Channel coordination with asymmetric cost information in assembly system

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Abstract
This paper studies an assembly system consists of two suppliers and one assembler, one supplier's production cost is private information. We design an optimal contract consisting of wholesale-price and subsidy to maximize the assembler's expected profit while ensuring the channel is coordinated, we also analyze the contract's properties.

Key words: cost information asymmetry, wholesale price, surplus subsidy

Introduction
Supply chain is a decentralized system consists of many independent parties, decision rights and information spread on the whole chain, which leads to information asymmetry among these parties. Nowadays many scholars focus on this problem and solve it by means of designing an incentive-compatible contract. Three primary areas where information asymmetries can occur relate to cost, demand and quality information.

In this paper, we consider the case of cost information asymmetry, which occurs in most manufacturing supply chains such as pharmaceuticals industry and communication industry (Traynor 2001, Agrell et al. 2004). (Chakravarty and Zhang 2006) study the optimal contracting problem between two firms collaborating on capacity investment with information asymmetry. (Bolandifar et al. 2010) study the optimal procurement contracts for the buyer under different compliance schemes and analyze their properties. (Li and Scheller-Wolf 2011) study supplier selection problem under information asymmetry with two different auction contracts: push and pull. (O¨zer and Raz 2011) study a supply chain with two suppliers competing over a contract to supply components to a manufacturer under information asymmetry. (Shen and Willems 2012) study a manufacturer–retailer system with private retail cost information, in contrast to the existing literatures, this paper demonstrates that channel coordination under asymmetric cost information is possible via a specific wholesale-buyback contract.

Assembly system always consists of multiple component suppliers and one manufacturer. To coordinate this channel, it is not only to achieve vertical coordination between these component suppliers and the manufacturer, but also have to achieve horizontal coordination among these component suppliers, so assembly system coordination problem is a hot topic in the area of supply chain research. (Yigal and Wang 2004) firstly study coordination in decentralized assembly systems with random demand, investigates two different contracts to achieve channel coordination. (Granot and Yin 2008) study a decentralized assembly system consisting of a single assembler who buys complementary components from independent suppliers under two contracting schemes: push and pull. (Leng and Parlar 2010) introduce a buy-back and lost-sales cost-sharing contract to coordinate an assembly supply chain consisting of multiple suppliers and one manufacturer. The above 3 papers have a common assumption that each supplier' s capacity is certain, now many scholars research assembly system coordination with uncertain yield, such as (Guler and Bilgic 2008, Yan et al. 2010) .

Our paper differs from prior papers in the following two aspects: (1) most existing papers related to cost information asymmetry concern the supply chain consist of single supplier- single manufacturer or single manufacturer- single retailer, few papers focus on cost information asymmetry in assembly system; (2) most papers related to this topic think that channel coordination under asymmetric cost information is not possible, only (Shen and Willems 2012) proves this possibility, similar with this paper, we prove channel coordination is also possible in assembly system with cost information asymmetry.

Model Description

We study an assembly system constituting of two suppliers and one manufacturer, each supplier supplies one kind of component, one unit of the final product consists of one unit of each of these two components. We denote c_1 as supplier 1's production cost, $\prod_1^-$ as supplier 1's reservation profit; c_2 as supplier 2's production cost and is his private information, $\prod_2^-$ as supplier 2's reservation profit. We define c_0 as the manufacturer's production cost, $\prod_m^-$ as his reservation profit; p as the price of the final product. Supplier 1 and supplier 2 ship their components to the manufacturer on consignment. Without losing generality, let H (h) denote the distribution (density) function of c_2 on a support $[\underline{c_2}, \overline{c_2}]$, the manufacturer knows the distribution function H, but not the exact cost realization. Finally we define $f(x)$ as the probability density function of the demand D and $F(x)$ as the cumulative distribution function.

Assumptions

(1) Supplier 2 is the manufacturer's major supplier, supplier 1 is his minor supplier, the manufacturer firstly determines supplier 2's price then determines supplier 1's.

(2) The distribution of the demand is increasing failure rate (IFR), the distribution of c_2 is decreasing reversed hazard rate (DRHR).

(3) For simplicity, assume that there are no holding costs or salvage values for unsold products or components.

Wholesale price-surplus subsidy under cost information asymmetry

We consider an incentive-compatible contract consisting of wholesale price and surplus subsidy to reveal supplier 2's private production cost and meanwhile coordinate the channel. With the two instruments of wholesale price and surplus subsidy, the following sequence of events unfolds in the presence of asymmetric supplier cost information. First, considering the estimate of supplier 2's production cost, the manufacturer offers a contract menu $\{w_2(c_2), s_2(c_2)\}$to supplier 2 consisting of wholesale price $w_2(c_2)$ and surplus subsidy $s_2(c_2)$. Second, supplier 2 accepts a set of wholesale price and surplus subsidy. Third, the manufacturer determines supplier 1's wholesale price $w_1(c_2)$ and surplus subsidy $s_1(c_2)$ according to supplier 2's choice and offers them to supplier 1. Forth, supplier 1 and supplier 2 choose their production quantity Q_i , respectively.

(Yigal and Wang 2004) proves that if the final product's price is 1$ in an assembly system, the channel coordination can be achieved when the manufacturer offers wholesale price and surplus subsidy contract to suppliers in the full information case, and the optimal decision satisfies $\frac{c_1-s_1}{\alpha_1-s_1}=\frac{c_2-s_2}{\alpha_2-s_2}=\cdots=\frac{c_n-s_n}{\alpha_n-s_n}=\overline{F}(Q)=\sum_{i=0}^{n}c_n$,where c_i, α_i, s_i represents supplier i's production cost, revenue share and surplus subsidy, respectively. Q denotes the optimal production quantity in the centralized system which satisfies $Q=\overline{F}^{-1}(\sum_{i=0}^{n}c_n)$. The conclusion shows that in order to achieve channel coordination, the manufacturer will make each supplier's optimal production quantity equals to the optimal production quantity in the centralized system through setting suppliers' revenue shares and surplus subsidies.

Consulting Yigal's conclusion, in the asymmetric information case, the optimal condition to achieve channel coordination is

$$\frac{c_1-s_1(x_2)}{w_1(x_2)-s_1(x_2)}=\frac{x_2-s_2(x_2)}{w_2(x_2)-s_2(x_2)}=\frac{C}{p}=\overline{F}(Q(x_2)) \tag{1}$$

where x_2 represents the production cost which supplier 2 reveals, and $C=c_1+x_2$.

After the channel is coordinated, the channel's total profit can be represented as:

$$\Pi_j(x_2)=(p-C)Q(x_2)-p\int_0^{Q(x_2)}F(y)dy \tag{2}$$

Proposition 1. If $(p-C)Q(c_2^0)-p\int_0^{Q(c_2^0)}F(y)dy=\prod_1^-+\prod_2^-+\prod_m^-$, then only when $c_2\le c_2^0$, the channel profit satisfies $\Pi_j(c_2)\ge\prod_1^-+\prod_2^-+\prod_m^-$.

Proof. $\frac{d\Pi_j(c_2)}{dc_2}=-Q(c_2)+(p\overline{F}(Q(c_2))-C)\frac{dQ(c_2)}{dc_2}=-Q(c_2)<0$, so $\Pi_j(c_2)$ decreases with respect to c_2, when $c_2=c_2^0$, we have $\Pi_j(c_2)=\prod_1^-+\prod_2^-+\prod_m^-$.Therefore, Proposition 1 is proved.

From proposition 1, we can conclude that when $c_2>c_2^0$, the manufacturer will not purchase components from the two suppliers, and $Q(c_2)=0$.

The profit of supplier 1, supplier 2 and the manufacturer can be respectively written as:

$$\Pi_1(x_2)=w_1(x_2)\min(Q(x_2),D)-c_1Q(x_2)+s_1(x_2)[Q(x_2)-D]^+$$

$$\Pi_2(x_2)=w_2(x_2)\min(Q(x_2),D)-c_2Q(x_2)+s_2(x_2)[Q(x_2)-D]^+$$

$$\Pi_m(x_2)=[p-w_1(x_2)-w_2(x_2)]\min(Q(x_2),D)-c_0Q(x_2)-[s_1(x_2)+s_2(x_2)][Q(x_2)-D]^+$$

When the manufacturer designs the incentive compatible contracts, he must consider the following constraints:

$$\Pi_2(x_2 \mid c_2) \le \Pi_2(c_2 \mid c_2) \quad (3)$$

$$\Pi_m(c_2) \ge \Pi_m^- \quad (4)$$

$$\Pi_2(c_2) \ge \Pi_2^- \quad (5)$$

$$\Pi_1(c_2) \ge \Pi_1^- \quad (6)$$

Constraint (3) represents the incentive-compatibility constraint (IC) which guarantees supplier 2 tell the true production cost, constraints (4), (5) and (6) are the individual rationality constraints (IR), which guarantee the participation from the two suppliers and the manufacturer.

In this section, the upper bound of c_2 is $\overline{U_2}$ rather than $\overline{c_2}$, and the lower bound of c_2 is $\underline{L_2}$ rather than $\underline{c_2}$, where $\underline{L_2}$ satisfies $\underline{L_2} \in [\underline{c_2}, \overline{U_2}]$. This is the cutoff policy introduced in the literature (Corbett et al. 2004, Ha 2001), and is adopted commonly in literatures of this topic.

Lemma 1. Supplier 2's optimal wholesale price and surplus subsidy satisfy:

$$w_2^*(c_2) = p - (c_0 + c_1) + (w_2^*(\underline{L_2}) + (c_0 + c_1) - p)e^{L(c_2)} \quad (7)$$

$$L(c_2) = \int_{\underline{L_2}}^{c_2} \frac{p\int_0^{Q(c')} F(y)dy}{(c' + (c_0 + c_1) - p)^2 Q(c') + p(c' + (c_0 + c_1) - p)\int_0^{Q(c')} F(y)dy} dc' \quad (8)$$

$$s_2^*(c_2) = \frac{pc_2 - w_2^*(c_2)C}{p - C} \quad (9)$$

Proof. From constraint (3) we obtain:

$$\frac{d\Pi_2(x_2 \mid c_2)}{dx_2}\Big|_{x_2=c_2} = \frac{dw_2(x_2)}{dx_2}[Q(x_2) + \frac{p}{C-p}\int_0^{Q(x_2)} F(y)dy] - \frac{p[w_2(x_2) + (c_0 + c_1) - p]}{(p-C)^2}\int_0^{Q(x_2)} F(y)dy$$
$$= 0$$

Therefore $\frac{dw_2(x_2)}{dx_2} = \frac{p[w_2(x_2) + (c_0 + c_1) - p]\int_0^{Q(x_2)} F(y)dy}{(p-C)^2 Q(x_2) + p(C-p)\int_0^{Q(x_2)} F(y)dy}$, consulting Shen's paper, we can derive supplier 2's optimal wholesale price as Eqs. (7) and (8), after substituting $w_2^*(c_2)$ into Eq. (1) we can derive supplier 2's optimal surplus subsidy as Eq. (9).

Lemma 2. $w_2^*(c_2)$ decreases with respect to c_2, $s_2^*(c_2)$ increases with respect to c_2, let $\Pi_2^*(c_2)$ denotes supplier 2's maximum profit, $\Pi_2^*(c_2)$ increases with respect to c_2.

Proof. Because $(p-C)^2 Q(c_2) + p(C-p)\int_0^{Q(c_2)} F(y)dy = (p-C)\Pi_j(c_2) > 0$ and

$w_2^*(c_2)+(c_0+c_1)-p<0$, we can obtain that $\frac{dw_2^*(c_2)}{dc_2}<0$, so $w_2^*(c_2)$ decreases with respect to c_2.

From Eq. (9), we obtain $\frac{ds_2^*(c_2)}{dc_2}=\frac{p[p-w_2^*(c_2)-(c_0+c_1)]-(p-C)C\frac{dw_2^*(c_2)}{dc_2}}{(p-C)^2}$, in the numerator, $(p-C)\frac{dw_2^*(c_2)}{dc_2}<0$ and $p-w_2^*(c_2)-(c_0+c_1)>0$, so $\frac{ds_2^*(c_2)}{dc_2}>0$, then $s_2^*(c_2)$ increases with respect to c_2.

Supplier 2's profit can be represented as $\Pi_2(c_2)=\frac{w_2(c_2)-c_2}{p-C}\Pi_j(c_2)$ after the channel is coordinated, let $M(c_2)=\frac{w_2^*(c_2)-c_2}{p-C}$, then $\frac{dM(c_2)}{dc_2}=\frac{\frac{dw_2^*(c_2)}{dc_2}}{p-C}+\frac{c_0+c_1+w_2^*(c_2)-p}{(p-C)^2}<0$, from proposition 1, we know that $\Pi_j(c_2)$ decreases with respect to c_2, so $\Pi_2^*(c_2)$ also decreases with respect to c_2.

The manufacturer can now find a menu of wholesale price and surplus subsidy by solving the following incentive-compatible truth-telling optimization problem:

Problem 1: $\max_{\{w_2(c_2),s_2(c_2)\}}\int_{\underline{L_2}}^{\overline{U_2}}\Pi_m(c_2)h(c_2)dc_2$

St (4) (5) (6) (7) (8)

Let $w(c_2)=w_1(c_2)+w_2(c_2)$, differentiating $\Pi_m(c_2)$ with respect to c_2 yields:

$$\frac{d\Pi_m(c_2)}{dc_2}=[\frac{p}{p-C}\int_0^{Q(c_2)}F(y)dy-Q(c_2)]\frac{dw(c_2)}{dc_2}-\frac{p(p-w_1(c_2)-w_2(c_2)-c_0)}{(p-C)^2}\int_0^{Q(c_2)}F(y)dy$$

Lemma 3. When $\frac{dw_1(c_2)}{dc_2}\le\frac{p[w_1(c_2)-c_1]\int_0^{Q(c_2)}F(y)dy}{(p-C)^2Q(c_2)+p(C-p)\int_0^{Q(c_2)}F(y)dy}$, $\Pi_m(c_2)$ increases with respect to c_2; otherwise, $\Pi_m(c_2)$ decreases with respect to c_2.

Proof. When $\frac{dw_1(c_2)}{dc_2}\le\frac{p[w_1(c_2)-c_1]\int_0^{Q(c_2)}F(y)dy}{(p-C)^2Q(c_2)+p(C-p)\int_0^{Q(c_2)}F(y)dy}$, with lemma 1 we can obtain $\frac{dw(c_2)}{dc_2}\le\frac{p(p-w_1(c_2)-w_2(c_2)-c_0)\int_0^{Q(c_2)}F(y)dy}{p(p-C)\int_0^{Q(c_2)}F(y)dy-(p-C)^2Q(c_2)}$, therefore $\frac{d\Pi_m(c_2)}{dc_2}\ge 0$. For the same reason, when $\frac{dw_1(c_2)}{dc_2}>\frac{p[w_1(c_2)-c_1]\int_0^{Q(c_2)}F(y)dy}{(p-C)^2Q(c_2)+p(C-p)\int_0^{Q(c_2)}F(y)dy}$, we can obtain $\frac{d\Pi_m(c_2)}{dc_2}<0$.

Proposition 2. When $\frac{dw_1(c_2)}{dc_2} \le \frac{p[w_1(c_2)-c_1]\int_0^{Q(c_2)} F(y)dy}{(p-C)^2 Q(c_2) + p(C-p)\int_0^{Q(c_2)} F(y)dy}$, if $\prod_1^- \le \prod_1(\underline{L_2}) \le \prod_j(\underline{L_2}) - (\prod_m^- + \prod_2^-)$, then supplier 2's optimal wholesale price can be represented as follow:

$$w_2^*(c_2) = p - (c_0 + c_1) + [(1 - \frac{\prod_2^-}{\prod_j(\overline{U_2})})(c_0 + c_1 + \overline{U_2} - p)]e^{L(c_2) - L(\overline{U_2})} \quad (10)$$

Proof. From lemma 3, we know that $\prod_m(c_2)$ increases with respect to c_2, the profit of the manufacturer can be represented as $\prod_m(c_2) = [1 - \frac{w_1(c_2) + w_2(c_2) - (c_1 + c_2)}{p - C}]\prod_j(c_2)$ (11) after the channel is coordinated. We can obtain $w_1(\underline{L_2}) + w_2(\underline{L_2}) \le (1 - \frac{\prod_m^-}{\prod_j(\underline{L_2})})(p - c_0 - c_1 - \underline{L_2}) + c_1 + \underline{L_2}$ (12) from constraint (4). Eq. (12) can be improved as $\prod_1(\underline{L_2}) \le \prod_j(\underline{L_2}) - (\prod_m^- + \prod_2^-)$, from proposition 1 we can know that $\prod_j(\underline{L_2}) - (\prod_m^- + \prod_2^-) \ge \prod_1^-$, so when $\prod_1^- \le \prod_1(\underline{L_2}) \le \prod_j(\underline{L_2}) - (\prod_m^- + \prod_2^-)$, constraint (4) can be satisfied.

From lemma 2, we know that $\prod_2(c_2)$ decreases with respect to c_2, and supplier 2's profit can be represented as $\prod_2(c_2) = \frac{w_2(c_2) - c_2}{p - C}\prod_j(c_2)$ after the channel is coordinated, so from constraint (5) we can obtain $\frac{w_2(\overline{U_2}) - \overline{U_2}}{p - (c_0 + c_1 + \overline{U_2})} = \frac{\prod_2^-}{\prod_j(\overline{U_2})}$ (13). Eq. (13) can be improved as $w_2(\overline{U_2}) = (1 - \frac{\prod_2^-}{\prod_j(\overline{U_2})})\overline{U_2} + \frac{\prod_2^-}{\prod_j(\overline{U_2})}(p - c_0 - c_1)$ (14), Combining Eqs (7), (8) and (14) we can obtain Eq. (10).

Proposition 3. When $\frac{dw_1(c_2)}{dc_2} > \frac{p[w_1(c_2)-c_1]\int_0^{Q(c_2)} F(y)dy}{(p-C)^2 Q(c_2) + p(C-p)\int_0^{Q(c_2)} F(y)dy}$, if supplier 1's profit satisfies $\prod_1^- \le \prod_1(\overline{U_2}) \le \prod_j(\overline{U_2}) - (\prod_m^- + \prod_2^-)$, then supplier 2's optimal wholesale price can also be represented as follow:

$$w_2^*(c_2) = p - (c_0 + c_1) + [(1 - \frac{\prod_2^-}{\prod_j(\overline{U_2})})(c_0 + c_1 + \overline{U_2} - p)]e^{L(c_2) - L(\overline{U_2})}$$

Proof. The proof is similar to the proof of proposition 2, which can be omitted here.

From lemma 2, we know $s_2^*(c_2)$ decreases with respect to c_2, so we can obtain $\underline{L_2}$ if we let $s_2^*(\underline{L_2}) = 0$.

From proposition 2 and proposition 3 we can see that the formulation of $w_2^*(c_2)$ is same in the two different cases of $\frac{dw_1(c_2)}{dc_2}$, therefore we can obtain proposition 4.

Proposition 4. When $c_2 < \underline{L_2}$, the manufacturer will not consider channel coordination ; When $c_2 > \overline{U_2}$, the manufacturer will not purchase from these two suppliers, and $w_1^*(c_2) = 0$, $w_2^*(c_2) = 0$; When $\underline{L_2} \le c_2 \le \overline{U_2}$, the optimal wholesale prices and surplus subsidies of supplier 1 and supplier 2 are as follows:

$$w_1^*(c_2) = \frac{\Pi_1^-}{\Pi_j(c_2)}(p - C) + c_2$$

$$s_1^*(c_2) = \frac{pc_1 - w_1^*(c_2)C}{p - C}$$

$$w_2^*(c_2) = p - (c_0 + c_1) + [(1 - \frac{\Pi_2^-}{\Pi_j(\overline{U_2})})(c_0 + c_1 + \overline{U_2} - p)]e^{L(c_2) - L(\overline{U_2})}$$

$$s_2^*(c_2) = \frac{pc_2 - w_2^*(c_2)C}{p - C}.$$

Proof. The manufacturer can determine supplier 1's wholesale price and surplus subsidy after supplier 2 reveals his true production cost, but $\{w_1(c_2), s_1(c_2)\}$ has a continuum of optimal solutions, so the manufacturer can choose one group from the continuum arbitrarily on the premise that supplier 1's profit is more than Π_1^-. Combining proposition 2 and proposition 3, the manufacturer will make supplier 1 only earns its reservation profit Π_1^- to maximize his profit, so we can obtain $w_1^*(c_2) = \frac{\Pi_1^-}{\Pi_j(c_2)}(p - C) + c_2$, $s_1^*(c_2) = \frac{pc_1 - w_1(c_2)C}{p - C}$.

In order to yield $w_2^*(c_2)$ and $s_2^*(c_2)$, we must find the optimal $\overline{U_2}$ to maximize the manufacturer's profit, by substituting $w_1^*(c_2)$ and $w_2^*(c_2)$ in to Eq. (11) we can obtain the manufacturer's expected profit represented as follows:

$$E(\Pi_m(\overline{U_2})) = -\Pi_1^- - (1 - \frac{\Pi_1^-}{\Pi_j(\overline{U_2})})(c_0 + c_1 + \overline{U_2} - p)\int_{\underline{L_2}}^{\overline{U_2}} \frac{e^{L(c_2) - L(\overline{U_2})}\Pi_j(c_2)}{p - (c_0 + c_1 + c_2)} h(c_2) dc_2 \qquad (14)$$

The concavity or convexity of $E(\Pi_m(\overline{U_2}))$ is not clear, in general, it could be non-concave and non-convex. Since Eq. (14) is a one- dimensional problem, it can be solved by a line search method. After finding the optimal cutoff point of $\overline{U_2}$, denoted as $\overline{U_2}^*$, we can determine $\overline{U_2} = \min(c_2^0, \overline{c_2}, \overline{U_2}^*)$.

Numerical Example

In this example, c_0=40, c_1=10, $\prod_1^- = 400$, $\prod_2^- = 600$, $\prod_m^- = 1000$, p=250. Supplier 2's production cost is assumed to be a uniform distribution [20,40] and the demand is assumed to be a uniform distribution [20,60]. It is found $\overline{U_1} = 26.2$, $\overline{U_2} = 40$, $\underline{L_2} = 20$.

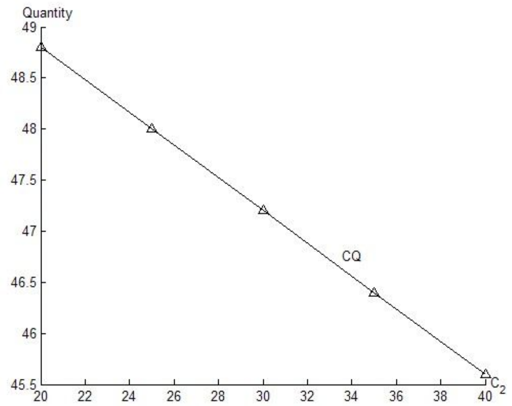

Figure 1- Supplier's optimal production quantity

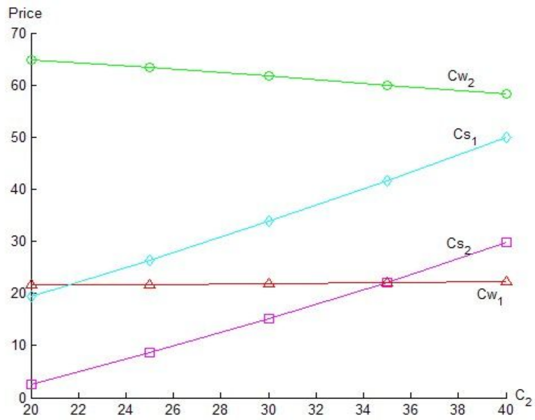

Figure 2- Supplier's optimal price and subsidy

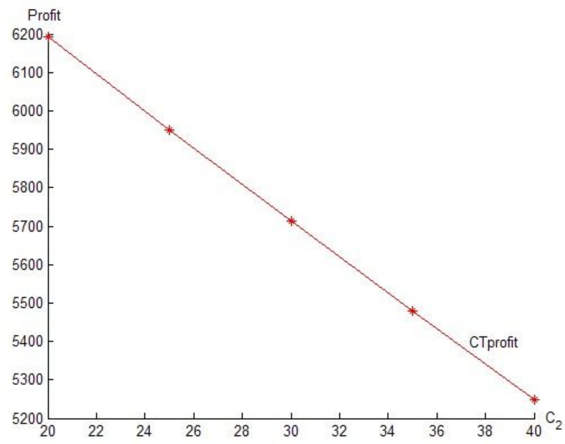

Figure 3- Channel's total profit

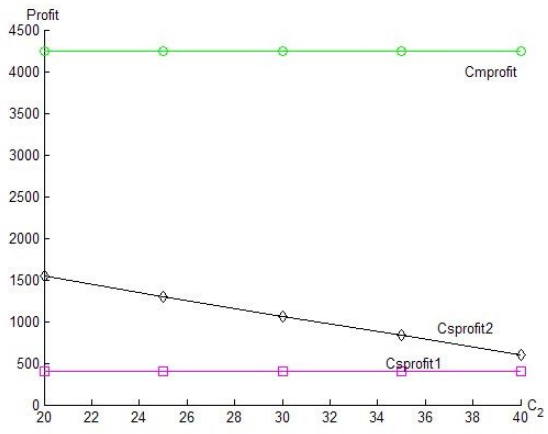

Figure 4- All parties' profits

In Fig.1, we depict the optimal production quantity of these two suppliers denoted by *CQ*. From Fig.1, we can see that *CQ* decreases with respect to c_2.

In Fig.2, we depict the optimal wholesale prices and surplus subsidies of supplier 1 and supplier 2, Cw_1, Cw_2, Cs_1, Cs_2 denotes supplier 1's optimal wholesale price, supplier 2's optimal wholesale price, supplier 1's optimal surplus subsidy and supplier 2's optimal surplus subsidy, respectively. From Fig.2, we can see that when c_2 increases, Cw_1 almost remains the same; Cw_2 decreases; Cs_1 and Cs_2 all increases. This is because the manufacturer decreases supplier 2's wholesale price to achieve channel coordination, and meanwhile increases supplier 2's surplus subsidy to prevent his dropping out due to profit loss. Regarding supplier 1, although Cw_1 keeps the same, CQ will decrease when c_2 increases, which leads to supplier 1's profit decreasing, so the manufacturer will increase supplier 1's surplus subsidy to guarantee it earn its reservation profit $\prod_1^-$.

In Fig.3, we depict the channel profit which denoted by CTprofit. From Fig.3, we can see CTprofit decreases with respect to c_2, this is because when c_2 increases, CQ will decrease and the total cost of the channel will increase.

In Fig.4, we depict supplier 1's profit, supplier 2's profit and the manufacturer's profit which denoted by Csprofit1, Csprofit2 and Csprofitm, respectively. From Fig.4, we can see that when c_2 increases, Csprofit1 always keeps still and equals to $\prod_1^-$; Csprofit2 decreases and Csprofitm keeps still too.

Conclusion

This paper considers an assembly system constituting of two suppliers and one manufacturer, one of the two suppliers has private production cost information, the manufacturer has to design an incentive- compatible contract to reveal this private cost and meanwhile coordinate the channel. We find that a contract consisting of wholesale price and surplus subsidy can help the manufacturer to realize these two goals.

There are several areas to extend this research. First, we can integrate both asymmetric cost information and asymmetric demand information into the problem setting. Second, we can study the case that all of the two suppliers have private production cost information.

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