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Collaborative carbon emission reduction in supply chains : an evolutionary game-theoretic study

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**Collaborative carbon emission reduction in supply chains:
an evolutionary game-theoretic study**

Abstract

Purpose: This paper employs an emerging phenomenon in China concerning collaborative carbon emission reduction (CCER) to investigate: firstly, the coordination of suppliers and manufacturers within supply chains to reduce carbon emissions, and secondly, the role of governmental policy in facilitating this process.

Design/methodology/approach: This paper draws upon evolutionary game theory (EGT) to develop an evolutionary game model for CCER for suppliers and manufacturers within supply chains. This includes a detailed analysis of the evolutionary direction and process in different areas, both with, and in the absence of, governmental subsidies.

Findings: The results demonstrate that CCER is path dependent and that its evolutionary process is influenced by the following four factors: (1) the initial status within supply chains; (2) the cost; (3) the additional benefit; and (4) the investment risk related to CCER. The research also reveals that the reward provided by manufacturers is rational over the long term, due to the excessive cost of incentives potentially preventing the implementation of CCER.

Originality/Value: This study represents the first attempt to investigate CCER within supply chains through the application of an evolutionary game-theoretic model. The investigation of multiple factors in the model will deepen understanding of the collaborative role required for the carbon emission reduction.

Keywords: collaborative carbon emission reduction; evolutionary game theory; supply chains; governmental policy

1. Introduction

The concept of a Circular Economy (CE) is driven by the skills required for a more sustainable economy and, as such, has attracted growing attention from a variety of stakeholders, i.e. governments, communities and customers (Geissdoerfer *et al.*, 2017; Genovese *et al.*, 2017). CE is designed to eliminate waste through cycles of assembly, use, disassembly and reuse, with virtually no leakages from the system, in terms of disposal or recycling (Spring and Araujo, 2017). However, CE can have an unintended negative impact on business sustainability. The recycling and reuse of certain materials demands the redesign of a product, including for manufacturers to replace many materials with those that are eco-friendly, while also modifying aspects of their processes to reuse certain materials. These actions can have a potentially negative impact on the environment, particularly as inefficient technologies employed in processing these new materials can lead to increased consumption of energy (Gurtoo and Antony, 2007). This is exemplified by Knight *et al.* (2005), who compared the environmental effect of wooden and steel doors, identifying that, while the reuse of steel saves wood, the processing involved in steel doors leads to a significant increase in energy consumption and environmental pollution. Therefore, in order to build greater CE, it is essential for businesses to improve their ability to reduce carbon emissions (European Climate Foundation, 2018).

The reduction of carbon emission can create a more effective CE by helping firms to conserve energy and manufacture more environmentally-friendly products (Bansal and Hoffmann, 2012). In addition, decarbonisation can assist companies in increasing market demand and reducing their production costs in emerging economy, such as China. For example, in response to these benefits, the Chinese government has dedicated itself to the design of a penalty mechanism, i.e. cap-and-trade, aimed at motivating firms to invest in carbon reduction technologies (Liu *et al.*, 2018; Wu *et al.*, 2016).

However, manufacturers are prevented from reducing the carbon emissions in an effective manner by a number of obstacles, i.e. high operational costs and the high demand for sustainable technologies. As identified by Huang *et al.* (2016), some companies, particularly those based in China, face additional obstacles to the reduction of carbon emissions, including: (1) insufficient enforcement; (2) insufficient levels of information; and (3) insufficient regulation systems. A manufacturer can seek help from supply chains to overcome these obstacles and achieve its sustainability objectives in a more efficient manner, i.e. a collaborative management of reducing carbon emissions (Chaabane *et al.*, 2012). Theißen *et al.* (2014) indicated that collaborative carbon reduction in supply chains can result

in a greater reduction of energy costs for suppliers and manufacturers, as well as satisfying the expectations of their customers, thus improving their reputation and alleviating the risks associated with climate change. This finding has been supported by industrial practices, with Walmart launching a sustainability platform to eliminate one gigaton of emissions in its global supply chains by the end of 2030 (Walmart, 2017) and further multi-national corporations (e.g. IBM) focussing on supporting their suppliers to develop and implement approaches to the reduction of carbon emissions (Paterson, 2014).

Within this context, there is a clear need for research into the adoption of collaborative carbon emission reduction (CCER) by companies working within supply chains. A number of studies have previously examined the impact of CCER on suppliers and manufacturers from various different perspectives based on classical game theory, i.e. order, inventory, the delivery process and investment in carbon reduction (e.g. Bazan *et al.*, 2017; Hua *et al.*, 2011; Jaber *et al.*, 2013; Palak *et al.*, 2014; Toptal *et al.*, 2014; Wahab *et al.*, 2011;). However, there has, to date, been a lack of research into the following issues: firstly, why individuals are motivated to obtain short-term payoffs during the process of CCER implementation by ignoring the interests of other members; and secondly, the methods they employ to evolve their strategies to focus on long-term benefits.

This study attempts to fill this gap by drawing upon evolutionary game theory (EGT) to understand the initial configuration of multiple subjects in CCER implementation, as well as the ways payoff related factors (i.e. cost, additional benefits, investment risks and governmental subsidies) can influence CCER. In particular, with reference to the emerging phenomenon on CCER under the cap-and-trade programme in China, this research is intended to deepen understanding of the collaborative role in carbon emission reduction by answering the following three research questions:

RQ1: How does the initial configuration of multiple subjects influence the implementation of CCER?

RQ2: How do various payoff-related factors influence the implementation of CCER?

RQ3: What is the role of governmental policy in facilitating CCER?

This paper offers a twofold contribution to the literature. Firstly, this study draws on EGT to identify how the initial proportion of strategic choice influences the implementation of CCER within supply chains. This identification can assist the government in understanding when to motivate firms to implement CCER and which factors are capable of influencing the efficacy of environmental policies. Secondly, the use of evolutionary game-theoretical analysis identifies the influence of factors related to cost and revenue on the implementation of CCER,

i.e. the initial carbon reduction investment and the operational fees related to collaboration. An examination of these factors can help firms decide whether or not to implement CCER, while also identifying on which factors to focus during a specific period of time.

The remainder of this paper is organised as follows: Section 2 discusses previous research in related fields. Section 3 provides an evolutionary game analysis of CCER, omitting the use of governmental subsidies. Section 4 examines the evolutionary direction and process of CCER when the government provides subsidies to focal companies. Section 5 undertakes the discussion and Section 6 outlines the limitations and future direction of study.

2. Related literature

As an effective method of improving the efficiency of carbon emission reduction, CCER has attracted considerable attention in the academic field. Existing studies on this regard can be divided into two streams: (1) double subject based CCER (Bazan *et al.*, 2017; Chen *et al.*, 2013; Hua *et al.*, 2016; Jaber *et al.*, 2013; Manikas and Kroes, 2015; Toptal *et al.*, 2014) and (2) multi-subject based CCER (Benjaafar *et al.*, 2013; Glock and Kim, 2015; Nurjanni *et al.*, 2017; Peng and Shiang, 2014; Shiraki *et al.*, 2016), of which the latter has a greater amount of related literature. The collaborative field of multi-subject based CCER does not limit the order cycle time or quantity, along with its production, emission reduction technology and new business models. In addition, this collaborative field can also be extended to: (1) the delivery process; (2) the location of suppliers; and (3) the choice of suitable partners.

2.1 Double subject based CCER

Prior research has explored how both upstream and downstream aspects can collaborate to reduce carbon emissions. For example, Chen *et al.* (2013) examined collaboration between suppliers and manufacturers to reduce their carbon emission costs without significantly increasing their overall cost. The study demonstrated the influence of various factors on the scale of emission reduction (i.e. operational adjustment; the tax rate; the level of emission penalties; and the carbon price), as well as the cost of various mechanisms, including carbon tax, cap-and-offset and cap-and-price. Hua *et al.* (2011; 2016) and Wahab *et al.* (2011) investigated how members within supply chains can reduce carbon emissions through the control of the order cycle time and quantity. Their results indicated that the frequency of orders tend to decrease, but, when the reduction of carbon emissions is taken into account, the optimal levels of orders can be seen to increase.

Jaber *et al.* (2013) established a two-echelon (i.e. vendor-buyer) supply chain model, containing a coordination mechanism to study members' optimal decisions, in order to examine the effectiveness of different emission trading schemes. Their study revealed that

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members of a supply chain can reach optimal production decisions under various different emission trading schemes. However, Toptal *et al.* (2014) and Dong *et al.* (2016) explored the collaborative investment of supply chain members into carbon reduction technology in different mechanisms. Toptal *et al.* (2014) found that members within the supply chain are more motivated to invest in environmental technologies containing tax or cap-and-trade policies than those subject to a cap policy. Similarly, Dong *et al.* (2016) claimed that the taking of joint decisions can assist supply chain members to reduce their production costs and increase their investment into carbon emission reduction technologies. Bazan *et al.* (2017) outlined how a manufacturer and a retailer remanufactured used items in a new VMI-CS coordination business model, identifying that the new collaboration model resulted in longer manufacturing and recovery times, but lower levels of emission and energy usage.

In summary, the above studies illustrate that carbon emissions can be effectively reduced through collaboration between an upstream and a downstream, and that the collaborative field could focus on: (1) the order cycle time (Manikas and Kroes 2015); (2) order quantity and production (Du *et al.*, 2013; Zhang and Xu, 2013); (3) investment into emission reduction (Swami and Shah, 2013).

2.2 Multi-subject based CCER

CCER has also been investigated in supply chains constructed by a single upstream and multi-downstream, or multi-upstream and a single downstream. For example, Benjaafar *et al.* (2013) investigated how collaboration between firms within supply chains influences their costs and carbon emissions, as well as the benefits of investment into carbon efficient technologies. They found that, in comparison to individual initiatives for carbon emission reduction, multi-subject based CCER results in lower costs and a more visible impact. Chaabane *et al.* (2012) demonstrated that, within the setting of a global supply chain, there can be an effective reduction of carbon emissions resulting from production created by a collaboration between multiple subjects. In their study, a Mixed-integer Linear Program (MIP) assisted the manager with the adoption of optimal strategies in relation to differing carbon reduction mechanisms.

Like the production process, the delivery process produces a large amount of carbon emissions, with transportation resulting in approximately 19% of global energy consumption, and 25% of energy-related carbon emissions (Palak *et al.*, 2014). Some studies have investigated this phenomenon in terms of how supply chain members can reduce carbon emissions by improving their fuel efficiency, selecting suitable methods of transportation and vehicle routines, as well as optimal locations (Glock and Kim, 2015; Shiraki *et al.*, 2016). In

general, local suppliers tend to be preferred when the cost of carbon reduction rises, along with higher levels of investment into carbon reduction technology. In addition, the effectiveness of carbon emission reduction can be influenced by a number of human related factors. It is therefore essential to put in place a decision support system for the selection of appropriate partners (i.e. suppliers, delivery companies and manufacturers), particularly as an optimal combination of partners can lead to a more efficient reduction in carbon emissions (Peng and Shiang, 2014). In addition, multi-subject based CCER contains a greater number of collaborative fields, i.e. the delivery process, the location of suppliers and the choice of suitable partners.

2.3 Aims of this study

The review of existing CCER literature has identified the existence of additional collaborative aspects to multi-subject based CCER. Such studies assume that all members of supply chains are motivated to implement CCER - this is inconsistent with conditions in the real world. Thus, some members of supply chains can lack awareness of the benefits of implementing CCER, due to being constrained by limited perceptual and computational capabilities (Shubik, 2002). Therefore, CCER is characterised by path dependence, i.e. companies can, over time, take a more professional approach to the adoption of CCER (Theißen *et al.*, 2014). Furthermore, CCER has a strong positive externality, with all participants in a supply chain motivated to follow suit, namely, they are willing to enjoy the revenue from invest in CCER made by their fellow members. However, it appears that previous research in the field has neglected this factor.

Recently, a number of studies have considered these issues by adopting EGT. Rather than focusing on the supply chain perspective, they have explored how two similar entities (e.g. air conditioner firms) can engage in a mutual gamble in adopting carbon reduction strategies (Zhao *et al.*, 2016) and how governments gamble with firms to achieve optimal equilibrium in reducing carbon emissions (Wu *et al.*, 2017). By contrast, this study analyses the implementation of CCER from the perspective of both the supply chain and EGT.

Table 1 makes a detailed comparison of existing research regarding CCER. It demonstrates that studies using the newsvendor, general game model and Economical Quantity Order (EOQ) model focus on double subject based CCER. However, studies employing Mixed Integer Programming (MIP) is concerned with a single upstream and multi-downstream, or multi-upstream and a single downstream based CCER. This current study differs from such previous studies in examining how multi-upstream and multi-downstream collaboratively manage carbon emissions over time. In addition, unlike

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previous research separately exploring the economic and environmental optimisation of CCER (Chaabane *et al.*, 2012; Du *et al.*, 2013; Swami and Shah, 2013), this study has a concentration of both its economic and environmental optimisation. Furthermore, when it comes to the collaborative field, the focus of the study is on a number of aspects that have not previously been simultaneously explored: (1) revenue; (2) cost; (3) operational risk; and (4) investment into carbon reduction (See Table 1).

Insert Table 1 About Here

3. Evolutionary game analysis of CCER

Appendix A outlines the basic assumptions of evolutionary game analysis. The potential strategy for suppliers (*S*) and manufacturers (*M*) is assumed to consist of either cooperation or non-cooperation. When manufacturers effectively undertake CCER (i.e. cooperation strategy), they share with their suppliers both energy conservation and emission reduction technologies, along with providing incentives for the reduction of carbon emissions. However, when manufacturers fail to implement CCER (i.e. non-cooperation strategy), they refuse to share energy conservation and emission reduction technologies, or to provide the necessary funds to encourage suppliers to increase their own investment into emission reduction technologies.

Similarly, when suppliers cooperate with manufacturers to reduce carbon emissions (i.e. cooperation strategy), they choose to share carbon emission reduction technologies with their manufacturers and offer cooperation in setting up a collaborative mechanism to reduce carbon emissions. However, if the suppliers fail to adopt CCER (i.e. non-cooperation strategy), they refuse to share carbon emission reduction technologies with manufacturers and also lack any motivation to set up a collaborative mechanism to reduce emissions. Correspondingly, the suppliers are then unable to benefit from incentives from their manufacturers.

3.1 Pay off matrix

In the payoff matrix, π_S and π_M form the normal payments made when suppliers and manufacturers fail to implement CCER. ΔV_S and ΔV_M are the additional payments made when suppliers and manufacturers work together to reduce emissions. During the process of CCER implementation, suppliers and manufacturers have separate initial investment costs C_S and C_M . When both the suppliers and manufacturers select to implement CCER, they need to

separately pay the operational fees C_{OS} and C_{OM} . Unlike suppliers, manufacturers are faced with a direct burden from customers desiring them to demonstrate increased social responsibility. This motivates them to offer suppliers incentives to undertake additional investment in carbon emission reductions (S). Both manufacturers and suppliers should be able to obtain revenue to cover the costs of the process of CCER implementation, i.e. the initial investment and the operational and incentive fees. Hence, the additional revenue is higher than investment in CCER, i.e. $\Delta V_S > C_S + C_{OS} - S$ and $\Delta V_M > C_M + C_{OM} + S$. The corresponding payoff matrix is presented in Table 2.

Insert Table 2 About Here

3.2. Revenue analysis of manufacturers and suppliers

1) Suppliers

When the suppliers S choose to reduce carbon emissions with manufacturers in a collaborative manner, the replicated dynamic equation of the suppliers is as follows:

$$\frac{d\alpha}{dt} = \alpha(U_{S1} - \bar{U}_S) = \alpha(1 - \alpha)[(\Delta V_S - C_{OS} + S + R_S)\beta - C_S - R_S] \quad (1)$$

2) Manufacturers

When manufacturers fail to cooperate with suppliers, the replicated dynamic equation of manufacturers is as follows:

$$\frac{d\beta}{dt} = \beta(U_{M1} - \bar{U}_M) = \beta(1 - \beta)[(\Delta V_M - C_{OM} - S + R_M)\alpha - C_M - R_M] \quad (2)$$

3.3 Stability analysis of equilibrium point

A simultaneous equation can be constructed using equations (1) and (2). The five systematic partial equilibriums are $O(0,0)$, $A(0,1)$, $B(1,1)$, $C(1,0)$ and

$$D\left(\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S}, \frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S}\right).$$

According to the assessment method provided by the *Jacobian* matrix, partial derivatives are taken for $\frac{d\alpha}{dt}$ and $\frac{d\beta}{dt}$, with the *Jacobian* matrix subsequently presented in equation (3). The equilibrium points were further analysed using the *Jacobian* matrix. The analysis is shown in Table 3.

$$J = \left[\begin{array}{cc} (1-2\alpha)[(\Delta V_S - C_{OS} + S + R_S)\beta - C_S - R_S] & \alpha(1-\alpha)(\Delta V_S - C_{OS} + S + R_S) \\ \beta(1-\beta)(\Delta V_M - C_{OM} - S + R_M) & (1-2\beta)[(\Delta V_M - C_{OM} - S + R_M)\beta - C_M - R_M] \end{array} \right] \quad (3)$$

Insert Table 3 About Here

The analysis of the five equilibrium points reveals that the partial equilibrium point $D(\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S}, \frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S})$ depends on the following four factors: (1) the initial status of the evolutionary game system; (2) the risk of loss; (3) initial investment and (4) additional payment of CCER. $O(0,0)$ and $B(1,1)$ (i.e. (Non-cooperation, Non-cooperation) and (Cooperation, Cooperation)) form two equilibrium points. Specifically, when the system reaches an evolutionary endpoint, this results in two possible outcomes from the final strategy adopted by both suppliers and manufacturers: (1) they all implement CCER, or (2) none of them implements CCER.

Equations (1) and (2) can separately obtain the phase image for suppliers and manufacturers. For suppliers: Firstly, the choice of cooperation strategy depends on the initial proportion of manufacturers whose strategy is cooperation (β). Secondly, when the initial proportion β is higher than $\frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S}$, all suppliers will finally choose the cooperation strategy (See Fig. 1(a)). If β is lower than $\frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S}$, all the suppliers will prefer the non-cooperation strategy (See Fig. 1 (b)). Finally, when β is equal to $\frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S}$, the suppliers may choose either a cooperation or non-cooperation strategy (See Fig.1(c)).

Similarly, when it comes to manufacturers, the motivation to choose a cooperation strategy depends on the initial proportion of suppliers whose strategy is that of cooperation (α). When α is higher than $\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S}$, all manufacturers are inclined to choose the cooperation strategy (See Fig. 2(a)). However, if α is lower than $\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S}$, they tend to choose the non-cooperation strategy (See Fig. 2(b)). Finally, when α is equal to $\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S}$, manufacturers may select either a cooperation or non-cooperation strategy (See Fig. 2(c)).

Insert Fig. 1 About Here

Insert Fig. 2 About Here

3.4 Factor analysis of CCER

This study provides a number of numerical examples to illustrate the mechanism of CCER, indicating how suppliers and manufacturers adopt CCER strategies under different circumstances. More specifically, there is an examination of the impact on the evolutionary process of CCER on: (1) different initial proportions of CCER implementation; (2) operational costs; (3) investment risks; (4) additional revenue; and (5) incentives.

In all numerical examples, the evolutionary time period is set as $[0, 100]$, and the initial numerical values are separately set as:

$(0.7, 0.1)$, $(0.4, 0.5)$, $(0.6, 0.4)$, $(0.9, 0.1)$, $(0.1, 0.7)$, $(0.4, 0.6)$ and $(0.1, 0.9)$.

The other values are set as:

$\Delta V_S = 7$, $C_S = 1$, $C_{OS} = 3$, $R_S = 2$, $\Delta V_M = 9.5$, $S = 0.3$, $C_M = 1.2$, $C_{OM} = 3.5$, $R_M = 1.5$, $R_S = 2$.

In this section, Fig. 3, Fig. 5, and Fig. 7 are evolutionary game sketches. Fig. 4, Fig. 6, Fig. 8, Fig. 9 and Fig. 10 form the corresponding numerical examples.

Fig. 3 is the initial evolutionary game-theoretical sketch, in which the other values (i.e. ΔV_S , C_S , C_{OS} , R_S , ΔV_M , S , C_M , C_{OM} , R_M and R_S) do not change. Fig. 4 shows how the different initial proportions influence the evolutionary direction to the point $O(0,0)$ or $B(1,1)$. In Fig. 4, the horizontal axis and vertical axis are separately represented by α and β , demonstrating how different initial proportions evolve to equilibrium point $O(0,0)$ or $B(1,1)$.

Insert Fig. 3 About Here

Insert Fig. 4 About Here

As shown in Fig. 4, the coordinate point side (i.e. $(0.7, 0.1)$ and $(0.1, 0.7)$) to the left of the saddle point $D(0.38, 0.48)$ evolves to the equilibrium point $O(0,0)$. However, the initial value (i.e. $(0.4, 0.5)$, $(0.6, 0.4)$, $(0.9, 0.1)$, $(0.4, 0.6)$ and $(0.1, 0.9)$) to the right side of the saddle point evolves to the equilibrium point $B(1,1)$. Thus, the evolutionary path relies on the initial proportion of how many of the individuals within supply chains implement CCER, i.e. the greater the initial proportion, the higher the potential for the evolutionary path to end

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up at the equilibrium point (Cooperation, Cooperation), while the smaller the initial proportion, the higher the possibility for the evolutionary path to end up at the equilibrium point (Non-cooperation, Non-cooperation).

Fig. 5 demonstrates how a change in operational costs C_{OS} and C_{OM} influences the evolutionary path of CCER. When there is an increase in both operation costs C_{OS} and C_{OM} , the denominator of the longitudinal and vertical saddle point also increases in comparison with the saddle point in Fig. 3. Fig. 6 demonstrates that when parameters such as the initial proportion and time period remain unchanged, but $C_{OS} = 3$ and $C_{OM} = 3.5$ are changed to $C_{OS} = 3.5$ and $C_{OM} = 4$, the original saddle point $D(0.38,0.48)$ increases to $D(0.403,0.517)$. In this case, the area of ABCD decreases and the area of ADCO increases, resulting in greater difficulties when it comes to the implementation of CCER. To illustrate, the point $(0.4,0.5)$, which previously evolved to $B(1,1)$, now evolves to $O(0,0)$ (See Fig. 6). The change of evolutionary path reveals the increased difficulties to establish agreement between suppliers and manufacturers on CCER when there is an increase in its operational cost of implementation (See Fig. 6).

Insert Fig. 5 About Here

Insert Fig. 6 About Here

Figure 7 further explores the impact of additional revenue ΔV_M and ΔV_S on the evolutionary path of CCER. When there is an increase in additional revenue ΔV_M and ΔV_S , there is a decrease in the denominator of the longitudinal and vertical saddle point, as shown in Fig. 7. As in the analysis given in the second part of this section, all values remain unchanged, apart from $\Delta V_S = 7$ and $\Delta V_M = 9.5$ becomes $\Delta V_S = 7.5$ and $\Delta V_M = 1$. In this case, the saddle point $D(0.38,0.48)$ decreases to $D(0.213,0.254)$. Correspondingly, the area ABCD increases and the area AOCD decreases, resulting in a lowering of the difficulties when it comes to the implementation of CCER. Fig. 8 demonstrates the initial proportion, such as $(0.7,0.1)$ and $(0.1,0.7)$, which previously evolved to $O(0,0)$, now evolving to $B(1,1)$. This leads to the conclusion that it is easier for all members of supply chains to implement CCER when extra revenues ΔV_M and ΔV_S are higher.

Insert Fig. 7 About Here

Insert Fig. 8 About Here

Finally, Fig. 9 and Fig. 10 present the impact on the evolutionary path of CCER of different incentive coefficients (S). To assist suppliers in implementing a cooperation strategy, manufacturers have the facility to provide suppliers with subsidies. In this **numerical example**, other parameters remain unchanged, apart from the incentive coefficient S .

Fig. 9 demonstrates the evolutionary path of CCER as implemented by manufacturers. In Fig. 9, the initial proportion of CCER implemented by suppliers and manufacturers is set as 0.45, the initial value of S is set as 0.3, the time period and step length are separately set as $[0, 100]$ and 0.01. Over time, despite all the suppliers and manufacturers implementing CCER at the endpoint, it takes less time for all manufacturers to choose a cooperation strategy when $S = 0.3$ than it does when $S = 1$. However, when $S = 3.5$, the increased incentive coefficient decreases the manufacturers' motivation to implement CCER, due to their revenue being greatly reduced by the exorbitant incentive.

Fig.10 illustrates how the incentive provided by manufacturers influences suppliers' decisions concerning CCER, including how the increase of incentives over a certain interval can motivate suppliers to implement CCER. To illustrate, it takes suppliers less time to adopt a CCER strategy when $S = 1$ than it does when $S = 0.3$. However, when $S = 3$, suppliers tend to choose a non-cooperation strategy. A comparison between Fig.10 and Fig.9 indicates that the proportion of suppliers choosing a cooperation strategy increases to its highest point before declining sharply to zero. This is due to higher incentive costs resulting in a lack of motivation among manufacturers to implement CCER. When there is a decline in the proportion of a cooperation strategy adopted by manufacturers, suppliers experience additional difficulties in receiving incentives and, thus also tend to adopt a non-cooperation strategy. Therefore, an exorbitant incentive provided by manufacturers negatively affects CCER implementation over the long term.

Insert Fig. 9 About Here

Insert Fig. 10 About Here

4. Evolutionary analysis of governmental participation

Environmental regulations implemented by the government are always directly in control of the focal company, as this influences the entire supply chain (Gurtoo and Antony, 2007). The focal company is therefore established as a positive example, encouraging all members

within the supply chain to develop emission reduction technologies. A complete governmental incentive system is essential to ensure all members of supply chains implement CCER (Borg *et al.*, 2006), while the government can also provide subsidies to focal companies in order to promote the implementation of CCER within supply chains. This study covers the general aspect of this issue, while at the same time considering manufacturers as the focal companies.

4.1. Basic model assumption

A payoff matrix was initially constructed (see Table 4). According to the basic model assumption, the government provides subsidies to the focal companies implementing CCER, with the motivation parameter w being:

$$w < \pi_M, \Delta V_S > C_S + C_{OS} - S \text{ and } \Delta V_M > C_M + C_{OM} + S.$$

Insert Table 4 About Here

4.2. The payment analysis of subjects

1) Suppliers

When one considers the conditions in which the government provides subsidies, the duplication dynamical equation model for suppliers S is:

$$\frac{d\alpha}{dt} = \alpha(U_{S1} - \bar{U}_S) = \alpha(1 - \alpha)[(\Delta V_S - C_{OS} + S + R_S)\beta - C_S - R_S] \quad (4)$$

2) Manufacturers

By the same token, the duplication dynamical equation model for manufacturers M is:

$$\frac{d\beta}{dt} = \beta(U_{M1} - \bar{U}_M) = \beta(1 - \beta)[(\Delta V_M + W - C_{OM} - S + R_M)\alpha - C_M - R_M] \quad (5)$$

3) The stability point analysis of the model

In comparison to the condition in which there is no consideration of the subsidy provided by the government, the duplication dynamic equation in this section holds a number of similarities with the equation in Section 3.2. The construction of a simultaneous equational model for equations (4) and (5) reveals the following five systematic partial equilibriums:

$$O(0,0), A(0,1), B(1,1), C(1,0) \text{ and } D\left(\frac{C_M + R_M}{\Delta V_M + w - C_{OM} + R_M - S}, \frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S}\right).$$

Similarly, $O(0,0)$ and $B(1,1)$ (i.e. (Non-cooperation, Non-cooperation) and (Cooperation, Cooperation)) form two equilibrium points. When equilibrium is reached in the

evolutionary game system, either all suppliers and manufacturers implement CCER or none implements CCER.

4.3. The factor analysis of CCER

A numerical example is also included in this section, in order to illustrate how governmental policy influences the mechanism of CCER. In Fig. 11, the horizontal coordinates and vertical coordinates are respectively represented by the initial proportion $\alpha = 0.5$ and $\beta = 0.3$, and the motivational parameter $w = 0$ (*Line 1*), $w = 0.5$ (*Line 2*), $w = 1$ (*Line 3*) and $w = 2$ (*Line 4*).

When the government fails to provide subsidies for the focal company ($w = 0$), the final equilibrium is (Non-Cooperation, Non-Cooperation) (i.e., point (0,0)). When this occurs, none of the members within the supply chain will, over time, cooperate to reduce carbon emissions (See *Line 1* in Fig. 11). However, when the government provides a level of subsidy to the focal company ($w = 0.5$), the strategic choice of suppliers and manufacturers still evolves to point (0,0) (*Line 2* in Fig. 11). The evolutionary speed of *Line 2* is slower in comparison to *Line 1* (i.e. *Line 2* is longer than *Line 1*). When the government further increases the incentive level ($w = 1$), the strategic choice of suppliers and manufacturers change to (Cooperation, Cooperation) (i.e. point (1, 1)). In this case, all suppliers and manufacturers ultimately implement CCER. When the government further increases the incentive level ($w = 2$), the strategic choice of suppliers and manufacturers will reach the point (Cooperation, Cooperation) more rapidly than when the incentive level w is 1 (i.e. *Line 4* is shorter than *Line 3*).

The above analysis leads to the conclusion that, when the initial status in the evolutionary game system is unable to motivate all suppliers and manufacturers to implement CCER, governmental subsidies can change the evolutionary direction and motivate all members of supply chains to implement CCER.

Insert Fig. 11 About Here

5. Discussion and conclusion

This study has employed the evolutionary model to examine the influence of the initial proportion of strategic choice, cost, additional benefit and the investment risk of CCER on its implementation. It has used evolutionary game-theoretical sketches and numerical examples to illustrate the implementation of CCER. In addition, it has discussed the circumstances

under which the government motivates focal companies to implement CCER. It has also determined differing results to that found in existing CCER literature, as discussed below.

Firstly, the ultimate decision of suppliers and manufacturers to adopt a CCER strategy is greatly influenced by the initial configuration of multiple subjects. Thus, all members of supply chains ultimately choose a non-cooperation strategy when the initial proportion of CCER implementation is on the left side of the saddle point D $\left(\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S' \Delta V_S - C_{OS} + R_S + S} \frac{C_S + R_S}{S} \right)$ (See figs. 3 and 4). However, all members of the supply chains will eventually choose a cooperation strategy when the initial proportion is on the right side of the saddle point. **This result differs from studies investigating multi-subject based CCER (Nurjanni *et al.*, 2017; Shiraki *et al.*, 2016), which consider that the optimal strategic choice of supply chain members is unchanged over time.**

Secondly, an improvement in operational costs results in an increase in the denominator of longitudinal and vertical saddle points, leading to members of the supply chain experiencing greater difficulties in selecting a cooperation strategy. Furthermore, the denominator of the longitudinal and vertical saddle point decreases when there is an improvement in additional revenues, facilitating members of the supply chain to implement CCER (See Figs. 7 and 8). **This finding is similar to the result of the study investigating double subject based CCER (Bazan *et al.*, 2017; Hua *et al.*, 2016). Although these studies are set in the context of an upstream and a downstream lacking any learning characteristics, they also demonstrate that the implementation of CCER proves simpler in the presence of a lower operation cost, combined with a greater level of additional revenue brought by CCER.**

Thirdly, manufacturers need to be cautious when subsidising suppliers during the implementation of CCER. Although high levels of subsidy can, over the short term, motivate suppliers to adopt cooperative strategies, these do not necessarily lead to the establishment of long-term collaboration (See Figs. 9 and 10). Hence, the subsidies provided by focal companies should attempt to make the saddle point posit on the right side of the initial proportions, in order to encourage members of the supply chain to adopt CCER in a both effective and efficient manner. This will prevent supply chain members evolving to the point at which they all adopt a non-cooperation strategy. **This finding is partially supported by the existing CCER literature, owing to the fact that exorbitant subsidies are seldom investigated (Dong *et al.*, 2017; Swami and Shah, 2013; Xia *et al.*, 2018).**

Finally, the decision of whether firms choose to employ a strategy of cooperation is strongly dependent on the nature of the policy put forward by the government. When the

initial status of the evolutionary game model evolves to where suppliers and manufacturers are disinclined to adopt cooperation strategies, the subsidies provided by the government can alter the evolutionary direction, motivating (or speeding up) the adoption of CCER by manufacturers and suppliers. This finding diverges from the conclusions reached by prior studies (e.g. Dong *et al.*, 2017; Manikas, *et al.*, 2015; Swami and Shah, 2013; Xia *et al.*, 2018), i.e. that the members of the supply chain are able to cooperate in the face of changing policies.

The above findings have significant implications, both practical and theoretical. From practical perspective, this research can assist firms within supply chains to identify the factors they need to consider when deciding whether to adopt the CCER strategy, such as initial investment, operational cost, extra payment of CCER and how many firms within the supply chain currently implement CCER. The consideration of these factors can help firms determine which carbon reduction strategy to adopt over different time periods. Additionally, the results obtained from the analysis can assist policy makers in identifying the most salient factors influencing the implementation of CCER. This can, however, help the government tailor the policy in favor of CCER. From theoretical perspective, the numerical example above highlights that motivating multiple members of supply chains to cooperate carbon emission reduction is not confined to factors such as operational cost, potential revenue and incentives. The initial proportion of members whose strategy is cooperation, and the average revenue of those adopting CCER, also play a notable role in the process of strategic diffusion. The consideration of these factors is conducive to improving the accuracy of the analysis concerning CCER.

6. Limitations and directions for future research

As an initial investigation into how multi-supplier and multi-manufacturer collaborate to reduce carbon emissions, this study has the limitation and therefore has the potential to be extended in three directions.

Firstly, due to the aim of this research being an exploration of the mechanism of CCER, there is no detailed analysis of its relevant parameters, i.e. operational costs, investment risks, additional revenue, and incentives. Therefore, in order to ensure the greater usability of this model, functions pertaining to the relevant parameters could be further specified and then introduced to the model.

Secondly, a systematic review of the existing literature regarding CCER has revealed an absence of the investigation from an empirical perspective. It could therefore prove beneficial to empirically test the efficiency of CCER and explore the cooperation between members

within supply chains aimed at reducing their carbon footprint.

Thirdly, it would also be beneficial to compare CCER practices in a number of different countries, in order to assist the government in selecting more suitable policies. This study explores the CCER issue with reference to the cap-and-trade programme launched in China. Given different policies taken in different countries, a comparative analysis of the effectiveness of carbon reduction in different contexts would provide governments with more rational decision making.

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Management Decision

Table 1 The comparison of existing studies

Number of Subjects		Methodology	Combination or Separation (Economic and environmental optimization)?	Collaborative Field	Paper
Upstream	Downstream				
Single	Single	Newsvendor model	Separation / Combination	Revenue, Order and emission reduction investment	Du et al. (2013); Manikas and Kroes (2014); Dong et al. (2016)
		General game model	Separation / Combination	Revenue, Order, production and carbon reduction investment	Swami and Shah (2013) ; Xia et al. (2018)
		EOQ	Combination	Cost, order, production, inventory and new business model	Wahab et al. (2011); Hua et al. (2011); Jaber et al. (2013); Toptal et al. (2014); Bazan et al. (2017)
Multi/Single	Single/ Multi	MIP	Separation / Combination	Revenue, Cost, location, carbon reduction investment, delivery process and selection of partners	Chaabane et al. (2012); Benjaafar et al. (2013); Palak et al. (2014); Glock and Kim (2017); Nurjanni et al. (2017); Zhang and Xu (2013); Shiraki et al. (2016)
Multi	Multi	EGT	Combination	Revenue, cost, operational risk and carbon reduction investment	This study

Table 2 The payoff functions of different strategies

		<i>P</i>	<i>M</i>	
			Cooperation	Non-cooperation
			β	$1 - \beta$
<i>S</i>	Cooperation	α	$(\pi_S - C_S - C_{OS} + \Delta V_S + S, \pi_M - C_M - C_{OM} + \Delta V_M - S)$	$(\pi_S - C_S - R_S, \pi_M)$
	Non-cooperation	$1 - \alpha$	$(\pi_S, \pi_M - C_M - R_M)$	(π_S, π_M)

Table 3 The stability analysis of evolutionary game

Equilibriums	<i>det(J)</i>		<i>tr(J)</i>		Outcomes
$O(0,0)$	$(C_S + R_S)(C_M + R_M)$	+	$-C_S - C_M - R_S - R_M$	-	ESS
$A(0,1)$	$(\Delta V_S - C_{OS} + S - C_S)(C_M + R_M)$	+	$\Delta V_S - C_{OS} + S - C_S + C_M + R_M$	+	Not stable
$B(1,1)$	$(\Delta V_S - C_{OS} + S - C_S)(\Delta V_M - C_{OM} - S - C_M)$	+	$C_{OS} + C_S + C_{OM} + C_M - \Delta V_M - \Delta V_S$	-	ESS
$C(1,0)$	$(C_S + R_S)(\Delta V_M - C_{OM} - S - C_M)$	+	$\Delta V_M + C_S + R_S - C_{OM} - S - C_M$	+	Not stable

Table 4 The evolutionary game analysis of collaborative emission reduction

		<i>P</i>	<i>M</i>	
			Cooperation	Non-cooperation
			β	$1 - \beta$
<i>S</i>	Cooperation	α	$(\pi_S - C_S - C_{OS} + \Delta V_S + S, \pi_M - C_M - C_{OM} + \Delta V_M - S + w)$	$(\pi_S - C_S - R_S, \pi_M)$
	Non-cooperation	$1 - \alpha$	$(\pi_S, \pi_M - C_M - R_M)$	(π_S, π_M)

Fig.1 Phase image of suppliers

Fig.2 Phase image of manufacturers

Fig. 3 The plane coordinate map of CCER evolutionary game

Fig. 4 The numerical example of CCER evolutionary game

Fig. 5 The plane coordinate map of CCER evolutionary game

Fig. 6 The **numerical example** of CCER evolutionary game

Fig. 7 The plane coordinate map of CCER evolutionary game

Fig. 8 The **numerical example** of CCER evolutionary game

Fig. 9 Different incentive coefficients on the evolutionary path of manufacturers

Fig. 10 Different incentive coefficients on the evolutionary path of suppliers

Fig. 11 The evolutionary analysis under different motivation strengths

Appendix A

There are four basic assumptions to EGT:

1. Populations: multi-participants can be found in the biological and social system, each with its own set of actions;
2. Pay off function - every action has a corresponding payoff;
3. Dynamics - the learning and imitating procedure should be revealed; and
4. Equilibrium - the evolution will converge to a stable state.

In addition, two core conceptions are included in EGT, i.e. the Evolutionary Stable Strategy (ESS) and Replicator Dynamics (RD). The former reveals the stable strategy set and the latter demonstrates the process of reaching stability. The ESS obeys two conditions: the first one is $\forall s, u(s^*, s) \leq u(s^*, s^*)$, and the second is $\forall s^* \neq s, u(s, s^*) = u(s^*, s^*) \rightarrow u(s^*, s) < u(s^*, s^*)$. The s^* , s and u are the original strategy, the mutation strategy, and the payoff formula. The RD is $\dot{\theta}_i(t) = \theta_i(t)[u_i(s_i) - \bar{u}_t]$.

Proof of Equation. (1)

When suppliers choose to cooperate with manufacturers to reduce carbon emissions, the payment formula for the suppliers is:

$$U_{S1} = \beta(\pi_S - C_S - C_{OS} + \Delta V_S + S) + (1 - \beta)(\pi_S - C_S - R_S) \quad (A.1)$$

When suppliers refuse to cooperate with manufacturers, the suppliers' payment formula is:

$$U_{S2} = \beta\pi_S + (1 - \beta)\pi_S = \pi_S \quad (A.2)$$

Then the expected payment formula for suppliers S is:

$$\bar{U}_S = \alpha U_{S1} + (1 - \alpha)U_{S2} = \alpha\beta(\Delta V_S + S - C_{OS} + R_S) - \alpha(C_S + R_S) + \pi_S \quad (A.3)$$

Then we take equation (A.1), (A.2) and (A.3) into the formulas $\frac{d\alpha}{dt} = \alpha(U_{S1} - \bar{U}_S)$, we obtain equation (1).

Proof of Equation. (2)

When manufacturers choose to cooperate with suppliers to reduce carbon emissions, the manufacturers' payment formula is:

$$U_{M1} = \alpha(\pi_M - C_M - C_{OM} + \Delta V_M - S) + (1 - \alpha)(\pi_M - C_M - R_M) \quad (A.4)$$

When manufacturers fail to cooperate with suppliers, the payment formula for manufacturers is:

$$U_{M2} = \alpha\pi_M + (1 - \alpha)\pi_M = \pi_M \quad (A.5)$$

Therefore, the expected payment formula for manufacturers (M) is:

$$\bar{U}_M = \beta U_{M1} + (1 - \beta)U_{M2} = \alpha\beta(\Delta V_M - S - C_{OM} + R_M) - \beta(C_M + R_M) + \pi_M \quad (A.6)$$

Then we take equations (A.4), (A.5) and (A.6) into the formula $\frac{d\beta}{dt} = \beta(U_{M1} - \bar{U}_M)$, and we obtain equation (2).

Proof of the Jacobi equation (3)

Note that equation (1) and equation (2) form the separately replicated dynamic equation of suppliers and replicated dynamic equation of manufacturers. By taking the first derivative of equation (1), we have:

$$\frac{d^2\alpha}{dt d\alpha} = (1 - 2\alpha)[(\Delta V_S - C_{OS} + S + R_S)\beta - C_S - R_S] \quad (A.7)$$

$$\frac{d^2\alpha}{dt d\beta} = \alpha(1 - \alpha)(\Delta V_S - C_{OS} + S + R_S) \quad (A.8)$$

By taking the first derivative of equation (2), we further have

$$\frac{d^2\beta}{dt d\alpha} = \beta(1 - \beta)(\Delta V_M - C_{OM} - S + R_M) \quad (A.9)$$

$$\frac{d^2\beta}{dt d\beta} = (1 - 2\beta)[(\Delta V_M - C_{OM} - S + R_M)\beta - C_M - R_M] \quad (A.10)$$

According to equation (A.7), equation (A.8), equation (A.9), equation (A.10) and the

formulas of Jacobi ($J = \begin{bmatrix} \frac{d^2\alpha}{dt d\alpha} & \frac{d^2\alpha}{dt d\beta} \\ \frac{d^2\beta}{dt d\alpha} & \frac{d^2\beta}{dt d\beta} \end{bmatrix}$), we have the equation (3).

Proof of saddle point

When α is not equal to 0 and 1, we make equation (A.1) equal to 0. We have:

$$\frac{d\alpha}{dt} = \alpha(U_{S1} - \bar{U}_S) = \alpha(1 - \alpha)[(\Delta V_S - C_{OS} + S + R_S)\beta - C_S - R_S] = 0$$

When β is not equal to 0 and 1, we make equation (A.4) equal to 0. We have:

$$\frac{d\beta}{dt} = \beta(U_{M1} - \bar{U}_M) = \beta(1 - \beta)[(\Delta V_M - C_{OM} - S + R_M)\alpha - C_M - R_M] = 0$$

According to the conditions provided above, β is equal to $\frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S}$, and α is equal to $\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S}$. Then we further have the saddle point $D(\frac{C_M + R_M}{\Delta V_M - C_{OM} + R_M - S}, \frac{C_S + R_S}{\Delta V_S - C_{OS} + R_S + S})$.

Proof of $\det(J)$

When α and β are equal to 0, we have: $\begin{vmatrix} -C_S - R_S & 0 \\ 0 & -C_M - R_M \end{vmatrix} = (C_S + R_S)(C_M + R_M)$

When α is equal to 0 and β is equal to 1, we have:

$$\begin{vmatrix} \Delta V_S - C_{OS} + S - C_S & 0 \\ 0 & -(\Delta V_M - C_{OM} - S - C_M) \end{vmatrix} = (\Delta V_S - C_{OS} + S - C_S)(\Delta V_M - C_{OM} - S - C_M).$$

When α is equal to 1 and β is equal to 1, we have:

$$\begin{vmatrix} -(\Delta V_S - C_{OS} + S - C_S) & 0 \\ 0 & C_M + R_M \end{vmatrix} = (C_S + R_S)(\Delta V_M - C_{OM} - S - C_M).$$

When α is equal to 1 and β is equal to 0, we have: $\begin{vmatrix} C_S + R_S & 0 \\ 0 & C_M + R_M \end{vmatrix} = (C_S + R_S)(\Delta V_M - C_{OM} - S - C_M).$

According to the four equations above, we get $\det(J)$.

Proof of Equation (4)

When suppliers choose to cooperate with manufacturers to reduce carbon emissions, the payment formula for suppliers is:

$$U_{S1} = \beta(\pi_S - C_S - C_{OS} + \Delta V_S + S) + (1 - \beta)(\pi_S - C_S - R_S) \quad (A.11)$$

When suppliers refuse to cooperate with manufacturers, the suppliers' payment formula is:

$$U_{S2} = \beta\pi_S + (1 - \beta)\pi_S = \pi_S \quad (A.12)$$

Then the expected payment function of suppliers S is:

$$\bar{U}_S = \alpha U_{S1} + (1 - \alpha)U_{S2} = \alpha\beta(\Delta V_S + S - C_{OS} + R_S) - \alpha(C_S + R_S) + \pi_S \quad (A.13)$$

Then we take equation (A.11), (A.12) and (A.13) into the formulas $\frac{d\alpha}{dt} = \alpha(U_{S1} - \bar{U}_S)$, we obtain equation (4).

Proof of Equation (5)

When manufacturers choose to cooperate with suppliers to reduce carbon emissions, the manufacturers' payment formula is:

$$U_{M1} = \alpha(\pi_M - C_M - C_{OM} + \Delta V_M - S + W) + (1 - \alpha)(\pi_M - C_M - R_M) \quad (A.14)$$

When manufacturers fail to cooperate with suppliers, the payment function of manufacturers is:

$$U_{M2} = \alpha\pi_M + (1 - \alpha)\pi_M = \pi_M \quad (A.15)$$

Therefore, the expected payment formula for manufacturers M is:

$$\bar{U}_M = \beta U_{M1} + (1 - \beta)U_{M2} = \alpha\beta(\Delta V_M - S - C_{OM} + R_M + W) - \beta(C_M + R_M) + \pi_M \quad (A.16)$$

Then we take equations (A.14), (A.15) and (A.16) into the formula $\frac{d\beta}{dt} = \beta(U_{M1} - \bar{U}_M)$, and we obtain equation (5).