Production and Low-carbon Investment Analysis in Make-to-stock Supply Chain

Y.C. Zhao, S.H. Choi*, X.J. Wang, A. Qiao, S.Y. Wang

Abstract— **Carbon emission has grown into a pressing issue around the world, arousing customer green awareness about emission in production of merchandise. As a major source of emission, the manufacturing supply chain has obligations and needs to reduce emission substantially. Indeed, reducing emission per product item enhances the green image of the product brand which is vital to the product sustainability in the market. Nevertheless, such endeavours require increasing low-carbon investment by the manufacturers and cooperation with the retailers, in addition to their traditional order quantity decisions. In this paper, we analyse the decision behaviour of manufacturers and retailers under the impacts of customer green awareness, with an aim to provide analytical and management insights into a profitable and sustainable supply chain. We propose three EOQ-based supply chain models, namely the centralised, decentralised and coordinated models, in which a manufacturer and a retailer make decisions for optimality of product sustainability and order quantity correspondingly. The centralised model is analysed as an ideal benchmark. While in the decentralised model, the decision route is assumed to be a classical Stackelberg Game, with the retailer being the leader and the manufacturer as the follower. Analytical solutions and properties are proposed for them respectively. After revealing the performance disparities and value loss in the decentralised supply chain, a cost-sharing contract of low-carbon investment is designed to help coordinate the supply chain. Numerical experiments validate that the coordinated supply chain can bring about win-win benefits with a dramatical increase in product sustainability. Moreover, increased market demand, wholesale price, and cost-sharing percentage all jack up the product sustainability. Several management insights are proposed to guide supply chain's decisions. It is found that a decentralised supply chain with coordination can enhance business sustainability and profitability close to an ideal, centralised one.**

Index Terms—**Low-carbon investment, EOQ Supply Chain, Customer Green Awareness, Cost-sharing Contract**

I. Introduction

GLOBAL warming has aggravated and aroused considerable concerns around the world. In the 2009 Copenhagen Accord and the 2015 Paris Agreement, the signatory countries pledged to assure the sustainability of our planet by limiting the rise in temperature to below 2ºC [1, 2].

Y.C. Zhao is with the Department of Industrial and Manufacturing Systems Engineering (IMSE), the University of Hong Kong, Hong Kong (email: u3003002@connect.hku.hk).

S.H. Choi is with the IMSE, the University of Hong Kong, Hong Kong (email: shchoi@hku.hk)

X.J. Wang is with IMSE, the University of Hong Kong, Hong Kong (email: kxjwang@connect.hku.hk).

A. Qiao is with IMSE, the University of Hong Kong, Hong Kong (email: u3516685@hku.hk).

S.Y. Wang is with IMSE, the University of Hong Kong, Hong Kong(email: wang0214@connect.hku.hk)

This commitment mandates serious efforts from every industrial sector. As a major source of emission, the manufacturing industry and its related supply chain are reportedly responsible for over 40% of the overall emissions in some countries [1, 3]. Although some manufacturers have attempted to reduce carbon emission through operational improvement, it is far from meeting the requirement. Moreover, without the cooperation throughout the supply chain, it is difficult for a manufacturer alone to be motivated to reduce emission substantially [4]. However, there is a lack of communication and coordination between the supply chain members to work towards a common goal of emission reduction, as each of them often considers its own profit only. Indeed, non-participation of one member would likely dampen the sustainable performance of the whole supply chain [2].

In addition, customers have become more inclined towards green products with relatively less emission during production. Such customer green awareness increases demand for products with a green brand image of relatively high sustainability [5]. In certain countries, carbon emission labelling of products has been a marketing standard to satisfy customers [6]. As such, new business models and markets should be recognised based on customer green awareness, which acts as a key driving force for manufacturers and retailers to move towards a sustainable supply chain [7].

Under this circumstance, low-carbon investment is imperative to enhancing product sustainability. There are two types of low-carbon investment. Direct low-carbon investment is to invest in the production of green energy and materials, and it often takes up huge amounts of capitals. To take advantage of investment flexibility, indirect low-carbon investment is preferable for manufacturers to choose the scale of using relatively expense renewable energy and green raw materials components from suppliers for manufacturing products. Although the unit production cost would inevitably increase, the emission would be reduced and hence the product sustainability enhanced accordingly. For instance, the cost of photovoltaic (PV) solar electricity and of thermal power electricity per kWh is US$0.125 and US$0.07 correspondingly, while the emission from PV solar electricity is reduced 80% compared with thermal power electricity [8, 9]. Therefore we refer "low-carbon investment" in this paper to "indirect low-carbon investment".

Traditionally, supply chain decisions usually emphasise on quantity and shipment times. Now, it is vital for the whole manufacturing supply chain to capture markets with increasing green awareness to maintain long-term business profitability and sustainability. However, a lack of coordination in the supply chain resulting from the self-profit nature of each member usually reduces the overall sustainability and profitability of the supply chain

(Advance online publication: 22 February 2017)

substantially [2, 10]. Therefore, it is necessary to develop a feasible coordination mechanism for balancing a trade-off among the cost of low-carbon investment, quantity decision and the short-term profit.

In the academic field, few research works have focused on low-carbon investment in manufacturing. They mostly take carbon emission as a cost source to study how to better shift the classical decision strategy to meet the regulations and limits induced by carbon emission [11], but often ignore the impact of customer green awareness on market demand. Hence, a great research gap exists in incorporating low-carbon investment decisions into the manufacturing supply chain, and in studying the decision behaviour of and possible coordination between the manufacturer and the retailer.

In this paper, EOQ-based supply chain models are proposed to study the centralised, decentralised and coordinated supply chains [12, 13], in which the retailer makes the decision for optimality of order quantity while the manufacturer makes the decision for product sustainability. EOQ-based model is very practical and easily implemented in real industry. Considering the impact of customer green awareness, a factor on sustainable market demand based on product sustainability will be added to the original fixed demand. In each turn, the retailer moves first to place an order quantity for the manufacturer produce.

The centralised supply chain is analysed first an idealised benchmark. Then the decentralised supply chain is studied to compare with the benchmark to its performance discrepancies. Subsequently, a low-carbon investment cost-sharing contract is proposed for the retailer to coordinate the decentralised supply chain. Analytical solutions and properties for these three models are elaborated and discussed. Numerical studies are conducted to validate our analysis.

The proposed models are aimed to help improve supply chain coordination and product sustainability in markets with customer green awareness. It can be shown that without feasible coordination, the manufacturer would be not willing to increase sustainability and the profits of both the manufacturer and the retailer are hampered. With our proposed low-carbon investment sharing cost contract, a win-win game can be achieved and sustainability improved significantly. It can be therefore implemented to help the supply chain strive for green development.

The rest of the paper is arranged as follows. In section II, some related research works are reviewed. In section III, the manufacturing scenario together with analytical models and solution processes are proposed. In section IV, several numerical studies are carried out to validate and help further analyse the model. Lastly, conclusions and further development work are discussed in section V.

II. LITERATURE REVIEW

This section reviews some related papers which consider carbon emission as a cost source or constraint and then analyses the current research about low-carbon investment, with an emphasis on the sustainable supply chain.

Carbon emission is usually taken only as a cost source or constraint. Benjiaafar et al. [14] considered carbon emission cost in the single stage EOQ model to analyse the influence of various carbon policies. Absi et al. [15], studied a multi-sourcing lot-sizing problem with carbon cap constraint. They analysed four types of carbon cap constraints to study the difference for the cost minimization. Yu Yugang et al. [16] presented a dynamic lot sizing problem with carbon emission constraint, while several researchers implemented carbon emission cost into a supply chain model. Toptal et al. [17] incorporated carbon emission cost into an EOQ-based two-stage supply chain with different carbon policies to analyse the solutions. Similarly, an EOQ-based supply chain with n-shipment times considering carbon emission cost was studied by Jaber et al. [18].

Nevertheless, none of the works above has studied low-carbon investment in manufacturing with product sustainability taken into consideration. Customer green awareness and its impact on market demand are also neglected in current research works. Moreover, emission reduction from operational improvement is not enough to realise the world's commitments to global warming.

Therefore, some empirical and non-profit organisation researchers have recently turned their attention to low-carbon investment and sustainable market to help improve manufacturing and supply chain operations [19-21]. Despite these preliminary studies, much research work has yet to be conducted to investigate low-carbon investment in manufacturing with consideration of sustainable market under the impacts of customer green awareness.

Zanoni et al. [22] studied the low-carbon investment problem with a price and environmentally sensitive demand. But they did not provide an analytical solution. In our previous work, an EOQ-based model was proposed to analyse quantity decision and low-carbon investment [23]. We studied the single stage EOQ-based joint quantity and low-carbon investment problem with carbon cap and tax policies [13].

In a two-stage supply chain, Ghosh et al. [24] utilised a market pricing model to study the low-carbon investment and pricing problem. Liu et al. [25] used a business model to study the decision of price and sustainability of product under competition.

However, few research has studied the manufacturing supply chain with low-carbon investment and customer green awareness. Empirical studies reported that current supply chains are too slow and without feasible coordination to meet the emission target [2, 4, 26].

Therefore, it is of great importance to further investigate into the manufacturing supply chain with low-carbon investment decision and customer green awareness, with an aim to develop feasible coordination schemes to improve manufacturing and supply chain operations. Only when the whole supply chain works together can emission from manufacturing supply chain be sufficiently reduced to assure business sustainability.

III. MODEL FOR PRODUCTION & LOW-CARBON INVESTMENT

A. The Supply Chain Scenario

We suppose an EOQ based two-stage supply chain, including a manufacturer and a retailer. In each turn, the retailer orders Q quantity and the manufacturer will manage a batch production upon receiving this order. Meanwhile, a decision for the sustainability of the product, i.e., measured by the amount of carbon emission reduction per product item and denoted as α , will be made by the manufacturer with an extra production cost per product item given by $c_e \cdot \alpha$.

In the market, increasing green awareness among customers will lead to a boost in demand for green products of relatively high sustainability. As such, we assume a sustainable market demand, $b \cdot \alpha$, will be added to the original demand, where *b* is defined as the sustainable market factor while the original demand D_0 is assumed known and fixed.

It is also assumed that the lead time for transportation is zero and the manufacturer utilises a lot-to-lot policy [27], *i.e.*, the quantity of batch production is exactly *Q*, to manage the replenishment of the retailer's inventory. The production rate of the manufacturer, denoted as P_M , is assumed to be fixed and larger than the realised demand *D*.

The game between two players in the supply chain is modelled as a classical Stackelberg Game, in which the retailer will act as the leader to order the quantity *Q* first and the manufacturer will take the follower to decide the sustainability level α . Inventory costs and setup costs are counted for them separately. The wholesale price *w* between them is assumed to be already negotiated and fixed. Hence, the profit models for the manufacturer and the retailer are exhibited as follows:

The retailer's profit function:

$$\begin{aligned} &\pi_R = D \cdot m_R - \frac{D}{Q} S_R - \frac{Q}{2} h_R \\ &s.t.\;\; D = D_0 + b\alpha \\ &\quad\;\; Q \ge 1 \end{aligned} \tag{1}$$

The manufacturer's profit function:

$$\begin{aligned} &\pi_M = D \cdot (m_M - c_e\alpha) - \frac{D}{Q} S_M - \frac{Q}{2}\frac{D}{P_M} h_M \\ &s.t.\quad D = D_0 + b\alpha \\ &\qquad\;\; 0 \le \alpha \le e_{\max} \end{aligned} \tag{2}$$

Where $m_R = p - w$ represents the retailer's gross revenue per product, and $m_M = w - c$ represents the manufacturer's gross revenue per product. S_R and S_M are the corresponding setup costs, and h_R and h_M are the corresponding inventory costs. P_M represents the production rate.

All these parameters are set as given and fixed. Constraint $Q \ge 1$ means that the quantity decision should at least be one and constraint $0 \le \alpha \le e_{\max}$ expresses that the sustainability of the product is limited by a maximised value e_{max}. It is reasonable that low-carbon investment cannot infinitely reduce the carbon emission of products.

B. Analysis of the Centralized Supply Chain

Firstly, we analyse the centralised supply chain model, in which the manufacturer and the retailer are assumed being in one company; therefore, the decision discrepancy between two members can be eliminated. A centralised model can be viewed as an idealised benchmark for the supply chain's profit, as shown below:

$$\begin{aligned} &\pi_C = D(m_c - c_e\alpha) - \frac{D}{Q} S_C - \frac{Q}{2}(h_R + \frac{D}{P_M} h_M) \\ &s.t.\;\; D = D_0 + b\alpha \\ &\qquad 0 \le \alpha \le e_{\max} \\ &\qquad Q \ge 1 \end{aligned} \tag{3}$$

Where $m_c = p - c$ represents the gross revenue of centralised supply chain and $S_C = S_M + S_R$ represents the setup cost of the supply chain.

A centralised model is similar to our proposed single-stage joint quantity and low-carbon investment model [13], with a difference in the holding cost of the manufacturer.

Substituting $\alpha = (D - D_0)/b$ into, we have:

$$\pi_C = -\frac{c_e}{b} D^2 + (m_c + \frac{c_e}{b} D_0 - \frac{S_c}{Q} - \frac{Qh_M}{2P_M}) D - \frac{Q}{2} h_R \tag{4}$$

Obviously Π_c is concave w.r.t. demand *D* when order quantity *Q* is given, and w.r.t. *Q* when *D* is given, respectively.

Therefore the optimal demand D_C^+ when *Q* is given and the optimal order quantity Q_C^+ when *D* is given for the centralized supply chain can be represented as:

$$D_C^+ = \frac{b}{2c_e}(m_c - \frac{S_c}{Q} - \frac{Qh_M}{2P_M} + \frac{c_e}{b} D_0) \tag{5}$$

$$Q_C^+ = \sqrt{\frac{2DS_c}{h_R + D \cdot h_M / P_M}} \tag{6}$$

Lemma 1: D_C^+ is bounded by $[D_0, \min\{D_{\max}, D_c^o\}]$, where $D_{\max} = D_0 + b \cdot e_{\max}$, $D_c^o = \frac{b}{2c_e}(\mathrm{m}_c + \frac{c_e}{b} D_0 - \sqrt{\frac{2S_c h_M}{P_M}})$ and $Q_C^o = \sqrt{\frac{2P_M S_C}{h_M}}$, with $Q_C^o > Q_C^+(D_{\max})$. Q_C^+ is bounded by $[Q_C^+(D_0),\ Q_C^+(D_{\max})]$.

It is important to note that, if $D_c^o < D_0$, the problem will be not applicable for low-carbon investment. Under this circumstance, the problem will regress to a classical EOQ problem with a fixed D_0 . Therefore, we assume that D_c^o should be at least larger than D_0 .

Replacing D^+ into Π_c , we can get:

$$\pi_c = \frac{b}{4c_e}(\mathrm{m}_c + \frac{c_e}{b}\mathrm{D}_0 - \frac{S_c}{Q} - \frac{Qh_M}{2P_M})^2 - \frac{Q}{2} h_R \tag{7}$$

By derivation, we have:

$$\begin{aligned} &\frac{\partial \pi}{\partial Q} = \frac{b}{2c_e}(m_c + \frac{c_e}{b} D_0 - \frac{S_C}{Q} - \frac{Qh_M}{2P_M})(\frac{S_C}{Q^2} - \frac{h_M}{2P_M}) - \frac{h_R}{2} \\ &\frac{\partial^2 \pi}{\partial Q^2} = \frac{1}{Q^3}(\frac{3S_c^{\,2}}{Q} + \frac{h_M^{\,2}}{4P_M} Q^3 - 2S_C(m_c + \frac{c_e}{b} D_0)) \end{aligned} \tag{8}$$

Proposition 1: In the feasible region of Q, $\frac{3S_c^{\,2}}{Q} + \frac{h_M^{\,2}}{4P_M} Q^3 - 2S_C(m_c + \frac{c_e}{b} D_0)$ is decreasing and $\frac{\partial^2 \pi}{\partial Q^2}|_{Q=Q_C^o} < 0$. When $\frac{\partial \pi}{\partial Q}|_{Q=Q_{\min}} > 0$, there will always exist a unique solution for $\frac{\partial \pi}{\partial Q}$ =0 in $[Q_C^+(D_0),\ Q_C^o]$.

The solution process for the centralised supply chain model can be shown as follows:

1. Check if $\frac{\partial \pi}{\partial Q}|_{Q=Q_{\min}} > 0$
2. When 1 is checked, solve $\frac{\partial \pi}{\partial Q}$=0 to get $Q_C^{\Diamond}$
3. $Q_C^* = \min\{Q_C^{\Diamond},\ Q_C^+(D_{\max})\}$, let $f = Q_C^+(D)$, $D_C^* = f^{-1}(Q_C^*)$, $\alpha^* = \alpha(D_C^*)$.

C. Analysis of the Decentralized Supply Chain

In a decentralised supply chain, the manufacturer and the retailer will make decisions for their own profit, instead of for the whole supply chain.

Assume that the information available for both members is symmetric and the retailer makes decisions first to send the order to the manufacturer. After receiving the retailer's order and considering customer green awareness, the manufacturer will decide on the product sustainability.

For the manufacturer, the expected optimal demand can be shown as:

$$D_M^+ = \frac{b}{2c_e}(m_M + \frac{c_e}{b}D_0 - \frac{S_M}{Q} - \frac{h_M}{2P_M}Q) \tag{9}$$

Substituting it into retailer's profit function, we get:

$$\pi_R = D_M^+ m_R - \frac{D_M^+}{Q}S_R - \frac{Q}{2}h_R \tag{10}$$

It is noted that the quantity decision is made by the retailer. Given a certain *D*, the optimal quantity decision made by the retailer will be $Q_R^+ = \sqrt{2DS_R / h_R}$.

Lemma 2: D_M^+ is bounded by $[D_0,\ \min\{D_{\max}, D_M^o\}]$, where $D_M^o = \frac{b}{2c_e}(\mathrm{m}_M + \frac{c_e}{b}\mathrm{D}_0 - \sqrt{\frac{2S_M h_M}{P_M}})$. D_M^+ achieves its maximum value D_M^o when $Q = Q_M^o = \sqrt{2P_M S_M / h_M}$. And Q_R^+ is bound by $[Q_R^+(D_0),\ Q_R^+(D_{\max})]$.

Similarly, we assume here that D_M^o will be at least larger than D_0. Since D_{max} is smaller than P_M, Q_M^o is definitely larger than $Q_R^+(D_{\max})$ when $S_M / h_M > S_R / h_R$.

By derivation, we have:

$$\begin{aligned} &\frac{\partial \pi_R}{\partial Q} = \frac{\partial D_M^+(Q)}{\partial Q}m_R - \frac{S_R}{Q^2}(\frac{\partial D_M^+(Q)}{\partial Q}\cdot Q - D_M^+(Q)) - \frac{h_R}{2} \\ &\frac{\partial^2 \pi_R}{\partial Q^2} = \frac{1}{Q^3}(\frac{3bS_R S_M}{c_e Q} - \frac{bm_R S_M}{c_e} - \frac{bm_M S_R}{c_e} - \mathrm{D_0 S}_R) \end{aligned} \tag{11}$$

Proposition 2: In feasible region of Q_R^+, $[Q_R^+(D_0), Q_R^+(D_{\max})]$, $\frac{3bS_R S_M}{c_e Q} - \frac{bm_R S_M}{c_e} - \frac{bm_M S_R}{c_e} - \mathrm{D_0 S}_R$ is strictly decreasing, and $\frac{\partial^2 \pi_R}{\partial Q^2}|_{Q=Q_M^o} < 0$. Therefore, either there exists a unique solution for $\frac{\partial \pi_R}{\partial Q} = 0$, or $\frac{\partial \pi_R}{\partial Q}$ >0 always holds.

The solution process for the decentralised model can be listed as follows:

1. Check if $\frac{\partial \pi_R}{\partial Q}|_{Q=Q_R^+(D_0)} > 0$
2. If 1 is checked, solve $\frac{\partial \pi_R}{\partial Q} = 0$ to get $Q_R^{\Diamond}$
3. If $Q_R^{\Diamond} \in [Q_R^+(D_{\min}), Q_R^+(D_M^+)]$, $Q_R^* = Q_R^{\Diamond}$, *otherwise*, Q_R^* = $Q_R^+(D_{\max})$
4. *If* $D_M^+(Q_R^{\Diamond}) < D_0$ *or* $D_M^+(Q_R^{\Diamond}) > D_{\max}$, D_M^* = $\arg\max_{D\in\{D_0, D_{\max}\}} \pi_M$, *otherwise*, $D_M^* = D_M^+(Q_R^{\Diamond})$

Since both members make decisions on their own information and cost parameters, the optimal expected quantity decision and the demand deviate from those of the whole supply chain.

Take optimal demand when order quantity is given as an instance:

$$\begin{aligned} &D_M^+ = \frac{b}{2c_e}(m_M + \frac{c_e}{b}D_0 - \frac{S_M}{Q} - \frac{h_M}{2P_M}Q) \\ &D_C^+ = \frac{b}{2c_e}(m_c - \frac{S_c}{Q} - \frac{Qh_M}{2P_M} + \frac{c_e}{b}D_0) \end{aligned} \tag{12}$$

The difference between D_M^+ and D_C^+ is:

$$D_C^+ - D_M^+ = \frac{b}{2c_e}(m_R - \frac{S_R}{Q}) \tag{13}$$

For a certain order quantity *Q*, the demand for the manufacturer in the decentralised supply chain is smaller. Moreover, the gap between D_C^+ and D_M^+ is enlarged when *Q* increases, so as the product sustainability.

Moreover, the difference between $\frac{\partial \pi_R}{\partial Q}$ and $\frac{\partial \pi_C}{\partial Q}$ will be:

$$\begin{aligned} &\frac{\partial \pi_C}{\partial Q} - \frac{\partial \pi_R}{\partial Q} = D_C^+ \frac{2c_e}{b}\frac{\partial D_C^+}{\partial Q} - (m_R - \frac{S_R}{Q})\frac{\partial D_M^+}{\partial Q} - \frac{S_R}{Q^2}D_M^+ \\ &= \frac{S_R}{Q^2}(D_C^+ - D_M^+) + D_M^+ \frac{2c_e}{b}\frac{\partial D_M^+}{\partial Q} \end{aligned} \tag{14}$$

Since $D_C^+ - D_M^+$ is positive, $\frac{\partial \pi_C}{\partial Q} - \frac{\partial \pi_R}{\partial Q}$ will be strictly positive when $Q \le Q_M^o$.

Proposition 3: when $S_M / h_M > S_R / h_R$, $Q_C^* > Q_R^*$, $D_C^* > D_M^*$, $\alpha_C^* > \alpha_R^*$. The manufacturer is not willing to increase the product sustainability and the retailer also provides a smaller order quantity.

Since the manufacturer's setup cost is usually higher than the retailer's order cost, and vice versa for the holding cost, $S_M / h_M > S_R / h_R$ usually holds.

Hence Proposition 3 holds in most situations. As such, when there is no coordination scheme, all decisions in the decentralised supply chain will be smaller than the corresponding centralised decisions.

This proposition provides an insight into the negative effects of performance discrepancies resulting from a lack of coordination. The retailer makes decisions for its own profit but does not recognise the importance of motivating the manufacturer to increase product sustainability, leading to a smaller realised demand. The manufacturer, on the other hand, cannot make moves before the retailer. Therefore when the manufacturer receives a smaller quantity, he/she will choose to balance the cost and profit by only marginally increasing the product sustainability.

Without coordination, the supply chain is not capable of narrowing the performance discrepancies to seize the demand boost from sustainable markets. Hence a greener supply chain cannot be achieved.

D. Investment cost sharing contract

To coordinate the supply chain, a designed contract between the retailer and the manufacturer can help bridge their decision discrepancies, jacking up the optimality of the supply chain.

From the previous analysis, it is emphasised that the retailer cannot provide enough incentives for the manufacturer to increase product sustainability. In the decentralised supply chain, low-carbon investment cost is undertaken only by the manufacturer; but in the centralised supply chain, it can be regarded as that the manufacturer and the retailer share the low-carbon investment cost.

What if the retailer is willing to share the low-carbon investment cost in the decentralised supply chain? Inspired by this, we suppose that the retailer endorses a contract with the manufacturer to share part of the low-carbon investment cost. For simplicity, we denote the contract by a given a certain sharing percentage ϕ as *ϕ-contract*, and the original decentralised supply chain problem can be viewed as a *0-contract* problem.

Therefore, the profit functions for the manufacturer and the retailer with an investment cost sharing contract are given by:

$$\begin{aligned}\pi_M^{\phi} &= D\cdot m_M-(1-\phi)D\cdot c_e\cdot\alpha-\frac{D}{Q}S_M-\frac{Q}{2}\frac{h_M}{P_M}D\\ \pi_R^{\phi} &= D\cdot m_R-\frac{D}{Q}S_R-\frac{Q}{2}h_R-\phi\cdot D\cdot c_e\cdot\alpha\end{aligned}\tag{15}$$

The decision steps in the ϕ-contract problem are the same in the decentralised model. For the manufacturer, the optimal demand $D_M^{\phi+}$ when order quantity Q is given will be:

$$D_M^{\phi+}=\frac{b}{2(1-\phi)c_e}\left(m_M+\frac{(1-\phi)c_e}{b}D_0-\frac{S_M}{Q}-\frac{h_M}{2P_M}Q\right)\tag{16}$$

From $D_M^{\phi+}$, it can be found that its maximum value will be $\frac{b}{2(1-\phi)c_e}\left(m_M+\frac{c_e(1-\phi)}{b}D_0-\sqrt{\frac{2S_Mh_M}{P_M}}\right)$, denoted as $D_M^{\phi o}$, when $Q_M^{\phi o}=\sqrt{\frac{2P_MS_M}{h_M}}$. In ϕ-contract problem $Q_M^{\phi o}=Q_M^{o}$.

Similarly, the difference between $D_M^{\phi+}$ and D^{+} will be:

$$D^{+}-D_M^{\phi+}=\frac{b}{2c_e}\left(m_R-\frac{S_R}{Q}\right)-\frac{b\phi}{2c_e(1-\phi)}\left(m_M-\frac{S_M}{Q}-\frac{Qh_M}{2P_M}\right)\tag{17}$$

Obviously, the disparity between the demands is narrowed by ϕ-contract, and the larger the ϕ, the smaller the gap is.

It can be expected that, with ϕ-contract, the retailer can get a higher demand by a smaller order quantity and the manufacturer can also save cost to invest more in product sustainability. Meanwhile, due to the demand increase, the retailer can also gain an increase in sales to offset the shared cost.

Substituting $D_M^{\phi+}$ into π_R^{ϕ}, we have:

$$\pi_R^{\phi}=D_M^{\phi+}m_R-\frac{D_M^{\phi+}}{Q}S_R-\frac{Q}{2}h_R-\phi D_M^{\phi+}c_e\left(\frac{D_M^{\phi+}-D_0}{b}\right)\tag{18}$$

Similarly, $Q_R^{\phi+}=\sqrt{\frac{2DS_R}{h_R}}$ represents the optimal quantity decision by retailer given a certain demand.

Lemma 3: $D_M^{\phi+}$ is bound by $[D_{\min},\min(D_M^{\phi o},D_{\max})]$ and $Q_R^{\phi+}$ is bound by $[Q_R^{\phi+}(D_{\min}),Q_R^{\phi+}(D_{\max})]$.

By derivation, we have:

$$\begin{aligned}\frac{\partial\pi_R^{\phi}}{\partial Q} &= \frac{\partial D_M^{\phi+}}{\partial Q}\left(\mathrm{m}_R+\frac{\phi c_e}{b}(\mathrm{D}_0-D_M^{\phi+})-\frac{S_R}{Q}\right)+\frac{S_R}{Q^2}D_M^{\phi+}-\frac{h_R}{2}\\ &\quad-\frac{\phi c_e}{b}\frac{\partial D_M^{\phi+}}{\partial Q}D_M^{\phi+}\\ \frac{\partial^2\pi_R^{\phi}}{\partial Q^2} &= \frac{\partial^2 D_M^{\phi+}}{\partial Q^2}\left(\mathrm{m}_R+\frac{\phi c_e}{b}(\mathrm{D}_0-D_M^{\phi+})-\frac{S_R}{Q}\right)-\frac{2\phi c_e}{b}\left(\frac{\partial D_M^{\phi+}}{\partial Q}\right)^2\\ &\quad-\frac{\phi c_e}{b}\frac{\partial^2 D_M^{\phi+}}{\partial Q^2}D_M^{\phi+}-\frac{2S_R}{Q^3}D_M^{\phi+}\end{aligned}\tag{19}$$

Proposition 4: Given ϕ, if $\frac{\partial\pi_R^{\phi}}{\partial Q}|_{Q=Q_R^{\phi+}(D_{\min})}>0$, $2S_R\ge\frac{\phi}{1-\phi}S_M$ and for $Q\in[Q_R^{\phi+}(D_0),Q_R^{\phi+}(D_{\max})]$, $m_R+\frac{\phi c_e}{b}(D_0-D_M^{\phi+})-\frac{S_R}{Q}\ge 0$ are satisfied, $\frac{\partial^2\pi_R^{\phi}}{\partial Q^2}$ is negative, π_R^{ϕ} is concave and exists an optimal solution.

It is noted that the first constraint is necessary but not sufficient for the concave property of the π_R^{ϕ}. It sets a limit for the setup cost between the manufacturer and the retailer. The second constraint means that the retailer's profit per product under ϕ-contract should be positive. It is reasonable that only when its original profit can offset the additional cost, will the retailer endorse such a cost-sharing contract with the manufacturer. Moreover, it can be proved that when the first constraint is satisfied, $m_R+\frac{\phi c_e}{b}(D_0-D_M^{\phi+})-\frac{S_R}{Q}$ is the increase in Q.

The solution process for the ϕ-contract problem is:

1. Given cost-sharing factor ϕ, check if $\frac{\partial\pi_R^{\phi}}{\partial Q}|_{Q=Q_R^{\phi+}(D_{\min})}>0$ and $m_R+\frac{\phi c_e}{b}(D_0-D_M^{\phi+}(Q_R^{\phi+}(D_0)))-\frac{S_R}{Q_R^{\phi+}(D_0)}>0$.
2. Solve $\frac{\partial\pi_R^{\phi}}{\partial Q}=0$ to get $Q_R^{\phi\!\!\!\circ}$.
3. If $Q_R^{\phi\!\!\!\circ}\in[Q_R^{\phi+}(D_{\min}),Q_R^{\phi+}(D_{\max})]$, $Q^{*}=Q_R^{\phi\!\!\!\circ}$, otherwise, $Q_R^{*}=Q_R^{\phi+}(D_{\max})$
4. If $D_M^{\phi+}(Q_R^{\phi\!\!\!\circ})<D_0$ or $D_M^{\phi+}(Q_R^{\phi\!\!\!\circ})>D_{\max}$, $D_M^{*}=\arg\max_{D\in\{D_0,D_{\max}\}}\pi_M^{\phi}$ otherwise, $D_M^{*}=D_M^{\phi+}(Q_R^{\phi\!\!\!\circ})$.

In the above three sessions, we have analysed the performance of a supply chain, which includes a manufacturer and a retailer, from the view of centralised and decentralised supply chains. Moreover, specific to the performance discrepancies in the decentralised supply chain, we have proposed a low-carbon investment sharing contract to better coordinate the supply chain members to narrow their performance discrepancies. In the following section, we validate the proposed model using numerical experiments.

IV. Numerical Demonstration

Several numerical experiments are carried out to reveal the decision discrepancies between centralised and decentralised supply chains, and then to highlight the performance of coordinated supply chain with ϕ-contract.

To help the supply chain members coordinate with each other, numerical studies will be implemented in various market situations and facility settings.

The benchmark setup is listed as follow. D_0=4000 units, b=140 units/kg, p=US$120, w=US$80, c=US$20, S_M=US$100, S_R=US$50, h_M=US$1, h_R=US$2, c_e=US$2/kg, e_{max}=20kg, e_p=40kg, P_M=1.5*D_{max}. This setup data can be applicable to an apparel manufacturer. For example, a branded woollen sweater can be sold at a price over 100$/unit at retailer such as Amazon.com, with its original material and manufacturing cost of only about 20$/unit. Indirect low-carbon investment here can be regarded as purchasing greener woollen fabric or power, combined with real market data, an additional cost per product of $2/kg or even higher can be predicted[28]. Market share is assumed to be growth with low-carbon investment. For a mature company, sales could be raised up to 13% by sustainability of business[29]. As for a developing business, the increase in market sales can be more dramatically. Therefore, we set b as 140 units/kg, which is 3.5%/kg increase of original market demand.

A. *Comparison between centralised and decentralised Supply Chain*

Based on the previous setup, the results for the decisions and profits in centralised and decentralised supply chain are shown in Table 1.

From Table 1 and Figure 1, it can be seen that the profit in the decentralised supply chain decreases 7%, along with a dramatical drop of quantity and sustainability levels, up to 28% and 94% correspondingly. This validates the conclusion that the decentralised supply chain will suffer value loss with smaller order decisions compared with the centralised supply chain. Moreover, the huge decrease in product sustainability verifies that without coordination, the supply chain cannot work well towards a green supply chain.

Besides, it is important to note that, in the decentralised supply chain, the manufacturer's profit is increased while the retailer's hampered.

Table 1. Result for Centralized and Decentralized SC

Supply Chain	π_C	π_R	π_M	Q	α
Centralized	430096.87	218537.55	211559.32	805.65	10.66
Decentralized	402109.04	162785.82	239323.22	583.10	0.66
Difference (%)	-7%	-26%	+13%	-28%	-94%

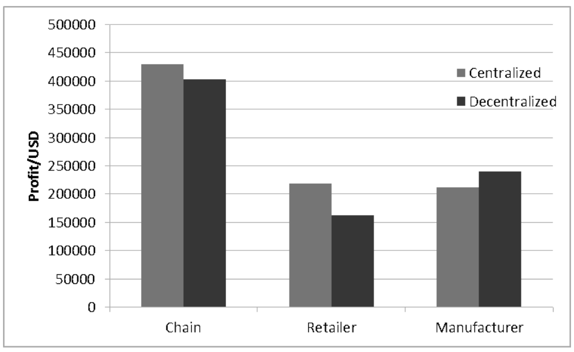

Fig. 1 Results for centralised and Decentralized SC

B. *Comparison with ϕ-contract coordinated supply chain*

To coordinate the supply chain, we assume in this section that the retailer is willing to share 30% of the investment cost of the manufacturer, *i.e.*, ϕ =0.3. The results are shown as follows:

Table 2 Comparison of Coordinated and Decentralized SC

Supply Chain	π_C	π_R	π_M	Q	α
Decentralized	402093.51	162786.25	239307.26	583.10	0.66
Coordinated	426355.44	177427.29	248928.15	530.20	7.07
Difference (%)	6%	9%	4%	-7%	965%

Table 2 shows that, with coordination, both the retailer and the manufacturer jack up their profits, meaning that this contract is win-win for both the supply chain members. Although the order quantity is reduced, the product sustainability increases nine times in comparison with the decentralised supply chain. As discussed in the previous section, although the order cost of the retailer increases, the increase in market demand by ϕ-contract brings about more revenue than the increased cost, leading to an increase in profit. For the manufacturer, the decrease in the low-carbon investment cost and the increase in market demand results in a larger increase in profit compared with the retailer.

Moreover, compared with Table 1, it is of great importance that the difference between the total profit of the decentralised and the centralised supply chains is small.

As such, the following management insight is suggested:

Management Insights 1: the uncoordinated decentralised supply chain only archives a lower production quantity and sustainability level, leading to a considerable value loss. With a low-carbon investment cost-sharing contract, both members in the supply chain can increase their profits, with a prominent increase in sustainability and a marginal decrease in order quantity. As such, the coordinated supply chain can improve the sustainability and profits of the whole supply chain.

C. *Sensitive analysis for three models*

So far, we have compared the three models under standard setups and proved the superior performance of the coordinated supply chain. Nevertheless, how profits and decisions of the three models in various market situations and facility settings will change is worth studying.

When the selling price varies from 100 to 150, the results are shown as follows:

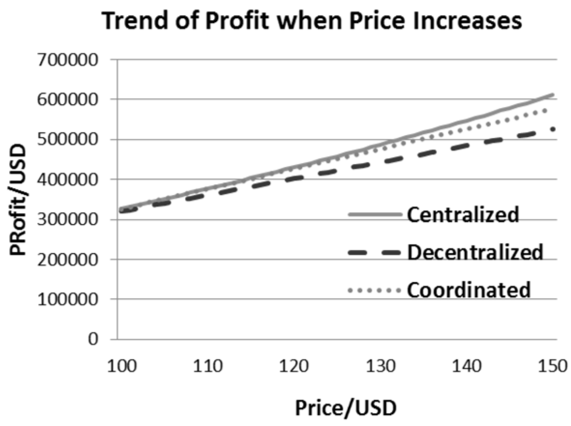

Fig. 2 Trend of Profit as Price Variations*1

*1: Centralized, decentralized and coordinated represent results of centralized supply chain, decentralised supply chain and coordinated supply chains respectively.

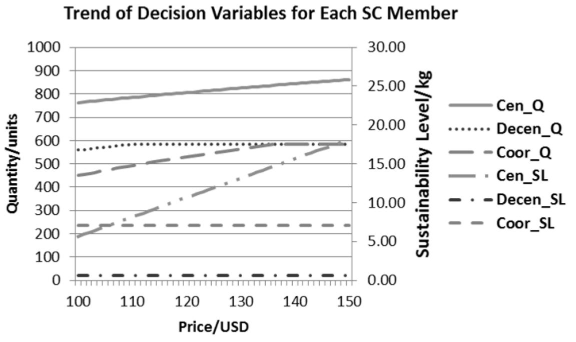

Fig. 3 Trend of Decision Variables as Price Variations[*2]

[*2]: *Cen_Q*, *Decen_Q*, and *Coor_Q* represent the quantity decisions in centralised, decentralised and coordinated supply chains respectively. *Cen_SL*, *Decen_SL* and *Coor_SL* represent the sustainability decisions of three models respectively.

From Figure 2 we can observe that, as price increases, the gap between the coordinated and centralised supply chains increases, while the gap between the coordinated and decentralised supply chains remains stable. This phenomenon can be explained by the results shown in Figure 3, in which the product sustainability for coordinated and decentralised supply chains does not change along with the price. Moreover, the difference between the quantity decisions is enlarged.

Since the wholesale price is not changed, the manufacturer's profit will not change as price increases, allowing the retailer to gain more profit. Hence we have:

Management Insight 2: Increasing the selling price will not change the product sustainability level of the coordinated and the decentralised supply chains but would enlarge their performance discrepancies.

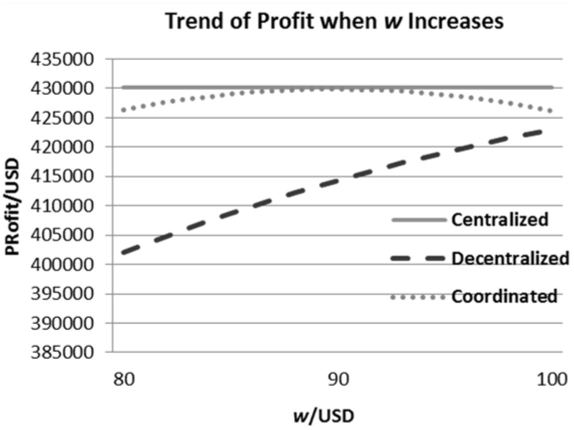

Fig. 4 Trend of Profit when Wholesale Price Varies

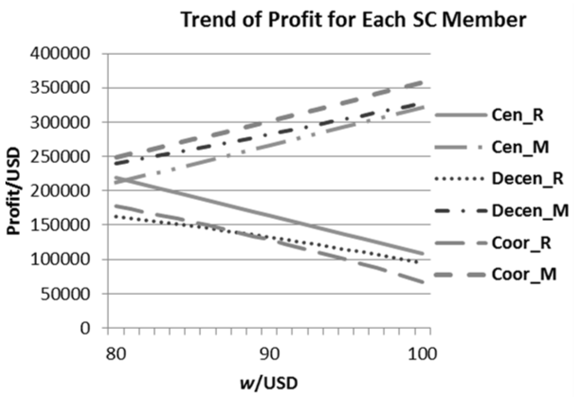

Fig. 5 Trend of Profit for SC Member as *w* varies[*3]

[*3]: *Cen_R*, *Decen_R*, and *Coor_R* represent the profit of retailer in centralised, decentralised and coordinated supply chain respectively. *Cen_M, Decen_M* and *Coor_M* represent the profit of manufacturer in the three models respectively.

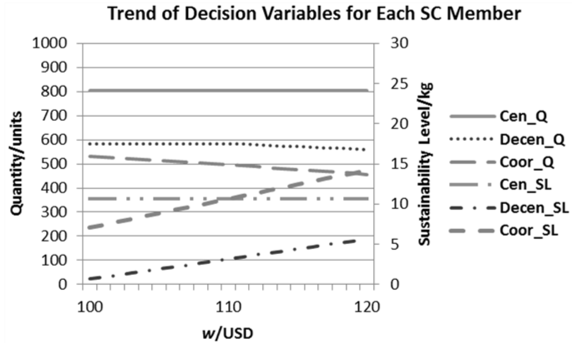

Fig. 6 Trend of Decisions for SC Members as *w* varies

As the selling price has little impact on product sustainability, we now turn to the wholesale price. Figure 4 shows the results when the wholesale price increases from 80 to 100, while Figure 5 shows the profits of the manufacturer and the retailer.

It can be seen that when the wholesale price increases, the profit of the decentralised supply chain increases. However, the profit of the coordinated supply chain tends to increase first and then decrease, meaning that there has an optimal wholesale price resulting from the coordination.

Looking into the profits of the retailer and the manufacturer separately, Figure 5 shows that when the wholesale price increases, the retailer suffers a loss while the manufacturer gains in profit. Moreover, the retailer's profit in the coordinated supply chain falls more quickly than that in the decentralised supply chain, and vice versa for the manufacturer's profit. Moreover, the order quantity in the centralised and the decentralised supply chains remains almost stable but falls slightly in the coordinated supply chain. The product sustainability, however, increases dramatically in the decentralised and the coordinated supply chains. From these observations, we propose the third management insight:

Management Insight 3: there exists an optimal wholesale price corresponding to a given cost sharing percentage. Increasing the wholesale price can drive the manufacturer to increase the product sustainability without obvious impact on quantity decision.

The profits of the retailer and the manufacturer are more likely influenced respectively by the change in the selling price and the wholesale price, and so as the order quantity and the product sustainability.

Recalling our analysis that decisions on product sustainability will be influenced by the sustainable market, it is worthwhile to study how decisions change under various sustainable markets.

Figure 7 shows the results when the sustainable market factor b changes from 140 to 300. It can be seen that the profit trends of the centralised and the coordinated supply chain are almost the same, while the gap between the profits of the centralised and the decentralised supply chain is enlarged. This phenomenon proves that no matter how sustainable market changes, the cost-sharing contract can always help keep the profit of the whole supply chain as that of the centralised one.

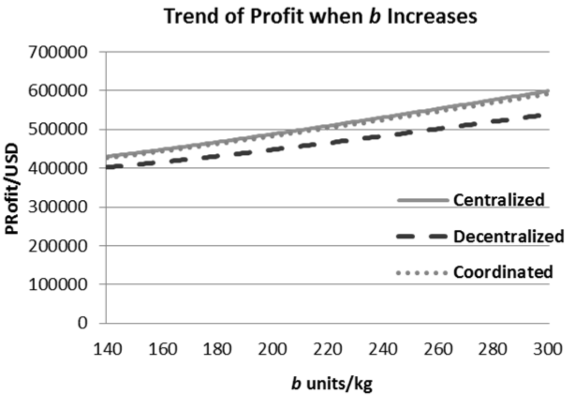

Fig. 7 Trend of profit when *b* varies

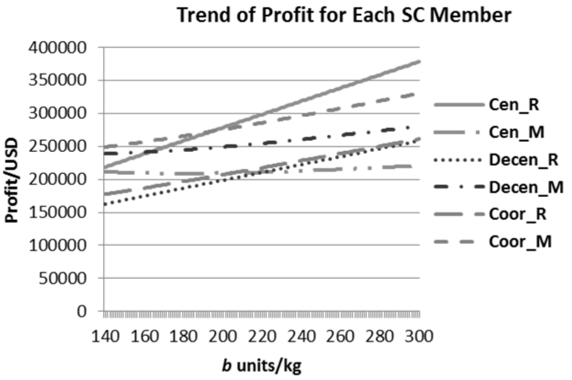

Fig. 8 Trend of Profit for SC Member as *b* varies

Moreover, as shown in Figure 8, the manufacturer in the coordinated supply chain benefits more from the boost of the sustainable market factor than in the decentralised supply chain. The sustainability level for three models shows the similar increasing trend, as shown in Figure 9.

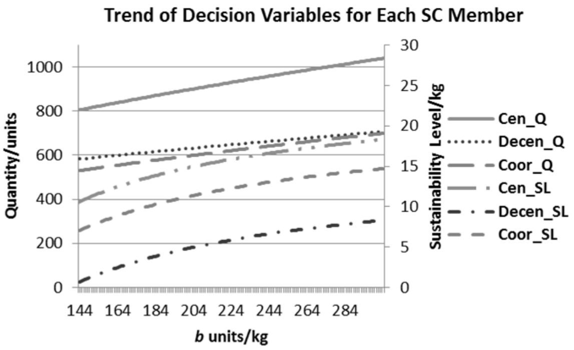

Fig. 9 Trend of Decisions for SC Member as *b* varies

This means that the impact of customer green awareness on demand can drive even the most unwilling manufacturer to increase the product sustainability. With feasible coordination, the product sustainability can almost triple that of the uncoordinated supply chain, and the order quantity also increases, despite less dramatically. Hence we have:

Management insight 4: Sharing of low-carbon investment cost works well under all kinds of sustainable markets, in which the manufacturer tends to benefit more than the retailer.

Nevertheless, it is important to study how to choose the cost-sharing factor ϕ. From our analysis, we know that ϕ will be constrained by *proposition 4*, but we have yet to find out whether or not the larger the ϕ, the better the coordination, for all feasible ϕ. When ϕ varies from 0.01 to 0.44, which is the largest factor we can choose for this setting in numerical study, the results are shown as follows:

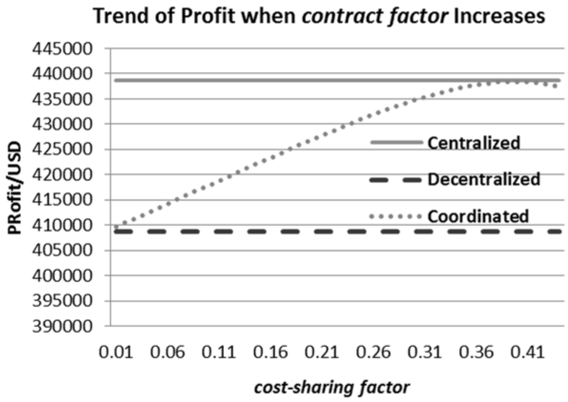

Fig. 10 Trend of profit when ϕ varies

From Figure 10, we can find the gap between the centralised and decentralised supply chain. As increases, the gap will be narrowed firstly and reach its best performance at ϕ=0.4. A comparison of the profit when ϕ is between 0.39 and 0.41 is shown in Table 3. The discrepancies between the centralised and the coordinated supply chains can be narrowed to only within 0.06%. This result further validates the feasibility and superior performance of the low-carbon investment cost-sharing contract.

Table 3 Comparison of profit for optimal ϕ

ϕ	0.39	0.40	0.41
Centralized SC	438737.9	438737.9	438737.9
Coordinated SC	438420.8	438455.5	438384.1
Difference	0.07%	0.06%	0.08%

Under the standard setting, it is optimal for the retailer to share 40% of the low-carbon investment cost for the manufacturer to optimise the chain's value. After that, the performance of the contract will reduce, proving that increasing ϕ is not always conducive to the performance of the whole supply chain.

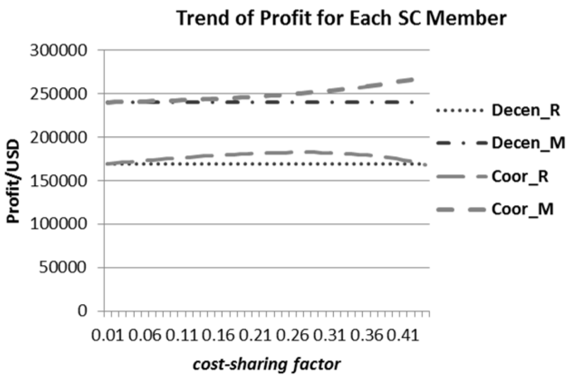

Fig. 11 Trend of Profit for SC Members as ϕ varies

Furthermore, according to the profit trend shown in Figure 11, the manufacturer's profit always increases with ϕ, while the retailer's profit is concave with ϕ, exhibiting an optimal factor. Apparently, the optimal ϕ for the retailer is different from the one for optimising the profit of the whole supply chain. Since the contract is proposed by the retailer, certainly he/she will choose the factor ϕ to optimise its own profit. Meanwhile for the manufacturer, as long as there is a cost-sharing contract offered from the retailer, the manufacturer would accept it, because this contract always increases his/her profit. Therefore, the negotiated contract factor ϕ is the one to optimise the retailer instead of the supply chain.

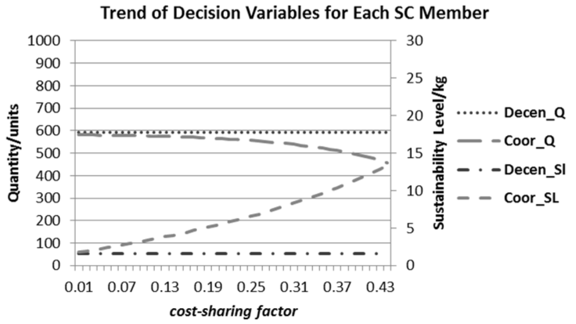

Fig. 12 Trend of Decisions for SC Members as ϕ varies

For the decision variables, the order quantity, and the product sustainability will decrease and increase both at an accelerated rate respectively, as shown in Figure 12. As such, we have:

Management Insight 5: The optimal contract factors ϕ for the whole supply chain and for the retailer are different. The negotiated contract factor ϕ will be dictated by the retailer, who will certainly choose the one to optimise his/her profit, instead of that of the whole supply chain.

V. Conclusion

This paper studies three kinds of supply chains based on EOQ model, namely the centralised, decentralised and coordinated supply chains. In the supply chain, the retailer orders a quantity of Q each turn from the manufacturer, who will subsequently produce with a lot-to-lot policy. The impacts on market demand of the consumer green awareness about the product sustainability, measured by the emission reduction per product, is considered. It is assumed that the manufacturer will make the low-carbon investment, despite at increased production cost, to increase product sustainability. To facilitate the study of the supply chain, we characterised the centralised supply chain as an idealised benchmark, and compare it with the decentralised one, in which retailer is assumed to be the leader and the manufacturer the follower.

It was found that there exist optimal solutions correspondingly for the centralised and the decentralised supply chain, as well as discrepancies among their decisions and optimal profits. Moreover, the profit, quantity and product sustainability in the decentralised supply chain are all smaller than those of the centralised supply chain.

As such, a low-carbon cost investment sharing contract was proposed for the retailer to provide motivation for the manufacturer to increase the product sustainability.

In numerical studies, we compared the profits for three models, showing the discrepancies in the decentralised supply chain and the performance of the cost-sharing contract. Moreover, sensitive analyses were carried out for selling price, wholesale price, sustainable market factor and the contract factor. Several management insights were proposed to facilitate decision making for the whole supply chain. It is emphasised that increasing the wholesale price, sustainable market factor and contract factor all leads to the enhancement sustainability.

With the help of a cost-sharing contract, the supply chain can increase its profit as well as product sustainability dramatically, which is win-win for both members under various market situations.

Nevertheless, there are some limitations which should be addressed in further development. First, it would be worthwhile to derive the mathematical solution to the optimal contract factor for more accurate decision for the retailer. Second, impacts of carbon policies should be taken into consideration. Third, the study for the wider range of supply chain should be considered and the EOQ-based supply chain with multi-shipment can be considered for more practical implementation. Finally, the product brand image should be studied and modelled to quantify the impacts of customer green awareness about product sustainability.

Appendix

Lemma 1:

$D_C^+ = \frac{b}{2c_e}(m_c - \frac{S_c}{Q} - \frac{Qh_M}{2P_M} + \frac{c_e}{b}D_0)$, *in which* $\frac{S_c}{Q} + \frac{Qh_M}{2P_M} \geq \sqrt{\frac{2S_c h_M}{P_M}}$ *when* $Q_C^o = \sqrt{\frac{2P_M S_C}{h_M}}$. *Therefore* D_C^+ *is bounded by* $[D_0,\ \min\{D_{\max}, D_c^o\}]$. *For* Q^+, *it is easy to prove that* $Q_C^o > Q_C^+(D_{\max})$ *and hence its feasible region is* $[Q_C^+(D_0),\ Q_C^+(D_{\max})]$.

Proposition 1:

For $\frac{\partial^2 \pi_C}{\partial Q^2}$, *obviously when* $Q \leq \sqrt{\frac{2P_M S_C}{h_M}}$, *which is larger than* Q_C^o, $\frac{3S_c^{\ 2}}{Q} + \frac{h_M^{\ 2}}{4P_M}Q^3 - 2S_C(m_c + \frac{c_e}{b}D_0)$ *is decreasing.*

Besides, $\frac{\partial^2 \pi_C}{\partial Q^2}$ *can also be written as:*

$$\frac{\partial^2 \pi_C}{\partial Q^2} = (\frac{\partial D_C^+(Q)}{\partial Q})^2 + D^+(Q)\frac{\partial^2 D_C^+(Q)}{\partial Q^2}$$

When $Q = Q_C^o$, $\frac{\partial D_C^+(Q)}{\partial Q} = 0$, $D_C^+(Q)\frac{\partial^2 D_C^+(Q)}{\partial Q^2} < 0$ *and* $\frac{\partial^2 \pi_C}{\partial Q^2} < 0$.

We prove that $\frac{3S_c^{\ 2}}{Q} + \frac{h_M^{\ 2}}{4P_M}Q^3 - 2S_C(m_c + \frac{c_e}{b}D_0)$ *is decreasing in the feasible region of Q and* $\frac{\partial^2 \pi_C}{\partial Q^2}$ *will be negative when* $Q = Q_C^o$. *Therefore,* $\frac{\partial \pi_C}{\partial Q}$ *will be either monotonously decrease or monotonously increase first then monotonously decrease.*

With the assumption that $\frac{\partial \pi_C}{\partial Q}|_{Q=Q_{\min}} > 0$ *and the fact that* $\frac{\partial \pi_C}{\partial Q}|_{Q=Q_C^o} = -\frac{h_R}{2} < 0$, *there exists a unique solution to* $\frac{\partial \pi_C}{\partial Q} = 0$. *If* $\frac{\partial \pi}{\partial Q}|_{Q=Q_{\min}} < 0$, $\frac{\partial \pi}{\partial Q}$ *will be smaller than 0 in the feasible region. Therefore the optimal solution is* $Q^+(D_0)$.

Proposition 2: It can be easily derived from the expression of $\frac{\partial^2 \pi_R}{\partial Q^2}$.

Proposition 4:

$$\frac{\partial^2 \pi_R^{\phi}}{\partial Q^2} = \frac{\partial^2 D_M^{\phi+}}{\partial Q^2}(m_R + \frac{\phi c_e}{b}(D_0 - D_M^{\phi+}) - \frac{S_R}{Q}) - \frac{2\phi c_e}{b}(\frac{\partial D_M^{\phi+}}{\partial Q})^2$$

$$-\frac{\phi c_e}{b}\frac{\partial^2 D_M^{\phi+}}{\partial Q^2} D_M^{\phi+} - \frac{2S_R}{Q^3} D_M^{\phi+}$$

For $-\frac{\phi c_e}{b}\frac{\partial^2 D_M^{\phi+}}{\partial Q^2} D_M^{\phi+} - \frac{2S_R}{Q^3} D_M^{\phi+}$, *it can be expressed as* $-\frac{D_M^{\phi+}}{Q^3}(2S_R - \frac{\phi}{1-\phi} S_M)$, *therefore when* $2S_R - \frac{\phi}{1-\phi} S_M$ *is positive,* $-\frac{\phi c_e}{b}\frac{\partial^2 D_M^{\phi+}}{\partial Q^2} D_M^{\phi+} - \frac{2S_R}{Q^3} D_M^{\phi+}$ *will be negative.*

When $(m_R + \frac{\phi c_e}{b}(D_0 - D_M^{\phi+}) - \frac{S_R}{Q})$ *is negative, obviously the whole expression is negative.*

REFERENCE

[1] C2es.org. (2015, 18 DEC. 2015). *Industrial Overview | Center for Climate and Energy Solutions.* . Available: http://www.c2es.org/energy/use/industrial

[2] M. C. Cassi Wright, Tara Norton. (2016). *From Agreement to Action: Mobilizing suppliers toward a climate resilient world*.

[3] Z. Liu, "China's Carbon Emissions Report 2015," *Harvard Kennedy School: Cambridge, UK,* 2015

[4] C. D. Project. (2015). *Carbon Action Report 2015*. Available: https://www.cdp.net/zh/research/global-reports/carbon-action-report-2015

[5] (2008, Product carbon footprinting: the new business opportunity. Available: https://www.carbontrust.com/media/84928/ctc744-product-carbon-footprinting-the-new-business-opportunity.pdf

[6] G. Edwards-Jones, K. Plassmann, E. York, B. Hounsome, D. Jones, and L. M. i Canals, "Vulnerability of exporting nations to the development of a carbon label in the United Kingdom," *environmental science & policy,* vol. 12, pp. 479-490, 2009.

[7] A. I. Jaakko Kooroshy, Brian Lee, Derek R. Bingham, Warwick Simons. (2015, The Low Carbon Economy. *(Goldman Sachs Global Investment Research)*. Available: http://www.goldmansachs.com/our-thinking/pages/new-energy-landscape-folder/report-the-low-carbon-economy/report.pdf

[8] Solarcellcentral.com. (2015, 19 DEC.). *Solar Electricity Cost vs. Regular Electricity Cost*. Available: http://solarcellcentral.com/cost_page.html

[9] S. Baldwin, "Carbon footprint of electricity generation," *London: Parliamentary Office of Science and Technology,* vol. 268, 2006.

[10] H. C. Aleyn Smith-Gillespie. (2016, Supply Chain Transformation and Resource Efficiency, how can big businesses save billions? Available: https://www.carbontrust.com/resources/reports/advice/supply-chain-transformation-and-resource-efficiency/

[11] D. Battini, A. Persona, and F. Sgarbossa, "A Sustainable EOQ Model: theoretical formulation and applications," *International Journal of Production Economics,* vol. 149, pp. 145-153, 2014.

[12] T. M. Choi, "Handbook of EOQ inventory problems," *AMC,* vol. 10, p. 12, 2014.

[13] Y. Zhao, S. Choi, X. Wang, and A. Qiao, "Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering 2016, WCE 2016, 29 June - 1 July, 2016, London, U.K.," pp. 641-646.

[14] S. Benjaafar, Y. Li, and M. Daskin, "Carbon footprint and the management of supply chains: Insights from simple models," *Automation Science and Engineering, IEEE Transactions on,* vol. 10, pp. 99-116, 2013.

[15] N. Absi, S. Dauzère-Pérès, S. Kedad-Sidhoum, B. Penz, and C. Rapine, "Lot sizing with carbon emission constraints," *European Journal of Operational Research,* vol. 227, pp. 55-61, 2013.

[16] Y. Yu, Z. Hong, C. Chu, and L. Liang, "A dynamic lot sizing model with carbon emission constraint and multi-mode production: A general property and a polynomially solvable case," in *Networking, Sensing and Control (ICNSC), 2013 10th IEEE International Conference on,* 2013, pp. 413-417.

[17] A. Toptal and B. Çetinkaya, "How supply chain coordination affects the environment: a carbon footprint perspective," *Annals of Operations Research,* pp. 1-33, 2015.

[18] M. Y. Jaber, C. H. Glock, and A. M. El Saadany, "Supply chain coordination with emissions reduction incentives," *International Journal of Production Research,* vol. 51, pp. 69-82, 2013.

[19] T. S. Schmidt, "Low-carbon investment risks and de-risking," *Nature Climate Change,* vol. 4, pp. 237-239, 2014.

[20] H. X. Wang Hailin, Zhang Xiliang, "A Comparative Analysis of the Post-2020 CO2 Emission Reduction Target Set by China and the United States," *ANNUAL REVIEW OF LOW-CARBON DEVELOPMENT IN CHINA (2015-2016),* 2015.

[21] E.-H. Kim and T. P. Lyon, "When does institutional investor activism pay? The Carbon Disclosure Project," *Unpublished Working Paper,* 2007.

[22] S. Zanoni, L. Mazzoldi, L. E. Zavanella, and M. Y. Jaber, "A joint economic lot size model with price and environmentally sensitive demand," *Production & Manufacturing Research,* vol. 2, pp. 341-354, 2014.

[23] A. Toptal, H. Özlü, and D. Konur, "Joint decisions on inventory replenishment and emission reduction investment under different emission regulations," *International Journal of Production Research,* vol. 52, pp. 243-269, 2014.

[24] D. Ghosh and J. Shah, "A comparative analysis of greening policies across supply chain structures," *International Journal of Production Economics,* vol. 135, pp. 568-583, 2012.

[25] Z. L. Liu, T. D. Anderson, and J. M. Cruz, "Consumer environmental awareness and competition in two-stage supply chains," *European Journal of Operational Research,* vol. 218, pp. 602-613, 2012.

[26] (2014, Why companies need emissions reduction targets. Available: https://b8f65cb373b1b7b15feb-c70d8ead6ced550b4d987d7c03fcdd1d.ssl.cf3.rackcdn.com/cms/reports/documents/000/000/848/original/Carbon-action-report-2014.pdf?1472035953

[27] A. Banerjee, "A joint economic-lot-size model for purchaser and vendor," *Decision sciences,* vol. 17, pp. 292-311, 1986.

[28] R. Kirchain, E. Olivetti, T. R. Miller, and S. Greene, "Sustainable Apparel Materials," 2015.

[29] S. G. Sheila Bonini. (2011, The Business of Sustainability: Putting it into Practice. Available: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/the-business-of-sustainability-mckinsey-global-survey-results