INCENTIVE MECHANISM FOR KNOWLEDGE SHARING IN E-COMMERCE SERVICE SUPPLY CHAIN: COMPLEMENTARITY, INTEGRATION AND RISK ATTITUDE

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ABSTRACT

In the E-commerce Service Supply Chain (ESSC), knowledge sharing among members is crucial for fast responses to the changing online market. We propose a knowledge sharing incentive model for the ESSC by incorporating knowledge complementarity and integration capacity. We develop two principal-agent based optimal incentive mechanisms for the ESSC under asymmetric information, when service providers are risk-neutral and risk-averse, respectively. Through numerical experiments, we examine in depth the impacts of the external uncertainty and risk-aversion degree on optimal incentive mechanisms. The incentive of knowledge sharing is found to be influenced by the knowledge complementarity of service providers, the knowledge integration capability of e-tailers, the risk-averse degree of service providers and the external uncertainty.

Keywords: E-commerce; Service supply chain; Incentive mechanism; Knowledge complementarity; Knowledge integration

1. Introduction

Modern enterprises, especially the e-tailers in the online market (e.g., eBay and Taobao), often outsource non-core business activities to external service providers (SPs) to keep themselves focused, flexible and dedicated to customer needs. Many once-internally-managed business functions, such as logistics, IT, finance and R&D activities, are now contracted out. Through the coordination of the e-tailer, these SPs constitute an E-commerce Service Supply Chain (ESSC). A noteworthy ESSC is UNIQLO, a leading private label apparel chain in Asia, which aspires to become No. 1 in the US apparel industry. It first launched its official flagship store on Taobao.com in April 2009. To keep it "small and beautiful", UNIQLO focuses on its core business of marketing and R&D, and delegates other business functions to nine specialized SPs. When it surprisingly became the top clothing store on Taobao.com six months later, many people could not believe that there were only four employees running the online store.

The competitiveness of online business is less about the scale or efficiency of the facility and more about the ability to understand and meet diverse market demands, which mainly depends on their competency in managing information. Thus, the ESSC needs to effectively gather knowledge from SPs and derive invaluable information into desired services and products to meet the challenges of the online business world. The dynamic capability can be acquired by exploiting the knowledge resources across organizational boundaries. In the course of knowledge sharing, each service provider acts as a complementary knowledge source, and the e-tailer plays the role of knowledge integrator and coordinator. However, lacking incentives have been cited as a major barrier to inter- (or intra-) organizational knowledge sharing [Lee & Ahn 2007; Yao et al. 2007].

Drawing on the concept of supply chain (SC) contract, this paper proposes incentive mechanisms to ensure members in the ESSC are willing to share knowledge. It contributes to the literature in two respects. First, our work raises the awareness of academics and practitioners on emerging knowledge management issues in e-commerce, around which more extensive research can be developed. Currently, no study on incentive mechanism design for knowledge sharing has focused on e-commerce's unique features: high specialization (complementarity), rapid information exchange and fusion (integration), and uncertainty (risk attitude). We aim to take advantage of revenue sharing concepts to motivate SPs to share complementary knowledge and also show how e-tailers can employ their knowledge integration skills to enhance profits. Second, the paper can advance the literature by uncovering and interpreting the impacts of external uncertainty and risk attitude on incentive mechanisms. The analytical conclusions would help future research on contract design in the ESSC and enrich the supply chain coordination theory. From the implementation perspective, this study provides valuable references for e-tailers to select fitting SPs and determine optimal compensation. It allows e-tailers to determine the optimal reward strategy as per service providers' risk appetites. The study can also aid SPs to create knowledge sharing strategies and improve the quality of their services. It offers insights for e-tailers to improve knowledge collaboration efficiency so as to build core competency in the online market.

The rest of the paper is organized as follows. In Section 2, we review the literature and summarize the theoretical backgrounds of knowledge sharing in the service supply chain. The organizational structure of the ESSC is proposed and the features of knowledge sharing in the ESSC are analyzed in Section 3. Section 4 sets up an improved moral hazard model with one principal and multi-agents for knowledge sharing among members in the ESSC. In particular, the knowledge complementarity of SPs and the knowledge integration ability of the e-tailer are jointly considered. Subsequently, we propose optimal incentive mechanisms for SPs under risk-neutral and risk-averse settings, respectively. Numerical studies are conducted in Section 5. Finally, we conclude the research, discuss the implications, and offer future research directions in Section 6.

2. Literature review

2.1. Service supply chain

The Service Supply Chain (SSC) has increasingly become an important management research area. Existing studies focus mainly on issues such as definitions, basic models, service capacity, and the relationship between the SSC and firm performance. For example, Ellram et al. [2004] constructs a general SSC management framework based on Hewlett-Packard, SCOR, and GSCF models. Baltacioglu et al. [2007] defines the SSC as a network of suppliers, consumers, SPs and other supporting units that provide resources necessary to produce services, transform resources into supporting and core services, and then deliver these services to customers. This framework has often been cited in SSC studies. Iakovaki et al. [2009] later argue that supply chain members need to cooperate and understand the impact of network cooperation. Then again, Yan et al. [2012] investigate IT SSC coordination mechanisms under both the SaaS (Software-as-a-Service) and the implementation agent models. By combining the two models' respective coordination mechanisms, they develop a new SSC contract for the IT industry. Both the general SSC and the industry-focused SSC strive to improve the theoretical base of the SSC by combining the extant supply chain management theory with the service industry's features.

Iakovaki et al. [2009] define the SSC as a knowledge-intensive network that employs interconnected resources from various organizations and transforms them into service offerings that enhance customized delivery. Despite the ubiquity of knowledge management literature, the incentive mechanism for knowledge sharing in the SSC is largely unexplored. Studies have shown that the most effective way to promote knowledge sharing between firms is through recognition and reward [Hansen et al. 1999; Liebowitz 2003; Nelson et al. 2006]. Others argue that the relationship between external rewards and knowledge sharing behavior may be inconsistent, signaling the importance of organizational context in the incentive contract design of knowledge sharing [Wang & Noe 2010].

2.2. Incentive mechanisms for knowledge sharing

Researchers in manufacturing supply chain has developed many incentive mechanisms based on contract theories, including quantity discount contracts, flexible quantity contracts, price discount contracts, return contracts, buy-back contracts and revenue sharing contracts [Cachon & Lariviere 2005]. Among them, revenue sharing contracting has been the prevailing model for supply chain coordination. Researchers of manufacturing supply chain focus on products' tangible attributes such as product price, level of inventory, and order quantity. However, there are obvious differences between intangible services and tangible products attributes. Contrasting to the manufacturing supply chain, the SSC is more knowledge-intensive, which highlights the incentive problem on knowledge collaboration among supply chain members.

There are various incentive mechanisms for knowledge sharing. Some incentive mechanisms may complement each other with respect to the impact on knowledge sharing behaviors, while others may be substitutes [Foss et al. 2010]. For example, a strong corporate culture may substitute for explicit monetary-based incentive. On the other hand, studies have documented that formal incentive mechanisms (extrinsic rewards by payment) may act against existing, informal ones (intrinsically motivated by psychological satisfaction) and such a combination may destroy knowledge sharing behavior and cause irreversible, long-term negative effects on organizational behavior [Osterloh & Frey 2000; Robertson & Swan 2003]. Lawson et al. [2009] investigate the impact of formal and informal socialization mechanisms on the level of knowledge sharing within inter-organizational product development projects and the subsequent effect on buyer firm performance.

Some researchers argue that knowledge in organizations needs to be treated as public good if it is to be available to everyone in the organization. But any public good is faced with the free-rider problem eventually leading to individuals under-contributing to the public good (thereby sharing less than required knowledge). Ba et al. [2001] contend that to deal with free-rider in knowledge sharing, one has to design a proper incentive-aligned mechanism that induces people to reveal their true valuation of knowledge. They note that without proper and necessary incentives, knowledge sharing is constrained and difficult to achieve. Economic and monetary incentives should be explored in knowledge sharing. Fey & Furu [2008] identify the relationship between subsidiary bonus pay based on multinational corporation performance and knowledge sharing between different units of the multinational.

Knowledge in the literature discussed above is generally viewed as an integral concept. The inherent properties of knowledge (e.g. knowledge complementarity) have great impacts on the design of incentive mechanism on knowledge sharing. However, the literature focusing on this prospective is still sparse.

2.3. Inter-organizational and E-commerce knowledge sharing

Inter-organizational knowledge sharing has recently received considerable attention in knowledge collaboration literature. Samaddar & Kadiyala [2006] model the relationships between organizations for knowledge creation as a Stackelberg leader-follower game. They find it important to maintain an optimal ratio between the leader's and the follower's marginal gains for the formation and continuation of the collaboration. Similarly, Ding & Huang [2010] formalize the dilemma of firms' collaborative knowledge creation and derive insights into the tension between knowledge sharing and knowledge protection. Li & Jhang-Li [2010] study the incentives of knowledge sharing in different communities of practice (COPs). They find that the benefit of knowledge sharing in the incomplete information setting is often the same as that in the complete information setting. Finally, Tiwana [2013] investigates the tension between specializing in service providers' own domains and maintaining knowledge in their partners' domains, and claims that inter-firm knowledge integration is necessary to effectively organize service outsourcing.

Existing literature on inter-organizational knowledge sharing mainly focuses on traditional manufacturing firms. However, the development of e-commerce compels the traditional knowledge management to enter into a new stage. Researchers begin to study knowledge sharing in e-commerce. Thuraisingham et al. [2002] look into the collaborative commerce (c-commerce), which combines e-commerce, knowledge management and collaboration. From this perspective, both intermediaries in E-collaboration and commerce collaborative systems play an vital role in E-commerce knowledge sharing [Sherer & Adams 2001; Yang et al. 2013]. Then again, Klein [2007] finds that customization and real-time information access have positive impacts on performance. The provider's level of trust in clients positively influences information exchange and client customization. Finally, Zheng & Yu [2010] use the SECI model to identify the driving force of knowledge sharing in the e-commerce ecosystem.

Although research on knowledge sharing in e-commerce is fast growing, to date, little attention is directed toward the optimal design of incentive mechanism on knowledge sharing. What are the essential characteristics of knowledge sharing in the ESSC? What impacts do they have? Our paper addresses these questions with an aim of identifying optimal incentive mechanisms. It improves knowledge sharing and maximizes the ESSC performance, and distinguishes from the conventional contract design in that it focuses on the unique attributes of the ESSC: complementarity, integration and risks.

3. Complementary knowledge sharing and integration in the ESSC

In the ESSC, e-tailers may outsource logistics, IT, finance, marketing and/or other business functions, and act as service integrators who deliver final services and products to customers in the online market. These providers often possess different knowledge and contribute to the ESSC heterogeneously. But as they all work toward serving the e-tailer and share the same business goal, they are all related. Their expertise and competencies are interconnected and complementary. By collecting the knowledge from various SPs, the e-tailer can consolidate the knowledge and put the idea of "small but beautiful" into practice. Figure 1 outlines the organizational structure of knowledge sharing in the ESSC. It implies that the ESSC possesses the characteristic of knowledge sharing in the context of outsourcing and the supply chain.

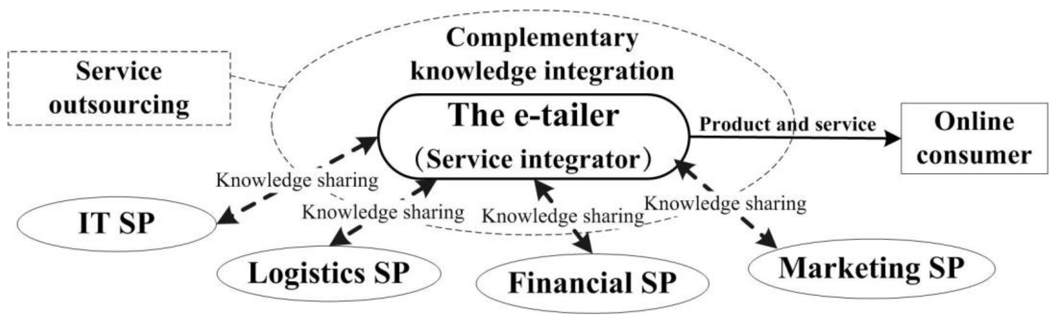

Figure 1: The Knowledge Sharing Structure of E-commerce Service Supply Chain (ESSC)

Complementary knowledge exchange takes place when the e-tailer outsource to various SPs, while knowledge consolidation is crucial for integrating the various SPs in the supply chain. We now examine knowledge sharing in the ESSC from the perspectives of complementarity and integration.

3.1. Knowledge complementarity: the motivation of knowledge sharing

Service providers often possess unique business capabilities and accumulate considerable knowledge to build their core competencies. For example, IT providers may be devoted to cloud computing; logistics SPs may be good at customer geographic distribution; while finance SPs may specialize in customer credit rating. For the ESSC consisting of SPs with various expertise, these SPs are more inclined to share knowledge. This leads to higher endogenous spillover rates among participating SPs to learn from other members of the ESSC. We call such an effect the knowledge complementarity capacity of SPs. For the ESSC, all these types of knowledge are complementary and necessary to fulfill the e-tailer's objective. Therefore, if SPs can honestly share their knowledge, and e-tailers can effectively integrate interrelated knowledge, then the ESSC can improve information quality and enhance performance.

Note that knowledge complementarity is often asymmetric. For instance, the knowledge of logistics SPs may have little complementarity to that of financial SPs, since financial products usually do not require transport and warehousing information. However, the knowledge from financial SPs could be very important to logistics SPs, as logistics service must entail financial data. Under information asymmetry, the willingness of SPs to share knowledge differs, as their ultimate gains from knowledge sharing vary significantly. In other words, the asymmetry of needs for complementary knowledge affects the incentive of knowledge sharing, which is a key assumption of our model.

3.2. Knowledge integration: the goal of knowledge sharing

In practice, the e-tailer can acquire knowledge through the knowledge network of service providers. To be a qualified coordinator of the ESSC, the e-tailer should be capable of accurately merging and consolidating these complementary knowledge and transforming them into competitive advantages. We call it the knowledge integration capacity of the e-tailer. As an intermediate node in the supply chain, the e-tailer strives to integrate complementary knowledge of all supply chain members and ensure their collaboration so as to meet the online market demand. The knowledge sharing and integration process can be divided into four stages:

1) Each SP shares its knowledge with the e-tailer.
2) After removing inconsistencies, the e-tailer consolidates all information received and aims to serve customer needs.
3) The e-tailer shares the integrated knowledge with SPs, who then combines this knowledge with their own expertise.
4) At last, new knowledge is created and all ESSC members reap benefits from knowledge sharing.

Through repeated interactions and collaboration, the ESSC performance can be greatly improved by the synergized knowledge. Figure 2 displays such a process.

We can see that the e-tailer plays a vital role in knowledge sharing in the ESSC, as it takes in complementary knowledge and bridges the gap between the SPs. Through working closely and attentively, the ESSC members can greatly improve the capability of the entire supply chain. As profits increase, SPs are further motivated to share more knowledge with the e-tailer. We will elaborate on such relationships and identify optimal incentive mechanisms through mathematical modeling next.

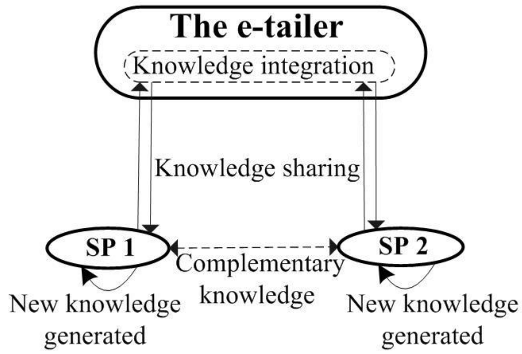

Figure 2: The Process of Complementary Knowledge Sharing and Integration

4. The incentive model and optimal mechanism

From the principal agency perspective, we design an optimal incentive mechanism for the e-tailor (principal) to interact with SPs (agents) for knowledge collaboration. The unique knowledge of each SP has complementary effects. In order to benefit from knowledge complementarity, the e-tailor may encourage SPs to share and effectively integrate their knowledge at the supply chain level. The design of the incentive mechanism is a multiple-agent Moral Hazard problem since information asymmetry exists between the e-tailor and SPs [Mookherjee 1984; Demski & Sappington 1984]. The SPs have more information about their knowledge-sharing activities than the e-tailor does, as the e-tailor usually cannot completely monitor the SPs. Therefore, the SPs are incentivized to act inappropriately as the interests of the e-tailor and the SPs often are not aligned. More specifically, each SP knows its own knowledge-sharing effort level, while the e-tailor cannot directly and fully observe a SP's effort level. As such, the e-tailor should propose an incentive contract based on the final output observed, which depends on SPs' knowledge-sharing efforts and exogenous random factors. To sum up, the principal-agent theory of incentive is to induce agents to take appropriate actions to optimize team production [Holmstrom 1982]. The sequence of this contract game under moral hazard can be encapsulated in Figure 3.

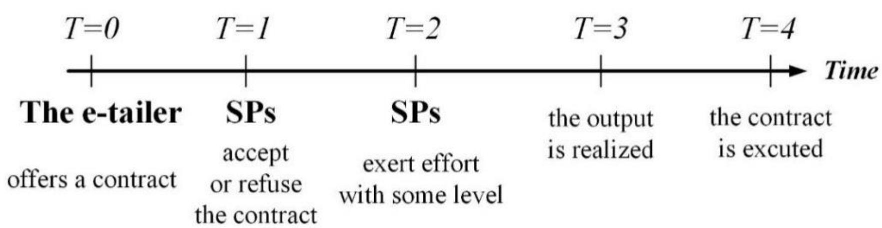

Figure 3: Timing of Contract for Knowledge Sharing under Moral Hazard

4.1. Model assumptions and notations

Without loss of generality, we assume an e-tailer collaborating with two service providers named SP1 and SP2. The two SPs not only work independently to help the e-tailer serve ESSC customers, but also are willing to cooperate and exchange knowledge with each other in due course. The e-tailer has to design an optimal compensation mechanism to motivate the SPs, so both SPs are incentivized to share complementary knowledge and improve the e-tailer's profit.

As knowledge sharing and integration are full of uncertainty and risk, different SPs may not have the same penchant towards the risk involved in knowledge sharing. Some "risk-neutral" SPs may be indifferent to the risk, while "risk-averse" providers may deem knowledge sharing too risky and costly. In this subsection (§4.1), we will discuss the knowledge complementarity effects of SPs and the knowledge integration effects of the e-tailer. Then, in §4.2 and §4.3, we will combine the complementarity and the integration effects to develop incentive models, one under risk-neutral and the other under risk-averse SPs. Table 1 summarizes the notations used in this research (see the Appendix A).

4.1.1. Knowledge complementarity effects of an SP

We assume the knowledge of an SP consists of two parts: the SP's own knowledge and the complementary knowledge absorbed from others. The total amount of SP i 's knowledge can be expressed as

$Q_i = q_i + \varphi(\mu_i, a_i)q_j$, where q_i is the original amount of SPi's knowledge, while q_j is the original amount of SPj's knowledge. For convenience, we assume the difference between the two SPs' knowledge amounts is negligible. We define μ_i $(0 < \mu_i < 1)$ as the degree of knowledge complementarity from SPj to SPi. Namely, μ_i indicates how much SPi needs SPj's knowledge. The complementary level of knowledge is asymmetric, i.e., μ_i is not necessarily equal to μ_j. Moreover, $a_i (a_i \geq 1)$ indicates the amount of efforts SPi exerted to acquire complementary knowledge, with $a_i = 1$ indicating no efforts were made. Finally, function φ signifies SPi's ability (i.e. his learning capability) to absorb the knowledge of others. It is a function of his own effort level a_i, as well as the degree of knowledge complementarity μ_i. For ease of illustration, we assume $\varphi(\mu_i, a_i) = \mu_i a_i$. This implies that it would be easier for one SP to assimilate the other SP's knowledge when the complementarity level increases, since knowledge is more likely to transfer from one to another when SPs possess different expertise. In addition, making efforts in SPs' own knowledge collaboration undoubtedly will improve their learning ability.

4.1.2. Output function of SP

Let SPi's output be the total amount of knowledge SPi has. Then we rewrite the output function as $Q_i = q_i + \mu_i a_i q_j + \theta_i$, where $q_i < Q_i < q_i + q_j$. θ_i is an exogenous random variable influencing SPi's output, which is normally distributed with $\theta_i \sim N(0, \sigma^2)$. A similar expression has been employed to assess the productivity growth in R&D by Griliches [1979]. Finally, we assume the reservation utilities of SP1 and SP2 are both v_0.

4.1.3. Cost function of SP

We assume the cost of an SP consists of two parts: the service production cost and the knowledge sharing cost. The production cost is the cost for SPs to provide service (e.g. IT, logistics, and finance) to the e-tailor, while the sharing cost involves the expense of acquiring knowledge from other SPs. Let m_i be the marginal production cost for SPi, and $m_i = m(Q_i) = M - Q_i$, where M is a fixed cost and Q is knowledge. Here, m_i decreases with Q_i, because when SPs possess more knowledge they are more capable of providing cheaper services.

Additionally, we assume SPi's knowledge sharing cost is $C(a_i) = \frac{1}{2}ba_i^2$, where b $(b > 0)$ is the cost coefficient of knowledge sharing, and $C(a_i) > 0, C'(a_i) > 0$ and $C''(a_i) > 0$ [Holmstrom & Milgrom, 1987]. It indicates that knowledge sharing comes with a strictly positive cost $(C(a_i) > 0)$, and the sharing cost rises as the effort level increases $(C'(a_i) > 0)$. Furthermore, as the effort level rises high, so does the marginal sharing cost $(C''(a_i) > 0)$. Our assumption is justifiable since it is widely recognized that there exists a limitation on SPs' capability to collaborate knowledge.

4.1.4. Incentive for complementary knowledge sharing

Assume SPi's total compensation received from the e-tailer is $\omega_i = \omega(Q_i) = \alpha + \beta Q_i$, where α is the fixed compensation and β $(0 \leq \beta \leq 1)$ is the incentive coefficient of knowledge sharing output. When $\beta = 1$, SPi will take up all risks and reap all benefits from the knowledge output. In contrast, when $\beta = 0$, SPi will not assume any risk or gain any benefit from the total output. Similar contract form has been adopted by Holmstrom & Milgrom [1987] to study intertemporal incentives.

4.1.5. Knowledge integration effects of the e-tailer

Besides negotiating contracts, the e-tailer also integrates complementary knowledge and enhances outputs. Let t be the e-tailer's ability to integrate knowledge and $1 < t < 3$, then the total output becomes $t(Q_1 + Q_2)$. The knowledge integration activities incur costs, which are proportional to the knowledge integration ability. Similar to the cost of knowledge sharing, we assume the cost of knowledge integration is $C(t) = \frac{1}{2}dt^2$, where d $(d > 0)$ is the cost coefficient of knowledge integration, and $C(t) > 0, C'(t) > 0$, $C''(t) > 0$. It also means that knowledge integration comes with a strictly positive cost, and the integration cost as well as the marginal integration cost, increase with the e-tailer's capability. This is justifiable since the e-tailor's ability to integrate knowledge is limited. Therefore, the total profit of the e-tailer can be expressed as $\pi = t(Q_1 + Q_2) - [\omega(Q_1) + \omega(Q_2)] - \frac{1}{2}dt^2$.

4.2. For risk-neutral SP

In a risk-neutral setting, a service provider's expected utility equals the expected net compensation. Based on these assumptions, we find SPi's expected utility is $E(\pi_i) = \alpha + \beta\left(q_i + \mu_i a_i q_j\right) - m(Q_i) - \frac{1}{2} b a_i^2$, i.e., the compensation received from the e-tailer, minus knowledge producing costs and knowledge sharing costs.

4.2.1. The Optimal Incentive Mechanism

After the e-tailer provides an incentive contract (offering α and β), SP1 and SP2 will decide their effort level on knowledge sharing with the aim to maximize their own utility:

$$\max_{a_1} E(\pi_1) = \alpha + \beta(q_1 + \mu_1 a_1 q_2) - [M - (q_1 + \mu_1 a_1 q_2)] - \frac{1}{2} b a_1^2$$

$$\max_{a_2} E(\pi_2) = \alpha + \beta(q_2 + \mu_2 a_2 q_1) - [M - (q_2 + \mu_2 a_2 q_1)] - \frac{1}{2} b a_2^2$$

Based on the first-order optimal condition for any α and β, we find the optimal effort levels of SP1 and SP2 are: $a_1^* = \frac{(\beta+1)\mu_1 q_2}{b}$ and $a_2^* = \frac{(\beta+1)\mu_2 q_1}{b}$. The respective amount of knowledge in SP1 and SP2 are Q_1^* and Q_2^*. If the e-tailer can predict the optimal action of the SP by offering α and β, then the e-tailer can design the optimal contract to maximize his own benefits. From the principal-agent theory, we have the following e-tailer optimization (ETO) model:

$$\max_{\alpha,\beta,t} \pi = t(q_1 + \mu_1 a_1^* q_2 + q_2 + \mu_2 a_2^* q_1) - 2\alpha - \beta(q_1 + \mu_1 a_1^* q_2 + q_2 + \mu_2 a_2^* q_1) - \frac{1}{2} d t^2$$

S.t.

$$\alpha + \beta(q_1 + \mu_1 a_1^* q_2) - m(Q_1^*) - \frac{1}{2} b {a_1^*}^2 \geq v_0 \qquad \text{(IR1)}$$

$$\alpha + \beta(q_2 + \mu_2 a_2^* q_1) - m(Q_2^*) - \frac{1}{2} b {a_2^*}^2 \geq v_0 \qquad \text{(IR2)}$$

$$\alpha + \beta(q_1 + \mu_1 a_1^* q_2) - m(Q_1^*) - \frac{1}{2} b {a_1^*}^2 > \alpha + \beta(q_1 + \mu_1 a_1 q_2) - m(Q_1) - \frac{1}{2} b a_1^2 \qquad \text{(IC1)}$$

$$\alpha + \beta(q_2 + \mu_2 a_2^* q_1) - m(Q_2^*) - \frac{1}{2} b {a_2^*}^2 > \alpha + \beta(q_2 + \mu_2 a_2 q_1) - m(Q_2) - \frac{1}{2} b a_2^2 \qquad \text{(IC2)}$$

The e-tailer aims to maximize his expected benefit subject to participation constraints (IR1, IR2) and incentive compatibility constraints (IC1, IC2). Participation constraints assure that each risk-neutral SP's knowledge sharing revenue outweighs its costs. Incentive compatibility constraints ensure that benefits obtained from making the optimal effort (a^*) to share knowledge are more than those obtained from any other effort level.

To induce SPs' knowledge-sharing effort, the e-tailer must find an optimal compensation contract subject to the constraints (IR1, IR2) and (IC1, IC2). Considering the cases of $\mu_2 \geq \mu_1$ and $\mu_2 < \mu_1$ respectively, we find the optimal incentive mechanisms for risk-neutral SP are (see detailed calculations in the Appendix B):

Case (1): When $\mu_2 \geq \max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{(3-t)q_1^2}}, \mu_1\right\}$, we have

$$\beta^* = \frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{2\mu_2^2 q_1^2} + \frac{t-1}{2}, \alpha^* = v_0 + M - q_1(\beta^*+1) - \frac{\mu_1^2 q_2^2(\beta^*+1)^2}{2b},$$

$$a_1^* = \frac{(\beta^*+1)\mu_1 q_2}{b}, a_2^* = \frac{(\beta^*+1)\mu_2 q_1}{b}.$$

Case (2): When $\mu_2 \leq \min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2-(q_2-q_1)b}{(t+1)q_1^2}}, \mu_1\right\}$, we have

$$\beta^* = \frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2}{2\mu_1^2 q_2^2} + \frac{t-1}{2}, \alpha^* = v_0 + M - q_2(\beta^*+1) - \frac{\mu_2^2 q_1^2(\beta^*+1)^2}{2b},$$

$$a_1^* = \frac{(\beta^*+1)\mu_1 q_2}{b}, a_2^* = \frac{(\beta^*+1)\mu_2 q_1}{b}.$$

Case (3): When $min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2-(q_2-q_1)b}{(t+1)q_1^2}}, \mu_1\right\} < \mu_2 < max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{(3-t)q_1^2}}, \mu_1\right\}$, we have

$$\beta^* = 1, \alpha^* = v_0 + M - 2\,min\left\{q_1 + \frac{\mu_1^2 q_2^2}{b}, q_2 + \frac{\mu_2^2 q_1^2}{b}\right\},$$

$$a_1^* = \frac{2\mu_1 q_2}{b}, a_2^* = \frac{2\mu_2 q_1}{b}.$$

4.2.2. Analysis and propositions

Cases (1)-(3) provide closed-form expression of optimal contracts (α^*, β^*). They indicate that the knowledge complementarity effects (μ_1, μ_2) of a risk-neutral SP have great impact on the optimal incentive mechanism (α^*, β^*). From these optimal contracts for a risk-neutral SP, we draw the following propositions:

Proposition 1: When the gap between the complementary effects of the two SPs is large, the optimal incentive coefficient β^* is positively correlated with the SP who has high complementarity, and inversely proportional to the SP who has low complementarity.

From case (1), we know $\beta^* = \frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{2\mu_2^2 q_1^2} + \frac{t-1}{2}$ when $\mu_2 \geq max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{(3-t)q_1^2}}, \mu_1\right\}$. It's easy to show that β^* increases with μ_1 for a fixed μ_2, and decreases with μ_2 for a fixed μ_1, given the assumption that the difference between q_1 and q_2 is negligible ($|q_1 - q_2|$ is relatively small).

In this case, the complementary knowledge absorbed from SP2 has little use to SP1, indicating that SP1 can only attain little benefit from knowledge sharing. As a result, SP1 is reluctant to share knowledge. On the contrary, the complementary knowledge absorbed from SP1 has great use to SP2. Thus SP2 is motivated to share knowledge, since he can reap much profit from knowledge sharing. Thus, given the same output of complementary knowledge sharing, risk-neutral SP2 attains higher benefits than SP1.

Likewise, similar results can be derived for case (2), as β^* increases with μ_2 for a fixed μ_1, and decreases with μ_1 for a fixed μ_2. In the following, we discuss case (3).

Proposition 2: When the complementarity effects of the two SPs are approximately equal, the knowledge complementarity levels of the risk-neutral SP have no effect on the optimal incentive coefficient β^*.

When the complementarity effects are approximately equal, i.e., when $\min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2-(q_2-q_1)b}{(t+1)q_1^2}}, \mu_1\right\} < \mu_2 < max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{(3-t)q_1^2}}, \mu_1\right\}$ as shown in case (3), the optimal incentive coefficient ($\beta^* = 1$) is unrelated to μ. Thus, the risk-neutral SP receives the compensation $\alpha + Q_i$ and reaps all the benefits of his output Q. Accordingly, the risk-neutral service providers assume all risks. From the perspective of the e-tailer, it is unnecessary to incentivize the risk-neutral SP1 and SP2 to share knowledge. In short, both service providers assume all the risks (and then take all the profits), so there is no need for the e-tailer to incentivize them.

Proposition 3: The optimal incentive coefficient β^* is positively correlated with the e-tailer's ability to integrate knowledge.

From cases (1)-(3), we know that optimal incentive coefficient β^* increases as knowledge integration coefficient t increases. The e-tailer's knowledge integration effort can multiply complementary knowledge sharing output to determine the improvement in the ESSC's total profits. Therefore, if the knowledge integration ability increases, the e-tailer can achieve higher profit by offering stronger incentive to SP. In short, the greater the knowledge integration coefficient t is, the larger the incentive coefficient β^* should be.

4.3. For risk-averse SP

In a risk-averse setting, we assume that the service provider's utility function has the characteristic of constant absolute risk-averse, $U(\omega_i) = -e^{-\rho\omega_i}$, where ρ represents SPs' Arrow-Pratt absolute risk-averse degree. And the larger ρ is, the more the SP is afraid of risk. Similar to Holmstrom & Milgrom (1987), we assume the SPs' risk costs are $\frac{1}{2}\rho * var(\omega_i) = \frac{1}{2}\rho\beta^2\sigma^2$, where σ^2 represents the uncertainty of knowledge sharing. Without loss of generality, we assume that $0 \le \rho \le 1$, $0 \le \sigma \le 1$. Based on these assumptions, we find the expected utility of SP**i** is $U_i = \alpha + \beta\left(q_i + \mu_i a_{i1} q_j\right) - m(Q_i) - \frac{1}{2}ba_i^2 - \frac{1}{2}\rho\beta^2\sigma^2$.

4.3.1 The optimal incentive mechanism

After the e-tailer provided an incentive contract, SP1 and SP2 will choose their knowledge sharing levels, respectively, so as to maximize their own expected utility. Namely,

$$\max_{a_1} \alpha + \beta(q_1 + \mu_1 a_1 q_2) - m(Q_1) - \frac{1}{2}ba_1^2 - \frac{1}{2}\rho\beta^2\sigma^2$$

$$\max_{a_2} \alpha + \beta(q_2 + \mu_2 a_2 q_1) - m(Q_2) - \frac{1}{2}ba_2^2 - \frac{1}{2}\rho\beta^2\sigma^2$$

According to the first-order optimal condition, for any α and β, the optimal effort level of SP1 and SP2 are $a_1^* = \frac{(\beta+1)\mu_1 q_2}{b}$, $a_2^* = \frac{(\beta+1)\mu_2 q_1}{b}$. The respective amount of knowledge in SP1 and SP2 are Q_1^* and Q_2^*. The e-tailer will speculate SPs' actions and design an optimal incentive contract to maximize his own profit. That is,

$$\max_{\alpha,\beta,t} \pi = t(q_1 + \mu_1 a_1^* q_2 + q_2 + \mu_2 a_2^* q_1) - 2\alpha - \beta(q_1 + \mu_1 a_1^* q_2 + q_2 + \mu_2 a_2^* q_1) - \frac{1}{2}dt^2$$

S.t. $\alpha + \beta(q_1 + \mu_1 a_1^* q_2) - m(Q_1^*) - \frac{1}{2}ba_1^{*2} - \frac{1}{2}\rho\beta^2\sigma^2 \ge v_0$ (IR1)

$\alpha + \beta(q_2 + \mu_2 a_2^* q_1) - m(Q_2^*) - \frac{1}{2}ba_2^{*2} - \frac{1}{2}\rho\beta^2\sigma^2 \ge v_0$ (IR2)

$$\alpha + \beta(q_1 + \mu_1 a_1^* q_2) - m(Q_1^*) - \frac{1}{2}ba_1^{*2} > \alpha + \beta(q_1 + \mu_1 a_1 q_2) - m(Q_1) - \frac{1}{2}ba_1^2 \quad \text{(IC1)}$$

$$\alpha + \beta(q_2 + \mu_2 a_2^* q_1) - m(Q_2^*) - \frac{1}{2}ba_2^{*2} > \alpha + \beta(q_2 + \mu_2 a_2 q_1) - m(Q_2) - \frac{1}{2}ba_2^2 \quad \text{(IC2)}$$

To induce SPs' knowledge-sharing effort, the e-tailer must find an optimal compensation contract subject to the constraints (IR1, IR2) and (IC1, IC2). Similar to the derivation under the risk-neutral setting, we find the optimal incentive mechanisms for the risk-averse SP are (see detailed calculations in the Appendix C):

Case(4): when $\mu_2 \ge max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2 - 2\rho b\sigma^2}{(3-t)q_1^2}}, \mu_1\right\}$,we have

$$\beta^* = \frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2+(t-1)\mu_2^2 q_1^2}{2(\mu_2^2 q_1^2+\rho b\sigma^2)}, \alpha^* = v_0 + M - q_1(\beta^*+1) - \frac{\mu_1^2 q_2^2(\beta^*+1)^2}{2b} + \frac{1}{2}\rho\beta^{*2}\sigma^2,$$

$$a_1^* = \frac{(\beta^*+1)\mu_1 q_2}{b}, \quad a_2^* = \frac{(\beta^*+1)\mu_2 q_1}{b}.$$

Case(5): when $\mu_2 \le min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2+(q_1-q_2)b+2\rho b\sigma^2}{(t+1)q_1^2}}, \mu_1\right\}$, we have

$$\beta^* = \frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2+(t-1)\mu_1^2 q_2^2}{2(\mu_1^2 q_2^2+\rho b\sigma^2)}, \alpha^* = v_0 + M - q_2(\beta^*+1) - \frac{\mu_2^2 q_1^2(\beta^*+1)^2}{2b} + \frac{1}{2}\rho\beta^{*2}\sigma^2$$

$$a_1^* = \frac{(\beta^*+1)\mu_1 q_2}{b}, a_2^* = \frac{(\beta^*+1)\mu_2 q_1}{b}.$$

Case(6): when

$min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2+(q_1-q_2)b+2\rho b\sigma^2}{(t+1)q_1^2}}, \mu_1\right\} < \mu_2 < max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2-2\rho b\sigma^2}{(3-t)q_1^2}}, \mu_1\right\}$, we have

$$\beta^* = 1, \alpha^* = v_0 + M + \frac{1}{2}\rho\beta^{*2}\sigma^2 - 2\,min\left\{q_1 + \frac{\mu_1^2 q_2^2}{b}, q_2 + \frac{\mu_2^2 q_1^2}{b}\right\},$$

$$a_1^* = \frac{2\mu_1 q_2}{b}, a_2^* = \frac{2\mu_2 q_1}{b}.$$

4.3.2 Analysis and propositions

The optimal incentive mechanism of the risk-averse SP has the following characteristics:

- When $\mu_2 \geq max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2-2\rho b\sigma^2}{(3-t)q_1^2}}, \mu_1\right\}$. For a given μ_2, β^* increases with the increase of μ_1. For a fixed μ_1, β^* decreases with the increase of μ_2.
- When $\mu_2 \leq min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2+(q_1-q_2)b+2\rho b\sigma^2}{(t+1)q_1^2}}, \mu_1\right\}$. For a given μ_2, β^* decreases with the increase of μ_1. For a fixed μ_1, β^* increases with the increase of μ_2.
- If $min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2+(q_1-q_2)b+2\rho b\sigma^2}{(t+1)q_1^2}}, \mu_1\right\} < \mu_2 < max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2-2\rho b\sigma^2}{(3-t)q_1^2}}, \mu_1\right\}$, then $\beta^* = 1$. The optimal incentive coefficient β^* is independent of the knowledge complementarity coefficient μ.
- The optimal incentive coefficient β^* is positively correlated with e-tailer's knowledge integration ability t.

As the optimal incentive coefficient (β^*) of risk-averse SP is influenced by the absolute risk aversion coefficient ρ and uncertainty factors σ, we have the following additional proposition:

Proposition 4: The optimal incentive coefficient for risk-averse SP is inversely proportional to the risk-averse degree of SP, knowledge sharing cost of SP and external uncertainty.

From cases (4)-(5), we can draw the conclusion that β^* is inversely proportional to the risk-averse degree ρ, knowledge sharing cost coefficient b and external uncertainty coefficient σ.

When the knowledge sharing cost coefficient b increases, the fixed cost of knowledge sharing increases, and SPi's knowledge sharing cost is $C(a_i) = \frac{1}{2}ba_i^2$. Similarly, when the absolute risk-averse coefficient ρ and the environmental uncertainty coefficient σ increase, the risk cost of knowledge sharing increases as well. Recall that the risk cost is the cost incurred by SP's risk, which is $\frac{1}{2}\rho\beta^2\sigma^2$. We thus conclude that higher fixed cost and risk cost in the knowledge sharing contract will lower the e-tailer's profit, forcing the e-tailer to cut his monetary incentives to the SP.

5. Numerical analysis

As the risk-neutral setting is a special case of risk-averse with $\rho = 0$, and propositions 1-3 are applicable to both cases, our numerical experiments will focus on the effects of risk-aversion on optimal incentive schemes. All the experiments are implemented on MATLAB platform [version 2013a]. The parameters chosen in the experiments are displayed in Figures 4-6.

Corresponding to Proposition 4, Figures 4(a)-(b) exhibit the relationship between optimal incentive coefficient (β^*) and risk-averse level (ρ) when $\mu_2 > \mu_1$ and $\mu_1 > \mu_2$, respectively, from which we have the following observations:

a) When SPs are risk-neutral ($\rho = 0$), the optimal incentive coefficients (β^*) are constant regardless of risk levels (σ=0.2, 0.4, 0.6 or 0.8), as the SPs are indifferent to risks.
b) When SPs are risk-averse ($\rho > 0$), β^* decreases with risk-averse level (ρ), because risk-averse SPs are reluctant to bear risks as ρ increases.
c) When SPs are risk-averse and ρ is fixed, β^* decreases with risk level (σ), because the revenue of the risk-averse SP will decrease with the increase of risks.

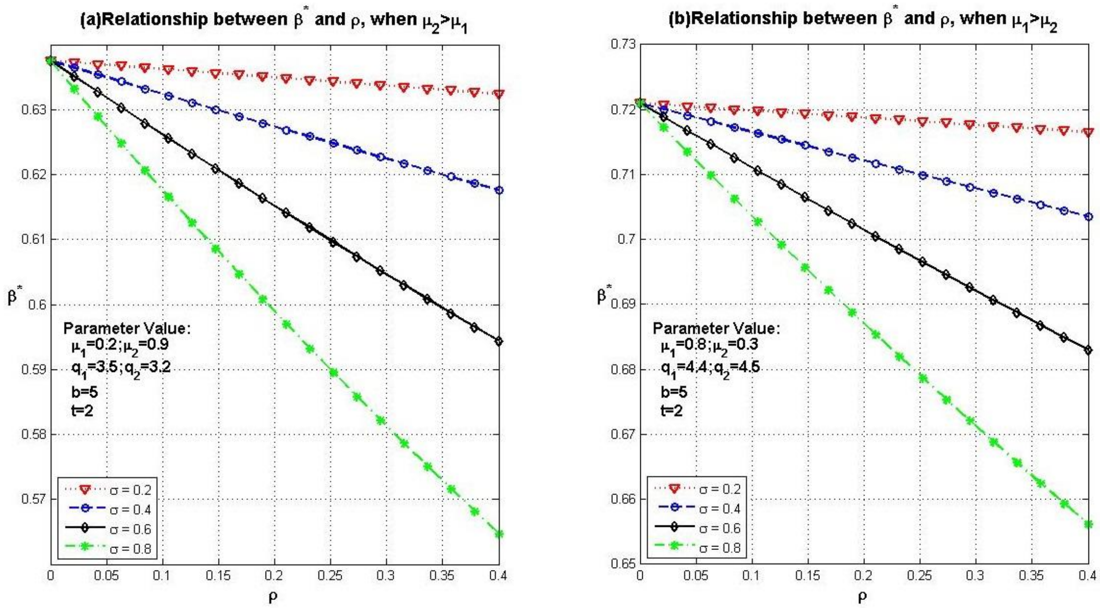

Figure 4: The relationships between the Optimal Incentive Coefficient (β^*) and the Risk-averse Level (ρ)

Corresponding to Proposition 1, Figures 5(a)-(b) give the relationship between the optimal incentive coefficient (β^*) and the complementarity effects (μ_1,μ_2), when $\mu_2 > \mu_1$ and $\mu_1 > \mu_2$, respectively. It shows that when SPs are risk-neutral ($\rho = 0$), β^* increases with the complementarity effect $\mu_1(\mu_2)$ for a fixed $\mu_2(\mu_1)$. The same observations can be found for risk-averse SPs (with ρ = 0.3, 0.5, 0.7 or 0.9). In short, regardless of the SP's risk preference, the optimal incentive coefficient (β^*) will increase when the knowledge complementarity coefficient (μ_1,μ_2) increases.

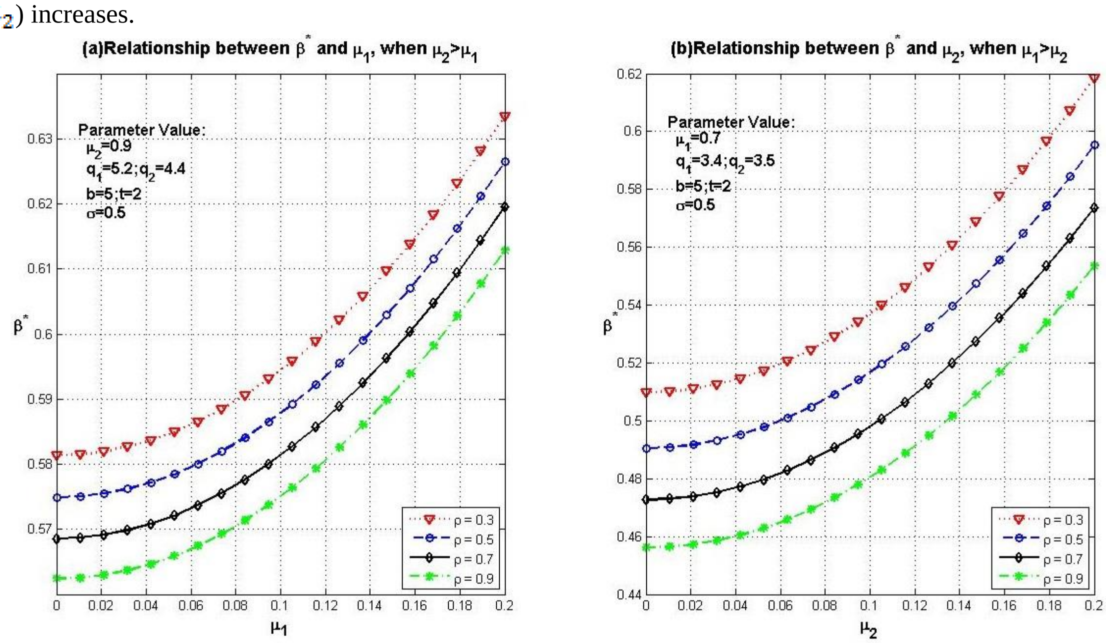

Figure 5: Optimal Incentive Coefficient (β^*) vs. Knowledge Complementarity Effects (μ_1,μ_2)

Finally, we examine the impacts of knowledge integration ability (t) on knowledge incentive contracts. As indicated in Proposition 3, Figure 5 shows the relationship between the optimal incentive coefficient (β^*) and the e-tailer's knowledge integration ability (t) under $\mu_2 > \mu_1$ and $\mu_1 > \mu_2$, respectively. From Figure 5, we find that

a) When risk-averse level (ρ) and risk level (σ) are fixed, optimal incentive coefficient (β^*) increases with the knowledge integration capability (t). This is because the risk-averse SP's revenue decreases as risk increases. Greater knowledge integration ability would lead to better ESSC performance, which would improve the SP's compensation and in turn incentivize more efforts on knowledge sharing, creating a virtuous circle.

b) For a constant ρ, at a fixed level of t, β^* will decrease when σ increases, because the risk-averse SP's revenue will decrease as risk increases (see Figure 6(a)).

c) Given a constant risk level (σ), when knowledge integration ability (t) is fixed, optimal incentive coefficient (β^*) decreases as risk-averse level (ρ) increases. This is because the risk-averse SP's revenue decreases as risk-averse level increases (see Figure 6(b)).

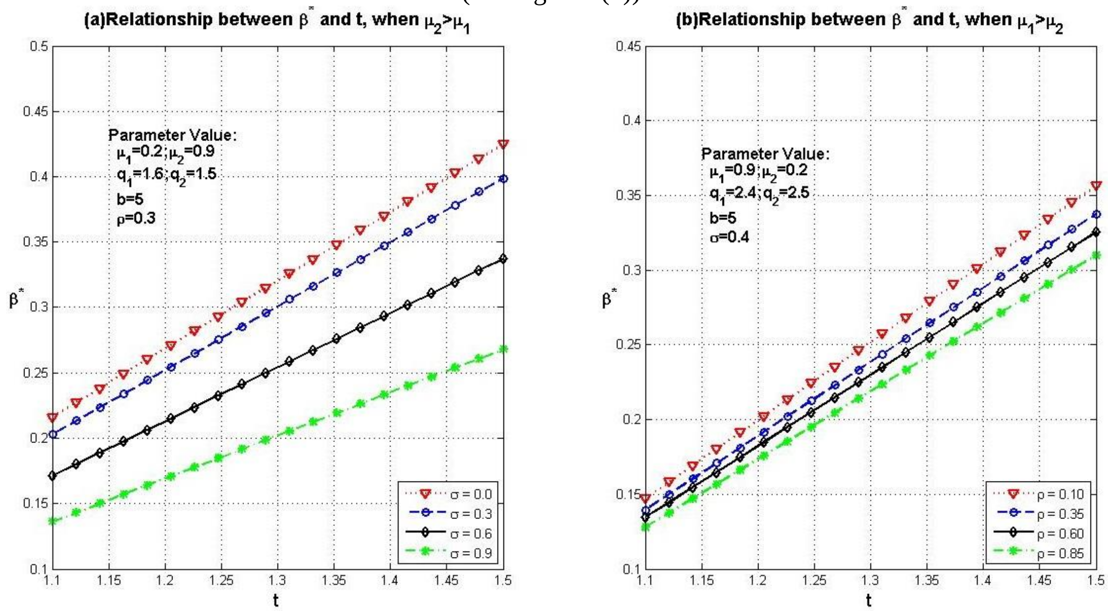

Figure 6: Optimal Incentive Coefficient (β^*) vs. Knowledge Integration Ability (t)

6. Discussion

Figures 4-6 give visual summary of the numerical-experimental results of our model. It shows that there exist specific correlations between optimal incentive schemes and three ESSC variables: knowledge complementarity, knowledge integration, and risk attitude. Our findings carry important managerial implications in helping e-tailer (the motivator and coordinator in ESSC) to promote knowledge collaboration.

First, e-tailers should pay attention to the service providers' risk attitude when designing the compensation contract on knowledge sharing. As shown in Figure 4, the optimal incentive coefficient is inversely proportional to SPs' risk-averse level. When SPs become increasingly risk averse, the e-tailer tends to reduce the revenue-sharing proportion given to SPs' knowledge-sharing efforts. It emphasizes on the principle of reciprocity and coherence of sharing risks and rewards among the e-tailer and SPs. That is, there is no need for the e-tailer to pay too much to SPs since they are reluctant to take risks in the ESSC's collaborative innovation based on knowledge sharing.

Second, the knowledge complementarity of SPs has great impacts on e-tailers' optimal incentive strategy, as well as the ESSC's productivity. As demonstrated in Figure 5, the optimal incentive coefficient relates positively to the knowledge complementarity of SPs. It indicates that, the e-tailer is willing to share a larger portion of revenue with SPs. As mentioned above, the complementarity capacities facilitate the knowledge transfer between SPs and improve the gains from learning from each other, which could increase the output of the ESSC as a whole. Therefore, it is rational for e-tailers to reward the SP with a higher percentage of revenue for her extra efforts in sharing knowledge, when the ESSC consists of multiple SPs with different expertise. Moreover, it implies that, when e-tailers choose SPs to form a service supply chain, the chosen service providers should be specialized and competent in their distinctive fields, so they can complement each other's knowledge and maximize the performance of the ESSC.

Finally, knowledge integration plays a vital role in knowledge collaboration and has great impacts on the incentive scheme. Figure 6 shows the optimal incentive coefficient relates positively to the knowledge integration ability of e-tailers. High knowledge integration capacities contribute to high level of revenue sharing with SPs, which make knowledge transfer more appealing to SPs and thus helps knowledge complementarity improve ESSC's performance. In other words, knowledge integration creates a virtuous cycle for knowledge collaboration between the e-tailer and SPs. Specifically, knowledge integration promotes knowledge sharing, which in turn promotes more knowledge integration. In this sense, it's essential for e-tailers to enhance their capacities to integrate dispersed knowledge among SPs, with the aim to consolidate diverse information and derive useful knowledge at the ESSC level.

7. Conclusion

In this paper, we introduce the concepts of knowledge complementarity and knowledge integration, and incorporate them in the knowledge sharing incentive models for the ESSC. Based on the principal-agent theory, two optimal incentive mechanisms are developed for knowledge sharing under asymmetric information, when SPs are risk-neutral and risk-averse, respectively. We find that the knowledge complementarity effects (μ_1, μ_2), the knowledge integration ability (t), the risk-averse degree (ρ) and the external uncertainty (σ) all impact optimal incentive (β^*) to varying degrees.

Distinctive models like ours are necessary as e-commerce has greatly expanded market scale and promoted knowledge specialization, making knowledge complementarity essential for ESSC success. Since a social network accelerates the flow and fusion of knowledge, the capability of integrating the knowledge and competently applying the synthesized knowledge often determine the survival of a firm. Moreover, the fast-changing online market and the intangibility of knowledge lead to much uncertainty in knowledge sharing. By taking into account the risk attitude, the complementarity degree and the integration capability, we ensure the proposed incentive contracts are effective and practicable for ESSC collaboration.

In our work, the activities of knowledge sharing and integration are limited to e-tailers and service providers, while consumers of the service supply chain are not taken into account. In the online market, consumer-driven and feedback mechanisms have fundamentally changed the role of consumers in the service supply chain, and have compelled customers to closely link with the e-tailer and service providers. Therefore, it would be beneficial for future research to incorporate customers' knowledge sharing activities in the ESSC incentive model. Also, we have hitherto solely focused on designing an incentive contract for an e-tailer with two SPs. Extending our model to study multiple service providers' complementary knowledge sharing would be an interesting and important future research topic.

Acknowledgement

This research is supported by National Basic Research Program of China (973 Program) (No. 2012CB315805), National Natural Science Foundation of China (No. 71420107027), National Natural Science Foundation of China (No. 71401053), MOE Project of Humanities and Social Sciences (No. 13YJC790100) and Natural Science Foundation of Hunan Province of China (No. 13JJ4040).

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Appendix A. Summary of Parameters and Variables

Table 1. Parameters and decision variables in our model

Notation	Description
q_i	Original amount of SPi's knowledge
Q_i	Total amount of SPi's knowledge and SPi's output
μ_i	Degree of knowledge complementarity from SPj to SPi
a_i	Amount of efforts SPi exerted to acquire complementary knowledge
θ_i	Exogenous random variable influencing SPi's output
v_0	Reservation utilities of SP
M	Fixed cost of knowledge producing costs of SP
b	Cost coefficient of knowledge sharing
α	Fixed compensation of knowledge sharing output
β	Incentive coefficient of knowledge sharing output
t	E-tailer's ability to integrate knowledge
π	Total profit of the e-tailer
ρ	Arrow-Pratt absolute risk-averse degree
σ	Uncertainty of knowledge sharing
$\varphi(\mu_i, a_i)$	SPi's ability to absorb the knowledge of others
$m(Q_i)$	Knowledge producing costs of SPi
$C(a_i)$	Knowledge sharing costs of SPi
$\omega(Q_i)$	SPi's total compensation received from the e-tailer
$U(\omega_i)$	SPi's utility in a risk-averse setting

Appendix B. Derivation of the Optimal Incentive Mechanism under Risk-Neutral

To develop the optimal knowledge sharing incentive mechanism, we consider the following two cases:

(I) when $\mu_2 \geq \mu_1$.

Recall that μ_i indicates how much SP $\mathbf{i}$ needs SP $\mathbf{j}$'s knowledge. So, $\mu_2 \geq \mu_1$ means SP2 needs SP1's knowledge more, and SP1's knowledge is more useful than that of SP2. From the constraints of the ETO model above, we know that SP2's compensation obtained from knowledge sharing is no less than that of SP1, so the equality for participation constraint (IR1) holds. Namely, when SP1 accepts the contract, SP2 will accept it, too. So the inequality for constraint (IR2) holds. Substituting $a_1^* = \frac{(\beta+1)\mu_1 q_2}{b}$,$a_2^* = \frac{(\beta+1)\mu_2 q_1}{b}$ and IR1 into the objective function, with $m(Q_1^*) = M - Q_1^* = M - (q_1 + \mu_1 a_1^* q_2)$, we have:

$$\max_{\alpha,\beta,t}(t-\beta)(q_1+\mu_1 a_1^* q_2 + q_2 + \mu_2 a_2^* q_1) - 2v_0 - 2\mathrm{M} + 2(\beta+1)(q_1+\mu_1 a_1^* q_2) - b a_1^{*2} - \frac{1}{2}dt^2$$

$$= \max_{\alpha,\beta,t}(t-\beta)\left(q_1+\mu_1\frac{(\beta+1)\mu_1 q_2}{b}q_2 + q_2 + \mu_2\frac{(\beta+1)\mu_2 q_1}{b}q_1\right) - 2v_0 - 2\mathrm{M} + 2(\beta+1)\left(q_1 + \mu_1\frac{(\beta+1)\mu_1 q_2}{b}q_2\right) - b\left(\frac{(\beta+1)\mu_1 q_2}{b}\right)^2 - \frac{1}{2}dt^2$$

.

Set the first derivative to zero. We find the optimal incentive coefficient without considering the restriction $(0 \leq \beta \leq 1)$ is

$$\bar{\beta} = \frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{2\mu_2^2 q_1^2} + \frac{t-1}{2}.$$

To ensure the above value is between 0 and 1, we define the optimal incentive coefficient as β^*:

$$\beta^* = \min\left\{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{2\mu_2^2 q_1^2} + \frac{t-1}{2}, 1\right\}.$$

Note that $\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{2\mu_2^2 q_1^2} + \frac{t-1}{2} \leq 1$ means

$$\mu_2 \geq \sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{(3-t)q_1^2}}.$$

Thus, the constraint $\mu_2 \geq \mu_1$ can be rewritten as

$$\mu_2 \geq \max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{(3-t)q_1^2}}, \mu_1\right\}.$$

The fixed payment can be expressed as

$$\alpha^* = v_0 + M - q_1(\beta^*+1) - \frac{\mu_1^2 q_2^2(\beta^*+1)^2}{2b}.$$

Substituting the optimal incentive coefficient β^* into a_1^* and a_2^*, we have

$$a_1^* = \frac{\mu_1 q_2}{b}\left(1 + \min\left\{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{2\mu_2^2 q_1^2} + \frac{t-1}{2}, 1\right\}\right),$$

$$a_2^* = \frac{\mu_2 q_1}{b}\left(1 + \min\left\{\frac{(q_1-q_2)b+(t+1)\mu_1^2 q_2^2}{2\mu_2^2 q_1^2} + \frac{t-1}{2}, 1\right\}\right).$$

(II) when $\mu_2 < \mu_1$.

Similarly, the optimal incentive coefficient and the fixed payment can be found as

$$\beta^* = min\left\{\frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2}{2\mu_1^2 q_2^2} + \frac{t-1}{2}, 1\right\}.$$

Note that $\frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2}{2\mu_1^2 q_2^2} + \frac{t-1}{2} \leq 1$ means

$$\mu_2 \leq \sqrt{\frac{(3-t)\mu_1^2 q_2^2-(q_2-q_1)b}{(t+1)q_1^2}}.$$

Thus, the constraint $\mu_2 < \mu_1$ can be rewritten as

$$\mu_2 \leq min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2-(q_2-q_1)b}{(t+1)q_1^2}}, \mu_1\right\}.$$

$$\alpha^* = v_0 + M - q_2(\beta^* + 1) - \frac{\mu_2^2 q_1^2(\beta^*+1)^2}{2b}.$$

Substituting the optimal incentive coefficient β^* into a_1^* and a_2^*, we have

$$a_1^* = \frac{\mu_1 q_2}{b}\left(1 + min\left\{\frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2}{2\mu_1^2 q_2^2} + \frac{t-1}{2}, 1\right\}\right),$$

$$a_2^* = \frac{\mu_2 q_1}{b}\left(1 + min\left\{\frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2}{2\mu_1^2 q_2^2} + \frac{t-1}{2}, 1\right\}\right).$$

Appendix C. Derivation of the Optimal Incentive Mechanism under Risk-Averse

To derive the optimal knowledge sharing incentive mechanism, we consider the following two cases:

(I) when $\mu_2 \geq \mu_1$.

When $\mu_2 \geq \mu_1$, SP2 needs SP1's knowledge more. From the constraints of the model above, we know that SP2's compensation obtained from knowledge sharing is no less than that of SP1, so the equality for participation constraint (IR1) holds. Namely, as long as SP1 accepts the contract, SP2 will accept the contract, i.e., the inequality for constraint (IR2) holds. Substituting $a_1^* = \frac{(\beta+1)\mu_1 q_2}{b}$, $a_2^* = \frac{(\beta+1)\mu_2 q_1}{b}$ and IR1 into the objective function proposed in Subsection 4.1.5, we have

$$\max_{\alpha,\beta,t}(t-\beta)\left(q_1+\mu_1\frac{(\beta+1)\mu_1 q_2}{b}q_2+q_2+\mu_2\frac{(\beta+1)\mu_2 q_1}{b}q_1\right)-2v_0-2M+2(\beta+1)\left(q_1+\mu_1\frac{(\beta+1)\mu_1 q_2}{b}q_2\right)-b\left(\frac{(\beta+1)\mu_1 q_2}{b}\right)^2-\frac{1}{2}dt^2.$$

Set the derivative of the above expression to zero, we have

$$\bar{\beta}=\frac{(q_1-q_2)b+(t+1)\mu_1^2q_2^2+(t-1)\mu_2^2q_1^2}{2(\mu_2^2q_1^2+\rho b\sigma^2)}.$$

To ensure $0 \leq \beta \leq 1$, we rewrite the optimal incentive coefficient as

$$\beta^*=\min\left\{\frac{(q_1-q_2)b+(t+1)\mu_1^2q_2^2+(t-1)\mu_2^2q_1^2}{2(\mu_2^2q_1^2+\rho b\sigma^2)},1\right\}.$$

Note that $\frac{(q_1-q_2)b+(t+1)\mu_1^2q_2^2+(t-1)\mu_2^2q_1^2}{2(\mu_2^2q_1^2+\rho b\sigma^2)} \leq 1$ means

$$\mu_2 \geq \sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2q_2^2-2\rho b\sigma^2}{(3-t)q_1^2}}.$$

Thus, the constraint $\mu_2 \geq \mu_1$ can be rewritten as

$$\mu_2 \geq \max\left\{\sqrt{\frac{(q_1-q_2)b+(t+1)\mu_1^2q_2^2-2\rho b\sigma^2}{(3-t)q_1^2}},\mu_1\right\}.$$

Then the fixed payment becomes

$$\alpha^*=v_0+M-q_1(\beta^*+1)-\frac{\mu_1^2q_2^2(\beta^*+1)^2}{2b}+\frac{1}{2}\rho\beta^{*2}\sigma^2.$$

Substituting the optimal incentive coefficient into a_1^* and a_2^*, we have

$$a_1^*=\frac{\mu_1 q_2}{b}\left(1+\min\left\{\frac{(q_1-q_2)b+(t+1)\mu_1^2q_2^2+(t-1)\mu_2^2q_1^2}{2(\mu_2^2q_1^2+\rho b\sigma^2)},1\right\}\right),$$

$$a_2^*=\frac{\mu_2 q_1}{b}\left(1+\min\left\{\frac{(q_1-q_2)b+(t+1)\mu_1^2q_2^2+(t-1)\mu_2^2q_1^2}{2(\mu_2^2q_1^2+\rho b\sigma^2)},1\right\}\right).$$

(II) when $\mu_2 < \mu_1$.

Similarly, the optimal incentive coefficient and fixed payment can be expressed as

$$\beta^*=\min\left\{\frac{(q_2-q_1)b+(t+1)\mu_2^2q_1^2+(t-1)\mu_1^2q_2^2}{2(\mu_1^2q_2^2+\rho b\sigma^2)},1\right\}.$$

Note that $\frac{(q_2-q_1)b+(t+1)\mu_2^2q_1^2+(t-1)\mu_1^2q_2^2}{2(\mu_1^2q_2^2+\rho b\sigma^2)} \leq 1$ means

$$\mu_2 \leq \sqrt{\frac{(3-t)\mu_1^2q_2^2+(q_1-q_2)b+2\rho b\sigma^2}{(t+1)q_1^2}}.$$

Thus, the constraint $\mu_2 < \mu_1$ can be rewritten as

$$\mu_2 \leq min\left\{\sqrt{\frac{(3-t)\mu_1^2 q_2^2+(q_1-q_2)b+2\rho b\sigma^2}{(t+1)q_1^2}}, \mu_1\right\}.$$

Then the fixed payment becomes

$$\alpha^* = v_0 + M - q_2(\beta^* + 1) - \frac{\mu_2^2 q_1^2(\beta^*+1)^2}{2b} + \frac{1}{2}\rho\beta^{*2}\sigma^2.$$

Substituting the optimal incentive coefficient into a_1^* and a_2^*, we have

$$a_1^* = \frac{\mu_1 q_2}{b}\left(1 + min\left\{\frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2+(t-1)\mu_1^2 q_2^2}{2(\mu_1^2 q_2^2+\rho b\sigma^2)}, 1\right\}\right),$$

$$a_2^* = \frac{\mu_2 q_1}{b}\left(1 + min\left\{\frac{(q_2-q_1)b+(t+1)\mu_2^2 q_1^2+(t-1)\mu_1^2 q_2^2}{2(\mu_1^2 q_2^2+\rho b\sigma^2)}, 1\right\}\right).$$