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COORDINATION OF ELDERLY HEALTHCARE SERVICE SUPPLY CHAIN WITH INFORMATION ASYMMETRY: DESIGNS OF OPTION CONTRACTS UNDER DIFFERENT DEMAND DISTRIBUTION STATUSES

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Abstract. This paper studies the issue of demand information asymmetry in an elderly healthcare service (EHS) system represented by a two-echelon elderly healthcare service supply chain (EHSSC) comprising an elderly service integrator (ESI) and a service provider (ESP). The goal of the ESI is to decide on how much service capacity is required for placing orders to the ESP, who directly serves the customers. Considering discrete and continuous demand distribution statuses, a centralised model with symmetric demand information and decentralised models with asymmetric demand information are developed to analyse the optimal ordering decisions and discuss the influence of information asymmetry. Furthermore, option contracts are applied to help coordinate the supply chain under asymmetric demand information based on different demand distribution statuses. Optimal option contract menus are designed for the ESP to promote the information sharing. Results show that the option contract can coordinate the EHSSC with asymmetric demand information under both discrete and continuous demand distribution statuses. The exercise price will be higher under lower demand information than that under higher demand information and the transfer payment will be less under lower demand information than that under higher demand information. Moreover, although the ESI has demand information superiority and can make use of opportunistic behaviour to maximise its own profit, the ESP as the leader can design the option contract to incentive the ESI to achieve true information sharing, and even obtain nearly all of the channel profit.

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1. Introduction

Today, both developing and advanced economies are facing the problems of increasingly aging populations as well as the need to meet diverse elderly healthcare service demands [1, 34]. China, which is not yet a fully developed economy, is finding this problem especially acute [29]. In this paper, Chinas community-based elderly healthcare service (EHS) system, considered an important elderly service system in the country, is investigated. The community-based EHS system combines the functions of home-based and institution-based EHS systems in China. There are mainly three players including the ESI, the ESP and the customer (*i.e.* the elderly) in Chinas community-based EHS system. The ESI, as the customers services agent like community service centre, is

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responsible for demand forecasting, receiving orders from the customer, selecting appropriate ESPs, purchasing services capacity from ESPs and supervising services performance. The ESP, as the ESIs agent, is responsible for producing services and providing the required services to the elderly according to the ESIs orders. This community-based EHS system has many advantages, including centralised control of service quality. However, it also has several disadvantages, including inefficiencies due to incentive issues among the ESI and ESP [25]. A common cause of these incentive issues is the information asymmetry among the ESI and ESP regarding demand forecasts. From the perspective of a supply chain, the ESI, who is closer to the customer and has demand information superiority over the ESP, would take the services demand as its own private information. In order to avoid order risks and pursue profit maximisation, the ESI might use this additional information strategically, sometimes to the extent of misrepresenting it to the ESP. Consequently, the ESP would bear the service capacity supply risks due to asymmetric demand information, which will affect the decisions on the supply chain coordination.

An important and growing research context about issues of supply chain coordination caused by information asymmetry can be characterised by an intense focus on the application of supply chain contracts [9], such as revenue sharing contract [7]. Due to the flexibility on the ordering quantity after further demand information, the option contract becomes an effective means to help hedge against ordering risks aggravated by the uncertain demand and to reduce double marginalization in the supply chain [18, 36, 40]. In many cases, option contracts benefit each party involved and increase profits across the whole supply chain [4, 22]. However, related studies about supply chain coordination with option contracts under information asymmetry are still few. Therefore, considering the information asymmetry, it is an interesting study on whether the ESP, as the inferior information side, could use the option contract to help coordinate the supply chain and motivate the ESI to share the true demand information.

Due to the diversity of the elderlys physical and mental health statuses, the ESI has to design the personalised service solution for each customer to guarantee his/her health, and the ESP will plan and allocate required services according to the ESIs needs. The diversity and personalisation of elderly healthcare services are therefore more complicated than those of other kinds of services and products, resulting in higher demand volatility. For instance, in some communities where the aged residents are in good physical and mental statuses and have self-care ability, the basic nursing care service can enough meet the elderlys demand. There is no needs to provide other special nursing services for certain customers. Hence, the demand for basic nursing care service is stable and continuous. However, if the elderlys physical and mental health is rather poor and unstable, some personalised and specialised services, which are perhaps at a small scale demand, are required. The demand for these services may present a discrete distribution status. Whats more, it is not easy to manage the forecasting of elderly services demand in one certain community since the demand significantly changes with the market operation as well as the elderlys health status [12, 32]. Hence, the demand distribution status can hardly be described in the EHS system, where discrete or continuous demand statuses can present. Under information asymmetry, it is worthy to discuss whether different demand distribution statuses could have different influences on the decisions of supply chain coordination and whether the option contract could take effect under different demand distribution statuses.

Therefore, the highlights of this paper are listed as follows. First, different from other related studies that focus on the healthcare services capacity allocation amongst the ESP and the customers, this paper explores the service capacity ordering strategies between the ESI and ESP within a game-theoretic setting to meet the uncertain demand. Second, the demand characteristics of elderly healthcare services and the behaviours of the ESI and ESP are considered to study their influence on the channel coordination of the elderly healthcare system. Third, the option contract is designed as an incentive to promote the information sharing and provide the ESI with the flexibility on decisions about service capacity orders.

In this paper, a community-based EHS system is modelled as a two-echelon elderly healthcare service supply chain (EHSSC) consisting of one ESI and one ESP. Optimal service capacity ordering decisions in the asymmetric demand information situations under different demand distribution statuses (discrete and continuous cases) are analysed for the ESI within an ESP-leader Stackelberg game setting. Further, combined with the loss sharing mechanism, option contracts are designed for the ESP to motivate the ESI with information advantage to share its true demand information and coordinate the supply chain. This study has practical and theoretical significance for the development of elderly healthcare services system under different demand distribution statuses and plays an important role in promoting the study of supply chain coordination under asymmetric demand information.

The remainder of this paper is organised as follows. The related literature is reviewed in Section 2. Section 3 describes the problem and presents the assumptions. Optimal service capacity ordering decisions and option contract menus are analysed in Section 4. Section 5 discusses and compares the optimal decisions in asymmetric demand information situations under different demand distribution statuses, and analyses the coordination conditions for the EHSSC. Finally, conclusions and possible extension of this study are presented in Section 6.

2. Literature review

To highlight the contributions of this study, representative literature is mainly reviewed from the two aspects: information asymmetry in healthcare service system and supply chain coordination under information asymmetry.

2.1. Information asymmetry in healthcare service systems

Information asymmetry has an important impact on the performance of healthcare service systems [23]. Shi and Zhang claimed that information asymmetry contributed to the high rising healthcare costs. They examined the existence of private information among the patient and healthcare institutions and further quantified its effect on the utilization of medical care services based on a copula-based hurdle model [31]. Yan *et al.* conducted a questionnaire survey to analyse differences between the transparency of information disclosure and related demands from the customers perspective, and further studied the influence of different levels of mandatory information disclosure on the relationship between the service providers and customers [39]. Lim used data from a survey sample of people aged more than 65 living in Seoul and Chuncheon, Korea, to study whether the doctors effort of effectively communicating with patient would ameliorate patients information problem. The results verified that, the doctors effort at sincerely helping patient understand and utilize health information by effective communication with patient can improve the patients asymmetric information problem and affect the patients use of medical care by way of its being a source of patients solid trust on doctor [19]. Existing studies about information asymmetry in healthcare are mainly conducted by using probabilistic and statistical analysis methodologies and focus on the behaviours among the service providers and customers [20, 24].

Different from the above studies, this paper studies the relationship between the healthcare services integrator and the services provider within a game-theoretic setting, which is an extension to the existing studies in which the healthcare coordination mainly focus on the resources allocation between the ESP and the elderly. Further, this work analyses the influence of asymmetric information on the coordination of elderly healthcare system. The asymmetric information in healthcare studies involves the information of health status, service quality level and capacity allocation [23], but demand information is the key factor influencing the service capacity planning in the healthcare service supply system. This paper further considers the demand information asymmetry among the ESI and the ESP within a supply chain setting and investigates its influence on the services capacity ordering decisions.

2.2. Supply chain coordination under information asymmetry

Supply chain coordination is always an issue of concern in manufacturing and industrial systems. Ebrahimi *et al.* investigated the coordination of promotional effort and replenishment decisions in a two-echelon supply chain including single supplier and single retailer. A coordination model based on delay in payment contract was proposed to motivate the retailer to participate in the joint decision-making model [10]. Hosseini-Motlagh *et al.* analysed and compared the performances of the entire supply chain consisting of a monopolistic manufacturer and two competing retailers under three game structures. A collaborative decision-making model was proposed by considering the individual profit of each supply chain member under different behaviours of competing retailers [13]. Nematollahi *et al.* illustrated how to coordinate the pharmaceutical supply chain with service level consideration through a multi-objective collaborative decision-making model [27]. Johari *et al.* proposed a bi-level credit period coordination scheme for a supplier–retailer supply chain with a periodic review replenishment policy and price-credit dependent demand [16]. Nouri *et al.* proposed a new compensation-based wholesale price contract for encouraging actors to take part in the joint decision-making scheme. Moreover, a profit sharing strategy based on the bargaining power of members was proposed for distributing the surplus profit between members [28].

With regard to studies about the information asymmetry in the supply chain, most focus on the cost structure [5, 8, 17] and demand information [15, 38]. Supply contracts including quantity discount contract [6], wholesale price contract [30] and buyback contract [21], under these information asymmetric situations have been studied extensively to help achieve supply chain coordination [37]. Xie *et al.* [35] studied the decisions of the wholesale price and service level in a service-oriented manufacturing supply chain under asymmetric demand information, and designed three types of contracts based on wholesale price contract and franchise fee contract to enhance the supply chain performance. Tran and Desiraju examined the value of group-buying mechanism for the channel management amongst the retailer and manufacturer. The group-buying mechanism was more beneficial to the manufacturer when the retailer was privately informed about market size [33]. Egri and Vancza studied a decentralised two-echelon supply chain where the customer and the supplier had asymmetric information, and presented a payment scheme with double compensation that could coordinate such a supply chain [11]. Akan *et al.* demonstrated that a menu of two-part tariffs and efficient service levels under asymmetric demand information could help achieve full information solution [2]. Similar to considering the demand information asymmetry, the differences of this study are to further take different demand distribution statuses into account and analyse their influences on service capacity ordering decisions in the EHS system. In addition, the option contract is proved to be an effective way to coordinate supply chain with disrupted demand [41]. Asian and Nie designed effective contract-based mitigation strategies that enable firms to ensure responsive backup capacity under demand uncertainty and supply disruptions by using the option contract [3]. Jazinaninejad *et al.* formulated an economic production quantity (EPQ) model within a manufacturer-buyer chain and developed a credit option contract to coordinate the production, pricing, and periodic review policy decisions [14].

Different from the above studies, this paper studies the coordination of service capacity between the ESI and ESP in an elderly healthcare service system. Currently, research on the coordination of the healthcare supply chain is still limited. This study is a starting point to provide guidance for further works on elderly healthcare coordination from the perspective of supply chain management. Whats more, this paper considers two different demand status, in both of which there are two kinds of demand classes amongst the elderly, to characterise the uncertain demand. In addition, the option contract is merely employed into the study of supply chain coordination under demand information asymmetry, which is also one significant difference of this study to examine the effect of option contract under information asymmetry on elderly healthcare service supply chain coordination.

3. Description and assumptions

With the high customer expectations on the service quality and service diversity, the government encourages ESPs to participate in the competition of elderly healthcare services market involving the physical care, housekeeping and so on. In order to meet the elderlys demand, the ESI has to seek more suitable ESPs. The ESP currently has greater power than the ESI in the elderly healthcare service supply chain. In this model, the relationship between the ESI and ESP is assumed to follow a Stackelberg game in which the ESP acts as the leader and the ESI as the follower. Here, the ESI aims at deciding on the optimal ordering quantity of service capacity with the objective of maximising the total profit, which is a function of the services revenue (collected from the elderly), minus the service capacity planning cost, loss due to service dissatisfaction, and loss due to service capacity limitation together. Both the ESI and ESP are risk neutral and completely rational. The sequence of the game is as follows. Before the elderly services demand is known, the ESP announces its

TABLE 1. Some basic parameters for models.

Symbol	Description
λ	$\lambda = m, \iota$, respectively represents the discrete and continuous demand distribution statuses
$m(n)$	$m = L, H(n = L, H)$ indicates the two kinds of demand information (low and high demand) under discrete demand status
$\iota(\kappa)$	demand information under continuous demand status
D_λ	Service demand under different demand distribution statuses
$F_\lambda(x)$, $f_\lambda(x)$	CDF and PDF of service demand under different demand distribution statuses
Q_{ip}^λ	Ordering quantity of service capacity for the EHSSC with demand information symmetry
Q_{mn}	Option quantity of service capacity for the ESI with demand information asymmetry
p_i	Sale price of per unit service capacity to the elderly for the ESI
c_p	Cost of per unit service capacity for the ESP
p_p	Wholesale price of per unit service capacity to the ESI for the ESP
o_λ	Option price of per unit service capacity under different demand statuses
e_λ	Exercise price of per unit service capacity under different demand statuses
c	Unit loss due to services capacity limitation for the ESI
c_s	Unit loss due to service dissatisfaction from the elderly
s	service satisfaction from the elderly
α	Probability of low demand under discrete demand status, and the probability of high demand is $1 - \alpha$
β	The ESIs sharing rate of loss due to service dissatisfaction
T_λ	Transfer payment under different demand distribution statuses
π_{ip}^λ	Profit of the EHSSC under different demand distribution statuses with information symmetry
π_{im}	Profit of the ESI under discrete demand distribution status with information asymmetry
π_{pm}	Profit of the ESP under discrete demand distribution status with information asymmetry
Π_p	Expected profit of the ESP under discrete demand status
$\pi_i(\iota, \kappa)$	Profit of the ESI under continuous demand distribution status with information asymmetry
$\pi_p(\iota, \kappa)$	Profit of the ESP under continuous demand distribution status with information asymmetry

wholesale price, options price (an agreed-upon price at which the ESI has the right, but not the obligation, to buy the service capacity on or before a specified date) and exercise price (a price at which the ESI can buy the service capacity when trading the option orders), then the ESI would determine options orders. When the demand is known, the ESP will provide the service capacity to meet the ESIs orders, as specified in the options contract. Specifically, if the service demand exceeds the option orders, the ESI will exercise the options orders and bear the loss due to limited service capacity. Otherwise, the options orders will be exercised according to the actual demand. Accordingly, the ESP directly serves the elderly by providing required services. Some basic parameters are presented in Table 1.

Since the ESI is closer to the service market, it has demand information superiority over the ESP. Assume the ESI knows of the true elderly healthcare service demand information in the community, while the ESP only knows of the demand probability distribution. Under the information asymmetry, the ESI may inform the ESP of untrue demand information to avoid ordering risks and get more benefits, while the ESP would bear risks of service capacity planning, hence the whole supply chain cannot achieve coordination. In order to eliminate the influence of demand information asymmetry on the ESP and whole supply chain, the ESP designs option contracts to motivate the ESI to share true demand information. Further, two demand distribution statuses are considered in this paper, namely the discrete demand and continuous demand.

Assume there are two kinds of demand information for discrete demand D_m $(m = L, H)$, which are low demand D_L and high demand D_H. The ESP only knows that the probability of low demand is α and the probability of high demand is $1 - \alpha$. The CDF $F_m(x)$ and PDF $f_m(x)$ $(f_m(x) \geq 0)$ of the service demand are common knowledge to both the ESI and the ESP. Furthermore, $F_m(x)$ is monotonically increasing and differentiable, and $F_L(x) \geq F_H(x)$ which means the high demand has higher randomness than low demand. Q_{mn} is the option quantity of service capacity when the true discrete demand information is m and the ESI claims the demand information n $(n = L, H)$. (o_n, e_n, T_n) is the option contract menu offered by the ESP under the discrete demand status, where o_n, e_n and T_n are respectively the option price, exercise price and the transfer payment provided by the ESI to the ESP under the discrete demand information n, and $o_n < e_n < p_i$. π_{im} and π_{pm} are respectively the profits of the ESI and ESP when the true discrete demand information is m.

As for continuous demand, assume the demand information is ι, $\iota \in [\underline{\iota}, \bar{\iota}]$ and $-\infty < \underline{\iota} < \bar{\iota} < +\infty$. Also, the ESP only knows CDF and PDF of demand information ι, respectively $G(\iota)$ and $g(\iota)$. When the demand information is ι, the CDF $F(x)$ and PDF $f(x)$ of the service demand are common knowledge to both the ESI and the ESP. when $\iota \in [\underline{\iota}, \bar{\iota}]$, assume $\partial F(x, \iota)/\partial \iota \leq 0$, hence when $\iota \leq \kappa$, $F(x, \iota) \geq F(x, \kappa)$, means the demand information distribution has the higher randomness with the increase of ι (namely the increase of demand). $Q(\iota, \kappa)$ is the option quantity when the true demand information is and the ESI claims the demand information κ. (o_κ, e_κ, T_κ) is the option contract menu offered by the ESP under the continuous demand status, where o_κ, e_κ and T_κ are respectively the option price, exercise price and the transfer payment provided by the ESI to the ESP under the demand information ι.

4. Service capacity ordering decisions with information asymmetry under different demand statuses

4.1. Basic models without the options contract: a benchmark

In case of demand information symmetry, centralised decisions for the EHSSC under different demand distribution statuses are first discussed as a benchmark, to verify the effect of option contract on supply chain coordination under different demand distribution statuses. The demand distribution status is λ under symmetric information, where $\lambda = m, \iota$ respectively denotes the discrete and continuous demand distribution status. The ordering quantity of service capacity for the EHSSC is Q_{ip}^{λ}. Thus, the expected profit of the whole supply chain can be presented as follow,

$$\begin{aligned}\pi_{ip}^{\lambda} &= [p_i - \beta(1-s)c_s] \min(D_\lambda, Q_{ip}^{\lambda}) - c(D_\lambda - Q_{ip}^{\lambda})^+ - c_p Q_{ip}^{\lambda} \\ &= [p_i + c - c_p - \beta(1-s)c_s] Q_{ip}^{\lambda} - [p_i + c - \beta(1-s)c_s] \int_0^{Q_{ip}^{\lambda}} F(x) \mathrm{d}x \\ &\quad - c\mu. \end{aligned} \tag{4.1}$$

Taking the derivative of equation (4.1),

$$\frac{\partial^2 \pi_{ip}^{\lambda}}{\partial {Q_{ip}^{\lambda}}^2} = -[p_i + c - \beta(1-s)c_s] f(Q_{ip}^{\lambda}).$$

To ensure the profit for the EHSSC, it requires that $p_i + c - \beta(1-s)c_s > 0$; besides, $f(Q_{ip}^{\lambda}) \geq 0$, then $\frac{\partial^2 \pi_{ip}^{\lambda}}{\partial {Q_{ip}^{\lambda}}^2} \leq 0$. Hence, π_{ip}^{λ} is a concave function, the optimal ordering quantity of service capacity is

$$Q_{ip}^{\lambda *} = F_{\lambda}^{-1}\left[\frac{p_i + c - (1-s)c_s - c_p}{p_i + c - (1-s)c_s}\right]. \tag{4.2}$$

If the demand distribution is discrete, when the demand information is low demand, namely $\lambda = L$, $Q_{ip}^{L*} = F_L^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}]$; when the demand information is high demand, namely $\lambda = H$, $Q_{ip}^{H*} = F_H^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}]$. If the demand distribution is continuous, $Q_{ip}^{\iota *} = F_{\iota}^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}]$.

4.2. Models with the options contract

In decentralised systems, the option contract will be applied to analyse the service capacity ordering decisions under different demand distribution statuses. In this model, the relationship between the ESI and the ESP is modelled as a Stackelberg game, where the ESP acts as the leader and ESI serves as the follower.

4.2.1. Decisions under discrete demand status

Considering the option contracts offered by the ESP, that is (o_L, e_L, T_L) and (o_H, e_H, T_H), the ESI will make a choice and determine the option ordering quantity Q_{mn}. When the demand information is m, and the ESI selects the option contract under demand information n, where $m, n = L, H$. Then, the ESIs profit can be indicated by

$$\begin{aligned}\pi_i = {} & [p_i - \beta(1-s)c_s]\min(D_m, Q_{mn}) - e_n \min(D_m, Q_{mn}) - o_n Q_{mn} \\ & - c(D_m - Q_{mn})^+ - T_n = [p_i + c - \beta(1-s)c_s - e_n - o_n]Q_{mn} \\ & - [p_i + c - \beta(1-s)c_s - e_n]\int_0^{Q_{mn}} F_m(x)\mathrm{d}x \\ & - c\mu - T_n. \end{aligned} \tag{4.3}$$

From equation (4.3), the optimal option ordering quantity for the ESI is

$$Q_{mn}^{*} = F_m^{-1}\left[\frac{p_i + c - \beta(1-s)c_s - e_n - o_n}{p_i + c - \beta(1-s)c_s - e_n}\right]. \tag{4.4}$$

Then,

$$\pi_i = [p_i + c - \beta(1-s)c_s - e_n]\int_0^{Q_{mn}} x f_m(x)\mathrm{d}x - c\mu - T_n \tag{4.5}$$

When the ESI's option ordering quantity satisfies equation (4.4), it can achieve its own profit maximisation. The ESP develops the option contract menus and incentive mechanisms according to the ESI's decisions, to coordinate the whole supply chain and minimize the impact of information asymmetry. Thus, the ESP's excepted profit can be represented by

$$\begin{aligned}\pi_p &= [e_n - (1-\beta)(1-s)c_s]\min(D_m, Q_{mn}) + o_n Q_{mn} - c_p Q_{mn} + T_n \\ &= [e_n + o_n - (1-\beta)(1-s)c_s - c_p]Q_{mn} \\ &\quad - [e_n - (1-\beta)(1-s)c_s]\int_0^{Q_{mn}} F_m(x)\mathrm{d}x + T_n. \end{aligned} \tag{4.6}$$

According to the revelation principle proposed by Myerson [26] and the objective of profit maximisation, the ESP's profit function can be described as the following linear programming problem:

$$\max \Pi_p = \alpha\pi_{pL}(o_L, e_L, T_L) + (1-\alpha)\pi_{pH}(o_H, e_H, T_H) \tag{4.7}$$

s.t.

$$\begin{aligned}\pi_{iL}(o_L, e_L, T_L, Q_{LL}) = {} & [p_i + c - \beta(1-s)c_s - e_L]\int_0^{Q_{LL}} x f_L(x)\mathrm{d}x \\ & - c\mu - T_L \geq 0 \end{aligned} \tag{4.8}$$

$$\pi_{iH}(o_H, e_H, T_H, Q_{HH}) = [p_i + c - \beta(1-s)c_s - e_H] \int_0^{Q_{HH}} x f_H(x) \mathrm{d}x - c\mu - T_H \geq 0 \tag{4.9}$$

$$\pi_{iL}(o_L, e_L, T_L, Q_{LL}) \geq \pi_{iL}(o_H, e_H, T_H, Q_{LH}) \tag{4.10}$$

$$\pi_{iH}(o_H, e_H, T_H, Q_{HH}) \geq \pi_{iH}(o_H, e_H, T_H, Q_{HL}), \tag{4.11}$$

where equation (4.7) is the EPS's object function with expected profit maximisation; constraints (4.8) and (4.9) are participation constraints to ensure that the ESI could accept the option contracts when it at least obtains the reservation profit, here assume the reservation profit is zero; constraints (4.10) and (4.11) are incentive compatibility constraints to ensure that the contract type coincides with the status of true demand information to achieve information sharing. In order to facilitate the following reasoning, Lemma 4.1 and its proof are first given.

Lemma 4.1. *$F_m(x)$ and $f_m(x)$ are respectively the PDF and CDF under discrete demand status m ($m = L, H$). $\forall x \geq 0$, $F_L(x) \geq F_H(x)$, $F_L(0) \geq F_H(0)$. Set $\varphi(x) = F_H^{-1}(F_L(x))$, then $\omega(x) = \int_0^{\varphi(x)} x f_H(x)\mathrm{d}x - \int_0^x x f_L(x)\mathrm{d}x$, which is non-negatively increasing in x, when $x \in [0, +\infty]$.*

Proof. As $F_H(\varphi(x)) = F_L(x) \geq F_H(x)$, and $F_H(x)$ is monotonically increasing, then $\varphi(x) \geq x$. Meanwhile, $F'_H(\varphi(x))\varphi'(x) = f_L(x)$, so $\omega'(x) = \varphi'(x) f_H(\varphi(x))\varphi(x) - x f_L(x) = f_L(x)[\varphi(x) - x] \geq 0$. Additionally, $\omega(0) = 0$, thus, $\omega(x)$ is non-negatively increasing in x, when $x \in [0, +\infty]$. □

Proposition 4.2. *With regard to the ESP's objective function, the participation constraints and incentive compatibility constraints can be equivalent to the following equations:*

$$T_L = [p_i + c - \beta(1-s)c_s - e_L] \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x - c\mu \tag{4.12}$$

$$T_H = [p_i + c - \beta(1-s)c_s - e_H] \int_0^{Q_{HH}} x f_H(x)\mathrm{d}x - [p_i + c - \beta(1-s)c_s - e_L] \left[\int_0^{Q_{HL}} x f_H(x)\mathrm{d}x - \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x\right] - c\mu. \tag{4.13}$$

Proof. According to Lemma 4.1, combining with constraints (4.8) and (4.11), constraint (4.9) can be proved

$$\begin{aligned}
\pi_{iH}(o_H, e_H, T_H, Q_{HH}) &= [p_i + c - \beta(1-s)c_s - e_H] \int_0^{Q_{HH}} x f_H(x)\mathrm{d}x - c\mu - T_H \\
&\geq [p_i + c - \beta(1-s)c_s - e_L] \int_0^{Q_{HL}} x f_H(x)\mathrm{d}x - c\mu - T_L \\
&\geq [p_i + c - \beta(1-s)c_s - e_L] \left[\int_0^{Q_{HL}} x f_H(x)\mathrm{d}x - \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x\right] \\
&\geq 0.
\end{aligned}$$

□

Then, constraints (4.14) and (4.15) can be derived according to constraints (4.8) and (4.11). First, the information rent can be indicated by

$$IR = \alpha\pi_{iL}(o_L, e_L, T_L) + (1-\alpha)\pi_{iH}(o_H, e_H, T_H). \tag{4.14}$$

From constraints (4.8), (4.9) and (4.11),

$$T_L \le [p_i + c - \beta(1-s)c_s - e_L] \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x - c\mu \tag{4.15}$$

$$\begin{aligned} T_H \le\ & [p_i + c - \beta(1-s)c_s - e_H] \int_0^{Q_{HH}} x f_H(x)\mathrm{d}x \\ & - [p_i + c - \beta(1-s)c_s - e_L] \left[\int_0^{Q_{HL}} x f_H(x)\mathrm{d}x \right. \\ & \left. - \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x \right] - c\mu. \end{aligned} \tag{4.16}$$

According to equation (4.14), the ESP would try to decrease the information rent caused by demand information asymmetry to zero, and improper T_L and T_H designed by the ESP would lead to the ESI's opportunism behaviour. Therefore, T_L and T_H are set to be equal to their maximum as Proposition 4.2.

Then, the ESP's expected profit can be represented by

$$\begin{aligned} \Pi_p =\ & \alpha\pi_{pL}(o_L, e_L, T_L) + (1-\alpha)\pi_{pH}(o_H, e_H, T_H) \\ =\ & \alpha \Bigg\{ [p_i + c - c_p - (1-s)c_s]Q_{LL} \\ & - [p_i + c - (1-s)c_s] \int_0^{Q_{LL}} F_L(x)\mathrm{d}x - c\mu \Bigg\} \\ & + (1-\alpha) \Bigg\{ [p_i + c - c_p - (1-s)c_s]Q_{HH} \\ & - [p_i + c - (1-s)c_s] \int_0^{Q_{HH}} F_H(x)\mathrm{d}x \\ & - [p_i + c - \beta(1-s)c_s - e_L] \left[\int_0^{Q_{HL}} x f_H(x)\mathrm{d}x \right. \\ & \left. - \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x \right] - c\mu \Bigg\}. \end{aligned} \tag{4.17}$$

Taking first-order derivatives on e_L, e_H, Q_{LL} and Q_{HH} from equation (4.17) as follows:

$$\frac{\partial \Pi_p}{\partial e_L} = (1-\alpha)[\int_0^{Q_{HL}} x f_H(x)\mathrm{d}x - \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x] \ge 0 \tag{4.18}$$

$$\frac{\partial \Pi_p}{\partial e_H} = 0 \tag{4.19}$$

$$\begin{aligned} \frac{\partial \Pi_p}{\partial Q_{LL}} =\ & \alpha\{[p_i + c - c_p - (1-s)c_s] - [p_i + c - (1-s)c_s]F_L(Q_{LL})\} \\ & + (1-\alpha)[p_i + c - \beta(1-s)c_s - e_L](Q_{HL} - Q_{LL}) f_L(Q_{LL}) \end{aligned} \tag{4.20}$$

$$\frac{\partial \Pi_p}{\partial Q_{HH}} = (1-\alpha)\{[p_i + c - c_p - (1-s)c_s] - [p_i + c - (1-s)c_s]\}F_H(Q_{HH}). \tag{4.21}$$

As $p_i+c-\beta(1-s)c_s-e_n > 0$, namely $e_n < p_i+c-\beta(1-s)c_s$, from equation (4.18), $e_L^* = p_i+c-\beta(1-s)c_s-\varepsilon$. There is not only one solution for e_H^* based on equation (4.19), but it satisfies $0 < e_H^* < p_i + c - \beta(1-s)c_s$. From equation (4.20), when $e_L^* = p_i + c - \beta(1-s)c_s - \varepsilon$, Q_{LL}^* satisfies $\alpha\{[p_i + c - c_p - (1-s)c_s] - [p_i + c - (1-s)c_s]F_L(Q_{LL}^*)\} + (1-\alpha)[p_i + c - \beta(1-s)c_s - e_L^*](Q_{HL}^* - Q_{LL}^*)f_L(Q_{LL}^*) = 0$, where $Q_{HL}^* = F_H^{-1}[F_L(Q_{LL}^*)]$. From equation (4.21), $Q_{HH}^* = F_H^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}]$. According to equation (4.5), $o_H^* = [1-F_H(Q_{HH}^*)][p_i + c - \beta(1-s)c_s - e_H^*]$, $o_L^* = [1 - F_L(Q_{LL}^*)]\varepsilon$.

Substituting e_L^*, e_H^*, Q_{LL}^*, Q_{HH}^* and Q_{HL}^* into equations (4.12) and (4.13), T_L^* and T_H^* can be obtained. Then, constraint (4.10) can be proved based on above optimal solutions.

Set $e_H^* \le e_L^*$, combined with equations (4.12) and (4.13),

$$\begin{aligned}
&\pi_{iL}(o_L, e_L, T_L, Q_{LL}) - \pi_{iL}(o_H, e_H, T_H, Q_{LH}) \\
&\quad = [p_i + c - \beta(1-s)c_s - e_L]\int_0^{Q_{LL}} x f_L(x)\mathrm{d}x - T_L \\
&\qquad - [p_i + c - \beta(1-s)c_s - e_H]\int_0^{Q_{LH}} x f_H(x)\mathrm{d}x + T_H \\
&\quad = [p_i + c - \beta(1-s)c_s - e_H]\left[\int_0^{Q_{HH}} x f_H(x)\mathrm{d}x - \int_0^{Q_{LH}} x f_L(x)\mathrm{d}x\right] \\
&\qquad - [p_i + c - \beta(1-s)c_s - e_L]\left[\int_0^{Q_{HL}} x f_H(x)\mathrm{d}x - \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x\right] \\
&\quad \ge [p_i + c - \beta(1-s)c_s - e_L]\left[\int_0^{Q_{HH}} x f_H(x)\mathrm{d}x - \int_0^{Q_{LH}} x f_L(x)\mathrm{d}x\right] \\
&\qquad - [p_i + c - \beta(1-s)c_s - e_L]\left[\int_0^{Q_{HL}} x f_H(x)\mathrm{d}x - \int_0^{Q_{LL}} x f_L(x)\mathrm{d}x\right] \\
&\quad \ge 0.
\end{aligned}$$

Hence, Proposition 4.3 can be got as follow.

Proposition 4.3. *Optimal option contract menus designed by the ESP under low and high demand information are:*

(i) *when the ESI claims the demand information as low demand,* $e_L^* = p_i + c - \beta(1-s)c_s - \varepsilon$, $o_L^* = [1 - F_L(Q_{LL}^*)][p_i + c - \beta(1-s)c_s - e_H^*]$, $T_L^* = [p_i + c - \beta(1-s)c_s - e_L^*]\int_0^{Q_{LL}^*} x f_L(x)\mathrm{d}x - c\mu$.

(ii) *when the ESI claims the demand information as high demand,* $0 < e_H^* < e_L^* < p_i + c - \beta(1-s)c_s$, $o_H^* = [1 - F_H(Q_{HH}^*)][p_i + c - \beta(1-s)c_s - e_H^*]$, $T_H^* = [p_i + c - \beta(1-s)c_s - e_H^*]\int_0^{Q_{HH}^*} x f_H(x)\mathrm{d}x - [p_i + c - \beta(1-s)c_s - e_L^*][\int_0^{Q_{HL}^*} x f_H(x)\mathrm{d}x - \int_0^{Q_{LL}^*} x f_L(x)\mathrm{d}x] - c\mu$.

From Proposition 4.3, $e_H^* \le e_L^*$ *and* $T_H^* \ge T_L^*$*, which indicate that the exercise price is higher under low demand information than that under high demand information, but the transfer payment is less under low demand information than that under high demand information.*

4.2.2. Decisions under continuous demand status

The ESP can use the option contract to motivate the sharing of demand information in the EHSSC as demonstrated in the previous section. Now, the study is extended to the case of continuous demand status.

When the demand information is ι, and the ESI selects the option contract (o_κ, e_κ, T_κ). The ESI would determine optimal ordering quantity $Q_i^*(\iota,\kappa)$. Thus, the ESI's profit can be indicated by

$$\begin{aligned}\pi_i(\iota,\kappa) &= [p_i - \beta(1-s)c_s]\min(D_\iota, Q_i(\iota,\kappa)) - e_\kappa \min(D_\iota, Q_i(\iota,\kappa)) \\ &\quad - o_\kappa Q_i(\iota,\kappa) - c(D_\iota - Q_i(\iota,\kappa))^+ - T_\kappa \\ &= [p_i + c - \beta(1-s)c_s - e_\kappa - o_\kappa]Q_i(\iota,\kappa) \\ &\quad - [p_i + c - \beta(1-s)c_s - e_\kappa]\int_0^{Q_i(\iota,\kappa)} F_\iota(x)\mathrm{d}x \\ &\quad - c\mu - T_\kappa. \end{aligned} \tag{4.22}$$

From equation (4.22), the optimal option ordering quantity for the ESI is

$$Q_i^*(\iota,\kappa) = F_\iota^{-1}\left[\frac{p_i + c - \beta(1-s)c_s - e_\kappa - o_\kappa}{p_i + c - \beta(1-s)c_s - e_\kappa}\right]. \tag{4.23}$$

Then,

$$\pi_i(\iota,\kappa) = [p_i + c - \beta(1-s)c_s - e_\kappa]\int_0^{Q_i(\iota,\kappa)} x f_\iota(x)\mathrm{d}x - c\mu - T_\kappa. \tag{4.24}$$

For the ESP, when the demand information is ι, and the ESI selects the option contract (o_κ, e_κ, T_κ), the ESP's profit function can be presented by

$$\begin{aligned}\pi_p(\iota,\kappa) &= [e_\kappa - (1-\beta)(1-s)c_s]\min[D_\iota, Q_i(\iota,\kappa)] + o_\kappa Q_i(\iota,\kappa) \\ &\quad - c_p Q_i(\iota,\kappa) + T_\kappa \\ &= [e_\kappa + o_\kappa - (1-\beta)(1-s)c_s - c_p]Q_i(\iota,\kappa) \\ &\quad - [e_\kappa - (1-\beta)(1-s)c_s]\int_0^{Q_i(\iota,\kappa)} F_\iota(x)\mathrm{d}x \\ &\quad + T_\kappa. \end{aligned} \tag{4.25}$$

Thus, the expected profit for the ESP is

$$E[\pi_p] = \int_{\underline{\iota}}^{\overline{\iota}} \pi_p(\iota,\iota) * g(\iota)\mathrm{d}\iota \tag{4.26}$$

s.t.

$$\pi_i(\iota,\iota) \geq 0 \tag{4.27}$$

$$\pi_i(\iota,\iota) \geq \pi_i(\iota,\kappa), \forall \iota \neq \kappa. \tag{4.28}$$

Also, constraint (4.27) is the participation constraint to ensure that the ESI could accept the option contracts when it at least obtains the reservation profit, here assume the reservation profit is zero; constraint (4.28) is the incentive compatibility constraint to ensure that the contract type coincides with the status of true demand information to achieve information sharing. Constraint (4.28) can be equivalent to the following conditions:

$$\frac{\partial \pi_i(\iota,\kappa)}{\partial \kappa}|_{\kappa=\iota} = 0 \tag{4.29}$$

$$\frac{\partial^2 \pi_i(\iota,\kappa)}{\partial \kappa^2}|_{\kappa=\iota} \leq 0. \tag{4.30}$$

Constraints (4.29) and (4.30) indicate the ESIs maximum profit can be obtained only when the contract type coincides with the status of true demand information, and the optimal option contract parameters can be derived as follows.

From equation (4.24) and constraint (4.27),

$$\begin{aligned}\frac{\partial \pi_i(\iota,\kappa)}{\partial \kappa}|_{\kappa=\iota} &= [p_i + c - \beta(1-s)c_s - e_\iota]\frac{\partial Q_i(\iota,\iota)}{\partial \iota}Q_i(\iota,\iota)f_\iota[Q_i(\iota,\iota),\iota] \\ &\quad - \frac{\partial e_\iota}{\partial \iota}\int_0^{Q_i(\iota,\iota)} x f_\iota(x)\mathrm{d}x - \frac{\partial T_\iota}{\partial \iota} \\ &= 0. \end{aligned} \tag{4.31}$$

Thus,

$$\begin{aligned}\frac{\partial T_\iota}{\partial \iota} &= [p_i + c - \beta(1-s)c_s - e_\iota]\frac{\partial Q_i(\iota,\iota)}{\partial \iota}Q_i(\iota,\iota)f_\iota[Q_i(\iota,\iota),\iota] \\ &\quad - \frac{\partial e_\iota}{\partial \iota}\int_0^{Q_i(\iota,\iota)} x f_\iota(x)\mathrm{d}x. \end{aligned} \tag{4.32}$$

Combined with (4.30)–(4.32), there is

$$\begin{aligned}\frac{\partial^2 \pi_i(\iota,\kappa)}{\partial \kappa^2}|_{\kappa=\iota} &= \frac{\partial e_\iota}{\partial \iota}\int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}\iota \\ &= \frac{\partial e_\iota}{\partial \iota}\lim_{\kappa\to\iota}\frac{\int_0^{Q_i(\kappa,\iota)} x f_\iota(x,\kappa)\mathrm{d}x - \int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x}{\kappa-\iota} \\ &\le 0, \end{aligned} \tag{4.33}$$

where $\frac{\partial e_\iota}{\partial \iota} \le 0$, then $\frac{\partial^2 \pi_i(\iota,\kappa)}{\partial \kappa^2}|_{\kappa=\iota} \le 0$.

Further,

$$\begin{aligned}\frac{\partial \pi_i(\iota,\iota)}{\partial \iota} &= [p_i + c - \beta(1-s)c_s - e_\iota]\frac{\partial Q_i(\iota,\iota)}{\partial \iota}Q_i(\iota,\iota)f_\iota[Q_i(\iota,\iota),\iota] \\ &\quad - \frac{\partial e_\iota}{\partial \iota}\int_0^{Q_i(\iota,\iota)} x f_\iota(x)\mathrm{d}x - \frac{\partial T_\iota}{\partial \iota} \\ &\quad + [p_i + c - \beta(1-s)c_s - e_\iota]\int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x. \end{aligned} \tag{4.34}$$

Combined with equations (4.32) and (4.34),

$$\frac{\partial \pi_i(\iota,\iota)}{\partial \iota} = [p_i + c - \beta(1-s)c_s - e_\iota]\int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x. \tag{4.35}$$

Then,

$$\pi_i(\iota,\iota) = \int_{\underline{\iota}}^{\overline{\iota}}\left\{[p_i + c - \beta(1-s)c_s - e_\iota]\int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x\right\}\mathrm{d}y. \tag{4.36}$$

Combined with equations (4.24) and (4.36), T_ι^* satisfies the equation (4.37),

$$T_\iota = [p_i + c - \beta(1-s)c_s - e_\iota]\int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x - c\mu$$

$$\begin{aligned}&= [p_i + c - \beta(1-s)c_s - e_\iota] \int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x \\ &\quad - \int_{\underline{\iota}}^{\bar{\iota}} \left\{ [p_i + c - \beta(1-s)c_s - e_y] \int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x \right\} \mathrm{d}y. \end{aligned} \tag{4.37}$$

Then, the optimal option price o_ι^* and exercise price e_ι^* can be derived From equation (4.25), when the demand information coincides with the contract type, the ESP's profit is

$$\begin{aligned}\pi_p(\iota,\iota) &= [e_\iota + o_\iota - (1-\beta)(1-s)c_s - c_p]Q_i(\iota,\iota) \\ &\quad - [e_\iota - (1-\beta)(1-s)c_s] \int_0^{Q_i(\iota,\iota)} F_\iota(x)\mathrm{d}x + T_\iota. \end{aligned} \tag{4.38}$$

From equation (4.23), $o_\iota = \{1 - F_\iota[Q_i(\iota,\iota)]\}[p_i + c - \beta(1-s)c_s - e_\iota]$, which is substituted into equation (4.38),

$$\begin{aligned}\pi_p(\iota,\iota) &= [p_i + c - (1-s)c_s - c_p]Q_i(\iota,\iota) \\ &\quad - [p_i + c - \beta(1-s)c_s - e_\iota]F_\iota[Q_i(\iota,\iota)]Q_i(\iota,\iota) \\ &\quad - [e_\iota - (1-\beta)(1-s)c_s] \int_0^{Q_i(\iota,\iota)} F_\iota(x)\mathrm{d}x + T_\iota. \end{aligned} \tag{4.39}$$

Further, substituting equation (4.37) into equation (4.39),

$$\begin{aligned}\pi_p(\iota,\iota) &= [p_i + c - (1-s)c_s - c_p]Q_i(\iota,\iota) \\ &\quad - [p_i + c - \beta(1-s)c_s - e_\iota]F_\iota[Q_i(\iota,\iota)]Q_i(\iota,\iota) \\ &\quad - [e_\iota - (1-\beta)(1-s)c_s] \int_0^{Q_i(\iota,\iota)} F_\iota(x)\mathrm{d}x \\ &\quad + [p_i + c - \beta(1-s)c_s - e_\iota]F_\iota[Q_i(\iota,\iota)]Q_i(\iota,\iota) \\ &\quad - [p_i + c - \beta(1-s)c_s - e_\iota] \int_0^{Q_i(\iota,\iota)} F_\iota(x,\iota)\mathrm{d}x \\ &\quad - \int_{\underline{\iota}}^{\bar{\iota}} \left\{ [p_i + c - \beta(1-s)c_s - e_y] \int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x \right\} \mathrm{d}y \\ &= [p_i + c - (1-s)c_s - c_p]Q_i(\iota,\iota) \\ &\quad - [p_i + c - \beta(1-s)c_s] \int_0^{Q_i(\iota,\iota)} F_\iota(x,\iota)\mathrm{d}x \\ &\quad - \int_{\underline{\iota}}^{\bar{\iota}} \left\{ [p_i + c - \beta(1-s)c_s - e_y] \int_0^{Q_i(\iota,\iota)} x f_\iota(x,\iota)\mathrm{d}x \right\} \mathrm{d}y. \end{aligned} \tag{4.40}$$

Combined equations (4.26) and (4.40),

$$\begin{aligned}E[\pi_p] &= \int_{\underline{\iota}}^{\bar{\iota}} \pi_p(\iota,\iota) * g(\iota)\mathrm{d}\iota \\ &= \int_{\underline{\iota}}^{\bar{\iota}} \Bigg\{ [p_i + c - (1-s)c_s - c_p]Q_i(\iota,\iota) \\ &\quad - [p_i + c - \beta(1-s)c_s] \int_0^{Q_i(\iota,\iota)} F_\iota(x,\iota)\mathrm{d}x \end{aligned}$$

$$-\frac{1-G(\iota)}{g(\iota)}\left\{[p_i+c-\beta(1-s)c_s-e_y]\int_0^{Q_i(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}x\right\}\Bigg\} g(\iota)\mathrm{d}\iota. \tag{4.41}$$

Set $\Psi(x)=[p_i+c-(1-s)c_s-c_p]Q_i(\iota,\iota)-[p_i+c-\beta(1-s)c_s]\int_0^{Q_i(\iota,\iota)} F_\iota(x,\iota)\mathrm{d}x-\frac{1-G(\iota)}{g(\iota)}\{[p_i+c-\beta(1-s)c_s-e_y]\int_0^{Q_i(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}x\}$, then, the EPS's profit maximization can be obtained by maximising $\Psi(x)$. According to equations (4.42)–(4.44), e_ι^* and $Q_i^*(\iota,\iota)$ can be derived as follows,

$$\frac{\partial\Psi(x)}{\partial e_\iota}=\frac{1-G(\iota)}{g(\iota)}\int_0^{Q_i(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}x\geq 0 \tag{4.42}$$

$$\begin{aligned}\frac{\partial\Psi(x)}{\partial Q_i(\iota,\iota)}&=[p_i+c-(1-s)c_s-c_p]-[p_i+c-(1-s)c_s]F_\iota[Q_i(\iota,\iota),\iota]\\&\quad-\frac{1-G(\iota)}{g(\iota)}[p_i+c-\beta(1-s)c_s-e_\iota]Q_i(\iota,\iota)f_\iota[Q_i(\iota,\iota),\iota]\\&=0\end{aligned} \tag{4.43}$$

$$\begin{aligned}\frac{\partial^2\Psi(x)}{\partial Q_i(\iota,\iota)^2}&=-[p_i+c-(1-s)c_s]f_\iota[Q_i(\iota,\iota),\iota]\\&\quad-\frac{1-G(\iota)}{g(\iota)}[p_i+c-\beta(1-s)c_s-e_\iota]\Bigg\{f_\iota[Q_i(\iota,\iota),\iota]\\&\quad+Q_i(\iota,\iota)\frac{f_\iota[Q_i(\iota,\iota),\iota]}{Q_i(\iota,\iota)}\Bigg\}\\&<0.\end{aligned} \tag{4.44}$$

From equation (4.42), $E[\pi_p]$ is increasing in e_ι, but $e_\iota<p_i+c-\beta(1-s)c_s$, hence $e_\iota^*=p_i+c-\beta(1-s)c_s-\varepsilon$. From equations (4.43) and (4.44), $Q_i^*(\iota,\iota)$ satisfies the $\frac{\partial\Psi(x)}{\partial Q_i(\iota,\iota)}=0$. Substituting e_ι^* into equation (4.24), $o_\iota^*=\{1-F_\iota[Q_i(\iota,\iota)^*]\}[p_i+c-\beta(1-s)c_s-e_\iota^*]$.

From equation (4.37), the optimal transfer payment T_ι^* can be represented by

$$\begin{aligned}T_\iota^*&=[p_i+c-\beta(1-s)c_s-e_\iota^*]\int_0^{Q_i^*(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}x\\&\quad-\int_{\underline{\iota}}^{\bar{\iota}}\left\{[p_i+c-\beta(1-s)c_s-e_\iota^*]\int_0^{Q_i^*(\iota,\iota)} yf_\iota(y,\iota)\mathrm{d}y\right\}\mathrm{d}x.\end{aligned} \tag{4.45}$$

Proposition 4.4. *Optimal option contract menus designed by the ESP under continuous demand status are:* $e_\iota^*=p_i+c-\beta(1-s)c_s-\varepsilon$, *where* $\varepsilon\to 0$; $o_\iota^*=\{1-F_\iota[Q_i^*(\iota,\iota)]\}[p_i+c-\beta(1-s)c_s-e_\iota^*]$, $T_\iota^*=[p_i+c-\beta(1-s)c_s-e_\iota^*]\int_0^{Q_i^*(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}x-\int_{\underline{\iota}}^{\bar{\iota}}\{[p_i+c-\beta(1-s)c_s-e_\iota^*]\int_0^{Q_i^*(\iota,\iota)} yf_\iota(y,\iota)\mathrm{d}y\}\mathrm{d}x$.

Proposition 4.5. e_ι^* *is decreasing in demand information* ι*, which means the option exercise price will be higher under lower demand information than that under higher demand information; while* T_ι^* *is increasing in demand information* ι*, which means the transfer payment will be less under lower demand information than that under higher demand information.*

Proof. From equation (4.33), $\frac{\partial^2\pi_i(\iota,\kappa)}{\partial\kappa^2}|_{\kappa=\iota}=\frac{\partial e_\iota}{\partial\iota}\int_0^{Q_i(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}\iota\leq 0$, but $\int_0^{Q_i(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}\iota\geq 0$, hence $\frac{\partial e_\iota}{\partial\iota}\leq 0$, e_ι^* is decreasing in demand information ι. When the demand information coincides with the contract type, $\frac{\partial Q(\iota,\iota)}{\partial\iota}\geq 0$. From equation (4.32), $\frac{\partial T_\iota}{\partial\iota}=[p_i+c-\beta(1-s)c_s-e_\iota]\frac{\partial Q_i(\iota,\iota)}{\partial\iota}Q_i(\iota,\iota)f_\iota[Q_i(\iota,\iota),\iota]-\frac{\partial e_\iota}{\partial\iota}\int_0^{Q_i(\iota,\iota)} xf_\iota(x)\mathrm{d}x\geq 0$, T_ι^* is increasing in demand information ι. □

5. Comparative analysis of decisions under symmetric and asymmetric information

Though above analysis, the option contract can promote the demand information sharing under discrete and continuous demand statuses with information asymmetry. In this section, the decisions of supply chain coordination under asymmetric demand information are discussed and compared with decisions in the centralised system under symmetric demand information.

(i) As demonstrated in Section 4.1, in case of discrete demand information symmetry, the optimal ordering quantity of service capacity under supply chain coordination satisfies $Q_{ip}^{m*} = F_m^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}]$, where $m = L, H$.

(ii) In case of continuous demand information symmetry, the optimal ordering quantity of service capacity under supply chain coordination satisfies $Q_{ip}^{\iota*} = F_\iota^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}]$.

(iii) In case of discrete demand information asymmetry, from equations (4.20) and (4.21), $Q_{LL}^* \to F_L^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}] = Q_{ip}^{L*}$ when $\varepsilon \to 0$, and $Q_{HH}^* = F_H^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}]$. Therefore, when the ESI claims the demand information as high demand, the EHSSC can achieve the supply chain coordination; when the ESI claims the demand information as low demand, the EHSSC can almost achieve the supply chain coordination. When $\varepsilon \to 0$, $IR = \alpha\pi_{iL}(o_L, e_L, T_L) + (1-\alpha)\pi_{iH}(o_H, e_H, T_H) = \varepsilon[\int_0^{Q_{HL}^*} xf_H(x)\mathrm{d}x - \int_0^{Q_{LL}^*} xf_L(x)\mathrm{d}x] \to 0$, which indicates the information rent offered by the ESP to the ESI also can be reduced to zero, thus the influence of information asymmetry on the supply chain coordination can almost be eliminated.

(iv) In case of continuous demand information asymmetry, from equation (4.43), when $p_i + c - \beta(1-s)c_s - e_\iota^* = \varepsilon \to 0$, $Q^*(\iota, \iota) \to F_\iota^{-1}[\frac{p_i+c-(1-s)c_s-c_p}{p_i+c-(1-s)c_s}, \iota] = Q_{ip}^{\iota*}$. Since the influence of information asymmetry cannot be eliminated totally, the optimal ordering quantity can be almost close to that in the centralised system. Therefore, the EHSSC can almost achieve the supply chain coordination. The information rent offered by the ESP can be reduced to zero: $\int_{\underline{\iota}}^{\overline{\iota}} \pi_p(\iota,\iota) * g(\iota)\mathrm{d}\iota = \int_{\underline{\iota}}^{\overline{\iota}} \{[1-G(\iota)][p_i + c - \beta(1-s)c_s - e_\iota^*] \int_0^{Q^*(\iota,\iota)} xf_\iota(x,\iota)\mathrm{d}x\}\mathrm{d}\iota \to 0$.

6. Conclusions and future works

In the EHSSC, since the service demand significantly changes with the market operation as well as the elderlys health status, the complicated demand change always brings order and supply risks for the ESI and ESP. Moreover, the elderly services demand distribution status is difficult to be described in the elderly healthcare service system, where discrete or continuous demand can present. Thus, under different demand distribution statuses, the ESI may take the service demand as its own private information to avoid service capacity ordering risks and pursue individual profit maximization. Consequently, the ESP would bear the service capacity supply risks due to asymmetric demand information.

This paper addresses the channel coordination for the EHS system under different demand distribution statuses in asymmetric demand situations. A community-based EHS system is modelled as a two-echelon EHSSC consisting of one ESI and one ESP. Considering discrete and continuous demand statuses, the centralised model with symmetric demand information and decentralised models with asymmetric demand information are developed to analyse the ordering decisions and discuss the influence of information asymmetry. Furthermore, option contracts are applied to coordinate the supply chain under asymmetric demand information based on different demand distributions. Optimal option contract menus are designed for the ESP to promote the information sharing.

Results show that the option contract can coordinate the EHSSC with asymmetric demand information under both discrete and continuous demand distributions. The ESP can set reasonable option contract menus when facing asymmetric information to help coordinate the elderly healthcare service system. Especially, the exercise price will be set higher under lower demand information than that under higher demand information and the transfer payment will be less under lower demand information than that under higher demand information. Furthermore, although the ESI has demand information superiority and can make use of opportunistic behaviour to maximize its own profit, the inferior information side, the ESP, as the leader can design the option contract to achieve true information sharing, and the channel profit is nearly obtained by the ESP, the ESI does not benefit from the information sharing.

This study advocates the coordination of elderly healthcare services system from the perspective of supply chain management, which helps highlight the roles of both the ESI and ESP and improve the EHS system for effective services capacity coordination. It has established the value of the options contract in achieving the services capacity coordination and promoting the information sharing, particularly when considering the information asymmetry between the ESI and ESP as well as demand distribution statuses. The model developed in this study provides a more practical method to solve the imbalance between the services capacity supply and demand due to information asymmetry. The results can also be used as a starting point to provide guidance for the development of EHS systems, both theoretically and practically.

This research can be extended in several directions in following works. First, since this paper studies the effectiveness of option contract on the channel coordination, the two cases of decentralised supply chain respectively under discrete and continuous demand statuses are analysed and the results derived from both of the cases are therefore compared with those in the centralised system. It is not the focus to compare the results obtained from each demand distribution (discrete and continuous) in this paper. Whats more, the impacts of information asymmetry on the EHSSC members profits and decisions are not extended in this paper. These will be studied in our next work. Second, this work demonstrates the effect of option contracts on supply chain coordination under the influence of asymmetric demand information. Service quality is also an important factor in the EHS system. The service quality of both the ESI and the ESP can also be private information for them. Therefore, an interesting extension is to examine the influence of asymmetric service quality information on ordering decisions and supply chain coordination. Third, a case study on the elderly healthcare system can make this model more practical. We have conducted related numerical experiments and sensitivity analysis based on a Chinas case, which will be highlighted in the next work.

References

[1] AgeInternational, Our ageing world, in statistics. https://www.ageinternational.org.uk/policy-and-research/ageing-international-development/ageing-factfile/ (2018).

[2] M. Akan, B. Ata and M.A. Lariviere, Asymmetric information and economies of scale in service contracting. *Manuf. Ser. Oper. Manage.* **13** (2011) 58–72.

[3] S. Asian and X. Nie, Coordination in supply chains with uncertain demand and disruption risks: existence, analysis, and insights. *IEEE Trans. Syst. Man Cybernet. Syst.* **44** (2014) 1139–1154.

[4] D. Barnes-Schuster, Y. Bassok and R. Anupindi, Coordination and flexibility in supply contracts with options. *Manuf. Serv. Oper. Manage.* **4** (2002) 171–207.

[5] X. Brusset, When manufacturers hold information back from strong suppliers. *RAIRO: OR* **50** (2016) 553–565.

[6] A. Burnetas, S.M. Gilbert and C.E. Smith, Quantity discounts in single-period supply contracts with asymmetric demand information. *IIE Trans.* **39** (2007) 465–479.

[7] G.P. Cachon and M.A. Lariviere, Contracting to assure supply: How to share demand forecasts in a supply chain. *Manage. Sci.* **47** (2001) 629–646.

[8] G.P. Cachon and F. Zhang, Procuring fast delivery: sole sourcing with information asymmetry. *Manage. Sci.* **52** (2006) 881–896.

[9] C.J. Corbett and X. de Groote, A supplier's optimal quantity discount policy under asymmetric information. *Manage. Sci.* **46** (2000) 444–450.

[10] S. Ebrahimi, S.-M. Hosseini-Motlagh and M. Nematollahi, Proposing a delay in payment contract for coordinating a two-echelon periodic review supply chain with stochastic promotional effort dependent demand. *Int. J. Mach. Learn. Cyber.* **10** (2019) 1037–1050.

[11] P. Egri and J. Vancza, Channel coordination with the newsvendor model using asymmetric information. *Int. J. Prod. Econ.* **135** (2012) 491–499.

[12] Y.Y. Fu, E.W.T. Chui, W.S. Kan and L. Ko, Improving primary level home and community care services for older people: the case of hong kong. *Int. J. Soc. Welfare* **27** (2018) 52–61.

[13] S.-M. Hosseini-Motlagh, M. Nematollahi, M. Johari and B.R. Sarker, A collaborative model for coordination of monopolistic manufacturer's promotional efforts and competing duopolistic retailers' trade credits. *Int. J. Prod. Econ.* **204** (2018) 108–122.

[14] M. Jazinaninejad, M. Seyed Hosseini, S.-M. Hosseini-Motlagh and M. Nematollahi, Coordinated decision-making on manufacturer's EPQ-based and buyer's period review inventory policies with stochastic price-sensitive demand: a credit option approach. *RAIRO: OR* **53** (2019) 1129–1154.

[15] Y. Jiang and A. Seidmann, Capacity planning and performance contracting for service facilities. *Decis. Support Syst.* **58** (2014) 31–42.

[16] M. Johari, S.-M. Hosseini-Motlagh, M. Nematollahi, M. Goh and J. Ignatius, Bi-level credit period coordination for periodic review inventory system with price-credit dependent demand under time value of money. *Transp. Res. Part E Transp. Rev.* **114** (2018) 270–291.

[17] Y. Li, X. Xu, X. Zhao, J.H.Y. Yeung and F. Ye, Supply chain coordination with controllable lead time and asymmetric information. *Eur. J. Oper. Res.* **217** (2012) 108–119.

[18] L. Liang, X. Wang and J. Gao, An option contract pricing model of relief material supply chain. *Omega* **40** (2012) 594–600.

[19] J.-Y. Lim, The effect of patient's asymmetric information problem on elderly use of medical care. *Appl. Econ.* **39** (2007) 2133–2142.

[20] J.-Y. Lim and C. Jo, The effect of patient's asymmetric information problem on medical care utilization with consideration of a patient's ex-ante health status. *Hitotsubashi J. Econ.* **50** (2009) 37–58.

[21] H. Liu and O. Ozer, Channel incentives in sharing new product demand information and robust contracts. *Eur. J. Oper. Res.* **207** (2010) 1341–1349.

[22] X. Liu, Q. Gou, L. Alwan and L. Liang, Option contracts: a solution for overloading problems in the delivery service supply chain. *J. Oper. Res. Soc.* **67** (2016) 187–197.

[23] R.L. Mendoza, Information asymmetries and risk management in healthcare markets: the US affordable care act in retrospect. *J. Econ. Issues* **51** (2017) 520–540.

[24] K.H. Miller, C. Ziegler, R. Greenberg, P.D. Patel and M.B. Carter, Why physicians should share PDA/smartphone findings with their patients: a brief report. *J. Health Commun.* **17** (2012) 54–61.

[25] A.C. Muhlbacher, V.E. Amelung and C. Juhnke, Contract design: the problem of information asymmetry. *Int. J. Integr. Care* **18** (2018) 1.

[26] R.B. Myerson, Incentive compatibility and the bargaining problem. *Econometrica* **47** (1979) 61–73.

[27] M. Nematollahi, S.-M. Hosseini-Motlagh, J. Ignatius, M. Goh and M.S. Nia, Coordinating a socially responsible pharmaceutical supply chain under periodic review replenishment policies. *J. Clean. Prod.* **172** (2018) 2876–2891.

[28] M. Nouri, S.-M. Hosseini-Motlagh, M. Nematollahi and B.R. Sarker, Coordinating manufacturer's innovation and retailer's promotion and replenishment using a compensation-based wholesale price contract. *Int. J. Prod. Econ.* **198** (2018) 11–24.

[29] South China Morning Post, China Offers Incentives to Develop Elderly Care in Face of "Alarming" Population Ageing. South China Morning Post, Hong Kong (2015).

[30] Y. Shen and S.P. Willems, Coordinating a channel with asymmetric cost information and the manufacturer's optimality. *Int. J. Prod. Econ.* **135** (2012) 125–135.

[31] P. Shi and W. Zhang, Private information in healthcare utilization: specification of a copula-based hurdle model. *J. Roy. Statist. Soc. Ser. A (Statist. Soc.)* **178** (2015) 337–361.

[32] N. Shukla, J. Keast and D. Ceglarek, Modelling variations in hospital service delivery based on real time locating information. *Appl. Math. Model.* **38** (2014) 878–893.

[33] T. Tran and R. Desiraju, Group-buying and channel coordination under asymmetric information. *Eur. J. Oper. Res.* **256** (2017) 68–75.

[34] Department of Economic United Nations and Population Division Social Affairs. World population ageing 2017 – highlights (st/esa/ser.a/397) (2017).

[35] W. Xie, Y. Zhao, Z. Jiang and P.S. Chow, Optimizing product service system by franchise fee contracts under information asymmetry. *Ann. Oper. Res.* **240** (2013) 12.

[36] H. Xu, Managing production and procurement through option contracts in supply chains with random yield. *Int. J. Prod. Econ.* **126** (2010) 306–313.

[37] X. Xu, Y. Ji, Y. Bian and Y. Sun, Service outsourcing under co-opetition and information asymmetry. *J. Oper. Res. Soc.* **68** (2017) 666–677.

[38] Y. Yan, R. Zhao and Y. Lan, Asymmetric retailers with different moving sequences: group buying vs. individual purchasing. *Eur. J. Oper. Res.* **261** (2017) 903–917.

[39] Y.-H. Yan, C.-M. Kung, S.-C. Fang and Y. Chen, Transparency of mandatory information disclosure and concerns of health services providers and consumers. *Int. J. Environ. Res. Publ. Health* **14** (2017) 53.

[40] L. Yang, R. Tang and K. Chen, Call, put and bidirectional option contracts in agricultural supply chains with sales effort. *Appl. Math. Model.* **47** (2017) 1–16.

[41] Y. Zhao, S. Wang, T.C.E. Cheng, X. Yang and Z. Huang, Coordination of supply chains by option contracts: a cooperative game theory approach. *Eur. J. Oper. Res.* **207** (2010) 668–675.