))q_l - (1 - x_h)\Delta q_h\right] \\
&\quad + w_h \left[p_h q_h - (c_h + r(\theta))q_h - K x_h^2\right] \\
&= w_l \left[p_l - c_l - r(\theta)\right] q_l + w_h \left[p_h - \left(c_h + \frac{w_l}{w_h}\Delta(1 - x_h)\right) - r(\theta)\right] q_h \\
&\quad - w_h K x_h^2 \\
&= w_l \left[a + g(\theta) - b p_l\right]\left[p_l - c_l - r(\theta)\right] \\
&\quad + w_h \left[a + g(\theta) - b p_h\right]\left[p_h - v_a - r(\theta)\right] - w_h K x_h^2.
\end{aligned}$$

We observe that the above optimization problem is separable in p_l and the pair $\{p_h, x_h\}$, as there are no cross terms between p_l and p_h or x_h. Taking the first order derivative of the expected profit with respect to p_l yields

$$\frac{\partial \Pi_r}{\partial p_l} = w_l[a + g(\theta) - 2bp_l + b(c_l + r(\theta))].$$

It is straightforward to verify that the second order derivative with respect to p_l is $-2bw_l < 0$, which establishes the concavity of the objective function in p_l. The optimal solution p_l^A then directly follows from the first order condition.

For the remaining two decisions $\{p_h, x_h\}$, we obtain the Hessian matrix as follows:

$$\begin{bmatrix} -2bw_h & -b\Delta w_l \\ -b\Delta w_l & -2Kw_h \end{bmatrix},$$

whose determinant is $b(4Kw_h^2 - b\Delta^2 w_l^2)$. Given the assumption that $4Kw_h^2 - b\Delta^2 w_l^2 > 0$, the Hessian matrix is negative definite, implying that the retailer's expected profit is jointly concave in p_h and x_h. The two first order derivatives are (note that v_a is a function of x_h):

$$\begin{aligned} \frac{\partial \Pi_r}{\partial p_h} &= w_h[a + g(\theta) - 2bp_h + b(v_a + r(\theta))], \\ \frac{\partial \Pi_r}{\partial x_h} &= w_l\Delta[a + g(\theta) - bp_h] - 2Kw_h x_h. \end{aligned}$$

The optimal solutions p_h^A and x_h^A are derived from solving the two first order conditions simultaneously. ■

Proof of Proposition 2.5

Through the analyses in the main text, we already know that the supplier's expected profit Π_s in Equation (2.13) may have up to three stationary points. Our remaining task is to determine which stationary point(s) is/are the global maximizer(s) of Π_s. To that end, we take the second order derivative of Π_s with respect to θ as follows:

$$\frac{d^2\Pi_s}{d\theta^2} = \left[-2\left(\frac{\partial x_h^A}{\partial \theta}\right)^2 + (1 - 2x_h^A)\frac{\partial^2 x_h^A}{\partial \theta^2}\right]. \tag{2.26}$$

As the number of stationary points depends on the number of roots to Equation (2.15), we examine the following three cases:

- Case 1: If Equation (2.15) has two different roots θ_1 and θ_2, as illustrated in Figure 2.2a, then there are three stationary points θ_1, θ_2, and θ^F. We next examine if they are local maximizers or minimizers. From Equation (2.26), we know that evaluated at either θ_1 or θ_2, the second order derivative $\frac{d^2\Pi_s}{d\theta^2} = -2\left(\frac{\partial x_h^A}{\partial \theta}\right)^2 < 0$. Therefore, both θ_1 and θ_2 are local maximizers.

  At θ^F, however, we can see from Equation (2.26) that the second order derivative $\frac{d^2\Pi_s}{d\theta^2}$ is equal to 0, because $\left.\frac{\partial x_h^A}{\partial \theta}\right|_{\theta=\theta^F} = 0$. Thus, we have to resort to the first order derivative in Equation (2.14) for further analysis. As can be seen from Figure 2.2a, we have $1 - 2x_h^A < 0$ in the vicinity of θ^F. Further, $\frac{\partial x_h^A}{\partial \theta}$ is positive on the left of θ^F, and negative on the right of θ^F. Therefore, $\frac{d\Pi_s}{d\theta}$ is negative on the left of θ^F, and positive on the right of θ^F. In other words, θ^F is a local minimizer of Π_s.

  In sum, in this case, the supplier's profit function Π_s is bimodal in θ, as illustrated in Figure 2.3b. Further, it is straightforward to obtain that the supplier's optimal expected profit is $\Pi_s^A = Kw_h/2$ at both maxima. We next substitute optimal solutions in Proposition 2.4 into Equation (2.13), and note that $x_h^A = 0.5$ and $w_l q_h^A \Delta = 2Kw_h x_h^A = Kw_h$. After some algebraic simplifications, we get the retailer's optimal expected profit as follows:

$$\Pi_r^A\Big|_{x_h^A=0.5} = \frac{1}{4b}\left\{w_l\left[\frac{2Kw_h}{\Delta w_l}+\frac{b\Delta(1+w_h)}{2w_h}\right]^2+w_h\left[\frac{2Kw_h}{\Delta w_l}\right]^2\right\}-\frac{Kw_h}{4},$$

which turns out to be totally independent of θ. This proves all claims in scenario A of the proposition.

If θ_2, the larger root of Equation (2.15), falls out of the feasible range, then θ_1 becomes the only maximizer of Π_s. This corresponds to scenario B of the proposition.

- Case 2: If Equation (2.15) has a unique root, then $\theta_1 = \theta_2$. In this case, θ_1, θ_2, and θ^F all consolidate to the same point, as illustrated in Figure 2.2b. We refer to this point as θ^F for convenience. As can be seen from Figure 2.2b, on the left of θ^F, we have $1 - 2x_h^A > 0$, and $\frac{\partial x_h^A}{\partial\theta} > 0$, so $\frac{d\Pi_s}{d\theta} > 0$. On the right of θ^F, we have $1 - 2x_h^A > 0$, and $\frac{\partial x_h^A}{\partial\theta} < 0$, so $\frac{d\Pi_s}{d\theta} < 0$. In other words, Π_s is increasing on the left of θ^F, but decreasing on the right of θ^F. Therefore, Π_s attains its global maximum at its only stationary point θ^F.

- Case 3: If Equation (2.15) has no root, as illustrated in Figure 2.2c, then it means the parametric conditions are such that $x_h^A < 0.5$ or $1 - 2x_h^A > 0$. Therefore, Π_s, as a univariate function of θ, has only one stationary point θ^F, similar to case 2 above. It is straightforward to verify that $\frac{\partial^2 x_h^A}{\partial\theta^2} \propto h''(\theta) - br''(\theta) < 0$, where $\propto$ stands for proportional to, as we omitted some positive coefficients for convenience of notation.

As a result, Equation (2.26) indicates that the second order derivative $\frac{d^2\Pi_s}{d\theta^2}$ is negative at θ^F, thus confirming the only stationary point θ^F as the global maximizer.

In both cases 2 and 3, the supplier's expected profit Π_s is unimodal, and its only stationary point θ^F is the global maximizer. This corresponds to scenario C of the proposition. ■

Proof of Lemma 2.2

Evidently, the optimization problem is separable in the two decisions p_l and p_h. Taking the first order derivative of the retailer's expected profit in Equation (2.16) with respect to p_l yields

$$\frac{\partial \Pi_r}{\partial p_l} = w_l g(\theta)[a - 2bp_l + b(c_l + r(\theta))].$$

It is straightforward to verify that the second order derivative with respect to p_l is $-2bw_l g(\theta) < 0$, which established the concavity of the objective function in p_l. The optimal solution then directly follows from the first order condition. Similar steps are followed to derive the optimal price p_h^F corresponding to the high type. ■

Proof of Proposition 2.6

The first order derivative of Π_r^F with respect to θ is

$$\frac{\partial \Pi_r^F}{\partial \theta} = \frac{g'(\theta)}{4b}\left\{w_l\left[a-b\left(c_l+r(\theta)\right)\right]^2+w_h\left[a-b\left(c_h+r(\theta)\right)\right]^2\right\} \\ -\frac{g(\theta)r'(\theta)}{2}\left\{a-b\left[w_lc_l+w_hc_h+r(\theta)\right]\right\},$$

and the second order derivative can be simplified to the following:

$$\frac{\partial^2 \Pi_r^F}{\partial \theta^2} = \frac{g''(\theta)}{4b}\left\{w_l\left[a-b(c_l+r(\theta)\right]^2+w_h\left[a-b(c_h+r(\theta))\right]^2\right\} \\ -g'(\theta)r'(\theta)\left\{a-b\left[w_lc_l+w_hc_h+r(\theta)\right]\right\} \\ +\frac{g(\theta)}{2}br'(\theta)^2-\frac{g(\theta)}{2}r''(\theta)(a-b\left(w_lc_l+w_hc_h+r(\theta)\right)).$$

Evaluating the second order derivative at the stationary point yields

$$\left.\frac{\partial^2 \Pi_r^F}{\partial \theta^2}\right|_{\frac{\partial \Pi_r^F}{\partial \theta}=0} = \frac{g(\theta)r'(\theta)}{2}\left[\frac{g''(\theta)}{g'(\theta)}\left[a-b(w_lc_l+w_hc_h+r(\theta))\right]+br'(\theta)\right] \\ -g'(\theta)r'(\theta)\left[a-b\left(w_lc_l+w_hc_h+r(\theta)\right)\right] \\ -\frac{g(\theta)}{2}r''(\theta)[a-b\left(w_lc_l+w_hc_h+r(\theta)\right)].$$

If it is negative, then Π_r^F in unimodal in θ, and the stationary point is the optimal solution. Clearly, a sufficient (but not necessary) condition for the above result to be negative is that $\frac{g''(\theta)}{g'(\theta)}\left[a-b(w_lc_l+w_hc_h+r(\theta))\right]+br'(\theta)<0$.

■

Proof of Proposition 2.7

All steps to prove this proposition are the same as those in the proof of Proposition 2.2. Details are thus omitted for brevity. ■

Proof of Proposition 2.8

The first order derivative of the supplier's expected profit Π_s in Equation (2.20) with respect to θ is

$$\frac{\partial \Pi_s}{\partial \theta} = \frac{1}{2} w_l \Delta \left\{ g'(\theta) \left[a - b(v_n + r(\theta) \right] - bg(\theta) r'(\theta) \right\}.$$

The second order derivative with respect to θ is

$$\begin{aligned} \frac{\partial^2 \Pi_s}{\partial \theta^2} &= \frac{1}{2} w_l \Delta \left\{ g''(\theta) \left[a - b(v_n + r(\theta)) \right] - g'(\theta) r'(\theta) \right. \\ &\quad \left. - b[g'(\theta) r'(\theta) + g(\theta) r''(\theta)] \right\} \\ &< 0, \end{aligned}$$

where the inequality follows from the assumptions that $g(\theta)$ is concave increasing and $r(\theta)$ is convex increasing. Given the concavity of Π_s, the optimal decision θ^N can be characterized by the first order condition. ■

Proof of Proposition 2.9

All steps to simplify the retailer's expected profit to Equation (2.22) are identical to those in the proof of Proposition 2.4, and are thus omitted for brevity.

We observe that the optimization problem in Equation (2.22) is separable in p_l and the pair $\{p_h, x_h\}$, as there are no cross terms between p_l and p_h or x_h. Taking the first order derivative of the expected profit with respect to p_l

yields

$$\frac{\partial \Pi_r}{\partial p_l} = w_l g(\theta)\left[a - 2bp_l + b(c_l + r(\theta))\right],$$

It is straightforward to verify that the second order derivative with respect to p_l is $-2bw_l g(\theta) < 0$, which establishes the concavity of the objective function in p_l. The optimal solution p_l^A then directly follows from the first order condition.

For the remaining two decisions $\{p_h, x_h\}$, we obtain the Hessian matrix as follows:

$$\begin{bmatrix} -2bw_h g(\theta) & -b\Delta w_l g(\theta) \\ -b\Delta w_l g(\theta) & -2Kw_h \end{bmatrix},$$

whose determinant is $bg(\theta)\left[4Kw_h^2 - bg(\theta)\Delta^2 w_l^2\right]$. Since $g(\theta)$ is concave increasing in θ on its support $[0,1]$, the assumption that $4Kw_h^2 - bg(1)\Delta^2 w_l^2 > 0$ guarantees that the Hessian matrix is negative definite. Therefore, the retailer's expected profit is jointly concave in p_h and x_h. The two first order derivatives are (note that v_a is a function of x_h):

$$\begin{aligned} \frac{\partial \Pi_r}{\partial p_h} &= w_h[a - 2bp_h + b(v_a + r(\theta))]g(\theta), \\ \frac{\partial \Pi_r}{\partial x_h} &= w_l\Delta[a - bp_h]g(\theta) - 2Kw_h x_h. \end{aligned}$$

The optimal solutions p_h^A and x_h^A are derived from solving the two first order conditions simultaneously. ■

Proof of Proposition 2.10

It suffices to show that θ_s, the solution to $\frac{\partial x_h^A}{\partial \theta} = 0$, is unique, as the remaining analysis is exactly the same as in the additive demand model.

The first order derivative of x_h^A with respect to θ is

$$\begin{aligned}\frac{\partial x_h^A}{\partial \theta} &= \frac{w_l w_h \Delta}{[4Kw_h^2 - bg(\theta)w_l^2\Delta^2]^2}\left\{bw_l^2\Delta^2(a - bv_n - br(\theta))g(\theta)\frac{\partial g(\theta)}{\partial \theta}\right.\\&\left.+ \left[4Kw_h^2 - bg(\theta)w_l^2\Delta^2\right]\frac{\partial[g(\theta)(a - bv_n - br(\theta))]}{\partial \theta}\right\},\end{aligned}$$

and the second order derivative, evaluated at the stationary point, can be simplified to

$$\begin{aligned}\left.\frac{\partial^2 x_h^A}{\partial \theta^2}\right|_{\frac{\partial x_h^A}{\partial \theta}=0} &= \frac{w_l w_h \Delta}{[4Kw_h^2 - bg(\theta)w_l^2\Delta^2]^2}\left\{bw_l^2\Delta^2 g(\theta)(a - bv_n - br(\theta))\frac{\partial^2 g(\theta)}{\partial \theta^2}\right.\\&\left.+ \left[4Kw_h^2 - bg(\theta)w_l^2\Delta^2\right]\left[\frac{\partial^2 g(\theta)}{\partial \theta^2} - 2b\frac{\partial g(\theta)}{\partial \theta}\frac{\partial r(\theta)}{\partial \theta} - bg(\theta)\frac{\partial^2 r(\theta)}{\partial \theta^2}\right]\right\}\\&< 0,\end{aligned}$$

where the inequality follows from the assumptions that $g(\theta)$ is concave increasing and $r(\theta)$ is convex increasing. This implies that x_h^A is unimodal in θ. Therefore, the stationary point θ_s is unique. ■

Proof of Proposition 2.11

Note that $x_h^A = 0.5$ in scenario A. Substituting this and other results in Proposition 2.9 into the retailer's expected profit yields the following after some simplifications:

$$\left.\Pi_r^A\right|_{x_h^A=\frac{1}{2}} = \frac{1}{4b}\left\{\frac{1}{g(\theta)}\left(\frac{2Kw_h}{w_l\Delta}\right)^2 + w_l g(\theta)\left[\frac{b(1+w_h)\Delta}{2w_h}\right]^2 + 2Kb(1+w_h)\right\} - \frac{w_h K}{4}.$$

It is then straightforward to obtain the following:

$$\Pi_r^A(\theta_1) - \Pi_r^A(\theta_2) \propto \left(\frac{2Kw_h}{w_l\Delta}\right)^2 - g(\theta_1)g(\theta_2)w_l\left(\frac{b(1+w_h)\Delta}{2w_h}\right)^2,$$

which implies that the retailer prefers θ_1 if and only if

$$\left(\frac{2Kw_h}{w_l\Delta}\right)^2 - g(\theta_1)g(\theta_2)w_l\left(\frac{b(1+w_h)\Delta}{2w_h}\right)^2 > 0.$$

After some algebraic simplifications, the above condition becomes

$$4Kw_h^2 > b\Delta^2\sqrt{g(\theta_1)g(\theta_2)w_l}(1+w_h)w_l. \tag{2.27}$$

Clearly, when the inequality sign in Equation (2.27) is reversed, then θ_2 is preferred by the retailer. ■

Proof of Corollary 1

- Part (a): the expressions for θ^F and θ^N come directly from Equations (2.7) and (2.9) by substituting $g(\theta) = G\sqrt{\theta}$ and $r(\theta) = R\theta^2$. The sensitivity analyses are straightforward.

- Part (b): From Equation (2.18), we obtain that θ^F solves the following equation:

  $$9(bR\theta^2)^2 - 10[a - b(w_lc_l + w_hc_h)](bR\theta^2) + [w_l(a-bc_l)^2 + w_h(a-bc_h)^2] = 0,$$

  which is quadratic in $bR\theta^2$. It is straightforward to see that θ^F is decreasing in R and independent of G and K.

The equation that characterizes θ^N follows from Equation (2.21). The sensitivity analyses are straightforward. ■

Chapter3

The Role of Live-Streaming Commerce in a Dual-Channel Supply Chain

3.1. Introduction

With the fast development of the Internet, customers' consumption pattern has been significantly changed and extended from traditional offline shopping to online shopping. We observe that a new business model has attracted considerable attention and been increasingly adopted by many companies in recent years: live-streaming commerce, which allows customers to "touch", "try", and purchase a product without going outside. Compared with previous online shopping, live-streaming shopping provides a new and diverse shopping experience through real-time communication and live interactions. Consumers can view the product, ask questions, share opinions, and communicate with other viewers through a chat box in real-time. If consumers are convinced, they place an order over the phones through an embedded link during the live session. Compared with traditional offline stores, live-streaming shopping eliminates consumers' transportation cost and the risk of product shortage. Consumers receive more information instantly through interactions and "try-on hauls" than simply browsing photos on websites. Live-streaming shopping first launched on Taobao.com in 2016. According to iResearch, China has 617 million live-streaming users at the end of 2020 and the live-streaming market is expected to exceed 4.9 trillion RMB in 2023 (iResearch, 2021). In recent years, many companies have started to adopt live-streaming commerce and have created their own live-streaming sites, such as Facebook and Amazon. YouTube is launching a new live-streaming shopping platform to integrate live shopping into YouTube so that viewers can purchase the product directly from the YouTube livestreamers they trust (The YouTube Team, 2021).

A common practice in live-streaming commerce is that a supplier collaborates with professional livestreamers, referred as "key opinion leaders" (KOLs), and sells products through the KOLs' live-streaming channels. KOLs normally have a stable audience pool and perform professionally in one or several fields. Collaborating with a top KOL may boost product demand tremendously. For example, Austin Li (Jiaqi Li), one of the most famous livestreamers in China, sold $1 billion in goods in a 12-hour live-streaming in October 2021, the month before Alibaba's annual shopping festival, and the views reached 250 million in that session (Bloomberg, 2021). It is rare to find another shopping method that can attract so many consumers at the same time and boost demand in such a short period. In general, a supplier could collaborate with a KOL in three different methods: "flash retailer", revenue-sharing, and two-part tariff contract. In "flash retailer", the supplier sells products in the KOL's stream by paying a fixed slotting fee, which is a common practice when launching a new product. Supplier could reach out a large audience pool and consumers are easier to convinced because of the KOL's endorsement. In revenue-sharing, a supplier designs a contract with a KOL. The KOL keeps a percentage of the revenue of live-streaming sales and the supplier earns the rest of the sales. A supplier may design a two-part tariff contract with KOL, where the KOL charges lower price in the live-streaming channel and a slotting fee to the supplier. In our paper, we focus on the second method, revenue-sharing contract.

Despite the massive advantages of collaborating with KOLs, it comes with a cost. Top KOLs always have strong bargaining power in price setting and the supplier has to agree on a revenue-sharing contract to reach a collaboration. It may be surprising to see a KOL has so much control on live-streaming channel, but in practice, some powerful KOLs would be able to manipulate the live-streaming channel decisions due to their influential profile. For example, Austin Li helped a litter-known brand, Florasis, a Chinese cosmetics brand founded in 2017, sold more than $700,000$ units setting powder on

November 11, 2019, and became one of the top 10 color cosmetic brands during the Tmall Global Shopping Festival in the following years (Retail in Asia, 2022). Florasis' Gross Merchandise Value (GMV) reaches $823.3 million in 2021, which almost doubles the GMV in 2020 (CosmeticsDesign-Asia, 2022). In this case, Austin Li highly involved in the price setting process. Florasis also benefits from the high demand in live-streaming channel and the potentially increased demand in traditional channel. In addition, KOLs charge commission fees, normally 20 to 30 percent of the sales in the live session, and leave the rest to the supplier (Yahoo!news, 2020). Some top KOLs also charge slotting fees for promoting the product during a live session and the commission fee can be as high as 60% to 70%. Many companies, especially some small or start-up companies, are starting to train their own employees and creating their own live-streaming channels. Instead of selling products on a KOL's stream by paying commission fees and sharing revenue, many companies operate their own shopping streams to maintain inventory efficiency, enrich brand loyalty with customer engagement, build customer trust, and improve demand forecasting.

For each channel, the owner has to have operation cost and media investment. For example, more media investment in advertising will cover a larger market size, increase the product exposure to customers, and eventually boost sales. Since live-streaming shopping has been widely employed by many companies as a new channel, it is important to understand the supplier's supply chain strategies in adopting a live-streaming channel and whether or not to collaborate with a KOL. In this paper, we consider four supply chain strategies: traditional channel only, live-streaming channel only, dual-channel with self-streaming, and dual-channel with collaboration. We define the first three strategies as "centralized settings" because the supplier decides the pricing and media investment for all channels; we define the fourth strategy as a "decentralized case" where the supplier decides the pricing and media investment for the traditional channel and the KOL makes optimal decisions for the live-streaming channel.

The rest of the paper is organized as follows. In section 2, we present the literature review. In section 3, we describe the model framework. In section 4 and section 5, we calculate the optimal solutions in centralized settings and one decentralized case. In section 6 we discuss the supplier's choice among different strategies. In section 7, we conclude our findings and propose future research directions.

3.2. Literature Review

This paper is the first to model live-streaming introduction in a dual-channel setting with a theoretical method considering consumers' preferences. We explore the optimal equilibrium solutions and the impact of live-streaming commerce on suppliers' supply chain strategy given consumers' different channel preferences. The relevant literature can be divided into three areas: dual-channel management, live-streaming commerce, and social influence and celebrity endorsement.

The dual-channel management has gained much attention in operations management and marketing. McGuire and Staelin (1983) investigate manufacturer's choice between a company store and a decentralized distribution system. Jeuland and Shugan (1983) explore the problems and solutions in a coordination system and conclude that a quantity discount contract can help to achieve the coordination. Rhee and Park (2000) present a hybrid channel model by dividing customers into two segments: a price-sensitive and a service-sensitive segment. Chiang et al. (2003) explain the benefit of introducing a direct channel and how it benefits the manufacturer and the retailer. Tsay and Agrawal (2004) study the channel conflict and coordination between manufacturer and retailer and provided a comprehensive review of quantitative models in dual-channel management. Yue and Liu (2006) analyze the benefit of sharing demand forecast in a dual-channel supply chain. Chen et al. (2008) consider a stochastic demand and add service and product availability competition for direct channel and retail stores. Cai (2010) compare four supply chain structures and suggest two Pareto-zone for supplier and retailer's channel selection. Wu et al. (2015) and Chen et al. (2017) adopts a utility function of a representative consumer to capture the demand functions by maximizing consumer utility. In our model, we evaluate the trade-off between an increasing market size by adopting the live-streaming channel and a potential channel competition.

The second area is the study of live-streaming commerce. live-streaming commerce is a new type of shopping experience that inherits characteristics from e-commerce and includes social media attributes that emend real-time interaction with livestreamer. Compared with traditional researches in celebrity endorsement which focus on celebrity-product fit, livestreamer endorsement starts to consider the impact of the endorser-customer relationship from the sellers' perspective. Wongkitrungrueng and Assarut (2018) prove that the customers' trust in the seller, not the product, is directly associated with customer engagement. Cheng et al. (2019) find that adopting a live video streaming can significantly boosts online sales. Park and Lin (2020) indicate that the congruence between the product and live content will increase customers' purchase intention. Wongkitrungrueng et al. (2020) identify adaptable strategies in live-streaming commerce from the seller's perspective and presents a comparison between live-streaming commerce, e-commerce, and offline commerce. Qi et al. (2021) compare manufacturer's strategies when contracting with two types of influencers: top influencer or regular influencer. We focus on the important aspects of the live-streaming channel which have not been extensively studied, the impact of live-streaming channel on price setting and media investment in a dual-channel supply chain, and suggests that the supplier's profit may be lower by collaborating with an influencer than hosting a live-streaming channel.

The third area is the study of social influence and celebrity endorsement. The problem of social influence and celebrity endorsement is widely studied in marketing and has received considerable attention in the literature. Lafferty and Goldsmith (1999) analyze the different impacts of an endorser and corporate credibility on customers' attitudes towards the brand and purchase intentions. Kamins (1990) present a series of "match-up" hypotheses to explain the importance between the celebrity, the brand, and the product-endorser fit. Escalas and Bettman (2009) suggest that a mismatch between celebrity and product can be less efficient and effective. Liang et al. (2011) and Liang and Turban (2011) present a framework that covers the key elements in social commerce and interprets the blooming of social commerce. Hackley and Hackley (2015) propose that the relationship between customer, brand, and celebrity is needed to be re-evaluated and re-shape with the fast development of media convergence. Chung and Cho (2017) explore how the use of social media affects endorser effectiveness and find that high trustworthy celebrity can lead to a high purchase intention. Carlson et al. (2020) find that as long as endorsers have a strong connection with the target audience, customers still respond favorably to the endorsement even if the endorser-brand fit is low, which explains why the livestreamer's influencing factor plays such an important role in the live-streaming marketing. Ye et al. (2021) provide an overview of the current influencer marketing research and make recommendations for future research in this field. Notably, these papers have employed a lot of different qualitative and quantitative methods to investigate the influence of celebrity-endorsement. Our research contributes to the theoretical analysis and explores the impact of social influence on supplier's profit.

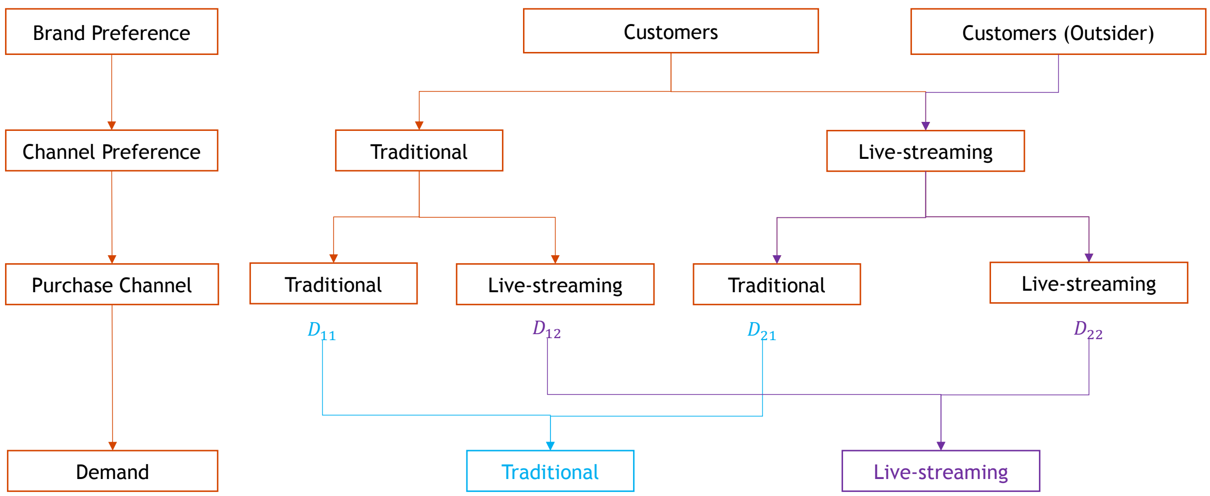
This paper extends the literature related to dual-channel management, live-streaming commerce, and social influence and celebrity-endorsement by addressing the following research questions: (i) how does the live-streaming channel influence level affect regular channel demand? (ii) what are the supplier's pricing and media investment decisions in a dual-channel supply chain? (iii) when should the supplier collaborate with a KOL?

3.3. Model Framework

We consider a setting where a supplier sells a product through traditional direct channel, live-streaming channel, or both. The supplier has two options when adopting a live-streaming channel, he can sell the product either through his own live-streaming channel or by collaborating with KOLs, who have advantages in terms of influence level, consumers' trust, audience size, and product exposure. If the supplier chooses self-streaming, he decides the prices and media investment for both channels given the live-streaming channel influence level. If the supplier sells a product through a KOL's live-streaming channel, the supplier decides the price and media investment of the traditional channel first and then the KOL makes decisions for the live-streaming channel. They will agree on a revenue-sharing contract and the KOL takes a percentage of the sales in the live-streaming channel. The influence level can be measured by the number of subscribers, the conversation rate, conversion rate, and the history of transaction data. It is rational to assume that a KOL with a high influence level often requests a relatively high revenue-sharing percentage.

Based on customers' channel preferences, we divide customers into two segments: one prefers traditional channel shopping and the other prefers live-streaming channel shopping. For the first segment, customers prefer to shop through traditional channels, such as offline stores or companies' direct websites. However, this segment customers may purchase from a live-streaming channel because of a traditional channel product shortage or the anticipation of a lower price in the live-streaming channel. Similarly, in the second segment, customers are familiar with the live-streaming selling platforms and prefer to purchase the product through live-streaming channel. Nevertheless, the second segment customers may be interested in the product by watching the live-streaming session but purchase the product from a traditional channel due to the time-sensitive of the live-streaming session. In addition, we consider customer switching behavior, where customers abandon a competitor's brand and purchase a product from the supplier. We define these customers as "outsiders", which increase the potential market demand of live-streaming channel. It is reasonable to assume that outsiders only prefer live-streaming shopping because customers with traditional channel preference from other brands will not be attracted to the live-streaming channel and exposed to the product. To facilitate our further discussion, we define the customer demand based on their preference and purchasing behavior. Customers who prefer a traditional channel and purchase from the traditional channel are defined as D_{11}; customers who prefer a traditional channel but purchase from a live-streaming channel are defined as D_{12}; customers who prefer a live-streaming channel but purchase from a traditional channel are defined as D_{21}, and customers who prefer live-streaming channel and purchase from a live-streaming channel are defined as D_{22}. Overall, Figure 3.1 classified customer demands into four categories depending on their shopping preference and purchase channel. The total demand in the traditional channel is $D_{11} + D_{21}$ and the total demand in the live-streaming channel is $D_{12} + D_{22}$.

Figure 3.1: Model Structure



To characterize each demand function, we adopt a utility function of a representative consumer introduced by Ingene and Parry (2004). This utility function has been widely used in economy, marketing, and operations management literature (Cai 2010; Hsiao and Chen 2013; Liu et al. 2014; Wu et al. 2015; Chen et al. 2017).

In the traditional channel preference, the utility function is as follows:

$$U_1 = \sum_{i=1,2}\left[\alpha_{1i}D_{1i} - \frac{D_{1i}^2}{2}\right] - \beta D_{11}D_{12} - \sum_{i=1,2} p_i D_{1i} + \sqrt{\gamma}k_1(D_{11}+D_{12}). \tag{3.1}$$

We use the first subscript 1 to denote a consumer who prefers a traditional channel, and i to represent the purchasing channel. $i = 1$ is the traditional channel and $i = 2$ stands for the live-streaming channel. α_{1i} are initial market sizes and D_{1i} are realized demands in each channel, respectively. β

measures channel substitution with a support of $[0,1]$. When β approaches 1, the channels are purely substitutes. When $\beta = 0$, the channels become independent. γ is the marginal increase in demand in response to a unit investment k_1 in a traditional channel.

Maximization of U_1 yields the demand for each customer segment as follows.

$$D_{11} = \frac{\alpha_{11} - \beta\alpha_{12} + \beta p_2 - p_1 + (1-\beta)k_1\sqrt{\gamma}}{1-\beta^2}, \tag{3.2}$$

$$D_{12} = \frac{\alpha_{12} - \beta\alpha_{11} + \beta p_1 - p_2 + (1-\beta)k_1\sqrt{\gamma}}{1-\beta^2}. \tag{3.3}$$

Similarly, the utility function of consumers who prefer live-streaming channel is given by

$$\begin{aligned} U_2 \;&=\; \sum_{i=1,2}\left[\alpha_{2i}(\theta)D_{2i} - \frac{D_{2i}^2}{2}\right] - \beta D_{21}D_{22} - \sum_{i=1,2} p_i D_{2i} \\ &\quad + \sqrt{\gamma}k_2(D_{21}+D_{22}), \end{aligned} \tag{3.4}$$

where θ is the influence level of the live-streaming channel with a support of $[0,1]$. $\alpha_{21}(\theta)$ is the initial market size for consumers who prefer live-streaming channel but purchase from a traditional channel. $\alpha_{22}(\theta)$ represents the initial market sizes for consumers who prefer a live-streaming channel and end up with a purchase in a live-streaming channel. We assume that $\alpha_{2i}(\theta)$ is increasing in θ since the higher the influence level, the larger the audience pool and more customers are expected to be attracted to live-streaming channel. D_{21} and D_{22} are the realized demand in two channels. The corresponding media investment in live-streaming channel is defined as k_2.

Maximization of the utility function yields the demand functions in each channel of customers who prefer live-streaming channel.

$$D_{21} = \frac{\alpha_{21}(\theta) - \beta\alpha_{22}(\theta) + \beta p_2 - p_1 + (1-\beta)k_2\sqrt{\gamma}}{1-\beta^2}, \tag{3.5}$$

$$D_{22} = \frac{\alpha_{22}(\theta) - \beta\alpha_{21}(\theta) + \beta p_1 - p_2 + (1-\beta)k_2\sqrt{\gamma}}{1-\beta^2}. \tag{3.6}$$

Therefore, the total demand in traditional channel is $D_{11} + D_{21}$ and the total demand in live-streaming channel is $D_{12}+D_{22}$, where demand functions are characterized by maximizing consumer utility functions.

Given the demand function, the total traditional channel profit π_1, which is the sum of two traditional channels' profit, can be described by

$$\pi_1 = (p_1 - c_1 - c)(D_{11} + D_{21}) - \frac{k_1^2}{2}. \tag{3.7}$$

Similarly, the total live-streaming channel profit π_2 is as follows

$$\pi_2 = (p_2 - c_2 - c)(D_{12} + D_{22}) - \frac{k_2^2}{2}. \tag{3.8}$$

In profit functions, c is the unit production cost. c_1 and c_2 denote the operation cost per item of the traditional channel and live-streaming channel, respectively. k_1 and k_2 are the media investment in each market. The quadratic function explains that investing in channels generates an incremental cost.

Assumption 1. *To guarantee the non-triviality of the solution, we impose the following constraints on all cases.*

(a) $\alpha_{11} > c + c_1$ *and* $\alpha_{21}(\theta) > c + c_1$.

(b) $\alpha_{12} > c + c_2$ *and* $\alpha_{22}(\theta) > c + c_2$.

(c) $0 \leq \gamma < 1$.

The first two constraints are to guarantee the positive demand. The constrain imposed on parameter γ is derived from the second order conditions of the profit function in the following dual-channel scenario.

3.4. Centralized Settings

In centralized settings, the supplier makes all operational decisions and sells products through a traditional channel, his own live-streaming channel, or both. In this section, we first study the two special cases to create a benchmark, the single channel supply chain strategies. Then we investigate the dual-channel supply chain structure and calculate the optimal solutions. Finally, we compare the three strategies in the presence of an influence level θ.

3.4.1 Strategy 1 and 2: Benchmark Cases

We first consider two special cases where the supplier sells products through a single channel, either a traditional channel or a live-streaming channel. In strategy 1, the supplier sells products in traditional channel only, where $\beta = 0$

and $D_{12} = D_{21} = D_{22} = 0$, and maximize utility with respect to D_{11} yields the $D_{11} = \alpha_{11} - p_1 + \sqrt{\gamma}k_1$. The supplier determines optimal price and media investment to maximize the expected profit.

$$\pi_t = (p_1 - c_1 - c)D_{11} - \frac{k_1^2}{2}, \tag{3.9}$$

In strategy 2, the supplier sells products in live-streaming channel only ($\beta = D_{11} = D_{12} = D_{21} = 0$) and the demand function is $D_{22} = \alpha_{22}(\theta) - p_2 + \sqrt{\gamma}k_2$. The objective function is as follows.

$$\pi_l = (p_2 - c_2 - c)D_{22} - \frac{k_2^2}{2}. \tag{3.10}$$

The optimal solutions are summarized in the following proposition.

Proposition 3.1. *Assume* $0 \leq \gamma < 1$,

(a) *in strategy 1, the supplier's optimal price and media investment, denoted by* p_t^C *and* k_t^C, *are*

$$p_t^C = \frac{\alpha_{11} + (1-\gamma)(c + c_1)}{2 - \gamma}, \quad k_t^C = \frac{\sqrt{\gamma}(\alpha_{11} - c_1 - c)}{2 - \gamma}; \tag{3.11}$$

(b) *in strategy 2, the supplier's optimal price and media investment, denoted by* p_l^C *and* k_l^C, *are*

$$p_l^C = \frac{\alpha_{22}(\theta) + (1-\gamma)(c + c_2)}{2 - \gamma}, \quad k_l^C = \frac{\sqrt{\gamma}[\alpha_{22}(\theta) - c_2 - c]}{2 - \gamma}. \tag{3.12}$$

Proposition 3.1 infers that the comparison of profits in strategy 1 and strategy 2 is depending on the parameters and the live-streaming channel influence level.

Lemma 3.1. *There exists a threshold point* θ_{tl}^{C}*, which can be characterized by the equation*

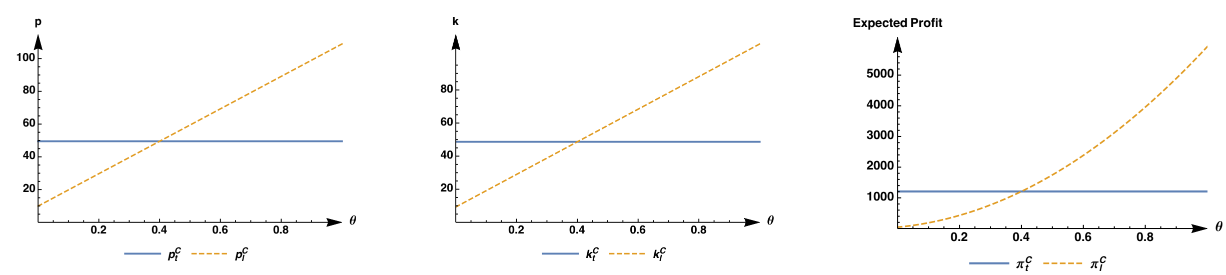
$$\alpha_{11} - c_1 = \alpha_{22}(\theta_{tl}^{C}) - c_2.$$

If $\theta < \theta_{tl}^{C}$*, the supplier should sell the product through the traditional channel. Otherwise, he should use the live-streaming channel.*

Figure 3.2 show that the live-streaming channel price, media investment, and expected profit increase in θ because of the increased market demand. This suggests that as the increase of θ, the live-streaming channel strategy will outperform the traditional channel strategy. It is because the price increases and more customers are attracted.

Figure 3.2: The Optimal Solutions of Strategy 1 and Strategy 2

(a) Price **(b)** Media Investment **(c)** Expected Profit



3.4.2 Strategy 3: Dual-Channel Case

In strategy 3, the supplier sells products through a dual-channel supply chain, the traditional channel and live-streaming channel. The supplier determines the prices and media investment in two channels simultaneously. As we have discussed earlier, customers who prefer the traditional channel may purchase in the live-streaming channel, and customers who prefer the live-streaming channel may become a customer of a traditional channel. The supplier's expected profit is the sum of two channels.

$$\max_{\{p_1,p_2,k_1,k_2\}} \pi_h = \pi_1 + \pi_2 \tag{3.13}$$

Proposition 3.2. *Assume* $0 \leq \gamma < 1$, *in strategy 3, the optimal channel prices* $p^D_{t|h}$ *and* $p^D_{l|h}$, *and the optimal media investment* $k^D_{t|h}$ *and* $k^D_{l|h}$ *in both channels can be expressed as:*

$$\begin{aligned}
p^D_{t|h} &= \frac{[2(1+\beta)-\gamma]\,[\alpha_{11}+\alpha_{21}(\theta)+2(c_1+c)]+\gamma[\alpha_{12}+\alpha_{22}(\theta)-2(2c_1+c_2+3c)]}{8(1+\beta-\gamma)}, \\
p^D_{l|h} &= \frac{[2(1+\beta)-\gamma]\,[\alpha_{12}+\alpha_{22}(\theta)+2(c_2+c)]+\gamma[\alpha_{11}+\alpha_{21}(\theta)-2(c_1+2c_2+3c)]}{8(1+\beta-\gamma)}, \\
k^D_{t|h} &= k^D_{l|h} = \frac{[\alpha_{11}+\alpha_{12}+\alpha_{21}(\theta)+\alpha_{22}(\theta)-2c_1-2c_2-4c]\sqrt{\gamma}}{4(1+\beta-\gamma)}.
\end{aligned}$$

When the supplier adopts a dual-channel supply chain, Proposition 3.2 shows that the channel prices depend on the parameters. It is straightforward to observe that the supplier will charge a higher price in traditional channel when $\alpha_{11}+\alpha_{21}(\theta)+2c_1 > \alpha_{12}+\alpha_{22}(\theta)+2c_2$; otherwise, the supplier charges a higher price in live-streaming channel. If operation costs are the same (i.e., $c_1 = c_2$), the supplier will charge a higher price to the larger market and yield a higher profit margin. If the initial market sizes are equal (i.e., $\alpha_{11}+\alpha_{21}(\theta) = \alpha_{12}+\alpha_{22}(\theta)$), a higher operation cost leads to a higher channel price. The media investments are always the same because we have assumed the demand margin in two channels are the same under the dual-channel supply chain.

Lemma 3.2. *In strategy 3, if* $\alpha_{11}+\alpha_{12}+\alpha_{21}(\theta)+\alpha_{22}(\theta)-2c_1-2c_2-4c>0$*, the optimal channel prices,* $p^D_{t|h}$ *and* $p^D_{l|h}$*, and media investments,* $k^D_{t|h}$ *and* $k^D_{l|h}$*, are*

(a) increasing in θ*,*

(b) decreasing in β*.*

Note that the condition in Lemma 3.2 is the sum of assumptions of demand functions to be positive. Thus, Lemma 3.2 is established on a weaker condition than our assumptions. Lemma 3.2 demonstrates that when a supplier launches a growing live-streaming channel (i.e., θ increases), price and media investment may increase because consumers who prefer the live-streaming channel are attracted and the market size increases. On the other side, for a given θ, if the channel competition becomes intense after introducing the live-streaming channel (i.e., β increases), the price and media investment will decrease. Thus, the supplier has to evaluate the trade-off between an increasing market size and a potential channel competition. Note that we have verified that demand for every segment is non-negative for all figures .

3.4.3 Performance of the Centralized Strategies

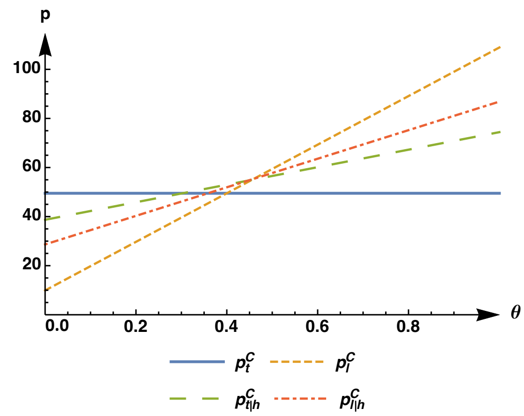
In this section, we compare the three strategies and discuss the supplier's decision in channel selection. Due to the complicated analytical results, we use numerical result to present our results. We use $c = 0.5$, $c_1 = 0.2$, $c_2 = 0.1$, $\gamma = 0.99$, $\beta = 0.4$, $\alpha_{11} = 50$, $\alpha_{12} = 10$, $\alpha_{21} = 10$, and $\alpha_{22} = 100$, where $\alpha_{21}(\theta) = \alpha_{21}\theta + 10$ and $\alpha_{22}(\theta) = \alpha_{22}\theta + 10$, for all numerical examples. The varying values will be specified wherever applicable.

Figure 3.3 plots the supplier's prices, media investment, and expected profit as a function of the live-streaming influence level θ to visualize the three strategies. As shown in Figure 3.3a, when θ closes to 0, switching to a dual-channel supply chain will cause the channel competition and the channel prices are lower than the price in strategy 1, the traditional channel only option. As the increase of θ, the prices increase because more customers are attracted. Figure 3.3c illustrates that the supplier's decisions depend on the level of the live-streaming channel. The supplier should only sell the product through traditional channel if the live-streaming influence level is lower than θ_1^C. That is, when θ is relatively low, introducing a live-streaming channel cannot attract enough customers to compensate the losses from channel competition and the increased media investment. When $\theta_1^C < \theta < \theta_2^C$, the increased demand and the investment reach an equilibrium and the supplier should employ a dual-channel supply chain. If the supplier can launch the live-streaming channel at a high influence level (i.e., $\theta > \theta_2^C$), which means the market size will increase tremendously after introducing the live-streaming channel, the supplier should sell product through the live-streaming channel only.

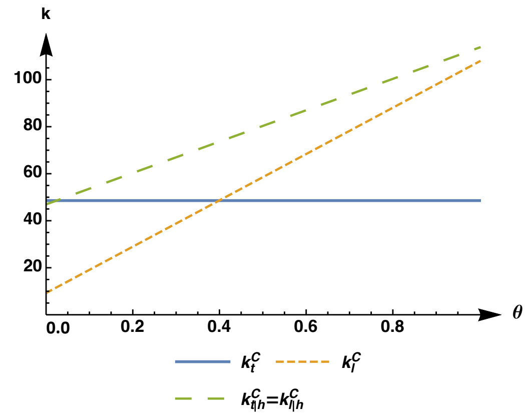
As shown in Figure 3.3d, we include a special case where the dual-channel supply chain dominates the single channel options when the channel substitution is low (i.e., $\beta = 0.2$). Assuming other parameters unchanged, a lower β means less channel substitution, and the supplier can take advantage of the increasing market size and employ a dual-channel supply chain for profit maximization.

Figure 3.3: Equilibrium Solutions of Centralized Strategies

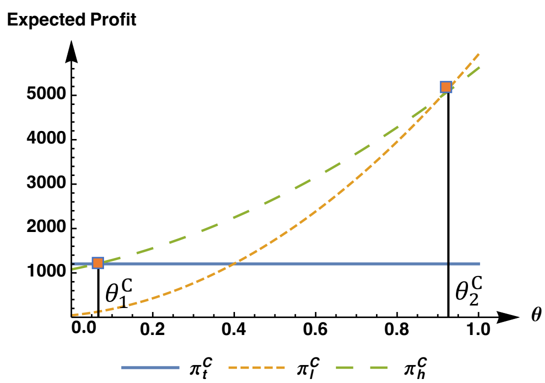
(a) Expected Profit ($\beta = 0.4$)



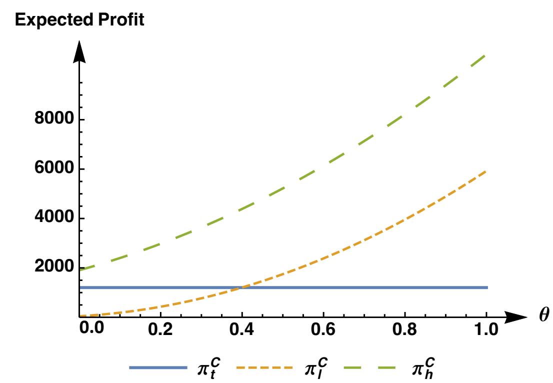
(b) Expected Profit ($\beta = 0.4$)



(c) Expected Profit ($\beta = 0.4$)



(d) Expected Profit ($\beta = 0.2$)



3.5. Decentralized Case

We now begin to analyze the decentralized case, where the supplier and the KOL maximize their profit, respectively. Instead of selling products through a supplier's in-house live-streaming channel, the supplier chooses to collaborate with a KOL and sells products through the KOL's live-streaming channel. They agree on a revenue-sharing contract that the KOL takes a percentage of the total revenue in the live-streaming channel. The revenue-sharing percentage, defined as $g(\theta)$, is determined by the market and we assume it is increasing in θ. To investigate the supplier's decision given a KOL's influence level, we formulate a two-stage problem. In stage 1, the supplier acts as the Stackelberg leader and determines the price (p_1) and media investment (k_1) of the traditional channel. In stage 2, the KOL determines the price (p_2) and media investment (k_2) of the live-streaming channel. To solve the two-stage problem, we employ the standard backward induction approach. Given the KOL's influence level θ, we begin with stage 2 to determine the KOL's optimal price and media investment, and go back to stage 1 to determine the supplier's optimal solutions.

In stage 2, the KOL's expected profit function can be described by

$$\max_{\{p_2,k_2\}} \pi_{ls} = [g(\theta)p_2 - c_2](D_{12} + D_{22}) - \frac{k_2^2}{2}. \tag{3.14}$$

In the above formulation, given the influence level θ, $g(\theta)p_2$ is the revenue that the KOL earns per unit in the live-streaming channel, c_2 is the operation cost, and k_2 is the media investment for maintaining the channel.

In stage 1, in anticipation of the KOL's response, the supplier determines his optimal price and media investment in the traditional channel to maximize his expected profit as follows.

$$\begin{aligned} \max_{\{p_1,k_1\}} \pi_{su} &= (p_1 - c_1)(D_{11} + D_{21}) + [1 - g(\theta)]p_2(D_{12} + D_{22}) \\ &\quad -c(D_{11} + D_{12} + D_{21} + D_{22}) - \frac{k_1^2}{2}. \end{aligned} \tag{3.15}$$

where p_1 is the price in tradition channel; $[1-g(\theta)]p_2$ is the unit revenue from live-streaming channel; c_1 and c denote the operation cost and production cost. k_1 is the media investment made in traditional channel.

Proposition 3.3. *In the decentralized case, the KOL's optimal price and media investment, defined as p_l^D and k_l^D, can be characterized by the following equations in terms of p_1 and k_1:*

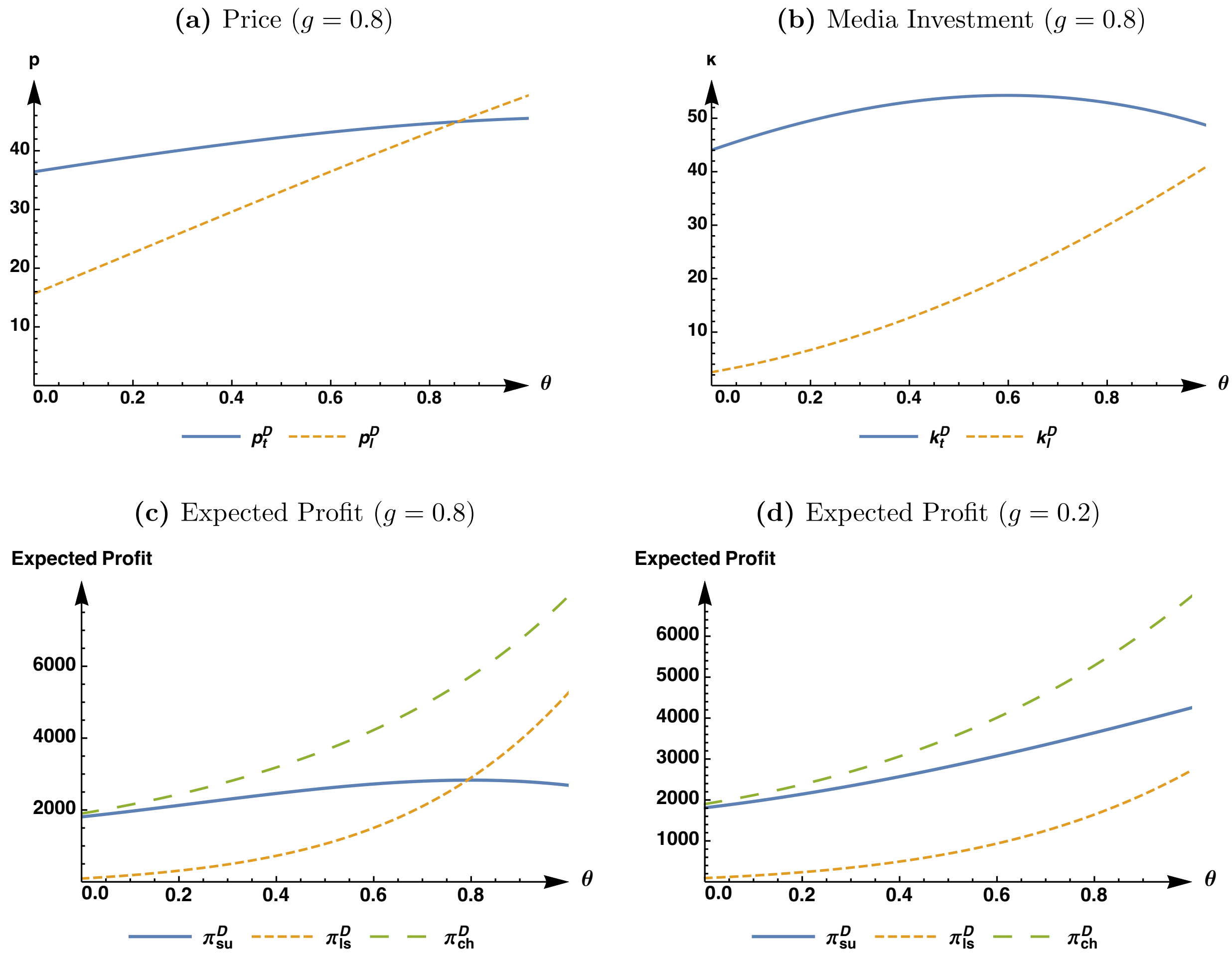
$$\begin{cases} \dfrac{\partial \pi_{ls}}{\partial p_2} = 0 \\ \dfrac{\partial \pi_{ls}}{\partial k_2} = 0 \end{cases}$$

The supplier's optimal price and media investment, defined as p_t^D and k_t^D, can be characterized by the following equations,

$$\begin{cases} \left.\dfrac{\partial \pi_{su}}{\partial p_1}\right|_{p_l^D, k_l^D} = 0 \\ \left.\dfrac{\partial \pi_{su}}{\partial k_1}\right|_{p_l^D, k_l^D} = 0 \end{cases}$$

Due to the complicated expression of optimal solutions, we present our outcomes through numerical results. We use the similar numerical in the centralized settings. To avoid triviality, we set $\alpha_{21} = \alpha_{21}\theta + 50$, $\alpha_{22} = \alpha_{22}\theta + 20$ and β=0.2. In addition, because the demand functions will be infinity when $g(\theta) = 0$, we assume $g(\theta) = g * \theta + 0.2$ where $g = 0.8$. When $\theta = 1$, $g(\theta) = 1$, which means the KOL take all revenues in the live-streaming channel. Figure 3.4a shows that the channel prices are depending on the parameters. It is interesting to note that when θ is close to 0, $g(\theta)$ is close to 0.2, which means the supplier earns around 80% revenue of the live-streaming channel. The supplier and KOL increase their media investment to attract customers. The KOL always benefits from the increased demand of customers who prefer traditional channel but purchase from live-streaming channel. However, if $g = 0.8$, as the increase of θ, the supplier's expected profit start to decrease. It is because the KOL takes most of the revenue in the live-streaming channel but the revenue of customers who prefer live-streaming channel but purchase from traditional channel cannot outpaces the negative impact of the supplier's media investment (Figure 3.4c). On the other hand, when $g = 0.2$, which means the supplier can obtain at least $1 - 0.2 * 1 * 0.2 = 60\%$ revenue from the live-streaming channel to guarantee a growing profit. In this case, both the supplier and KOL's expected profit are increasing in θ as shown in Figure (3.4d).

Figure 3.4: Equilibrium Solutions of Decentralized Case



3.6. Supplier's Decision

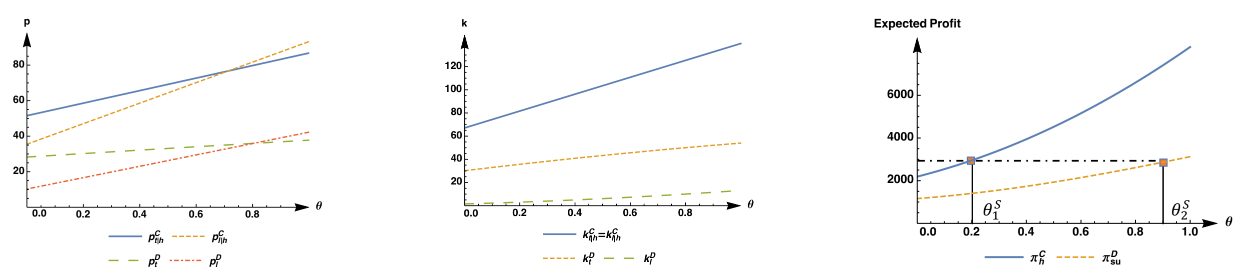
In the centralized strategies, we have discussed whether a supplier should adopt the dual-channel supply chain compared with a single channel structure. In the decentralized case, we investigated the impact of the revenue-sharing contract on the supplier and KOL's optimal decisions. In this section, we compare the two cases and study the impact of live-streaming channel on supplier's profit.

Figure 3.5 plots the optimal price, media investment, and supplier's expected profit in both centralized and decentralized cases given a basic numerical setting. In Figure 3.5, the channel prices and media investment in the centralized strategies are always higher than the ones in the decentralized case. Compared with the centralized settings, this collaboration in the decentralized case increases the price competition faced by the supplier and the KOL. The supplier has to maintain a relatively high level media investment to guarantee the demand in traditional channel. However, because the KOL could benefit from the supplier's media investment in the second stage, the KOL has less incentive to make an investment in media to attract customers, which results in a lower live-streaming channel media investment compared with the centralized strategies. The KOL's decreased media investment worsens the demand of customers who prefer live-streaming channel but purchase from traditional channel.

In Figure 3.5c, we identify the supplier's expected profit in centralized and decentralized cases. For any given θ, the supplier's expected profit is always higher in the centralized settings. However, in practice, the supplier's influence level is normally smaller than the KOL's influence level. As shown in Figure 3.5c, if the supplier's self-streaming influence level is θ_1^S with a corresponding profit $\pi_h(\theta_1^S)$, he should only collaborate with a KOL whose influence level is greater than θ_2^S. If the KOL's influence level is less than θ_2^S, the supplier's profit in the decentralized case is less than the profit that he can generate in the centralized strategies, $\pi_h(\theta_1^S)$. In reality, we do observe that some suppliers suffer from collaborating with a KOL. Although the KOL can attract more customers than self-streaming, the supplier's expected profit is lower in the decentralized case due to the revenue sharing. Our findings suggest that the supplier should carefully consider the impact of revenue-sharing contract and the KOL's influence level. Collaboration with a KOL maybe not in the best interest of the supplier.

Figure 3.5: Comparison Results of Two Cases

(a) Price **(b)** Media Investment **(c)** Supplier's Expected Profit



*Note that to better fit the two cases into one figure, we assume $g = 0.2$, $\gamma = 0.81$, $\beta = 0.15$, $\alpha_{21}(\theta) = \alpha_{21}\theta + 34$, and $\alpha_{22}(\theta) = \alpha_{22}\theta + 10$.

3.7. Conclusion

Motivated by the observations of the fast-growing live-streaming commerce, we study the impact of live-streaming channel on suppliers' supply chain. We consider multiple centralized settings and one decentralized case, and characterize the optimal channel prices and media investment in each strategy and compare the supplier's profit to understand how the live-streaming channel influences the supplier's decisions.

We first show that the supplier's decisions depend on the trade-off between the potential increase in market size and the channel competition. The supplier should insist on the traditional channel if the live-streaming channel cannot increase the market significantly. Otherwise, the supplier should employ a dual-channel supply chain or a single live-streaming channel to maximize his profit. Note that if the degree of channel substitution is low, the dual-channel supply chain might dominate the single-channel options, i.e., the supplier will benefit from the live-streaming channel demand increasing without losing many profits in the traditional channel.

Second, we analyze the revenue-sharing contract between a supplier and a KOL and find that the supplier's profit may decrease by collaborating with a top KOL. Particularly, we find that a top KOL may behave as a "free rider" if the revenue share percentage is high. It is because the supplier has to make investment to attract consumers who prefer traditional channel, but the KOL takes most of the revenue from customers who prefer traditional channel but purchase from live-streaming channel. The KOL takes advantage of the supplier's investment in traditional channel and still keeps a large portion of the live-streaming channel revenue.

Third, given the decreased profit margin and the revenue-sharing setting, our findings suggest that the supplier's expected profit may be lower by collaborating with a KOL whose influence level is higher than the supplier's, even though the KOL could attract more customers to the live-streaming channel.

This paper sheds light on the contract design between suppliers and KOLs. We have considered the revenue-sharing contract between a supplier and a KOL and revealed the trade-off between channel investment and market size expansion, which can be treated as a special case with zero slotting fee. It would be interesting to investigate the case of a two-part tariff, where the KOL still retains a percentage of the live-streaming channel revenue and charges a slotting fee to the supplier. In our paper, we fixed the slotting fee and normalized it to 0. A possible direction for future research is to incorporate the exogenous and endogenous fixed fees to the KOL. The fixed slotting fee depends on the KOL's influence level. Intuitively, if the slotting fee is exogenous, the KOL would charge a lower price in the live-streaming channel, and the corresponding live-streaming channel demand increases, which increases the sales in the live-streaming channel. However, the regular channel demand will decrease because of channel competition. Thus, by introducing the exogenous slotting fees, the trade-off is the increasing demand in live-streaming channel and the decreasing demand in traditional channel. Another interesting and valuable research direction is when the slotting fee is endogenously determined by the KOL. Because the slotting fee is increasing with the KOL's influence level, the supplier may charge a higher price in the traditional channel to make up for the slotting fee. The traditional channel demand decreases and live-streaming channel demand increases due to channel competition. In addition, the KOL would charge a lower price in the live-streaming channel which will boost the sales even further.

Another research opportunity exists in terms of the revenue-sharing percentage. In our model, the sharing effect is equally split between the supplier and the KOL, and the percentage is determined by the market. We estimate the impact of influence level on the price and investment only. Hence, how an endogenized revenue-sharing percentage would change the modeling results remains an open question and is left for future research. Finally, motivated by the recent increase in reported incidents of livestreamers misleading promotions and fake advertising, future work can investigate the impact of customer trust and engagement on the supply chain profit, which is highly dependent on reputation and customer loyalty. It would be interesting to investigate the case of multiple KOLs collaborating with the same supplier and examine the competition among KOLs. When a supplier chooses to collaborate with several KOLs, the same product will be offered by different KOLs on the same platform. A customer may be attracted by the price or purchase from a trustworthy KOL by paying a premium.

3.8. Appendix: Technical Proofs

Proof of Proposition 3.1

We present the proof of optimal solution of Scenario 1, the Scenario 2 could be proved by using the similar approach. We replace D_{11} with $D_{11} = \alpha_{11} - p_1 + \sqrt{\gamma}k_1$ in Equation (3.9) and differentiate the profit profit π_{11} with respect to p_1 and k_1, yields the Hessian matrix

$$\begin{bmatrix} -2 & \sqrt{\gamma} \\ \sqrt{\gamma} & -1 \end{bmatrix},$$

whose determinant is $2 - \gamma$. Given the assumption that $\gamma < 2$, the Hessian Matrix is negative definite. Thus the profit function is jointly concave in p_1 and k_1. The first order derivatives are

$$\frac{\partial \pi_t}{\partial p_1} = \alpha_{11} + c_1 + k_1\sqrt{\gamma} - 2p_1,$$
$$\frac{\partial \pi_t}{\partial k_1} = \sqrt{\gamma}(p_1 - c_1) - k_1.$$

The optimal solutions p_t^C and k_t^C are derived from solving the two first order conditions simultaneously. ■

Proof of Lemma 3.1

We first replace the optimal solutions in the objective functions and simplify the equations, respectively.

$$\pi_t^C = \frac{(\alpha_{11} - c_1 - c)^2}{2(2-\gamma)}$$
$$\pi_l^C = \frac{[\alpha_{22}(\theta) - c_2 - c]^2}{2(2-\gamma)}$$

We obtain the threshold point θ_{tl}^C by setting the above two equations equal.

$$\begin{aligned} \frac{(\alpha_{11} - c_1 - c)^2}{2(2-\gamma)} &= \frac{[\alpha_{22}(\theta_{tl}^C) - c_2 - c]^2}{2(2-\gamma)} \\ \alpha_{11} - c_1 &= \alpha_{22}(\theta_{tl}^C) - c_2 \end{aligned}$$

■

Proof of Proposition 3.2

We first substitute the demand functions, Equation (3.2),(3.3),(3.6)(3.6),into Equation (3.7) and (3.7) to obtain the expressions of profit function, Equation (3.13). Differentiating the profit function $\pi_h = \pi_1 + \pi_2$ with respect to p_1, p_2, k_1 and k_2 yields the Hessian Matrix as follows:

$$\begin{bmatrix} \frac{4}{-1+\beta^2} & \frac{4\beta}{1-\beta^2} & \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} \\ \frac{4\beta}{1-\beta^2} & \frac{4}{-1+\beta^2} & \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} \\ \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} & -1 & 0 \\ \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} & 0 & -1 \end{bmatrix},$$

Given $0 \leq \beta \leq 1$ and assume $0 \leq \gamma < 1$, we have

$$\frac{4}{-1+\beta^2} < 0, \quad -1 < 0$$

$$\begin{vmatrix} \frac{4}{-1+\beta^2} & \frac{4\beta}{1-\beta^2} \\ \frac{4\beta}{1-\beta^2} & \frac{4}{-1+\beta^2} \end{vmatrix} = \frac{16}{1-\beta^2} > 0,$$

$$\begin{vmatrix} \frac{4}{-1+\beta^2} & \frac{4\beta}{1-\beta^2} & \frac{\sqrt{\gamma}}{1+\beta} \\ \frac{4\beta}{1-\beta^2} & \frac{4}{-1+\beta^2} & \frac{\sqrt{\gamma}}{1+\beta} \\ \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} & -1 \end{vmatrix} = -\frac{8(2+2\beta-\gamma)}{(1-\beta)(1+\beta)^2} < 0,$$

$$\begin{vmatrix} \frac{4}{-1+\beta^2} & \frac{4\beta}{1-\beta^2} & \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} \\ \frac{4\beta}{1-\beta^2} & \frac{4}{-1+\beta^2} & \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} \\ \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} & -1 & 0 \\ \frac{\sqrt{\gamma}}{1+\beta} & \frac{\sqrt{\gamma}}{1+\beta} & 0 & -1 \end{vmatrix} = \frac{16(1+\beta-\gamma)}{(1-\beta)(1+\beta)^2} > 0.$$

It can be shown that Hessian matrix is negative definite and the profit function is jointly concave in p_1, p_2, k_1, k_2. Solving the first order conditions simultaneously

$$\frac{\partial \pi_h}{\partial p_1} = 0, \quad \frac{\partial \pi_h}{\partial p_2} = 0, \quad \frac{\partial \pi_h}{\partial k_1} = 0, \quad \frac{\partial \pi_h}{\partial k_2} = 0.$$

yields the optimal solution $p^C_{t|h}$, $p^C_{t|h}$, $k^C_{t|h}$ and $k^C_{l|h}$.

■

Proof of Lemma 3.2

We take the first order derivative of $p^C_{t|h}$ and $p^C_{t|h}$ with respect to θ yield

$$\frac{\partial p^C_{t|h}}{\partial \theta} = \frac{\frac{\partial \alpha_{21}(\theta)}{\partial \theta}[2(1+\beta)-\gamma)] + \frac{\partial \alpha_{22}(\theta)}{\partial \theta}\gamma}{8(1+\beta-\gamma)},$$

$$\frac{\partial p^C_{t|h}}{\partial \theta} = \frac{\frac{\partial \alpha_{22}(\theta)}{\partial \theta}[2(1+\beta)-\gamma)] + \frac{\partial \alpha_{21}(\theta)}{\partial \theta}\gamma}{8(1+\beta-\gamma)},$$

Because we assume $\alpha_{21}(\theta)$ and $\alpha_{22}(\theta)$ are increasing in θ and $0 \leq \gamma < 1$, the first order derivatives are always positive. Thus the optimal prices are increasing in θ.

Next, we calculate the first order derivative of $p^C_{t|h}$ and $p^C_{l|h}$ with respect to β

$$\frac{\partial p^C_{t|h}}{\partial \beta} = \frac{\partial p^C_{l|h}}{\partial \beta} = -\frac{\gamma\left[\alpha_{11} + \alpha_{12} + \alpha_{21}(\theta) + \alpha_{22}(\theta) - 2c_1 - 2c_2 - 4c\right]}{8(1+\beta-\gamma)^2}.$$

The first order derivatives are always negative if

$$\alpha_{11} + \alpha_{12} + \alpha_{21}(\theta) + \alpha_{22}(\theta) - 2c_1 - 2c_2 - 4c > 0.$$

For $k^C_{t|h}$ and $k^C_{l|h}$, θ only appears in numerator and β exists in denominator. It is straightforward to conclude that media investment $k^C_{t|h}$ and $k^C_{l|h}$ are increasing in θ and decreasing in β. ■

Proof of Proposition 3.3

First, we solve the KOL's optimal decisions of p_2 and k_2.

We replace the Equation (3.3) and (3.6) into Equation (3.14) and take derivatives with respect to p_2 and k_2. We derive the Hessian matrix

$$\begin{bmatrix} \frac{4}{-1+\beta^2} & \frac{g(\theta)\sqrt{\gamma}}{1+\beta} \\ \frac{g(\theta)\sqrt{\gamma}}{1+\beta} & -1 \end{bmatrix},$$

whose determinant is $\frac{g(\theta)[4(1+\beta)-g(\theta)\gamma(1-\beta)]}{(1+\beta)(1-\beta^2)}$. Because $0 \leq g(\theta) \leq 1$, $0 \leq \gamma < 1$, and $0 \leq \beta \leq 1$, these assumptions guarantee that $4(1+\beta) - g(\theta)\gamma(1-\beta) > 0$ and the Hessian matrix is negative definite. Therefore, the KOL's expected profit is jointly concave in p_2 and k_2.

The two first order derivatives are

$$\begin{aligned}
\frac{\partial \pi_{ls}}{\partial p_2} &= \frac{1}{1-\beta^2}\{g(\theta)\left[\alpha_{12}+\alpha_{22}-\beta(\alpha_{11}+\alpha_{21})+\sqrt{\gamma}(k_1+k_2)(1-\beta)\right. \\
&\qquad \left. + 2\beta p_1 - 4p_2\right] + 2c_2\}, \\
\frac{\partial \pi_{ls}}{\partial k_2} &= \frac{\sqrt{\gamma}\left[g(\theta)p_2 - c_2\right]}{1+\beta} - k_2.
\end{aligned}$$

The optimal solutions p_l^D and k_l^D are derived from solving the two first order conditions simultaneously.

$$\begin{aligned}
p_l^D &= \frac{1}{g(\theta)\left[4-g(\theta)\gamma+\beta(4+g(\theta)\gamma)\right]}\{\left[2-g(\theta)\gamma+\beta(2+g(\theta)\gamma)\right]c_2 \\
&\qquad + g(\theta)(1+\beta)\left[\alpha_{12}+\alpha_{22}-\beta(\alpha_{11}+\alpha_{21})+2p_1\beta+\sqrt{\gamma}(1-\beta)k_1\right]\}, \\
k_l^D &= \frac{\sqrt{\gamma}\left\{g(\theta)\left[\alpha_{12}+\alpha_{22}-\beta(\alpha_{11}+\alpha_{21})+2p_1\beta+\sqrt{\gamma}(1-\beta)k_1\right]-2c_2\right\}}{4-g(\theta)\gamma+\beta[4+g(\theta)\gamma]}.
\end{aligned}$$

Second, we substitute p_l^D and k_l^D into Equation (3.15) and take derivatives with respect to p_1 and k_1. The second order derivatives are as follows.

$$\begin{aligned}
\frac{\partial^2 \pi_{su}}{\partial p_1^2} &= \frac{4}{(1-\beta)[4-g(\theta)\gamma+\beta(4+g(\theta)\gamma)]^2}\left\{2\beta^3[6-g(\theta)(2-\gamma)]\right. \\
&\qquad -[4-g(\theta)\gamma]^2+\beta[2g^2(\theta)\gamma^2-4g(\theta)\gamma-16] \\
&\qquad \left.-\beta^2[g^2(\theta)\gamma^2+g(\theta)(4+6\gamma)-12]\right\}, \\
\frac{\partial^2 \pi_{su}}{\partial p_1 \partial k_1} &= \frac{2\sqrt{\gamma}[8+\beta^2[8-g(\theta)(4-\gamma)]+\beta[16-g(\theta)(4-\gamma)]-2g(\theta)\gamma]}{[4-g(\theta)\gamma+\beta(4+g(\theta)\gamma)]^2}, \\
\frac{\partial^2 \pi_{su}}{\partial k_1^2} &= \frac{-1}{[4-g(\theta)\gamma+\beta(4+g(\theta)\gamma)]^2}\left\{16-4[1+g(\theta)]\gamma+g^2(\theta)\gamma^2\right. \\
&\qquad \left.+\beta[32-2g^2(\theta)\gamma^2]+\beta^2[16+4[1+g(\theta)]\gamma+g^2(\theta)\gamma^2]\right\}.
\end{aligned}$$

The determinant of the Hessian matrix is

$$\frac{4\left\{16-4[2+g(\theta)]\gamma+g^2(\theta)\gamma^2+\beta^3[\gamma-2g(\theta)(\gamma-2)+\gamma]+\beta[16+4g(\theta)\gamma-2g^2(\theta)\gamma^2]+\beta^2[2g(\theta)(2+\gamma)+g^2(\theta)\gamma^2+7\gamma-12]\right\}}{(1-\beta)[4-g(\theta)\gamma+\beta[4+g(\theta)\gamma)]^2}.$$

We first prove $\frac{\partial\pi_{su}^2}{\partial p_1^2} < 0$. Because the denominator is positive, we need to prove the numerator is always negative. Note that β is the channel substitution effect and $g(\theta)$ is the percentage of revenue-sharing. They both have a support of $[0, 1]$. Besides, we have assumed that $0 \leq \gamma < 1$. In the feasible region, the maximum of the numerator is -32 when $g(\theta) = 0$, $\beta = 1$ and $\gamma = 0.314$. Therefore, the numerator is always negative and the denominator is positive. We proved $\frac{\partial\pi_{su}^2}{\partial p_1^2} < 0$.

Similarly, we can prove that $\frac{\partial\pi_{su}^2}{\partial k_1^2}$ is negative. The denominator is positive and we need to prove the numerator is always negative. The maximum of the numerator is -9 when $g(\theta) = 1$, $\beta = 0$ and $\gamma = 1$.

For the determinant of the Hessian Matrix, the denominator is positive and the minimum of the numerator is 32 when $g(\theta) = 1$, $\beta = 1$ and $\gamma = 0.15$.

Thus, we have proved that the Hessian Matrix is negative semidefinite and the supplier's expected profit function is jointly concave in p_1 and k_1 in the feasible region.

We then solve the first order conditions for the optimal price p_t^D and media investment k_t^D in the traditional channel, and substitutes the expressions of p_t^D and k_t^D into the result of p_l^D and k_l^D to obtain the optimal solutions in the live-streaming channel. ■

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The Impact of Cost Auditing on Supply Chain Social Responsibility

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Live-streaming or Not: Optimal Ordering Decisions with Contract Design and Demand Forecast Updating

- with Zhengping Wu
- In Preparation for Submission

The Role of Live-streaming Selling Platforms in a Dual-channel Supply Chain with Demand Uncertainty

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• POMS Annual Conference 2021, Virtual	05/2021
• INFORMS Annual Conference 2020, Virtual	11/2020
• DSI Annual Conference 2020, Virtual	11/2020
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Doctoral Consortium Fellow

- 2nd Online Doctoral Workshop on Supply Chain Analytics
- POMS Annual Conference 2021, Virtual
- Kellogg-Wharton OM Workshop, Virtual
- 1st Online Doctoral Workshop on Supply Chain Analytics, Virtual
- DSI Annual Conference, New Orleans, LA
- POMS Annual Conference 2021, Washington, DC

Lean Six Sigma Green Belt Project Consultant 09/2015-05/2016
Baylor Medical Center *Garland, Texas*

- Applied the "Define, Measure, Analyze, Improve, and Control" (DMAIC) strategy to analyze the current scheduling process and identify bottlenecks
- Collected and analyzed historical data to clarify root causes of cancellations

- Drew the process maps with Visio to improve patient scheduling efficiency

Process Improvement Consultant 01/2015-05/2015
Fritz Industries, Inc. *Mesquite, Texas*

- Analyzed production data of Liquid process to identify potential problems in production delays
- Applied Lean principles and time studies to investigate the production process and proposed a new system to optimize inventory
- Developed a detailed Excel-based review checklist based on production standards to evaluate employee performance

HONORS AND REWARDS

- Doctoral Fellowship, Syracuse University
- Dean's Excellent Scholarship (top 3%), UT-Dallas
- Outstanding Freshman Scholarship (top 3%), Tianjin University of Technology

MISCELLANEOUS

- Certification: Lean Six Sigma Green Belt
- Computer: Mathematica, Python, SAS, R, LaTex
- Language: Mandarin (Native), English (Fluent)
- Society of Actuarial (SOA) Exams: Exam P (Probability), Exam FM (Financial Mathematics)