Low-carbon supply chain management in emerging economies
Guest Editors: Kannan Govindan and Tsan-Ming Choi
Guest editorial

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Introduction
Greenhouse gas emissions resulting from human activity are increasingly causing changes in our climate, the consequences of which, such as global warming, will be predictably severe. As a result, low carbon emission has become a national development strategy in many countries. For example, some developed countries have inspired a paradigm shift in industrial and technical competition by increasing investment in the low-carbon economic field; formulating and implementing various bills, plans and strategies; and strengthening the implementation of low-carbon strategies. Developing countries, such as China, India, Brazil, Russia and South Africa, have also placed great importance on low-carbon development by issuing a series of laws and regulations to oversee the whole flow of the manufacturing, logistics, circulation and recycling of a product.

Controlling carbon emissions, a concern originally stemming from pure transportation or production systems, has now become a serious challenge in the field of supply chain management (SCM). A redesign of the whole global supply network is needed to achieve a coordinated supply chain system under the latest, increasingly restrictive regulations. As a result, many critically important research questions remain unresolved, such as how does one promote low-carbon SCM and erase sustainability barriers in developing countries. Under these circumstances, it is evident that there is an urgent need for research related to emerging economies because traditionally these nations serve as a production base for many products’ global supply chains in the “non-carbon concern era”.

For this special issue we received a total of 26 submissions, and, after a rigorous review and revision process, we accepted five papers for publication. In the following paragraphs, we provide a short review of each of the accepted papers, and we emphasize its major contribution.

The first paper, “Contingency theory, climate change, and low-carbon operations management”, addresses the following research questions:

RQ1. How do the perceptions of contingencies resulting from climate change at the supply chain level lead to an eventual restructuring of procedures for organizational low-carbon management?

RQ2. How does the relationship between contingencies and change affect the managers’ perceptions of benefits by adopting practices of low carbon operations management?

This paper utilized an interview-based research methodology with ten high-level managers in sustainability and related areas from seven leading companies located in Brazil. The authors determined that an adequate low-carbon management structure is vital to improve the organizations’ perceptions of the benefits from its adoption. In addition, the authors found that low-carbon management initiatives tend to emerge from an organization’s existing environmental management systems, and that controlling and monitoring climate contingencies at the supply chain level should be permanent and systematic.

The second paper, “Constructing a process model for low-carbon supply chain cooperation practices based on the DEMATEL and the NK Model”, developed an integrated multi criteria decision-making model for introducing and implementing relational supply chain practices for low-carbon supply chains. To validate the proposed model, the author utilized empirical data from three manufacturing organizations in China. The results provided a sequence of relational practices for guiding the organizations and their suppliers for healthy and low-carbon development. This paper also provides insights into the basic organizational steps required; the organization should first develop product development cooperation, then exchange carbon knowledge, implement effective governance and lastly build a trust relationship with its suppliers for low carbon cooperation.

“Low carbon supply chain with energy consumption constraints: case studies from China’s textile industry and simple analytical model” is the third selection, which discusses low-carbon supply chain practices in China’s textile industry. In this work, the authors examine how energy consumption constraints affect the optimal decisions of the supply chain members. They then address the supply chain coordination issue using two case studies from Chinese textile companies. The results suggest that textile companies must develop clean technologies to reduce carbon emissions in the production process under the energy consumption enforcement. In addition, another necessary step is to derive the optimal decisions of the supply chain members to reveal that supply chain coordination can be achieved if the manufacturer properly sets the reservation wholesale price. The production capacity may fulfill partial market demand under a wholesale price (or cost sharing) contract.

The fourth paper, “Contract and incentive mechanism in low-carbon R&D cooperation”, aims to offer the producer a menu of incentive contracts to reduce carbon emissions. These incentives will apply not only in the research and development stage but also in the recycling process of the product; a two-stage closed-loop system can be realized. The results reveal that discriminating between different types of R&D researchers may hurt the producer’s profit, but the updated screening contract can inspire R&D researchers to act more transparently which will be beneficial in reducing carbon emissions.

The authors of this piece thank all the authors who submitted papers for the supplementary information (SI) and the reviewers who helped review the manuscripts in a timely manner. Special thanks go to Professor Beverly Wagner, editor-in-chief of Supply Chain Management: An International Journal, Claire Jackson (publisher) and Amy Barson (content editor), for their constant support right from the beginning until the SI project is completed.
“On green market segmentation under subsidy regulation”, the fifth selection, analyzes the role of government subsidy policy to provide a better understanding of the market balance between regular (high-carbon) and green (low-carbon) products. This work uses a Stackelberg game framework to study the interaction between the government’s subsidy regulations and firms’ marketing regimes. This study also explores three marketing regimes and identifies the conditions under which each regime should be adopted by a particular firm. Based on the proposed framework, regulators can gain a deeper understanding of green subsidy policies and assist focal companies in acquiring a better appreciation of green marketing segmentation.

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Contingency theory, climate change, and low-carbon operations management

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Abstract
Purpose – Drawing on the theory of contingency, the aim of this work is to understand how supply chain-related contingencies, arising from climate change, are related to changes in the organisational structure of firms. Further, the authors explore how this relationship influences the perception of sustainability managers on the adoption of low-carbon operations management practices and their related benefits.
Design/methodology/approach – To achieve this goal, this research uses NVivo software to gather evidence from interviews conducted with ten high-level managers in sustainability and related areas from seven leading companies located in Brazil.
Findings – The authors present four primary results: a proposal of an original framework to understand the relationship between contingency theory, changes in organisational structure to embrace low-carbon management, adoption of low-carbon operations practices and benefits from this process; the discovery that an adequate low-carbon management structure is vital to improve the organisations’ perceptions of potential benefits from a low-carbon strategy; low-carbon management initiatives tend to emerge from an organisation’s existing environmental management systems; and controlling and monitoring climate contingencies at the supply chain level should be permanent and systematic.
Originality/value – Based on the knowledge of the authors, to date, this work is the first piece of research that deals with the complexity of putting together contingency theory, climate-change contingencies at the supply chain level, organisational structure for low-carbon management and low-carbon operations management practices and benefits. This research also highlights evidence from an emerging economy and registers future research propositions.

Keywords Sustainability, Climate change, Low carbon, Emerging economies, Sustainable operations, Low-carbon economy Sustainable innovation, Sustainable supply chain

Paper type Research paper

1. Introduction
Few studies address the risks of climate change-related contingencies in supply chains in emerging economies and the consequent necessary responses from businesses (Gasbarro and Pinkse, 2016; Winn et al., 2011; Slawinski et al., 2015). This paper aims to understand how companies structure and maintain their low-carbon operations management and how they consider the constraints arising from climate change at the supply chain level. In addition, we also reveal the benefits that organisations could achieve by adopting operational practices of managing carbon emissions.

Climate change is a subject that generates global risks and uncertainties (Kuklick and Demeritt, 2016; Carrao et al., 2016) due to a series of extreme weather events that have occurred in recent years (Winn et al., 2011; Slawinski et al., 2015); these events have had negative impacts, not only for companies but also for industrial operations (Gasbarro and Pinkse, 2016). Challenging weather events, such as storms, hurricanes and extreme droughts, tend to generate restrictions that can devastate supply chains.

These weather events have a strong influence on supply chain operations because they may directly impact facilities and compromise their access to natural resources and raw materials (Dasaklis and Pappis, 2013; Havercort and Verhagen, 2008; Busch and Hoffmann, 2007), thus creating...
carbon-related restrictions in supply chains. However, in addition to the occurrence of extreme events, there are other supply chain-related contingencies which may affect organisations because of climate change, such as the emergence of new regulations, technologies and additional costs.

In this work, better organisational performance results from the fit between organisational structure and the external environment in which a company is inserted (Volberda et al., 2012). Organisations should consider climate change and its contingencies to optimise their overall performance. The organisational strategies related to climate change can be a source of competitive advantage and strong performance in the market (Kolk and Pinkse, 2004; Lee, 2012a). Good organisational performance, in the context of climate change, can be obtained through various benefits, as highlighted in the literature (Hoffman, 2005). However, if a company does not consider supply chain constraints resulting from climate change when managing carbon reductions, it may not be prepared to be effective in its actions to reduce emissions nor to achieve benefits from these initiatives.

Carbon management in industrial companies is presented in the literature as being a management process that requires a critical view from top managers. Effective managers must consider the following issues: managing risk (Weinhofer and Busch, 2013), an assessment of capabilities and trade-offs (Pinkse and Kolk, 2010), the establishment of policies and objectives for the reduction of CO₂ (Lee, 2012a), the definition of strategic actions (Pesonen and Horn, 2014), opting for either reduction, compensation or searching for zero emissions (Weinhofer and Hoffmann, 2010), a potential search for external partners to carry out the actions of low-carbon management (Kolk and Pinkse, 2004), a study on the benefits from projects developed by a company (Bocken et al., 2012) and, finally, the weighting of issues of climate change in organisational routines (Boiral, 2006).

Therefore, a question that guides this article is: How do the perceptions of contingencies resulting from climate change at the supply chain level lead to an eventual restructuring of procedures for organisational low-carbon management? Another question that needs to be addressed is: How does the relationship between contingencies and change affect the managers’ perception of benefits by adopting practices of low-carbon operations management?

Recent trends justify the relevance of this research. The recent Conference of the Parties of the United Nations (UN) (COP-21) in Paris showed the intention of global leaders in setting targets to reduce CO₂ emissions to combat climate change (UNFCCC, 2015). It has the potential to influence organisational routine and strategy. Another fact is related to the extreme drought that occurred in several countries in Latin America (WWAP, 2016). Among these countries, Brazil witnessed a severe water crisis between 2014 and 2015 (The Guardian, 2015; Reuters, 2016) that affected the local economy, people’s wellbeing and supply chain activities due to disruptions in the water supply.

These extreme events are not isolated; in fact, they tend to repeat themselves, so organisations can face many challenges to deal with the contingencies of climate change. In this sense, this work presents an integrated framework to help companies understand low-carbon management in terms of supply chain management contingencies. It also encourages the adoption of low-carbon operations management and helps organisations to better perceive potential benefits. To address these issues, interviews were held with managers of national and multinational companies in Brazil. Brazil was selected for the study due to its economic and geographic relevance and the severe supply chain disruptions it has experienced due to climatic events (drought resulting in water scarcity).

This article is structured as follows: Section 2 presents the concepts of managing carbon from the perspective of the theory of contingency and the potential benefits that businesses can achieve from this. In Section 3, the research method used and the instruments used for data collection and analysis are given. Section 4 presents the results, and Section 5 gathers the discussions and propositions from these results. Finally, in Section 6, the conclusions, contributions and limitations of the study are presented.

2. Theoretical background

Emissions of gases that cause climate change have become more intense since the beginning of the industrial revolution (IPCC, 2014). According to Slawinski et al. (2015), emission levels have reached the point where, from now, climate-related physical impacts will be observed on a large scale. Thus, climate has become a source of challenges for organisations (Winn et al., 2011) due to the disruptions it can cause in supply chain operations.

While uncertainties increase, managers will need more information on climate change to restructure their businesses (Gordon and Narayanan, 1984). In this context, the theory of contingency is relevant (Lawrence and Lorsch, 1967) because it deals with organisational management due to external events.

For Drazin and Van de Ven (1985), the proposition that the structure and processes of an organisation should be adapted to its organisational context, either to survive or to be effective, is central to the theory of contingency. However, Sousa and Voss (2008) note that studies in operations management have not fully explored the richness of the influence that contextual issues can have.

The impacts of climate change-related supply chain disruptions are difficult to predict (Winn et al., 2011) and uncertainties from the external environment influence the approach to green practices (Lo and Shiah, 2016). Because of this, the theory of contingency is paramount; managers should consider the constraints arising from climate change to develop strategies capable of conducting low-carbon operations management and, as a consequence, achieving the organisational performance desired.

As there is no unique way to apply the theory of contingency (Horisch, 2013), this work adopts the term strategy for climate change (Lee, 2012a, 2012b), as companies deal with risk-related contingencies from climate change that affects their supply chains. Thus, this research follows the theory of contingency and suggests four main variables of study: contingency factors; internal organisation structure for low-carbon management; adoption of low-carbon operations practices; and effects on performance (Drazin and van de Ven,
Contingencies are defined as outside events that affect organisations, over which organisations cannot exert direct control (Sousa and Voss, 2008). This article lists four possible contingencies resulting from climate change that can affect the management of supply chains: lack of resources and difficulty of access to raw materials; new advances in technology; regulations; and extra costs. These contingencies are derived from the fact that organisations already face, or will face, supply chain-related disruptions, such as lack of resources and limited availability of raw materials (Smith, 2013; Haverkort and Verhagen, 2008). In addition, companies may be forced to seek new technologies (Busch and Hoffmann, 2007; Plambeck, 2012; Aben et al., 2010). Organisations can also face social and governmental challenges, and new regulations may require taxes, which increase costs, changing the way the companies act globally (Jeswani et al., 2008; Choi et al., 2013; Hitchcock, 2012; Lo, 2010; Burritt et al., 2011).

The second variable, the internal organisational structure for low-carbon management, is related to the capabilities that a company has to ensure to promote actions to adapt to emergent contingencies (Gordon and Narayanan, 1984; Volberda et al., 2012). Renukappa et al. (2013) state that it is important for a company to manage internal factors, such as:

- the commitment and the establishment of leadership to low-carbon management;
- written policies related to climate change;
- establishment of specific job positions to deal with carbon management;
- systems of rewards for the initiatives of reduction of carbon;
- training programmes for employees; and
- creating a performance reporting procedure for emissions.

In this regard, organisations can define their internal structure through their supply chains by enacting climate change policies (Lee, 2011), aligning objectives and targets to reduce CO₂ emissions (Gopalakrishnan et al., 2012), selecting their suppliers carefully (Dou et al., 2015) and sharing their information about CO₂ emissions with suppliers (Jira and Toffel, 2013).

The third variable is the adoption of low-carbon operations practices. Per Sousa and Voss (2008), these practices can be seen as actions that organisations take in response to current or future contingencies. Thus, this work uses low-carbon operational practices called “products”, “processes” and “logistics” (Bottcher and Muller, 2015).

Finally, this research aims to understand the relationship between climate-change contingencies and firms’ performance. We opted for the benefits outlined by Hoffman (2005), namely:

- improvement in risk management;
- access to new sources of capital;
- anticipation and the influence of climate regulations;
- improvement in human resource management;
- identifying new markets;
- improving the reputation of company; and
- operational improvement.

We believe that companies obtaining these low-carbon management benefits are also improving their overall performance.

Figure 1 provides a summary of the theoretical background herein explored.

3. Research method

This research adopts a qualitative approach, which has made use of in-depth interviews (Ketokivi and Choi, 2014). Interviews with experts were necessary for this research due to the fact that managers are members of organisations that decide on how to react to environmental contingencies (Horisch, 2013; Russo and Harrison, 2005; Faes and Matthyssens, 2009).

The interviews were conducted with managers of seven companies. The number of companies herein investigated is aligned with the number of companies suggested by other
similar studies on the theme of climate change (Okereke and Kung, 2013; Burritt et al., 2011; Aben et al., 2010). Brazil was chosen because more research is needed on climate change in developing countries (Lee, 2012b; Wang et al., 2013).

The choice for large companies is explained by the fact that the larger the size, the greater the exposure to regulations and pressure from stakeholders (Lee, 2012b). In addition, larger companies generally have greater financial resources to invest in low-carbon management (Boiral, 2006; Boiral et al., 2012; Wang et al., 2013). The companies belong to the sectors of energy, retail, manufacturing and agriculture.

The interview script (Appendix) allowed the collection of data during the interviews (Ketokivi and Choi, 2014; Yeung, 1995; Rowley, 2012). In total, ten managers were interviewed, including managers with expertise in sustainability, environment, supply chain, logistics and facilities management.

The interviews were conducted during 2015 and 2016. The total duration of the interviews was around 7 h, with each interview averaging 54.34 min. In this way, the number of interviewees and the duration of interviews is aligned with the literature (Galbreath, 2014; Rowley, 2012).

To start the procedure of data collection, researchers – after determining the companies that would be researched – made contact via phone and email with managers to explain the research objectives and themes (Ketokivi and Choi, 2014; Galbreath, 2014; Rowley, 2012). Once the invitation to participate and the interview schedule was accepted, the interview script was sent to respondents in advance (Yeung, 1995; Galbreath, 2014; Rowley, 2012). The interviewees were able to prepare and organise their thoughts, as well as access secondary data to respond to the issues more clearly.

The script was developed by selecting the contingency factors that impact organisations and how organisations have dealt with them. The internal organisational factors were used to formulate the questions regarding management initiatives. Finally, questions about benefits noted by managers from low-carbon operations were designed.

Secondary data, including information from sustainability reports, internal newspapers and information contained on the websites of the companies investigated, were collected and material from the database of the Carbon Disclosure Project (CDP) as suggested by others (Gasbarro and Pinkse, 2016; Jira and Toffel, 2013; Sullivan, 2009; Burritt et al., 2011; Matisoff, 2013).

All interviews were recorded, so that there would be no loss of data during the conversations. For qualitative data analysis, the interviews were transcribed. We used the NVivo software, recommended by the literature, for qualitative research (Wright, 2009; Galbreath, 2014; Gasbarro and Pinkse, 2016; Solomon et al., 2011). Finally, a tabulation of the data collected was conducted (Ketokivi and Choi, 2014; Voss et al., 2002).

4. Profile of the cases

The first studied company is called Alpha, a multinational company in the food manufacturing sector. It has been operating in Brazil for decades. Currently, the company participates in the CDP and GHG Protocol-Brazil programmes, in addition to receiving a low-carbon seal from the Brazilian federal government. We interviewed a manager in continuous improvement who work for the environmental department of the company.

The second company is Beta, a Brazilian company in the energy sector with operations in the country for more than 100 years. It has operations in the generation, processing and marketing of electric power, as well as service operations. The company engages in extensive participation in programmes, initiatives and indexes related to sustainability, such as the CDP, GHG Protocol-Brazil, Corporate Sustainability Index (ISE-BOVESPA), Dow Jones Sustainability Emerging Markets (DJSI Emerging Markets), and it actively participates in the conferences of the UN. We interviewed a manager of sustainability at the company headquarters in São Paulo who has worked for six years in the environmental area of the company.

The third company is Gamma, a multinational company based in São Paulo engaged in the sector of food and beverages with operations in Brazil. The company participates in the GHG Protocol and in the UN Global Compact. It fabricates such products as desserts and yoghurts. The interviewees were a manager for the supply chain and an environmental manager.

The fourth company is Delta, a multinational company in electronics manufacturing with more than 50 years of experience in the market. The company surveyed has no operational unit in Brazil but does have a headquarters and outsourcing production. The company participates in initiatives such as COP and GHG Protocol at the global level, in addition to the Dow Jones Sustainability Emerging Markets (DJSI Emerging Markets) and the UN Global Compact. We interviewed the Brazil-Argentina manager for sustainability.

Sigma, the fifth company, is a Brazilian company in the sector of agriculture in the market for over 20 years. The company has signed a public commitment with Greenpeace to fight deforestation in the Amazon. It also participates in the CDP, GHG Protocol-Brazil, the Forest Footprint Disclosure and Corporate Sustainability Index (ISE-BOVESPA). We interviewed the manager of sustainability.

The sixth company is Omega, a multinational company in the retail sector, with operations in Brazil since 1990s. The company participates in the programmes of CDP and GHG Protocol at the global level and the Climate Forum of the Ethos Institute. In addition, the company has a programme for sustainability in Brazil, wherein it works with around 30 suppliers on issues of sustainability. We interviewed three employees here: a coordinator of sustainability for Brazil, a manager of transport and logistics for Brazil and the facilities coordinator.

The seventh company is Theta, a multinational company in the sector of agriculture based in Brazil since the 1960s. The company participates in CDP and the GHG Protocol-Brazil, in addition to having signed the New York declaration on Forests and joined the Roundtable on Sustainable Palm Oil (RSPO). We interviewed the manager of sustainability.

Table I summarises the information.
5. Results

5.1 Supply chain disruptions caused by natural events and others risks

The first variable herein analysed is the contextual factors or contingencies of climate change at the supply chain level. This work has highlighted four possible contingencies of climate change that can affect organisations, which are resource scarcity or difficulty of access to raw materials, new regulations, technological advances, and additional operational costs.

When it comes to scarcity of resources and access to raw materials, five companies mentioned a particular episode and some have risk management practices in place for their sources of supply chain level resources. Alpha recently went through a shortage of onions, replacing the commodity with onion powder, and Sigma stated that there was a large water savings programme when Brazil experienced a long drought between the years of 2014 and 2015. In the case of Beta, the interviewee said that the shortage of water for hydroelectric generation of energy meant the use of thermoelectric power instead:

So, if there is a low level of reservoir, it can be replaced by another source, for example thermoelectric plant, which was what happened last year and this year (interviewee, Beta).

With regard to regulations, six companies had some kind of regulations that affected their operations or that they had to meet to not be penalised. Omega demanded from its logistics partners the use of better fuel in their trucks to transport their goods (IBAMA, 2009), and Theta built a new sugar cane plant in accordance with the law on Brazilian biodiesel (Brazil, Law No. 11.097/2005). A Gamma interviewee pointed to the need to meet the legislation for the pollution emitted from trucks (CETESB, 2009).

Another point that we evaluate are emissions from trucks and the trucks from third parties as well. When trucks enter the factory, staff conducts environmental evaluations (interviewee, Gamma).

Necessary technological advances were also considered by studied companies as something that forced the change. Of the seven companies studied, five showed some change in technology that helped reduce CO₂ emissions. Gamma reported that the new technologies acquired by the organisation are strongly related with eco-efficiency and meet international standards for emissions because they follow guidelines from Europe. The manager of Delta said that the company produces electronic products and keeps in mind the goal of reducing emissions:

I would say that the staff promotes reduction of emissions to the extent that when we develop new servers and computers that consume less energy we are collaborating to reduce emissions (interviewee, Delta).

Finally, regarding the variable additional costs arising from climate change, all seven companies reported to a greater or lesser extent that they had suffered some financial impact due extreme weather events. Beta and Omega reported that they had indicators of cost per CO₂ emissions produced for their operations. Sigma also highlighted extra cost due to scarcity of water in 2015 when it had an increase by 26 per cent. The manager of Theta said that the company monitors water shortage in its operations:

So, for example, do we monitor the cost of not having water? Yes, we do. We have measures to prevent this from happening and also have measures to mitigate the event from happening. We have had events of this nature that we believe are related to climate change (interviewee, Theta).

It can be said that all companies have established a management committee to deal with issues relating to water scarcity as a consequence of the water crisis that occurred in Brazil in the years 2014-2015. It can be summarised that Beta and Theta engage in a comprehensive management of all of the factors considered (resources, regulations, technology and cost), with constant monitoring and management of risk. Gamma reports that there is a team that monitors the development of legislation to facilitate its application when enacted.

Table II summarises climate change contingencies in the seven companies.

5.2 Enabling an organisational structure for carbon management

Inner organisational structure for carbon management is subdivided into factors of structuring of companies that help answer climate change and the factors that relate to monitoring and controlling emissions. Of the seven companies, Beta, Delta, and Theta have policies on climate change. However, climate change is considered as an item included into a broader sustainability policy. Beta highlights a policy for climate change, a fact that is also found in the company’s annual report:

The items number eight and nine of our policy are specific to climate change and in parallel, to strengthen them, we have a proper declaration for climate change (interviewee, Beta).

In relation to targets and goals, six of the seven companies have that items in their management policy. Alpha and Omega highlight goals and objectives relating to energy efficiency, whereas the other companies have targets on reducing emissions. The exception is the lack of emissions reduction targets in Sigma.

Regarding the hierarchy of job positions relating to climate change, only Beta and Theta have a committee responsible for the theme but neither of them specifies an exclusive position for activities relating to carbon management.

[...] among other responsibilities, we manage carbon governance, which includes internal planning and institutional relationships (interviewee, Beta).

The item “reporting of emissions” was found in all companies. Companies in the CDP disseminate data on CO₂ emissions in
their annual sustainability reports. However, Beta and Sigma stand out by participating in the BOVESPA Index (ICO2); in fact, Beta even disseminates its results on a prestigious Stock Exchange.

Three companies (Beta, Gamma and Theta) report having some type of training on the reduction of carbon in place. Theta reports the existence of workshops and training relating to the change of land use. Beta highlights the role of the behaviour of employees towards emission reductions:

[. . .] employees need to know their role day-to-day, and that the role will contribute to the reduction of emissions (interviewee, Beta).

Respondents were asked whether the company’s employees received some reward for their results pertaining to emissions reductions achieved. Managers do not gain remuneration for instituting climate change, except the senior managers of Beta are rewarded for achieving reduction targets.

Finally, the internal management of information relating to climate change was found in four (Alpha, Beta, Gamma and Theta) of the seven companies surveyed. The data shows that the management of information flows throughout data panels, in which systematisation of data is routinely performed.

Table III summarises internal organisational structure of carbon management policies in the seven companies studied.

The monitoring of emissions was highlighted in all annual reports of the companies and also reported by the respondents in all seven companies. Companies seek to monitor their carbon emissions on a daily basis by means of indicators and consolidate them annually. Omega reports the calculation made for the monitoring of emissions in its fleet of trucks:

So how do I calculate the amount of carbon dioxide avoided? We use a measure per litre of fuel (interviewee, Omega).

Regarding the possible managerial approaches (reducing, compensating or zero-emission), five of the seven companies seek to reduce their emissions. The manager of the company Beta declares the adoption compensation and zero emissions:

One example is that we’ve bought credit to compensate for the issue of a plant out here within the group (interviewee, Beta).

Finally, the respondents were asked about the extent of managing different types of emissions. The surveyed companies, Beta, Delta and Sigma are working on Types 1, 2 and 3 of emissions, whereas Alpha, Gamma and Theta, only Types 1 and 2. Omega only reported emissions for the GHG Protocol in 2008, which included Types 1 and 2, referring to the consumption of electric power and transport. Table IV summarises the organisational structure of the monitoring and control of emissions.

5.3 Low-carbon operations practices

Alpha has actions for adequate land use in place, and it has begun the exchange of fuel for power generation and standardising the size of trucks with logistics partners.

Beta is engaged in three types of operational practices. The company offers products and services with eco-efficiency to public buildings, low-income communities and for businesses with intensive use of electrical energy. In relation to its process, the company uses biomass for production of electrical energy, replacement of mineral oil for vegetable oil in electrical transformers and investing in wind farms and photovoltaic panels for the production of energy. The company has an initiative in low-carbon logistics and uses electric cars in their operations.

Gamma features actions related to low-carbon processes and logistics. Processes that are highlighted include the exchange of diesel oil for steam generation, reduction in the consumption of electric energy when cooling milk and the exchange of gas-based forklifts with electric ones. As for the practices of logistics it declares, the use of trackers to determine the best routes, to facilitate vehicle exchange and to efficiently maintain its fleet for fuel consumption.

Delta declares the adoption of low-carbon products and logistics. The interviewee said that products consume less energy during their use. It seeks to reduce the number of trips using transport logistics with suppliers of raw material through a better scheduling plan.

Sigma is engaged in the control of deforestation when managing cattle in the Amazon, and uses renewable fuels for energy production.

Omega reports improvements in its thermodynamic refrigeration units and the switch of fluorescent lights for...
LEDs. Logistics has improved considerably because it has used software to optimise routes.

Finally, Theta engages in three types of low-carbon operations management operational practices. “Product” is related to the production and certification of biodiesel on a commercial scale. “Process” is the use of biomass for energy production and proper use of soil, avoiding deforestation in different regions of the country, including the Amazon region. The practices of “logistics” are exchanges of transport modals and intensified exchange of road with rail.

Table V summarises the operational practices adopted by the seven companies surveyed.

5.4 Benefits from adopting low-carbon operations practices

The first type of benefit was access to new sources of capital. Companies may receive investments and financial contributions when they act proactively in the context of climate change. Only companies Beta and Theta get this benefit. Theta exemplifies the government’s incentive to produce biodiesel, whereas Beta ensures that disclosures of rates of emission/sustainability on the stock market attract the attention of investors for the company:

For people looking to buy shares or for a bank that will finance us, they will look at carbon management aspects (interviewee, Beta).

Thereafter, an improvement in the company’s reputation is beneficial because it lowers criticism from stakeholders and improves the company’s standing in the marketplace. Four companies perceive this benefit: Beta, Theta, Delta and Sigma. Beta associates the benefit with new sources of capital. Theta reports that customers of large multinationals sought to understand how it engages in soil management. Delta and Sigma say their attitude directly influences the consumer’s behaviour:

[. . .] our consumers have access to a tool that we offer. It is called Carbon Footprint Calculator and every customer can calculate emissions based on energy consumption [. . .] (interviewee, Delta).

The third benefit, identification of new markets, concerns the provision of new technologies or services related to climate change. In this case, Beta reports that it identified the opportunity to acquire a company to generate energy from renewable non-polluting forms: wind and solar power. Theta reports that it realised this benefit after the promulgation of the law on biodiesel; in fact, the company built a new plant for the production of fuel:

[. . .] we built a plant for the production of biodiesel here in Brazil. This is a regulation that has had an impact that I consider positive and inclusive and that generates other related impacts that are, in my view, quite useful (interviewee, Theta).

The fourth benefit refers to the improvement of human resource management. It is considered as a way to improve morale within the company, reducing costs of hiring and training new employees and increasing productivity in the workplace through actions to combat climate change. Of particular note is Gamma, in which the interviewed recounts the feeling of employees:

[. . .] they feel motivated, yes. They think “I have identified something related to environment” (interviewee, Gamma).

The fifth type of benefit is anticipation and influence on the climate. This consideration addresses the possible benefits of new regulations in the market of carbon credits and the creation of new taxes; it also considers the possible influence that the industry can exert so regulations may be softened.

Beta reports that it needs to draw up an inventory of emissions and send it to the governmental authority, and this will help the government to create taxation or penalties in the future. Finally, Theta recounts its participation in the regulation of deforestation:

For example, the forest code, we participated in the processes [. . .] we were able to anticipate, to help, and even to promote this new legislation that we believe is very important and relevant (interviewee, Theta).

An inventory of emissions is a way in which the Government verifies companies in a specific sector which are carbon intensive and creates a tax or penalty (interviewee, Beta).

The sixth type of benefit is improvement in risk management. This deals with the expected loss and extra costs caused by physical damage to structures and facilities and government regulations in certain economic sectors. Gamma reports that it is able to anticipate any kind of regulation because there is a team dedicated to managing risk-related issues within the company. Theta reports they constantly manage their energy usage and resources, and those actions make it more resilient to possible interruption of operations. Beta reports that its risk management provides distribution of power without interruptions by electrical discharges.

This operating model makes us a little more resilient, let’s say that those impacts are very relevant and that they occur with some frequency: energy shortage, and the shortage of water, in particular (interviewee, Theta).

The final benefit is operational improvement. This benefit relates to improvement in efficiency, reduction of waste in the production process and optimisation of fleets used in transport, among others. Five of companies realise this benefit: Alpha, Beta, Gamma, Omega and Theta. In general, they recognise that there are operational improvements as a result of dealing with the issue of climate change.

Table VI summarises the perception of respondents regarding the benefits of adopting low-carbon operations practices.
<table>
<thead>
<tr>
<th>Operational practices of low carbon management</th>
<th>Alpha</th>
<th>Beta</th>
<th>Gamma</th>
<th>Delta</th>
<th>Sigma</th>
<th>Omega</th>
<th>Theta</th>
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</thead>
<tbody>
<tr>
<td><strong>Products/services</strong></td>
<td>–</td>
<td>Provision of services for energy efficiency</td>
<td>Reduction of weight of packaging</td>
<td>Provision of new products with better carbon-efficiency</td>
<td>–</td>
<td>–</td>
<td>Production of biodiesel</td>
</tr>
<tr>
<td>Processes</td>
<td>Change in land use</td>
<td>Use of biomass for energy generation</td>
<td>Replacement of fuel to generate its energy</td>
<td>Cold manufacturing–milk</td>
<td>Control of deforestation in the Amazon Biome</td>
<td>Improvements in the structures of chillers</td>
<td>Generation of its own energy</td>
</tr>
<tr>
<td>Logistics</td>
<td>Exchange of fuel to generate its own energy</td>
<td>Investment in solar and wind energy</td>
<td>Replacement of oil in electrical transformers</td>
<td>Replacement of gas-powered lift trucks per outlet</td>
<td>Generation of its own energy</td>
<td>Exchange of fluorescent lights by LED</td>
<td>Change in land use</td>
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</table>
Organisations that face risks from climate change trigger a more structured approach to management of climate risks.

According to the theory of contingency, when faced with external contingencies, organisations change internally in terms of organisational structure (Sousa and Voss, 2008; Schneider et al., 2014; Horisch, 2013; Gordon and Narayann, 1984). Overall, the studied companies do not have a managerial structure with all the characteristics suggested by the literature (Lee, 2012a). The climate policies found in three of the seven companies show that the issue of climate change tends to be part of the environmental policy previously established.

In relation to targets and objectives, most of the companies seek to establish goals for the reduction of impacts and better efficiency. To this fact, it is observed that all employees have a certain way of managing their responsibilities towards achieving these goals and objectives. On the other hand, except in the cases of Beta and Theta, businesses do not have high hierarchical job positions to perform activities closely linked to climate change.

In general, Beta, Gamma and Theta train their employees by embedding the climate change in their training sessions on environmental issues. However, the companies do not establish training unique to the topic in their daily routines of training.

Rewards for achieving such goals and objectives still remain an exception. Only Beta report that its managers receive some kind of reward for achieving the reduction targets proposed by the organisation.

The reporting of emissions occurs in all the companies interviewed. They are looking for ways to share their efforts to combat carbon emissions and participate in the CDP. This objective is accompanied, in many cases, by managing emissions information that passes through all the hierarchical levels of the company.

In this way, neither complete adherence was found in the managerial structure for low-carbon management when compared with what is proposed in the literature in terms of defining policies, roles, goals and objectives and training (Lee, 2012a; Renukappa et al., 2013) nor was there a systematisation of data for communication and definition of proper climate change strategies and action plans (Pesonen and Horn, 2014). The only companies that are approaching this kind of structure are Beta and Theta, in which there is a definition of climatic aspects in the environmental policy of the companies, existence of goals and objectives, communication of results and indicators, systematisation of information management by a committee that is responsible.

---

Table VI Benefits to adopting low carbon operational practices

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Alpha</th>
<th>Beta</th>
<th>Gamma</th>
<th>Delta</th>
<th>Sigma</th>
<th>Omega</th>
<th>Theta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources of capital</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Organisation’s reputation</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Identifying new markets</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Human resource management</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Anticipation of regulations</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Improving risk management</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Operational improvement</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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6. Discussion

Using the theoretical perspective of contingency, this work has sought to identify first if the studied companies have already witnessed some contingencies relating to climate change that have created difficulties at the supply chain level and then to determine how they manage these contingencies in their operations.

Each organisation was questioned about the existence of possible risk management. Beta and Theta stand out by having risk management in place for contingencies (Weinhofer and Busch, 2013; Pinkse and Kolk, 2010). The other organisations present a less comprehensive risk management. In this way, it appears that companies react to the context of climate change when they witness risks to their operations.

With regard to the regulations related to climate change, the studied companies also witnessed such contingencies. Some reported the need to issue a report at the end of each year for regulatory agencies of the government, and others reported the need to monitor the emissions level of trucks and the addition of chemical additives as per the law for the reduction of emissions of CO₂ or equivalent.

Finally, all companies have reported, in some way, that climate change affected their business in financial terms. The 2015 CDP questionnaires confirm that extreme weather events affected their facilities, supply of raw materials and the sale and distribution of their products. Hence, each company reported climate-change related disruptions at the supply chain level.

Therefore, companies do face contingencies arising from climate change, and they try to monitor them as much as possible. However, some of the companies have a more structured and better way of managing risk (Beta and Theta).

In general, the companies studied have been monitoring at least one contingency (scarce resources, new regulations, technological advances or extra costs). As a way to synthesise the results, it seems that there is a relationship between contingencies arising from climate change and corporate attention paid to risk management. Thus, it is possible to put forward the following proposition for future studies:

P1 Organisations that face risks from climate change.

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for carbon emissions, as well as training and rewards for managers.

Hence, one can check for an integration of factors related to climate change and environmental management in organisations, because there is no exclusive and totally different approach for low-carbon management currently in existence (Renukappa et al., 2013; Lee, 2012a; Pesonen and Horn, 2014). Thus:

**P2** Organisations integrate low-carbon management initiatives into the previously existing environmental management structure.

Some companies that have little internal structure to deal with climate change seek a way to compensate for that lack by adopting control and monitoring of emissions (Alpha, Delta and Sigma). It seems that these cases focused on monitoring and controlling emissions as a way of compensating for the lack of managerial structure. However, to adopt practices of low-carbon operations (products, processes and logistics), organisations should seek to align the managerial levels, strengthen the need for managerial support for monitoring practices of low-carbon and then ensure the most appropriate response to the contingencies faced are enacted (Correia et al., 2013; Schneider et al., 2014; Horisch, 2013).

It was noted that the adoption of practices of low-carbon operations management of three companies (Alpha, Delta and Sigma) do not present a wide and innovative variety of activities related to reducing CO₂ emissions. These practices of low-carbon operations management run by these companies are similar to the practices studied in the literature (Okerke and Künig, 2013; Sharma and Henriques, 2005; Pourhafrani et al., 2014; Daneshi et al., 2014; Islam and Olsen, 2014) and seems to confirm a statement made by Renukappa et al. (2013) that the practices related to logistics prevail initially in organisations.

In relation to the monitoring and control of emissions, three companies (Alpha, Delta, and Sigma) have an appropriate management in place. All three have an inventory of emissions and two of them (Alpha and Delta) state that their actions are designed to reduce CO₂ emissions.

The benefits perceived by the respondents from all three companies (Alpha, Delta and Sigma) are also reduced. The interviewee from Alpha says it realises the operational improvements, whereas the interviewees from Delta and Sigma declare the importance of these practices to improve the reputation of the company.

**P3a** There is emphasis on managerial monitoring and control of emissions, with little explanation on the adoption of low-carbon practices and the perception of their benefits. The adoption of low-carbon practices and the perception of benefits tend to be related more to the organisational structure in charge of climate change issues.

Thus far, the discussion has analysed the results aligned with the theory of contingency. In other words, if there is no internal suitable organisational structure, there will be few practices and few perceived benefits. However, this article also found two other cases, Gamma and Omega, in which the companies diversify their practices of low-carbon management, adopting a wide range of practices in terms of products, processes and logistics.

According to the theory of contingency, if a company diversifies its operations, it does not guarantee greater effectiveness in its performance (Sousa and Voss, 2008; Drazin and van de Ven, 1985; Volberda et al., 2012; Horisch, 2013). Beta, Theta and Gamma, showed greater contingency management of climate risks, but only Beta and Theta may be considered internally well-structured according to the literature (Renukappa et al., 2013; Lee, 2012a; Pesonen and Horn, 2014).

In terms of benefits, both Beta and Theta illustrate almost all the types of benefits listed by Hoffman (2005). Gamma was more restricted and declared the improvement of human resource management, anticipation of regulations and operational improvement. Omega mentions only operational improvement.

Thus, by drawing on the concepts of contingency management, companies may diversify their actions to reduce CO₂ emissions but do not guarantee the effectiveness of these practices (Sousa and Voss, 2008; Drazin and van de Ven, 1985; Volberda et al., 2012; Horisch, 2013). Therefore, it is the structure for managing low-carbon that matters and leads the company to realise more benefits. Consequently:

**P3b** According to the perspective of the theory of contingency, even if an organisation diversifies its practices towards low-carbon operations management, these practices themselves do not guarantee benefits. What matters is the organisational structure which supports carbon management.

Alpha, Gamma, Sigma, Omega and Theta state that they have made changes in their logistical activities to reduce their emissions. These companies utilize software and dedicated teams for the monitoring of logistics with objective of optimising routes and exchanging vehicles to reduce fuel consumption and emissions. The focus on low-carbon logistics, therefore, is aligned to the literature (Handler et al., 2014; Islam and Olsen, 2014; Norlund and Gribkovskaia, 2013).

If we examine the companies Beta, Theta, Gamma and Omega together, the practices of low-carbon operations are more prominent than low-carbon logistics. Thus, this finding suggests alignment with an affirmation by Böttcher and Müller (2015) which states that companies give more importance to the practices of processes than to the logistics. However, both Beta and Theta have diversified their actions by adopting three possible practices.

Therefore, taking into account the cases studied and the use of the theory of contingency, the better the structure for low-carbon management, the greater the variety of low-carbon operations management practices adopted. Thus:

**P3c** From the perspective of the theory of contingency, the better the organisational structure for managing climate change, the greater the adoption of the three types of practices of low-carbon operations management.
7. Conclusion

This article has explored how organisations deal with the contingencies arising from climate change at the supply chain level. We adopted the perspective of the theory of contingency to discuss how companies understand climate change-related issues, how climate change is translated into creating a structure for managing issues of low-carbon within the companies and how the companies adopt low-carbon operations management and realize its related benefits. The theoretical background was analysed considering the Brazilian context. Through interviews with managers of seven large companies from different sectors in Brazil, a country that has recently witnessed climatic adversity (drought), it was possible to obtain the following major evidence:

- A suitable structure for managing carbon emissions (definition of management of climate risks, policies and targets to reduce CO₂ emissions, training the staff and communication of results) is essential to improve the perception of the benefits derived from the adoption of low-carbon operations management practices (products, processes and logistics).
- Initiatives for controlling and monitoring of carbon emissions seem to be insufficient to allow managers to recognise the benefits of embracing climate change strategies.
- Controlling and monitoring of climate contingencies should be something permanent and systematic (risk management) to enable a suitable organisational structure for managing carbon emissions and, consequently, for improving the perception of benefits.
- Low-carbon management initiatives are started from environmental management systems that already exist. Therefore, organisations interested in starting a strategy for managing emissions may have already commenced working on environmental systems and practices to start embracing low-carbon management practices.
- The findings of this research can potentially contribute to teaching case studies for discussing the implications of climate change in business strategy and the impacts of contingency theory for planning inner organisational structure in response to climate change risks.

Future research could explore the research propositions highlighted in Section 6 and pursue further discussions to promote additional evidence on the complex issues of climate change contingencies, supply chain, low-carbon operations management and the benefits of low-carbon management in emerging economies.

Finally, it should be emphasised that the exploratory nature of the study has its limitations. Therefore, it is suggested that the propositions made are still subject to confirmation and any tentative generalisations can be seen as fragile.

References


of Climate Change Strategies and Management, Vol. 5 No. 3, pp. 304-323.


Further reading


Appendix. Script of interviews

- How are scarcity of natural resources, raw materials and restricted access to resources managed by the company? How are these threats identified, assessed and avoided? Provide examples.
- Has the company ever faced any new government law that modified its actions in the market as well as the demand for its products? How did the company manage this problem? How does the company analyse its capabilities to act in the context of climate change? Provide examples.
- How does the company adopt/follow trends regarding new low-carbon technologies? How often does the company purchase or update its technologies? Cite examples.
• How does the company monitor its operations costs to adapt to climate change issues? What are the types of costs? Cite examples.
• Has the company adopted a climate change policy? When was this policy adopted? Does the climate change policy have support from all managers in the company?
• Are there positions in the company for dealing with climate change issues? Is there any kind of annual report through which the company reports its performance to stakeholders? Cite examples.
• Does the company have a specific training for employees regarding low-carbon operations? What are rewards the company provides to employees when they take part in actions in this context? How does the company monitor and manage the information about greenhouse gas emissions? Cite examples.
• Does the company have indicators to update its low-carbon operations? Does the company look to compensate, reduce or achieve carbon independence? Does the company focus on its internal processes or consider the supply chain?
• Has the company adopted practices of low-carbon products? What are the initiatives? What are the benefits managers noted in adopting practices of low-carbon production? Explain further.
• Has the company adopted low-carbon processes? What are the initiatives? Examples? What are the benefits the manager noted in adopting low-carbon processes? Explain further.

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Constructing a process model for low-carbon supply chain cooperation practices based on the DEMATEL and the NK model

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Yijie Dou
Center for Industrial and Business Organization, Dongbei University of Finance and Economics, Dalian, China

Abstract

Purpose – This paper aims to introduce a joint DEMATEL and NK methodology to develop a process model for introducing and implementing relational supply chain practices for low-carbon supply chains. Using this process model as a guide, insights into specific practices and how to implement these relational practices to achieve competitive advantage across organizations are introduced.

Design/methodology/approach – Low-carbon cooperation practices framework based on the relational view is developed. A methodology based on DEMATEL and the NK model is used to construct a sequential process model for introducing and implementing these relational practices. Empirical data from three manufacturing organizations in China are utilized to validate the model.

Findings – Initial results provide a sequence of relational practices for guiding those organizations and their suppliers for healthy and low-carbon development. Interdependencies between relational practices are analyzed and evaluated from four aspects. Insights into the broader application of the methodology and initial results from both a research and managerial perspective are presented, especially with consideration of the China, an emerging economy, context.

Research limitations/implications – The methodology remains relatively abstract in nature, yet the tool can provide very useful interpretations and information for both researchers and practitioners.

Practical implications – This paper stipulates that in addition to internal operational practices, the relational practices between buyer and supplier may be equally important to achieve a low-carbon outcome, especially in supply chain setting. This paper also shows that not only the relational practice itself but also the implementation sequence of the relational practices can relate to performance. According to the authors’ initial results, organizations in this study should first develop product development cooperation, then exchange carbon knowledge and implement effective governance and last build a trust relationship with its suppliers for low-carbon cooperation.

Originality/value – This is one of the few approaches that directly evaluates and identifies the interdependencies among relational practices and to construct a process model for introducing and implementing low-carbon supply chain cooperation. It is also the first time that the NK model has been integrated with DEMATEL. Focusing on Chinese supply chain carbon emissions concerns is also a unique perspective.

Keywords China, Decision-making, Performance, DEMATEL, Green supply chains, Low-carbon performance
Low-carbon supply chain cooperation, Process framework, NK model

Paper type Research paper

1. Introduction

Climate change due to anthropogenic-based carbon and greenhouse gas emissions has become the most pernicious environmental problem ever to face humanity. As an emerging economy, China has contributed to the greatest greenhouse gas, carbon, emissions as compared to any country in the world. China is facing international pressures to curb its carbon releases, domestic pressures to manage its fossil-energy supply and high levels of air pollution. In response to these concerns, China’s government has implemented a bold national strategy for energy conservation and carbon emissions mitigation (Liu et al., 2013). Organizations are aware and planning for this legislation in addition to concerns raised by other stakeholders, including communities, supply chain partners and shareholders. A variety of practices is at the disposal of these organizations and supply chains to reduce their carbon footprint.

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Low-carbon supply chain cooperation practices
Chunguang Bai, Joseph Sarkis and Yijie Dou

Why the supply chain focus? The World Business Council for Sustainable Development and the World Resources Institute (WRI, 2009) reported that at least 80 per cent of carbon emissions are produced through the supply chain. Chinese organizations represent the largest contributor to the global supply chain. For example, Walmart alone has almost 20,000 tier-one suppliers in China (Plambeck et al., 2012).

In response to these environmental pressures, increasingly numerous voluntary low-carbon practices are at the disposal of these organizations and supply chains to reduce their carbon footprint. Organizations can adopt a variety of carbon reduction practices with suppliers including low-carbon procurement, low-carbon production, low-carbon inventory management and improved supply chain network design (Elhedhli and Merrick, 2012; Lee, 2011).

However, these practices have focused for the most part on reducing emissions due to the physical processes and operational practices involved (Benjaafar et al., 2013). While there is clearly value in such practices, they tend to overlook some potentially significant and effective efforts, especially organizational activities focusing on relational practices for reducing carbon emissions. Examples of relational supplier–buyer practices may include building trust relationships and carbon knowledge exchange (CKE) for low-carbon cooperation (Hongjuan and Jing, 2011).

Green supply chain cooperation’s (SCC’s) practices in improving the organizational performance has been empirically supported (Vachon and Klassen, 2008; Zhu and Sarkis, 2004), but the theoretical framework to guide focal organizations and suppliers in making decisions on how to introduce and implement various relational practices are limited, specifically within a low-carbon SCC context. In other words, there is a big challenge for organizations and supply chains which and what kind of implementation sequence or which practices are jointly implemented that can lead to better low-carbon performance in all processes. However, this topic has not been analytically investigated by the current published research, the existing literature has supported the proposition that the order of implementation or the joint implementation of practices will have an impact on the final results (Govindan et al., 2015; Zhu et al., 2013; Cua et al., 2001).

Limited research has focused on the order of implementation of greening practices in organizations, and especially those related to reducing carbon emissions in supply chains. The basic research question in this study is:

RQ1. Whether organizations can define a sequential implementation of relational supply chain practices to achieve a low-carbon emissions supply chain. If so, how can they do this?

In addressing this RQ1, the objectives and contributions of this study are manifold. These contributions include:

• identification of a relational practices framework for low-carbon SCC from a relational view and a comprehensive literature review;
• developing a multi-criteria decision-making (MCDM) model that integrates the DEMATEL method and the NK model which can evaluate the interdependencies between the relational practices, identify the performance outcomes of the combination of practices and construct a sequential implementation order model among the relational practices;
• applying this methodology using empirical data to develop a fixed process model to better introduce low-carbon relational practices; and
• to help low-carbon supply chain management (SCM) managers better control and investigate various areas of relational practices in low-carbon SCC.

To help meet these objectives, this paper is organized as follows: Section 2 provides an overview of identified relational practices for low-carbon SCC implementation based on the relational view and literature. Formal models in this area are identified with an overview comparison between existing models and the methodology proposed here. The basic concepts associated with DEMATEL method and NK model are then introduced in Section 3. A methodology that integrates the DEMATEL method and the NK model is developed and applied in a Chinese manufacturing industry field setting to evaluate relational practices of low-carbon SCC in Section 4. These initial results provide some specific insights and implications that will be evaluated in Sections 5 and 6. The final section with summary and conclusion incorporates additional discussion and identifies limitations and future research directions.

2. Background

This section provides some background on the literature related to the relational view and why it is important for understanding and managing a low-carbon supply chain (Section 2.1). In Section 2.2, the relational view also provides some foundation for the practices that will be included in the decision framework and models. Section 2.3 provides some background on green and carbon supply chain performance measures that can also be used in the evaluation models. Finally, in Section 2.4 multiple criteria models used to manage and make decisions to support low-carbon supply chains. This background sets the stage for the development of the DEMATEL and NK model and its application.

2.1 The importance of low-carbon supply chain cooperation

Integrating environmental criteria into SCM has become an important strategic issue for many organizations (Validi et al., 2015; Bai et al., 2012; Gupta and Palsule-Desai, 2011). Scholars have increasingly investigated how environmental and social sustainability issues should be integrated into supply management within different contexts such as green supply chain management (GSCM) (Sarkis, 2003; Malviya and Kant, 2015; Silvestre, 2015), environmental SCM (Walker et al., 2008), ecological SCM (Bai et al., 2012) and sustainable SCM (Seuring, 2013; Bai and Sarkis, 2010a).

Recently, as a sub-disciplinary focus, low-carbon SCM has attracted greater attention in academia and practice (Acquaye et al., 2014; Hitchcock, 2012; Tseng and Hung, 2014; Validi et al., 2014a). Generally speaking, low-carbon SCC is a GSCM practice focused on a low-carbon economy
environment (Hongjuan and Jing, 2011). While low-carbon emissions SCM has become popular, few studies have been published on how low-carbon SCC can improve business process’ low-carbon performance and enhancing corporate sustainability competitiveness.

Close cooperation among supply chain partners is needed to meet low-carbon supply chain objectives. The interests across a supply chain may vary across organizations with a certain degree of controversy and conflict existing on whether and how low-carbon management should be managed (Hongjuan and Jing, 2011). This controversy and conflict can seriously limit cooperative efforts across member organizations and their supply chains (Deutsch, 2015). Several organizational theories including the resource-based view, transaction cost economics, agency theory have been used to understand how supply chain member organizations implement SCC practices to generate competitive advantage (Zhu et al., 2010; Lee and Cheong, 2011; Zailani et al., 2012). We believe that an underutilized and important perspective not captured by the other theories is the relational view, which considers the joint performance and cooperation aspects associated with the buyer–supplier relationships.

The relational view is a useful theoretical lens which can be used to explain inter-firm linkages as a strategy for gaining relational rents and competitive advantage (Dyer and Singh, 1998). Relational rent and competitive advantage is defined as a supernormal profit jointly generated in an exchange relationship that cannot be created by either firm in isolation and can only be created through the joint contributions of the collaborative partners (Lavie, 2006). Relational rents are possible when collaborative partners combine and exchange specific assets, knowledge and capabilities through relation-specific investments, inter-firm knowledge-sharing routines, complementary strategic endowments and effective governance (EG) mechanisms.

Several studies have shown how competitive advantage can be developed by the combination of strategies existing in different organizations in the supply chain (Dyer and Singh, 1998). For example, using a survey of North American manufacturers, Vachon and Klassen (2008) examine the impact of environmental collaborative activities on manufacturing performance considers the relational view and the natural resource-based view of the firm. Caó and Zhang (2011) uncover the nature of supply chain collaboration and explore its impact on firm performance from four perspectives: transaction cost economics, resource-based view, relational view and extended resource-based view. In addition, the relational view has been applied to resilience of supply chains (Wieland and Wallenburg, 2013) and hospital supply chain performance (Chen et al., 2013). The relational view has yet to see effective and explicit application GSCM research (Sarkis et al., 2011). In this study, it provides a good fit with the low-carbon SCC, as the organizations are trying to establish an ongoing relationship that can reduce emissions that otherwise could not be fully managed by organizations independently. Therefore, this theory still needs to be studied and particularly in emerging economy countries and general GSCM research. We expand on how the relational view is incorporated into our study in the next section.

2.2 A framework of low-carbon supply chain cooperation practices

Organizations have at their disposal a broad variety of supplier practices to curb CO₂ releases and limit environmental damage (Hsu et al., 2013). Previous studies have addressed carbon management in supply chain from various perspectives, including product design, materials purchasing, manufacturing, remanufacturing, network design, reverse logistics and inventory management (Elhedhli and Merrick, 2012; Tridech and Cheng, 2011; Hua et al., 2011; Lee, 2011; Validi et al., 2014a, 2014b). However, these practices have focused for the most part on reducing emissions due to the physical processes and operational practices involved (Benjaafar and Daskin, 2013).

While there is clearly value in focusing on such practices, they tend to overlook a potentially significant strategy for emissions reduction, one that is driven by relational practices. For example, an organization and its suppliers can build a trust relationship and CKE for low-carbon cooperation.

The number of relational practices in SCC can be extensive and continues to grow (Govindan et al., 2015). Understanding the roles and relationships among these relational practices can provide management with additional informed insight into how to effectively manage and implement these relational practices. For example, low-carbon objectives should be first established before initiating cooperation with suppliers, suppliers will also need to set their objectives (Shaw et al., 2012). These low-carbon objectives may guide and support other relational practices such as providing training for CO₂ releases improvement or low-carbon technological advice in weaker supply chain activities (Lee, 2011). Sometimes there are foundational EG activities such as low-carbon evaluation that may set the stage for helping an organization and its suppliers to build a trusting relationship. Thus, the relationship among these relational practices and the order of their implementation can have a profound impact on the final carbon reduction performance results. Therefore, organizations need to determine how and when they should develop and implement these relational practices. That is, some relational practices will be more basic or foundational (influencing implementation of other relational practices) or more evolutionary or consequential (affected by implementation of other relational practices). In recognition of this fact, we introduce a formal methodology to investigate which and what kind of implementation sequence for relational practices leads to the best overall low-carbon performance in the supply chain of an organization.

Additionally, the breadth and locus of low-carbon SCC practices has not been well documented. This study will characterize the low-carbon relational practices into low-carbon product development cooperation (PDC), CKE, EG and trust (TRU) to explain the low-carbon performance due to supply chain’s strategic focus. These major, initial classifications are based on general dimensions of the relational view. A summary of these dimensions of relational practices from the literature is shown in Table I.

2.2.1 Low-carbon product development cooperation

Low-carbon product development collaboration can be defined as the direct joint involvement of an organization with its suppliers in production of low-carbon products. Prior
Table I A comprehensive listing and strategies of low-carbon relational practices

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Relational practices</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon product development cooperation (PDC)</td>
<td>Low carbon procurement</td>
<td>PDC1</td>
</tr>
<tr>
<td></td>
<td>Cooperation with suppliers for low-carbon design</td>
<td>PDC2</td>
</tr>
<tr>
<td></td>
<td>Cooperation with suppliers for low-carbon production</td>
<td>PDC3</td>
</tr>
<tr>
<td></td>
<td>Cooperation with suppliers for low-carbon objectives</td>
<td>PDC4</td>
</tr>
<tr>
<td>Carbon knowledge exchange (CKE)</td>
<td>We inform suppliers of low-carbon evolving needs</td>
<td>CKE1</td>
</tr>
<tr>
<td></td>
<td>We share low-carbon knowledge of core business processes with suppliers</td>
<td>CKE2</td>
</tr>
<tr>
<td></td>
<td>We and our suppliers exchange information to help establish low-carbon plan</td>
<td>CKE3</td>
</tr>
<tr>
<td></td>
<td>We provide low-carbon technological advice to suppliers</td>
<td>CKE4</td>
</tr>
<tr>
<td>Effective governance (EG)</td>
<td>We provide supplier with clear feedback about low-carbon evaluation</td>
<td>EG1</td>
</tr>
<tr>
<td></td>
<td>Carbon verification</td>
<td>EG2</td>
</tr>
<tr>
<td></td>
<td>Carbon disclosure and report</td>
<td>EG3</td>
</tr>
<tr>
<td></td>
<td>Carbon accounting and inventory</td>
<td>EG4</td>
</tr>
<tr>
<td>Trust (TRU)</td>
<td>We construct consistent low-carbon goals</td>
<td>TRU1</td>
</tr>
<tr>
<td></td>
<td>We are competent and effective in our interactions on carbon emissions controls</td>
<td>TRU2</td>
</tr>
<tr>
<td></td>
<td>We are honest in our business practices with respect to carbon emissions</td>
<td>TRU3</td>
</tr>
<tr>
<td></td>
<td>We would act in our partners best interest with respect to carbon emissions</td>
<td>TRU4</td>
</tr>
</tbody>
</table>

Notes: Strategies: Zhu et al. (2010); Chen et al. (2013); Bai and Sarkis (2010b); Hsu et al. (2013); Kolk and Pinkse (2004)

literature (Zhu et al., 2010; Vachon and Klassen, 2008) on inter-organizational green cooperation reveals that encouraging supplier involvement in product development between supply chain partners usually requires both companies invest in proprietary resources and capabilities or relation-specific investments.

These cooperation strategies try to improve the competence of the whole supply chain. The theory is that these activities would be carried out only when each organization benefits (Hongjuan and Jing, 2011). In a rich collaborative context, organizations and suppliers jointly plan for the reduction of environmental impact from production processes and products. Four specific relational practices from green supply chain collaboration literature (Zhu et al., 2010) are identified including procurement, product design, production processes and production objectives.

2.2.2 Carbon knowledge exchange

Inter-organizational knowledge exchanges in low-carbon supply chains involve practices of transferring or disseminating carbon knowledge in buyer-supplier relationships to develop new capabilities (Cheng et al., 2008). The organizational learning literature suggests that inter-organizational learning through knowledge sharing between partners is critical to competitive success (Chen et al., 2013). Organizations encounter challenges when implementing carbon management initiatives because such practices are complex and most employees are unaware of carbon management knowledge (Hsu et al., 2013). A higher degree of CKE allows members of supply chains to organize low-carbon production, operations, inventory and distribution planning (Fahimnia et al., 2015; Zakeri et al., 2015). This knowledge is also necessary to make rational use of resources and building competitive advantages (Madhok and Tallman, 1998). Four important knowledge exchange practices from the literature are identified for adoption to promote low-carbon consciousness in the supply chain: inform suppliers of low-carbon evolving needs, share low-carbon knowledge for core business processes, exchange information to help establish low-carbon plan and provide low-carbon technological advice (Chen et al., 2013; Bai and Sarkis, 2010b).

2.2.3 Effective governance

Governance methods between supply chain partners may be considered a formal safeguard to a relationship (Wagner and Bode, 2014). Business management systems are important governance mechanisms. A significant fraction of large companies has effectively established the basic management systems and processes necessary to manage their GHG emissions and related business risks (Sullivan, 2009). Suppliers also need to establish a management system as a platform for effectively collecting carbon emissions data from their organizational or product scopes (Hsu et al., 2013). Carbon accounting and inventory is an essential step in developing governance strategies and evaluating progress for controlling supply chain carbon emissions as the baseline needs to be set (Kolk and Pinkse, 2004). Four important EG practices are identified from the carbon management literature, including feedback about low-carbon evaluation, carbon verification, carbon disclosure and report and carbon accounting and inventory (Hsu et al., 2013; Kolk and Pinkse, 2004).

2.2.4 Trust (TRU)

Trust is regarded as an organization’s belief that its supply chain partners will perform efforts that will result in positive outcomes and will not take unexpected actions that result in negative outcomes for the organization (Anderson and Narus, 1990; Horvath, 2001). However, competition may occur when the organizations and their suppliers need to capture specific business values created in the market or to protect their own interests. Trust between supply chain partners is viewed as a complementary resource and capability (Kwon and Suh, 2004). Effective low-carbon supply chains must make sure that the supply chain partners have established some level of inter-organizational trust (Cousins et al., 2006). Trust can build stronger relationships between organizations...
and avoid the risk of changing suppliers or buyers leading to longer-term efforts for change and emissions minimization (Chen et al., 2013). Four important trust practices which play key roles in cooperation are identified from green supply chain collaboration literature, including consistent low-carbon goals, competent and effective in interactions on carbon emissions controls, honest in business practices with respect to carbon emissions and act in our partners best interest with respect to carbon emissions (Chen et al., 2013; Bai and Sarkis, 2010b).

2.3 Performance measures for low-carbon supply chain management
Supply chain performance metrics and measures have traditionally focused on price, quality, delivery and flexibility dimensions when evaluating performance (Bai and Sarkis, 2012). For green supply chains, there was a shift in performance measures to include a balance of economic, environmental and social dimensions (Bai et al., 2015; Varsei et al., 2014; Bhattacharya et al., 2014; Yusuf et al., 2013; Chia et al., 2009). As an emerging subfield in GSCM, carbon management in supply chains has been viewed as a method to establish low-carbon competitive advantage (Hsu et al., 2013). SCC’s practices in improving the supply chain performance has been empirically supported (Sharma et al., 2016). It has become more complicated as a result of increased environmental and low-carbon pressures, as more companies now consider carbon emission issues in the measurement of their supply chain performance (Tseng and Hung, 2014). The reduction of carbon emissions has become a key strategic issue in the low-carbon SCM for mitigating global warming (Chen, 2017). Several studies addressed the CO₂ emission issue in SCM operational practices (Chaabane et al., 2012; Sundarakani et al., 2010). Compared to the individual organizational operational practices, relational practices are less transparent and visible and thus more difficult to manage.

It is clear that low-carbon relational practices are related to performance. In addition, the order of implementation of these practices, and their joint implementation, will also be related to performance. (Govindan et al., 2015; Cua et al., 2001). However, as far as we know, there have been no studies which have constructed a model to describe the order of implementation and final performance results. In addition, how to measure performance based on order of implementation or joint implementation of practices has not been well studied. Therefore, the multi-stage, multi-criteria methodology introduced here is meant to aid in managing relational practices implementation to reduce supply chain carbon emissions. The methodology aims to help organizations analyze the relationship between low-carbon performance in the supply chain and the order of implementation or the joint implementation of relational practices.

2.4 Multi-criteria decision modeling for low-carbon supply chain management
Low-carbon SCM implementation is difficult due to complexities and lack of effective decision-making tools (Bai et al., 2015; Montabon et al., 2007). Few studies provide MCDM methods for low-carbon supplier management. For example, Hsu et al. (2013) utilize the DEMATEL to identify the influential criteria of carbon management in green supply chains for improving the overall carbon management performance of suppliers. Hsu et al. (2014) presents a model for evaluating carbon performance of suppliers by utilizing analytic network process (ANP) and VOIKR method. Lin et al. (2015) constructs an integrated new product development framework for developing new products by utilizing FANP-QFD, FFMEA and GP methods. Kuo et al. (2015) develop a framework of the supplier evaluating process for carbon management by integrating fuzzy ANP and fuzzy TOPSIS approaches.

But when it comes to situations where organizations have limited resources, tools and knowledge on how to guide them in implementing a low-carbon strategy across the supply chain is lacking. In other words, there is a big challenge for organizations and supply chains how to plan a step-by-step introduction of low-carbon strategy based on the limited resources. Similarly, Murphy and Poist (2003) mentioned that there is a lack of a unified framework about green practices, particularly a guiding framework to help companies to implement the relevant practical activities. Not only is low-carbon relational practice itself related to performance, the order of implementation or the joint implementation of practices will have an impact on the final performance results (Govindan et al., 2015; Cua et al., 2001). However, as far as we know, there have been no studies which have constructed a model to describe the order of implementation and final performance results. In addition, how to measure performance based on order of implementation or joint implementation of practices has not been well studied. Therefore, the multi-stage, multi-criteria methodology introduced here is meant to aid in managing relational practices implementation to reduce supply chain carbon emissions. The methodology aims to help organizations analyze the relationship between low-carbon performance in the supply chain and the order of implementation or the joint implementation of relational practices.

Some MCDM tools can be used to assess the relationship between relational practices and performance and to help and guide organizations to select the best relational practice. Yet most MCDM tools developed to address these issues are limited to a static evaluation. These MCDM methods do not typically include or can predict the dynamic performance results of the implementation sequence of relational practices, along with the changes of different strategies (Campanella and Ribeiro, 2011). And these MCDM tools are mainly used for selection decision, it is difficult to be used to build theory model. That is to say there is little application of MCDM tools in implementing a low-carbon strategy across the supply chain. Therefore, in this paper, we model practice-level order changes as more likely to result in reduced carbon emissions in a complex adaptive system that is goal-directed.

A simulation based analytical, methodological, cognitive mapping approach can provide valuable information for relationships between the implementation order of supply chain relational practices and performance. It is unclear about the sequence of relational practices implementation. Among the simulation methodologies in studying organization and
innovation, the NK model (1993) has become a useful tool not only in understanding the past and current situations but also in providing a landscape view (Levinthal, 1997) of the possible path for the future. Thus, an analytical simulation analysis tool such as the NK fitness landscapes can help construct a process framework through the fitness landscape concept to gain insights as to how implementation order of relational practices for managing low-carbon supply chains (Celo et al., 2015; McKelvey, 1999).

The efforts of low-carbon SCC can be conceptualized as a complex system in that decisions made by the supply chain managers not only affect the performance of those relational practices implemented but also often influence the interactions and dependencies between those practices. However, it is difficult to describe the interdependencies among practices using only the NK model. DEMATEL is used to determine interdependencies among the relational practices, which supplements the NK model. DEMATEL is advantageous in revealing the relationships among factors and results in a relationship matrix among various relational practices on prominence and cause/effect axes (Büyüközkan and Çifçi, 2012). The relationship, prominence and cause/effect information can serve as inputs to the NK model. The NK model then can generate a fitness landscape which represents performance results corresponding to each combination of relational practices. The NK model uses search strategies to navigate within the fitness landscape to find positions of greatest fitness, in this case the best low-carbon strategy. DEMATEL also can prioritize factors based on the type of relationships and severity of their effects on other factors (Shao et al., 2016; Bai and Sarkis, 2013).

3. DEMATEL and NK model background

To construct a process framework from empirical data, DEMATEL and the NK fitness landscapes model (NK method) are integrated to develop an integrated methodology. In this section, we briefly described the fundamental concepts of the DEMATEL method and the NK method before proceeding with the details of the integrated methodology.

3.1 DEMATEL

DEMATEL is used for developing and analyzing a causal relationship using matrices or digraphs of a system of components. The matrices or digraphs portray relationships between components with strengths of relationships quantitatively portrayed. It also can be used to rank components. DEMATEL has been successfully utilized in many research areas including business process management, supplier selection and GSCM (Su et al., 2016; Bai and Sarkis, 2013; Büyüközkan and Çifçi, 2012).

To apply DEMATEL, this paper refines the version used by Fontela and Gabus (1976) and proposes four main steps: 1) generating the direct-relation matrix; 2) normalizing the direct-relation matrix; 3) attaining the total-relation matrix; and 4) producing a causal/effect diagram.

3.2 The NK fitness landscapes model

The NK model (Kaufman, 1993) provides a simple yet powerful analytical framework to study organizational problem solving using adaptive searches. While NK was developed to model the evolution of biological systems towards greater fitness, it has been more recently applied to management research for studies on such topics as organizational learning (Dosi et al., 2011), organizational adaptation (Gavetti and Levinthal, 2000), organizational structure and design (Siggelkow and Rivkin 2005) and organizational innovation (Almirall and Casadesus-Masanell, 2010). Although the NK model has recently gained broad acceptance within the organizational research literature, it is still relatively unknown within the SCM literature, especially in the field of environmental or low-carbon SCM (Fan and Lee, 2012).

For the NK model, a complex adaptive system, in this case a supply chain, is conceptualized as operating in an environment (e.g. low-carbon strategy) involving N components and K interactions among these components. The first parameter N represents the number of individual components c = <c<sub>1</sub>,...,c<sub>K</sub>> in a given system, where c<sub>i</sub> can take the value of 0 or 1. The number of possible configurations for a system comprising N components is 2<sup>N</sup>. Each configuration is associated with a fitness value, performance, if that particular configuration is implemented. The second parameter K defines the degree of dependence between the components of a system. K represents the number of other components in the system that affect the fitness value of each component. The value of K can range from 0 to N−1. A fitness value depends not only on the choice made concerning that component (c<sub>i</sub> = 0 or 1) but also on choices made regarding K other components that interact with the focal component.

The NK model which has two primary features (Kaufman, 1993). The first feature is a stochastically generated fitness landscape, where “higher peaks” correspond to better solutions or combinations of components. The second feature is the agent(s) that search a given landscape in an effort to improve their “fitness” or performance. The system uses search strategies to navigate within the fitness landscape to find positions of greatest fitness, in this case the best low-carbon strategy. These search strategies are heuristics and routines that the system uses to configure and reconfigure the values of the N components. If a new system fitness value is greater than its current fitness value, the system moves to the new configuration, which is the position on the landscape. In this study, the NK model identifies a best landscape path for improving supply chain relationship performance from among various landscape paths.

The degree of interaction between components, K, is used to adjust the shape of the path landscape. If K = 0, then all components are independent, and there is one globally optimal configuration of components. As K increases, the components become more interdependent. Higher values of K result in more local peaks along the landscape. Performance differences become more pronounced when a change is made to any one of the N components with increases in K (Kaufman, 1993). K serves as a measure of system complexity because as K increases, the web of dependencies increases and with a greater ruggedness to the landscape (Oyama et al., 2015).

An application example of the process construction for low-carbon SCC and performance using the joint DEMATEL
and NK methodology with inputs from three China organizations is now presented.

4. Case background and application

4.1 Sample case company characteristics

The three large-scale case companies selected for the field study evaluation for low-carbon SCC relational practices and performance are equipment manufacturing organizations within China. The three field study companies recently reported improved performance in lowering carbon emissions after implementation of low-carbon SCC relational type practices. Therefore, each had a substantial understanding of these relational practices and their interactions. To refine and comprehensively analyze their experiences, we used a questionnaire to collect data from the supply chain executives within this company. We provide some background on the respondents. The goal of the field study is to further evaluate the feasibility and outcomes of the methodology using practitioner input.

The three case study organizations are located in industrialized Northeast China and can be representative of industrial organizations in emerging economies, especially those in China. These organizations are now described briefly.

The first selected case, Company A that is a private enterprise, is one of the largest resource recycling companies in China that also develops new technology and equipment for the industry. Due to its large-scale reuse and recovery of waste electronic products, waste vehicles, waste plastics and hazardous solid waste, Company A has been awarded by China government two important honorary titles: “The national demonstration industry park” and “the urban mineral demonstration base”, which demonstrate and commend this company’s best practices in E-waste recycling. Using its suppliers and international academic organizations, low-carbon technologies such as recycling technology, waste plastics modification technology and used vehicles remanufacturing technology have been developed and applied successfully. Company A is also the national circular economy education demonstration base, working on circular economy and low-carbon publicity and education. Company B is a joint venture enterprise and is one of the largest home appliance manufacturers in China. Company B has cooperated with global suppliers such as BASF, Bayer, Mitsubishi, Panasonic to develop low-carbon technologies and products. To improve their low-carbon performance of the whole life cycle of products, Company B has required supplier involvement in product design since 2000. Currently, many products in Company B have gained China low-carbon product accreditation initiated by the Ministry of Environmental Protection.

Company C, a foreign-owned organization, is one of the largest photo frame manufacturers in China. To improve environmental performance and mitigate purchasing costs, Company C has innovated expanded polystyrene (EPS) regenerating technology, viably using waste EPS to replace wood. To address the problem in collection process of EPS, Company C collaborated with its supply chain members to develop a compacting machine, effectively reducing the size of EPS foam for easier transportation. Currently, Company C has become a leading company in the industry of EPS waste foam reduction, recycling and reuse worldwide. Based on information from the organization, one million trees over eight years have been saved, and 150,000 tons of carbon emissions have been reduced, all related to low-carbon practices in Company C and its supply chain.

The research team met with a mix of operations, purchasing and environmental managers who were working in local divisions. Data were gathered by informing the management team for each company on the purpose of the study and an overview of each of the decision variables. Directions and a discussion for completing data using various methods were completed. Consensus results from among the participating managers on the relative matrix relationships was the goal.

4.2 Methodology and application

A DEMATEL and NK joint methodology is introduced to construct a process framework of low-carbon SCC using data from the three Chinese organizations. DEMATEL is used to build the relative relationship model for the strategies and relational practices for low-carbon SCC. The NK method is used to construct the process framework for the strategies and relational practices. The relational practices are based on the relational view dimensions identified in Section 2.2. The process framework can be used to support a low-carbon SCC plan. This DEMATEL and NK methodology is composed of the following major steps, with some examples from the case organizations data to exemplify the methodology.

Step 1: design the low-carbon SCC data structure

The general NK model data structure is first defined in this step. This structure is necessary so that appropriate data and requirements are identified. The NK model is defined by \( NK = (N, SN_h, K_h, SK_h) \). \( N \) and \( SN_h \) are the low-carbon SCC strategies and practices as first defined in Table I and use the relational view theory (Dyer and Singh, 1998) dimensions.

The general strategy domain-related factors are those that provide a general competitive advantage. At the next level are relational practices related to each relational strategy. \( K_h \) and \( SK_h \) will represent the degree of dependence between the strategies and relational practices of a low-carbon SCC.

\[ N = 4 \text{ low-carbon SCC relational strategies including PDC, CKE, EG and trust. Each strategy comprises various relational practices. According to the SCM literature, four relational practices (} SN_h = 4; h = 1, 2, 3, 4) \text{ are identified (Table I).} \]

The complexity of the low-carbon SCC is defined by the amount and patterns of interdependencies among decision variables. DEMATEL will be used to identify the interdependencies among the strategies and the relational practices. To identify the performance of each strategy or relational practice, an additional object, low-carbon performance, is introduced into each interdependencies matrix. This requires five \( 5 \times 5 \) matrices (7). That is, there will be one strategic-level matrix and four relational practices matrices, one for each strategy. \( t_{ij} \) will represent how much strategy (or relational practice) \( j \) influences the value contribution of strategy (or relational practice) \( i \).

In summary, one main NK model for low-carbon strategy will be formed with four strategies (PDC, CKE, trust and EG) and one low-carbon performance factor to capture the relationships of the relational strategies and practices on
overall carbon performance. Four NK sub-models for each strategy with four relational practices and their strategy level will be formed. The overall data structure for low-carbon SCC is summarized in Figure 1.

Step 2: establishing the direct-relation matrices for each organization

To measure the interdependency relationship between decision variables $c_i$ for $i = 1, 2, \ldots, n$, $E = 3$, China organizations were asked to make sets of paired comparisons using linguistic terms. A five-level linguistic scale is used with the following scale items: no influence, very low influence, low influence, high influence and very high influence. The numbers for these linguistic terms are defined in Table II. Three matrices, each corresponding to an organization, were completed. In general, Matrix $M^e$ is the initial direct-relation matrix. For simplicity, denote $M^e$ as:

$$
M^e = \begin{bmatrix}
0 & m^e_{12} & \cdots & m^e_{1n}

& 0 & \cdots & m^e_{2n}

& \vdots & \ddots & \vdots

& m^e_{n1} & m^e_{n2} & \cdots & 0
\end{bmatrix}
$$  \hspace{1cm} (1)

In the empirical cases, the strategy direct-relation matrices $M^e$ are initially populated by having evaluators of each organization $e$ introduce the pairwise influence relationships ($m^e$) between the strategies and low-carbon performance factor in a $5 \times 5$ matrix. Sub-direct-relation matrices $S_{M^e}$ for each strategy $h$ are populated by evaluators within each of the three organizations using pairwise influence relationships ($s_{M^e}$) between the relational practices and their influence of their respective strategic level in a $5 \times 5$ matrix. All the principal diagonal elements are initially set to a value of zero ($0 = \text{no influence}$). A strategic pairwise influence matrix for one of the organizations is shown in Table III. For example, in Table III, according to the respondents from Organization 1, PDC has high influence on carbon reduction in the supply chain performance, with a value of 3. The four relational practices pairwise influence matrices for the same organization are shown in Table IV. For brevity, the remaining matrices for other China organizations are not shown.

Step 3: develop the aggregate direct-relation matrices

The direct-relation matrices for the organizations are aggregated into a matrix $M$ by simple average using expression (2):

$$
M = \frac{1}{E} \sum_{i=1}^{E} M^e
$$  \hspace{1cm} (2)

The strategy direct-relation matrices $M^e$ and sub-direct-relation matrices $S_{M^e}$ for the three organizations will be integrated into an aggregate strategy direct-relation matrix $M$ and four aggregate relational practices direct-relation matrices $S_{M^e}$ ($h = 1, \ldots, 4$) for a total of five aggregated matrices. The aggregated strategy direct-relationship matrix and four sub-direct-relation matrices are shown in Tables V and VI, respectively.

Step 4: normalizing the aggregate direct-relation matrices

On the basis of the overall direct-relation matrix $M$, the normalized direct-relation matrix $N$ can be obtained through expressions (3) and (4):

$$
s = \frac{1}{\sum_{i=1}^{E} \sum_{j=1}^{n} m_{ij}} \hspace{1cm} i,j = 1, 2, \ldots, n
$$  \hspace{1cm} (3)

Table II The respondents’ assessments of linguistic terms and number

<table>
<thead>
<tr>
<th>Linguistic terms</th>
<th>Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>No influence (N)</td>
<td>0</td>
</tr>
<tr>
<td>Very low influence (VL)</td>
<td>1</td>
</tr>
<tr>
<td>Low influence (L)</td>
<td>2</td>
</tr>
<tr>
<td>High influence (H)</td>
<td>3</td>
</tr>
<tr>
<td>Very high influence (VH)</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 1 A NK model for low-carbon supply chain cooperation
For the case organizations, a strategy direct-relation matrix \( M \) and four sub-direct-relation matrices \( S_M \) will be normalized to matrices \( N \) and \( S_N \) (\( h = 1, \ldots, 4 \)), respectively. The normalized strategy direct-relationship matrix and four sub-direct-relationship matrices are shown in Tables VII and VIII.

\[
N = s \cdot M \tag{4}
\]

Step 5: determining total relation matrices.
The total relation matrix \( T \) is determined by expression (5) where \( I \) represents an \( n \times n \) identity matrix:

\[
T = N + N^2 + N^3 + \cdots = \sum_{i=1}^{\infty} N^i = N(I - N)^{-1} \tag{5}
\]
For the case organizations, a strategy total relation matrix \( T \) and four sub-total relation matrices \( ST_h \) will be determined from the normalized matrices \( N \) and \( SN_h \) separately. The strategy total relation matrix and four sub-total relation matrices are shown in Tables IX and X.

**Step 6: developing the causal influence of factors.**

This DEMATEL step consists of two sub-steps.

**Sub-step 1:** determine row (\( R_i \)) and column (\( D_j \)) sums for each row \( i \) and column \( j \) from the total relation matrix \( T \). That is:

\[
R_i = \sum_{j=1}^{n} t_{ij} \forall i
\]

\[
D_j = \sum_{i=1}^{n} t_{ij} \forall j
\]

The row values \( R_i \) represent the sum of influence by a factor \( i \) on other factors for low-carbon SCC. Similarly, the column values \( D_j \) represent the sum of direct and indirect influence that decision variable \( j \) is affect by from the other decision variables.

For the case organizations, these values are determined for each of the matrices including the strategy total relation matrix \( (T) \) and four sub-total relation matrices \( (ST_h) \). The values \( R_i \) and \( D_j \) are shown in Tables XI and XII.

**Sub-step 2:** determine the overall importance or prominence \( (P_i) \) of factor \( i \) and net effect \( (E_i) \) of factor \( i \) using expressions (8) and (9).

\[
P_i = \{R_i + D_i \mid i = j\}
\]

\[
E_i = \{R_i - D_i \mid i = j\}
\]

The value \( P_i \) shows the total net cause and effect index. A larger \( P_i \) means a greater connected relationship of factor \( i \) with other factors. The \( E_i \) value shows the net cause or effect that the factor \( i \) has overall. If \( E_i > 0 \) then factor \( i \) is a net cause or foundational factor. If \( E_i < 0 \), then factor \( i \) is a net effect factor (Tzeng et al., 2007).

For the case organizations, these results are determined for the strategic total relation matrix \( (T) \) and four relation matrices \( (ST_h) \) shown in Tables XI and XII, respectively.

In the next steps, the NK model is utilized to simulate a low-carbon strategy process to get the best performance for the given interdependencies from the total relation matrices also from a given complexity measure \( (K = 3) \).
Interdependencies within a system are defined by a network of inter-relationships. With this setup, the strategic NK model can be represented in a parsimonious form, an NK model consisting of four strategies and four relational practices for each strategy (or practice). To capture the essence of the low-carbon SCC in a realistic yet parsimonious form, an NK model consisting of \( N = 4 \) strategies and \( S_{N1}, \ldots, S_{N4} \) relational practices for each strategy is developed and applied. Each strategy or practice can be determined from the total relation matrix \( T \) or from the relation sub-matrices \( ST_h \). The relationship between the strategy (or practice) and low-carbon performance (or strategy level) as the fitness value for a strategy (or practice) using expression (10):

\[
f_i = t_{in}
\]

where \( t_{in} \) is the relationship between the strategy (or practice) and low-carbon performance (or strategic level factor) in the total relation matrix \( T \). Similarly, the strategy level \( sc_i \) of a strategy will be ignored in the relation matrices \( ST_h \). These will result in the structure interdependencies matrix \( INF \) or four sub-interdependencies matrices \( INF^i \) scores, using expression (11).

\[
INF_i = t_{ij} \quad \text{for } i = \{1, \ldots, n \}
\]

Given that \( K = 3 \), according interdependencies matrix \( INF \) (or four sub-interdependencies matrices \( INF^i \)), which represent each strategy (or practice) in the system is affected by all other three strategies (or practices). In other words, each
strategy (or practice) is dependent upon \( K \) other strategies (or practices) in determining its fitness value.

Sub-step 3: identify the overall fitness value for each strategies (or practices) configuration. This objective now is to find the overall fitness value point for the various configuration landscapes. The overall fitness value, \( F \) (calculated using expressions (12) and (13)), of the system is the sum of the values assigned to each fitness value of the strategies \( c_i \) (or practices) which are implemented \( (c_i = 1) \) and the interdependencies with other strategies \( c_j \) (or practices) that are also implemented \( (c_j = 1) \):

\[
F = \sum_{i=1}^{N} d_i \quad \text{for} \quad c_i = 1 \tag{12}
\]

\[
d_i = f_i + \sum_{j \in \{i|G_{ij} = 1\}; j \neq i} f_j \cdot \text{INF}_j \quad i \neq j \tag{13}
\]

For example if PDC is the only general SCC strategy implemented, then the overall fitness value \( F = 0.072 \) of the system is equal to the fitness value \( f_i = 0.072 \) of PDC. If trust (TRU) strategy is implemented separately, the system fitness value \( F = 0.034 \) which is equal to the fitness value \( f_i = 0.034 \) of TRU. If the joint strategies of PDC and trust (TRU) are to be implemented, then interdependent values are to be considered. For example, the value of PDC influence on trust (TRU) is 0.068, which is the value of \( \text{INF}_{14} \) from Table IX. The other direction of the interdependency \( \text{INF}_{14} = 0.063 \), also from Table IX. The overall fitness value is then equal to:

\[
F = (\sum_{i=1}^{N} d_i) = 0.072 + 0.034 + 0.072 \cdot 0.068 + 0.034 \cdot 0.063 = 0.113.
\]

The overall fitness values for the various relational strategy and practices configurations are summarized in Tables XIII and XIV. With four strategies (or relational practices) and a decision made in each strategy (or relational practice) that takes on one of the two values (0 or 1), a total of 16 possible configurations of 0 and 1s are shown in the first four columns

<table>
<thead>
<tr>
<th>PDC( (c_i) )</th>
<th>EG( (c_i) )</th>
<th>CKE( (c_i) )</th>
<th>TRU( (c_i) )</th>
<th>Fitness value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.072</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.050</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.056</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.034</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.130</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.136</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.113</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.113</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0.090</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0.097</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.201</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.176</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0.184</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.159</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.254</td>
</tr>
</tbody>
</table>
practices implementation. It may have been viewed by the respondents to be the important initial step for a successful overall conclusion.

The next important strategic step for managing a supply chain carbon reduction is for the organizations and their suppliers to exchange carbon knowledge. Third, organizations and their suppliers should implement EG practices. Finally, organizations and their suppliers should work on building mutual trust relationship.

It is interesting that the order is as such, the Chinese respondents believe that involvement in more instrumental, less personal cooperation efforts will lead to building further trust. The instrumental aspects of actual directed strategic efforts will lead to greater performance improvements than building an organizational trust relationship. The issue of trust in China is very important, but, in many situations, the trust may already be assumed, as the Guanxi relationships play a large initial role (Tsang, 1998). Also, given these initial cooperative relationships, this kind of trust relationship would be easier to establish. Two observations can be made. First, this approach can help identify a sequential process to achieve its goals based on managerial preferences and perceptions. Second, there might be more than one process to achieve the goal and allows some flexibility, especially as the number of alternative factors (strategies) increases. The process is to determine the biggest bang for the buck. This approach has been supported in the practice literature for project management where the typical argument is to find quick wins with high payback (Coronado and Antony, 2002; Flaig, 2005). Removing barriers to acceptance of specific strategies may also derive from greater performance results; thus, careful selection of the order of strategies and practices may be important.

Table XIV. The overall fitness values for each relational practice configuration

<table>
<thead>
<tr>
<th>$s_1^j$</th>
<th>$s_2^j$</th>
<th>$s_3^j$</th>
<th>$s_4^j$</th>
<th>PDC</th>
<th>CKE</th>
<th>EG</th>
<th>TRU</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
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<td>0.060</td>
<td>0.066</td>
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<td>0.058</td>
<td>0.053</td>
<td>0.066</td>
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<tr>
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<td>0.052</td>
<td>0.059</td>
<td>0.067</td>
</tr>
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<td>0.142</td>
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<td>0.139</td>
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<td>1</td>
<td>0.123</td>
<td>0.128</td>
<td>0.126</td>
<td>0.140</td>
</tr>
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<td>0.106</td>
<td>0.129</td>
<td>0.133</td>
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</tr>
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<td>0.139</td>
<td>0.130</td>
</tr>
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<td>0.211</td>
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<td>1</td>
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<tr>
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<td>1</td>
<td>0.185</td>
<td>0.192</td>
<td>0.205</td>
<td>0.210</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>0.255</td>
<td>0.284</td>
<td>0.288</td>
<td>0.300</td>
</tr>
</tbody>
</table>

Figure 2. An optimal process of low-carbon SCC for four strategies

(a) The value of low-carbon performance for each combination; (b) the 3D-visualization of the landscape; (c) the best optimal process of low-carbon SCC for four strategies.
Implementation helps to reduce psychological barriers for project implementation.

Overall, there were 16 potential practices that can be used to achieve each strategy. The process in this methodology was to prioritize at two levels. If the methodology is focused at the 16 practices level of analysis, it would become complex, along with other difficulties. The estimation of the values becomes increasingly difficult and inaccurate when the factor (practice) in question is influenced by too many other factors (practices). When a large number of decision factors is involved, their interactions may not be easily evaluated with lack of experience and data. Third, the number of possible combinations grows exponentially with the number of factors, time resource put constraints on finding an optimal process (Frenken, 2006). There are 16 practices, and the number of possible combinations to be estimated would be $2^{16}$. Instead, the methodological design of a double layer structure, a strategy layer and a practice layer helps to ease complexity concerns but allows consideration of some implementation processes and priorities.

But the methodological concerns may not address all issues. At the practices level, the assumption is that the practices will be achieved before all the benefits of the strategic performance can be accrued. Some remodeling may allow for interactions across strategic groups and practices, but complexity issues may arise. In this case, potentially focusing only on the largest contributing practices within a strategy may help to determine whether a certain threshold of performance has been achieved. But given that these general perceptual values from organizational experts, the methodology would need to be validated by actual performance measures. The results here would be general guidelines for implementation of projects.

To understand the implications of interdependence on performance and the interdependencies among relational practices, the methodology employs a 3D visualization of the “landscape” for each strategy. This visualization helps to illustrate the complex interactions and priorities within the framework.

**Figure 3** The 3D visualization of the “landscape” for each strategy

**Figure 4** A process framework for low-carbon supply chain cooperation practices
practices, let us return to the DEMATEL results shown in Tables X and XII.

At the relational practices level, information can be gleaned by the most important practices for each strategy. Evaluating the contributions of each of these relational practices can help identify which ones can be prioritized. The individual relational practices for each respective strategy with the highest contributions for their specific relational strategies include “cooperate with suppliers for low-carbon objectives” (PDC4) in PDC, “inform suppliers of low-carbon evolving needs” (CKE1) in CKE, “carbon verification” (EG2) in EG and “act in our partners’ best interest” (TRU4) in TRU. Combined with the conclusion of the general process framework, supply chain managers should consider prioritizing the implementation of these four practices, maybe even overall, if the goal is to implement all strategies. Organizations also have more confidence in the introduction of other practical activities based on the performance results of the biggest contributors of these lower level relational practices to the strategic relational elements.

5.2 Research implications

The results presented in this paper have several implications for low-carbon SCC practitioners and researchers alike. The implications for China are discussed first. As a country, China is facing domestic and international pressures to reduce its carbon emissions, especially from industrial production and practices. Industry and the government should help guide enterprises to implement low-carbon SCM to decrease more carbon emissions. It is a necessity for organizations to seek potential collaboration with partner firms so that a low-carbon supply chain network can be established (Zhu and Geng, 2013). The tool and initial study presented here provides potential insights not only for the respondent companies but also for professional industrial organizations and the government in such a way to aid companies identify practices and implementation processes. Strengthening the establishment of policies to motivate enterprises to establish advanced collaborative strategies gradually and improve their competitive ability is a capability of the methodology presented here if used appropriately and broadly. In China, the implementation of low-carbon SCM is still in the very early stages, enterprises and their supply chains can gain some intuitive guidance from the theoretical knowledge and evaluation presented here.

These guiding principles can include the major identified strategies and their linkages to the practices. Overall plans for inter-organizational coordination situations would include increasing the capabilities for low-carbon product development, dissemination of carbon knowledge clearly and efficiently, developing stable and continuous coordinating relationships and increasing EG capabilities across the supply chain. More specifically, Chinese organizations can work with foreign collaborators to help develop and benchmark collaboration efforts, using some of the guidance provided in the practices, strategy, performance relationships of the models presented in this paper. They can also develop appropriate mechanisms to for organizational and supply chain learning with domestic and foreign partners (Zhu and Geng, 2013). These initial findings and the process model can help establish a management system as a platform to collect carbon emissions data from a supply chain perspective. Whether it is product or process information, the systemic mechanisms need to be in place because these are the initial steps identified as potentially having the greatest supply chain carbon emissions reductions. Managing the carbon emission of a product across the supply chain is clearly a strategically important next step for China to reduce carbon emissions and mitigate climate risks.

More broadly, the approach in this paper can provide some initial guidance on the successful and effective implementation of low-carbon SCC, especially when considering the performance of the relationship, not just on individual organizational practices. The organization can introduce different practices in a sequential process for the best performance management. For small and medium-sized organizations that have limited resources, the incremental implementation process may be the only feasible alternative to build a more complete program for reduction of carbon emissions. They can also select a combination with limited practices according to their own resources and landscape to get the best performance. The processes provide a sequential relationship and will allow for foundational and high performing practices to be initially identified (e.g. first DEMATEL may identify the foundational “causal” practice or strategy, and then the NK method to build on that to determine the greatest beneficial practices that would get implemented).

Although we did identify a process, another research implication comes from identifying and categorizing, in general, the relational strategies and practices for carbon reduction in the supply chain. The practices identified in this study can serve as a checklist that comprehensively covers possible low-carbon SCC practices that can generate competitive advantage. The additional goal is to raise the awareness of critical issue of the importance of relational practices involved in implementing low-carbon SCC systems.

5.3 Managerial implications

Over the past 30 years, China’s increased economic growth has been accompanied by high environmental costs and is the largest emitter of carbon emissions, albeit less than originally thought (Liu et al., 2015a). In response to this issue, various mechanisms have been utilized to manage carbon emissions including various trading schemes (Liu et al., 2015b). The Chinese central government recognizing the broader importance of environmentally sustainable development has included a variety of regulatory policies to implement such as the innovative circular economy and low-carbon economy policies (Bai et al., 2015). China has set a goal to cut 1,651Mt of carbon emission by 2020 to achieve the target of reducing carbon emissions per unit of gross domestic product by 40-45 per cent compared to 2005 (Liu et al., 2013). However, there still exist many barriers and challenges.

Manufacturing industries and their supply chains accounts for a large part of the total volume of carbon emissions. China has become the world’s factory and manufacturing industries play key roles in Chinese economy. The topic of corporate sustainability in China’s corporations has been of great interest for the past decade in academia and practice (Bai et al., 2015). The expansion to the supply chain both...
Low-carbon supply chain cooperation practices
Chuanguang Bai, Joseph Sarkis and Yijie Dou

Low-carbon PDC is the first relational practice in the identified sequential implementation process. This implies that organizations and their suppliers should start with PDC with intent to identify consistent low-carbon objectives and complete specific low-carbon activities for providing a sustainable competitive advantage. The PDC result could be a “portfolio” of low-carbon objectives considered essential for success within low-carbon cooperation activities. These low-carbon objectives and production can better guide other low-carbon relational practices, such as exchange products-related carbon knowledge, governance cooperation practices according low-carbon objectives and building a trust relationship based on the consistent low-carbon objectives. Within the PDC activities, low-carbon objectives should first be identified, implementing low-carbon design according to objectives, then low-carbon procurement from the supplier and finally implementing low-carbon production after procurement are the remaining sequential PDC activities. The objectives-design-procurement-production process is consistent with supply chain collaboration steps.

ROKE was the second major set within the implementation sequence for relational activities. For the most effectiveness, CKE should be implemented after PDC to improve the efficiency of low-carbon cooperation and solve cooperative risk issues. Alternatively, the transfer of knowledge is largely constrained by the content of low-carbon products. Within the general CKE relational practice, organizations should first inform low-carbon evolving needs to suppliers and let those suppliers gain an understanding of their low-carbon business and share low-carbon knowledge of core business processes with suppliers and then establish a low-carbon plan according to evolving needs. Finally providing low-carbon technological advice to suppliers to help smooth the implementation of the plan should then occur. Organizations can utilize cross-functional teams to drive the CKE.

EG is the third major relational practice in the sequential implementation process. EG mechanisms can help organizations to implement management to monitor and control the impact of itself on the natural environment (Montabon et al., 2007). EG can help further support implementation PDC and CKE relational activities. Only when the PDC and CKE are completed should the organization develop EG activities. The sequence for EG activities includes actively achieving low-carbon certification to get an environmentally friendly image, implementing routine monitoring such as low-carbon evaluation and carbon accounting, and then release carbon disclosure and reports according to low-carbon evaluation results or carbon accounting.

Trust, according to the field study respondents, is in the last position in this sequential implementation process. Trust, is complementary resource that can be derived from these other activities and seems like a natural outcome. It can help justify the results and build stronger relationships between organizations to avoid the risk of changing suppliers (Chen et al., 2013). Building trust is a long-established element for successful supply chains, the trust building process needs some activities to show that success can occur and why it is a later process here. In trust (TRU), acting in a partner’s best interest with respect to carbon emissions is the base for establishing trust; and consistent and honest low carbon goals can be constructed and implemented simultaneously. Achieving the goal of competent and effective carbon emissions controls is the final major activity for building trust in a joint carbon emissions relational practice.

This process model for low-carbon SCC can be generally applicable to all respondent companies in two ways. One is, as a strategic tool, used to plan and guide low-carbon cooperation. Another one is, as a remedial process, used to correct obvious low-carbon cooperation deficiencies. Also, the results provide an initial starting point for discussion of why these activities should occur in the sequential steps. Complementary project management tools, such as Gantt charts and critical path methods can be used to further evaluate the relationships of the various activities. The methodology provides a sequential process and implementation process for an initial and important project management structure that involves both buyers and suppliers.

6. Conclusions
The industrial reduction of carbon emissions is most effective for organizations when consideration of the supply chain. For this reason, low-carbon SCC is currently receiving significant practical and research attention. One of the core issues is that given the relative novelty of carbon emissions reductions planning in the supply chain, the process and determination of implementation sequences for a wide variety of low-carbon SCC practices is not easy to determine. Our study examined how this complex relationship could be evaluated for organizations. Specifically, we were interested in how to guide organization to successful and effective implement and introduce different practices of low-carbon SCC step-by-step to arrive at a high-performance situation. The nature of interdependencies and the difference of practices combination affect complex low-carbon SCC projects, making sense of these relationships is one of the goals and contributions of this study, especially within the context of an emerging economy country, such as China, situation.

Initially, we identify low-carbon cooperation practices using the relational view and a comprehensive literature review. Although this paper cannot claim to be exhaustive in its review of low-carbon cooperation practices, the model does provide a comprehensive set of the low-carbon SCC implementation low-carbon cooperation strategies and practices and highlights the relationships that are likely to exist between the practices.

The low-carbon SCC implementation practices were evaluated through a strategic evaluation methodology utilizing a structural and simulation modeling tool based on DEMATEL and the NK model with managerial input from three manufacturing companies in China. Methodologically,
we have also made a contribution to the NK approach through a more complete integration of DEMATEL to determined interdependencies among relational strategies and practices. DEMATEL helped to delineate the structure of various interdependencies among the relational practices, addressing some the NK model limitations.

The methodology is useful for integrating the perceptions and perspectives of various companies and experts. The results of the evaluation of the case companies provided some initial insights into importance of practices and the sequencing of these practices. The ordering based on performance expectations was somewhat surprising, but the instrumental nature of the cooperation strategies seemed to play a larger role than building organizational trust. Clearly, this is only a small example of the technique and various practices, and strategies may have different relationships in differing contexts. The Chinese situation, although having high concerns for carbon reduction, can have differing priorities than more developed countries. The initial results of the process framework determined in the case study can serve as a reference for other situations and industries.

The introduction of this decision support and systems evaluation methodology is a contribution to the literature on low-carbon SCC implementation and provides some initial insight into practices in China. It can also serve as a foundation for further research, there is still a room for an improvement that can provide fodder for further research in this domain.

First, this paper provides a theoretical process model to guide organizations on how to implement these relational practices. Understanding the contextual conditions under which kind of implementation sequence for relational practices is effective needs to be further investigated (e.g., number of suppliers and depth of supply chain). Sousa and Voss (2008) suggested that research should shift from the evaluation of the value of a best practice to the understanding of the contextual conditions under which it is effective. Among other factors, environmental uncertainty and dependence relationships have been identified as contextual factors which may affect the effectiveness of a best practice (Wong et al., 2011). We can further research on focus on the contexts for which these relational practices are most effective. Then, it is possible for managers support the necessary conditions to which an appropriate implementation sequence for relational practices would have on performance outcomes.

Second, the process model proposed that these organizations and their suppliers should work on building mutual trust relationship in the last step. There are many studies that take trust as an initial step of SCC (Chen et al., 2013), which is inconsistent with practical conclusions. The main reason is that trust and other relational practices have an effect role and cause role. In addition, organizations will not implement a relational practice in one step or implement another relational practice after finishing another relational practice, it could be a more complex and non-linear implementation process. This issue needs to be investigated from a project management perspective. Furthermore, we should consider the implementation level of relational practices. That is these practices may have differing levels of effectiveness depending on how wide or deep the relational practices are implemented. A complex process model which can show level of a relational practice can be reached before another can be implemented can be investigated for future methodologies and studies.

Third, this model remains relatively abstract in nature in that actual implementation of the activities did not occur by the companies, only a potential plan was delineated. Although the organizations found this type of approach useful, they felt there were some limitations. First, one of the concerns of the organizations is that for each relational practice only no or full (0 or 1) implementation is considered. The case company respondents felt that there are partial implementations depending on resources that needed to be allowed of the level of the implementation for each relational practice. Second, the metric of fitness, measured on a scale of 0-1, is a proxy for system performance, but such a metric is rather abstract. The case companies wished to have a numerical result of the performance and an indication of how much performance can be achieved for each step. Therefore, further research could investigate how to map component performance and system performance to more meaningful metrics.

Finally, the proposed methodology was implemented with a numerical example in three manufacturing companies of China. This is a small sample helping to justify and validated the approach. A broader study to identify more general implications of the actual practice and broader industry insights is still needed. Although some initial interesting insights can be developed from the case companies here, whether the process framework and importance of these factors hold for a broader set of organizations needs investigation. Following up with actual implementations would further validate the study. Also, application and integration of other decision support approaches would help to extend the analysis. To solve the uncertainty of a human’s subjective judgments, other concepts such as “grey” and “fuzzy” system theory can be applied and be a useful tool for management by further integrating intangibility valuations. These are fertile areas for further research.

As we can see, even though some limitations and disadvantages do exist within this study, there is an opportunity to investigate how this tool can be used to expand low-carbon SCC implementation. We feel this formal analytical methodology plays an important role in improving low-carbon SCC strategy and operations, especially when it is in a situation where complex environments exist. We have provided some directions for future research and development with this approach, evaluating how organizations implement and identifying dynamic decision environments will be useful as this issue matures within developing and developed industries and regions.

References


Low-carbon supply chain cooperation practices

Chunguang Bai, Joseph Sarkis and Yijie Dou


Further reading


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Low carbon supply chain with energy consumption constraints: case studies from China’s textile industry and simple analytical model

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Abstract
Purpose – This paper aims to discuss the low carbon supply chain practices in China’s textile industry. To curb greenhouse gas emissions, the Chinese government has launched restrict regulatory system and imposed the energy consumption constraint in the textile industry to guarantee the achievability of low carbon economy. The authors aim to examine how the energy consumption constraint affects the optimal decisions of the supply chain members and address the supply chain coordination issue.

Design/methodology/approach – The authors conduct two case studies from Chinese textile companies and examine the impact of energy consumption constraints on their production and operations management. Based on the real industrial practices, the authors then develop a simple analytical model for a low carbon supply chain in which it consists of one single retailer and one single manufacturer, and the manufacturer determines the choice of clean technology for energy efficiency improvement and emission reduction.

Findings – From the case studies, the authors find that the textile companies develop clean technologies to reduce carbon emission in production process under the energy consumption enforcement. In this analytical model, the authors derive the optimal decisions of the supply chain members and reveal that supply chain coordination can be achieved if the manufacturer properly sets the reservation wholesale price (WS) despite the production capacity can fulfill partial market demand under a WS (or cost sharing) contract. The authors also find that the cost-sharing contract may induce the manufacturer to increase the investment of clean technology and reduce the optimal WS.

Originality/value – This paper discusses low carbon supply chain practices in China’s textile industry and contributes toward green supply chain development. Managerial implications are identified, which are beneficial to the entire textile industry in the developing countries.

Keywords China, Energy consumption, Low carbon, Textile supply chain

Paper type Research paper

1. Introduction

The topic of greenhouse gas (GHG) has been of great interest in the past decade in both academic and practitioners’ studies. There is a strong scientific consensus that the global climate is changing due to the GHG emissions (Shi et al., 2012). This emission is growing rapidly, particularly in the emerging economies of China and India. To lessen the negative impact to the environment, there is a need to reduce the GHG emissions and execute low carbon supply chain. Low carbon supply chain addresses the control and reduction of the GHG emission across the value chain (Govindan and Sivakumar, 2016; Nishitani et al., 2016). The GHG emissions can be quantified by a ratio of GHG emission in production to the quantity produced (Verfaillie and Bidwell, 2000). This ratio can then be used as an indicator to assess the low carbon supply chain performance (Acquaye et al., 2014).

To curb GHG emissions and develop a low carbon economy, various types of regulations and technologies have been imposed by worldwide governments and organizations for limiting the energy consumption (Hitchcock, 2012). This is particularly true in the textile and apparel industry in China. The Chinese government has posed the strict regulation to limit energy consumption in the textile-related factories for facilitating low carbon supply chains since 2010 (Ministry of Industry and Information Technology of the People’s Republic of China, 2010). Under this regulation, the amount of energy consumed in production is limited. In other words, production capacity is constrained. In China, recent trends in...
environmental protection have focused on the development of cleaner technology in textile production and manufacturing, which can lower the GHG emissions by reducing the energy consumption (Lin and Zhao, 2016; Huang et al., 2017). To avoid the possibility of low production capacity, therefore, firms develop the clean technology to explore different alternative ways of manufacturing practices that use a lesser amount of energy and emit a lesser amount of energy-related carbon (Halldorsson and Svanberg, 2013).

Low carbon emission has become the national development strategy in China (Tian et al., 2014). In the pursuit of profit maximization, international textile and apparel firms take advantage of low production costs as well as good product quality in China. However, notice the terrible air pollution; the Chinese government has raised the environmental awareness and imposed the environmental regulatory system. The State Council of China has recently set up two national energy savings and emission reduction goals as a part of the national 12th five-year plan (Zhu and Geng, 2013). The Chinese government puts significant pressure on textile manufacturers, as textile manufacturing and production are always regarded as an unsustainable sector with large amounts of GHG emission. Therefore, the Chinese government has launched the regulations by imposing an energy consumption constraint to control carbon emission in the textile supply chain. As energy (i.e. electricity) is mainly generated by coal in China (Xue et al., 2013), the massive consumption of coal is a direct cause of China’s environment deterioration with large amount of carbon emission. With the increasing scarce energy resources and the need for sustainable development, China’s textile industry faces considerable energy constraints, as the Chinese government has the 12th five-year plan for the textile industry in which energy consumption of unit industrial added value should be reduced by 20 per cent every year (Ministry of Industry and Information Technology of the People’s Republic of China, 2012). The government has also stipulated the cap of energy consumption at corporate level to become a low carbon economy (Ministry of Industry and Information Technology of the People’s Republic of China, 2010).

Sustainability issues are crucial to the textile and apparel industry, as the textile manufacturing and production processes cause seriously social and environmental impact within supply chain (Shen and Li, 2015). Many textile and apparel brands such as H&M, Uniqlo and The North Face have incorporated green practices into their supply chain and required their suppliers (i.e. manufacturers) to produce the products in a sustainable manner such as carbon emission reduction. Recent technological advances create the potential to generate clean technology and improve energy efficiency to facilitate a low carbon supply chain. With technological progress, it can help to save energy. On the other hand, Nguyen et al. (2015) address that increasing energy efficiency and clean energy consumption is the cheapest and fastest way to reduce GHG emissions. Energy efficiency investments in a manufacturing setting are generally a technology and equipment to achieve this goal. However, large buyers such as H&M are more willing to manage their supply networks rather than invest in clean energy technology adoption at the individual supplier sites (Nguyen et al., 2015).

In this paper, we present two case studies and discuss the low carbon supply chain practices with energy consumption constraints in China’s textile and apparel industry. We identify that the textile manufacturers implement the clean technology to reduce energy consumption. Based on the observation from the industrial practice, we develop a simple analytical model to analyze the optimal strategies that the supply chain partners should adopt in low carbon supply chain. More specifically, we focus on the following research questions:

RQ1. How does an energy constrained manufacturer make the choice of clean technology investment decisions in the low carbon supply chain?

RQ2. How do the operation decisions of manufacturer and retailer affect the low carbon supply chain?

RQ3. Under what conditions does a retailer share the investment cost of clean technology?

To address these questions, we conduct the case studies in two Chinese textile manufacturers. We find that solar water heating (SWH) and heat energy recycling (HER) systems are used to increase energy efficiency and reduce carbon emission in textile supply chain. In addition, we discuss the important insights regarding the clean technology implementation of each investigated company. Based on the real industrial practices, we develop a two-echelon supply chain model with the energy consumption constraints and derive the optimal retail price, wholesale price (WS) and choice of clean technology of the supply chain members. We find that supply chain coordination can be achieved if the manufacturer properly sets the reservation WS even though the production capacity is not able to fulfill all the demand under a WS (or cost sharing) contract. By comparing the cost sharing and WS contracts, the cost-sharing (CS) contract can motivate the manufacturer to adopt clean technology and reduce the optimal WS.

This paper is organized as follows. In Section 2, we review the related literature. Section 3 describes our case study, and Section 4 examines analytical model based on the practices of the investigated cases. Section 5 concludes the paper with general remarks and managerial implications and discusses the future research opportunities. All of the technical proofs are relegated to the Appendices.

2. Literature review

There is abundant literature on green supply chain (for the details of green supply chain literature review, please refer to Brandenburg et al., 2014; Govindan et al., 2014; Govindan et al., 2015). For example, Corbett and Klassen (2006) indicate that adopting environmental practices can improve the overall performance of supply chain. Cholette and Venkat (2009) examine the energy and carbon emissions in a supply chain. They find that the change of supply chain design significantly varies the energy consumption and carbon emission. Diabat and Govindan (2011) study the reasons of green supply chain implementation and find that government regulation and legislation in GHG emission are the most important drivers that affect its implementation. Plambeck (2012) examines the strategies of operations and supply chain
to reduce GHG emissions. He provides an industrial example on how the giant retailer, Wal-Mart, can profitably reduce GHG emission under the direct and indirect control in supply chain. Recently, Krass et al. (2013) and Drake et al. (2016) consider the emission tax in their studies. Specifically, Krass et al. (2013) use the environmental tax to motivate the adoption of clean technology. They find that a relatively high tax in emission may motivate a switch to a cleaner technology. However, they argue that if the capital cost of cleaner technologies is subsidized, taxation is efficient and the negative environmental effect would be less. Plambeck (2013) discusses various clean technologies and their corresponding operations management challenges. He finds that the adoption of solar panels would profitably reduce carbon emission in operations. Moreover, Plambeck (2013) also addresses that solar panels are more efficient than fossil fuels when generating energy. However, companies may face different environmental challenges and government policies when implementing the solar panels. This is consistent with our findings from the textile and apparel industry in terms of launching the solar panels to reduce carbon emission in production process. Drake et al. (2016) study how emission tax and cap-and-trade regulation affect the firm’s technology choice. They find that technology investment can increase total capacity. In addition to reducing the carbon emission, increasing energy efficiency is another method to achieve a low carbon supply chain (Wu et al., 2014). By using clean technologies, companies can increase their energy efficiency in production and operations. It is important that GHG abatement can identify the percentage of existing carbon emission that is reduced through the clean technology implementation (Zabaniotou and Androu, 2010).

The literature has widely investigated the impacts of buy-provided incentives in supply chain. Zhang and Liu (2013) consider a green supply chain which supplies green products. They find that the revenue-sharing contract can coordinate the supply chain and provide incentive for cooperation. Swami and Shah (2013) study the greening efforts in a two-echelon supply chain and find that a two-part tariff contract could help to coordination the supply chain. Dong et al. (2014) examine a supply chain with sustainability-dependent demand. They find that the revenue-sharing contract provides incentive to achieve supply chain coordination. In this paper, we also examine the buy-provided incentives in a textile supply chain. Different from the existing literature, we find that the CS contract could increase the investment on the choice of clean technology but may not be able to achieve channel coordination in a low carbon supply chain.

Low carbon supply chains of textile and apparel products have received much attention from scholars. Shaw et al. (2012) adopt the fuzzy analytical hierarchy process (AHP) and fuzzy multi-objective linear programming to develop a low carbon supply chain for supplier selection. The proposed supplier selection model considers GHG emission, carbon emission cap of material sourcing, quality rejection percentage, late delivery percentage, budget constraint and demand. The proposed model is numerically illustrated by an apparel manufacturing company in India. Nagurney and Yu (2012) develop a novel model to study the low carbon fashion supply chain from the perspectives of manufacturing, transportation and shortage. They find that adopting environmental pollution-abatement technologies (i.e., clean technology) can improve supply chain performance. Choi (2013) examines the impact of carbon footprint taxation scheme in fashion quick response system. He finds that local sourcing is more desirable for a low carbon fashion supply chain. Dibat et al. (2014) explore the sustainable supply chain management system in textile sector and reveal the adoption of green practices such as low carbon strategy as one of five key enablers in textile supply chain. Nakajima et al. (2015) introduce material flow cost accounting method and conduct a survey with listed Japanese firms to evaluate the requirements and difficulties of facilitating a low carbon supply chain. Jakhar (2015) investigates the performance evaluation and a flow allocation decision model for the textile and apparel sustainable supply chain. Similar to our paper, Jakhar uses the multi-methodological approach, where survey data are collected and analyzed and the structural equation modeling, fuzzy AHP and fuzzy multi-objective linear program are applied. Zhou et al. (2016) consider the fairness concern of the retailer and examine the equilibrium decisions under the co-op advertising contract and the co-op advertising and emission reduction cost sharing (CA-ERCS) contracts in a low carbon supply chain. They analytically analyze that only the CA-ERCS contracts can help to achieve coordination.

Fashion consumers are growing to have social and environmental awareness (Shen, 2014). This is particularly true in China because of serious air pollution. Chinese consumers have been aware of the importance of reducing carbon emission and other polluted emission (Zhu et al., 2013). This awareness directly influences consumers’ eco-fashion consumption decision, and the consumers are more willing to make purchase if that textile and apparel supply chain are more sustainable (Shen et al., 2014). We summarize the review on low carbon supply chain-related literature in Table I. This study contributes to the exiting literature by considering the optimal pricing and choice of clean technology in China’s textile and clothing industry.

3. Case study

Case study is an approach to examine a phenomenon in its natural setting by gathering data from multiple sources (Benbasat et al., 1987). In this section, we present two case studies to illustrate the process that Chinese textile companies have to go through in practice to develop a low carbon supply chain with energy consumption constraints. The data collected from multiple sources help to enhance the reliability of the findings (Yin, 2009). Our data collection consists of multiple methods which include face-to-face semi-structured interviews with staff members from investigated companies, publicly available news and statistics from the company’s websites and annual reports.

3.1 Case 1: HF company[1]

3.1.1 Company background

HF Company was founded in 1973 and is a leading manufacturer for many international fashion brands. The company specializes in dyeing and printing of various textile products, as well as producing the silk woven garments and
knitted apparel products. The dyeing and printing process is energy consumed with large amount of carbon and water footprint. Carbon and water footprint are of great concern for HF in supply chain management. HF has a total area of 250,000 m² in the city of Hangzhou, China, with a workforce of more than 2,000 employees. According to the land size, HF is one of the largest land owners in the textile industry in China. Current annual output is approximately seven million

Table I A summary of the review on low carbon supply chain-related literature

<table>
<thead>
<tr>
<th>Papers</th>
<th>Approach</th>
<th>China specific?</th>
<th>Textile related?</th>
<th>Core findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Brito et al.</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>The awareness of reducing carbon emission directly influences consumers’ eco-fashion consumption decision</td>
</tr>
<tr>
<td>Cholette and Venkat (2009)</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>Supply chain configurations can result in vastly different energy and emissions consumption</td>
</tr>
<tr>
<td>Zabaniotou and Andreou (2010)</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>The most economically interesting energy option for a bio-energy unit is found in the investigated textile plant in Northern Greece</td>
</tr>
<tr>
<td>Diabat and Govindan (2011)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>A case study of manufacturing firm in southern India is developed to check the validity of interpretive structural modeling and the drivers affecting the implementation of green SC management</td>
</tr>
<tr>
<td>Shaw et al. (2012)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>A green supplier selection model is proposed, and it can be applied for uncertain environment</td>
</tr>
<tr>
<td>Plambeck (2012)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Companies can profitably reduce GHG emissions, and SC coordination and innovation need effective climate policy</td>
</tr>
<tr>
<td>Nagurney and Yu (2012)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Adopting environmental pollution-abatement technologies (i.e. clean technology) can improve channel performance in a low carbon fashion SC</td>
</tr>
<tr>
<td>Choi (2013)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Local sourcing is more desirable for a low carbon fashion SC with carbon footprint taxation scheme</td>
</tr>
<tr>
<td>Krass et al. (2013)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>The environmental taxes alone may not be sufficient to coordinate the SC, and consumer rebates are often sufficient to achieve coordination without the use of subsidies</td>
</tr>
<tr>
<td>Zhu et al. (2013)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Chinese consumers aware the importance of reducing carbon emission and other polluted emission</td>
</tr>
<tr>
<td>Zhu and Geng (2013)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Chinese manufacturers should wisely allocate investment and human resources to implement green SC practices</td>
</tr>
<tr>
<td>Drake et al. (2016)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Expected profits are higher and expected emission is less under cap-and-trade, but expected production is larger under an emissions tax</td>
</tr>
<tr>
<td>Dong et al. (2014)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Revenue sharing contract provides incentive to achieve SC coordination with sustainable-dependent demand</td>
</tr>
<tr>
<td>Diabat et al. (2014)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Safety perspective enablers provide additional motivation for sustainable SC adoption</td>
</tr>
<tr>
<td>Shen (2014)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Sustainable practices such as carbon emission reduction has been considered in the supplier selection process; Fashion firms tend to develop the low carbon SC from many different ways</td>
</tr>
<tr>
<td>Shen et al. (2014)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>The awareness directly influences consumers’ eco-fashion consumption decision in the low carbon SC</td>
</tr>
<tr>
<td>Jakhar (2015)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>A partner selection and flow allocation decision-making model are proposed in the low carbon SC</td>
</tr>
<tr>
<td>Nakajima et al. (2015)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Promoting MFCA in the SC requires firms to define the environmental indicators, explain the performance of the MFCA and execute information sharing with SC partners</td>
</tr>
<tr>
<td>Zhou et al. (2016)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>With the consideration of the retailer’s fairness concern, SC coordination is achieved under co-op advertising and emission reduction cost sharing (CA-ERCS) contracts</td>
</tr>
<tr>
<td>This paper</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Low carbon SC practices are adopted in China’s textile industry; Optimal strategies of the choice of clean technology and pricing are identified</td>
</tr>
</tbody>
</table>

Notes: “E = Empirical study; C = Case study; A = Analytical study
units in woven garments and five million in knitted garments. The annual productive capacity is about 12 million meters in both printed fabric and dyed fabric with energy consumption constraints from government.

3.1.2 Solar water heating system in the HF
HF set up the SWH system in 2007, which was one of the pioneers in the whole textile industry. The SWH system is used to converse the energy obtained from sunlight to renewable energy for water heating by the solar panels which are installed on the roof of the workshop buildings. The heated water can be used for the production processes of dyeing (Figure 1). The sufficient size of the workshop-building roof is one of the main reasons for HF to install the large amount of solar panels. The SWH system reduces the quantity of power and capacity of steam used to heat the water. Despite the technology implementation incurs large amount of financial resource, it can reduce indirect carbon emission and production cost caused by power and steam consumption.

The SWH system is designed to deliver hot water based on the energy obtained from solar panels. However, there sometimes may not have sufficient solar heat gains to deliver adequate hot water in winter. For example, the capacity in winter may not be as large as that in summer, which is true in HF. The company has considered this issue with more appropriate resource arrangement. Thus, according to the energy availability in various seasons in a year, the supply plan of power consumption and steam consumption have been well managed by HF.

According to the interview conducted with the operation manager of HF, it is known that the installation cost of the SWH system is about ¥12m. On the other hand, the costs used to cover the salary of the maintenance personnel and the power charge for the water pump to inject the water into the system (and then transmit the heated water into the production department with the adequate supply of sunlight) is ¥700 per day.

To calculate the operational cost of this system, we consider the daily operational cost of using the SWH system in HF as \(U_{HF}\), the amount of water this system can heat every day is \(H_{HF}\), the efficiency of heating 1 ton of water to steam is \(E_{HF}\), and the cost per ton of steam is \(S_{HF}\). As a result, the daily operational cost can be determined as follows:

\[ U_{HF} = H_{HF} \times E_{HF} \times S_{HF} \]

HF enjoys the benefits of rebound effect[2] after launching the SWH system. With SWH system, HF generates more energy, which further increases production capacity and reduces the carbon emission. The manager addressed that this SWH system has created great value for both capacity and low carbon production since it was first installed in 2007.

3.1.3 Insights from the HF
3.1.3.1 Roof-use requirement for solar panels. The textile factories can use solar power as an option to mitigate the energy crisis, which has significantly influence the production capacity and efficiency. However, roof size in workshop buildings is an important factor for the companies to check the feasibility of solar panel installation. Roof size partially implies land size, which is a big challenge in China as most of the good land available for textile factory would be strategically located in east coastal provinces, where the land price is increasingly expensive. Thus, the tradeoff between return of solar panel installation and land availability is the critical determinant for the textile company that whether the SWH system is adopted.

3.1.3.2 Energy uncertainty from solar panel. Weather and seasonality leads to the energy uncertainty from the solar panels. To make full use of energy from the solar panels, the firms should manage the energy uncertainty by adopting the SWH system based on the weather forecast. For example, firms can arrange the energy intensive production such as fabric weaving, knitting, dyeing, printing in summer season because of a longer duration of sunlight. What is more, the company should manage energy uncertainty effectively by checking the changes of weather with professional weather forecast organizations. Based on the weather forecast, the company can purchase alternative source of energy timely when the solar energy is insufficient to support the water heating.

**Figure 1** The operational process of the SWH system
3.1.3.3 Low carbon procurement practices. It has the market forces that the supply chain should adopt low carbon procurement practices. The international buyers require its upstream suppliers to adopt clean technology and practices that result in low carbon emission and energy efficiency. After implementing the solar panels, the company had generated significant amount of green energy. By utilizing solar panels, the company could generate extra energy and increase its production capacity, which are an alternative way for the reduction of GHG emission. Moreover, the low carbon procurement practices are also influenced by governments. The Chinese government has developed the low carbon practices through legislation and via a regulator requiring the companies adhere to certain environmental standard. All these external pressures can increase drivers for textile manufacturers to adopt low carbon procurement practices and develop low carbon supply chain.

3.2 Case 2: FH Company[3]

3.2.1 Company background
FH Company was founded in 2003. It is engaged in manufacturing a wide range of knitted fabrics such as yarn dyeing, fabric knitting, dyeing and finishing for many international fashion buyers. The FH has a total area of 320,000 m² with a workforce of more than 3,300 employees. The company owns 510 circular knitting machines, 270 dyeing machines and 75 finishing machines. Current monthly output is approximately 5,000 tons of dyeing and printing knitted fabrics.

3.2.2 Heat energy recycling system in the FH
The FH set up the HER system in 2013. The HER system utilizes thermal energy from high-temperature sewage that would normally be wasted. The HER system can significantly increase energy efficiency, thereby reducing energy cost and carbon emission simultaneously. The system consists of two concentric pipes. The hot dyeing and printing sewage (average temperature: 55°C) flow into the internal pipe when the clean water with normal temperature flow into the internal pipe. Through the heat exchange, the clean water will heat up from 20°C to 45°C and then can be used in production (Figure 2).

According to the interview from manager of the FH, the technology of the first HER system was not well developed, and the pipe was easy to be clogged by fluff. What is worse, the FH recognized that it is difficult to clean the pipes. Therefore, the company had already replaced the old equipment. The installation cost of the first system and the latest system are ¥0.4m and ¥1.6m, respectively. This installation cost is a kind of clean technology investment, which had significantly burdened the cash flow for the FH. The operation cost of the latest system per day is ¥1,100 according to the current production capacity. Therefore, annual operation cost is about half million RMB. It is economically reasonable that if the FH can gain half million RMB from extra production capacity generated from extra energy generated by the HER system. The FH produces 22,000 tons of hot dyeing and printing sewage per day and 40 per cent sewage flow into the system.

Similar to the SWH system, we consider the daily operational cost of using the HER system in FH as \( U_{FH} \), the amount of water this system can heat every day is \( H_{FH} \), the efficiency of heating 1 ton of water to steam is \( E_{FH} \) and the cost per ton of steam is \( S_{FH} \). As a result, the daily operational cost can be calculated as follows:

\[
U_{FH} = H_{FH} \times E_{FH} \times S_{FH}
\]

The FH heats 2,200 tons of fresh water for various production processes such as scouring and soaping every day. The daily production usually consumes 0.050 ton of steam to heat 1 ton of water and the cost per ton of steam is ¥180. As a result, under such textile production system, the daily operational cost of FH with the use of HER system is:

\[
U_{FH} = 2200 \text{ tons} \times 0.050 \text{ ton of steam to heat 1 ton of water} \times 180 \text{ RMB per ton of steam} = 19800 \text{ RMB}
\]

What is more important, the FH reduces the indirect carbon emission caused by steam consumption. The FH also enjoys the rebound effects from implementing the HER system. Based on the environmental performance of FH, the local government encourages the company to take more energy conservation and emission reduction measures by giving the company about ¥1m as subsidy. This financial reward drives FH to develop the low carbon supply chain practices.

3.2.3 Insights from the FH
3.2.3.1 Technology investment cost. Clean technology incurs large amounts of investment. In the past, the HER system was totally ignored due to the high implementation cost and immature development on clean technology. Nowadays, the HER has been embraced slowly and is expected to go far more ahead in textile production and manufacturing. Large-scale development and utilization of clean energy is unlikely to be achieved in a short time. With high technology investment cost, the textile manufacturers desire to cooperate with government or non-profit
organizations to develop the low carbon supply chain practices and reduce technology investment cost.

3.2.3.2 Financial reward/support. Insignificant financial gain is the key obstacle for textile manufacturers to implement low carbon practices in production even under external pressures. Thus, with the consideration of the financial performance, providing capital support or reward is an important incentive for the company to implement the low carbon strategy in the supply chain. This can be developed as a low interest rate for solar panel investment or a cash incentive from government/business partners. Because of the huge amount of investment cost for the clean technology implementation, the textile manufacturer also prefers the support from other’s supply chain partners. One possible way is to design a long-term cooperation contracts which can provide capital or technical assistance for the manufacturer to adopt the clean technology for production and result in a long-term growth in profitability. From a long-term perspective, clean technology improvement is the fundamental way for energy efficiency and emissions reduction.

3.2.3.3 Low carbon production. After implementing the HER system, the company saves steam for water heating. The HER system makes the efficient use of thermal energy from sewage and brings less waste emission to the environment over production cycle. In other words, the energy efficiency is increased and carbon emission is reduced in production and manufacturing process. The textile manufacturers should also learn the low carbon supply chain practices from their counterparts. Moreover, size of manufacturer may be an important factor on the implementation of low carbon supply chain practices, and, therefore, only the large manufacturers may have sufficient financial and human resources to support proactive low carbon supply chain practices.

3.3 Summary
Based on the two case studies on the adoption of clean technology for improving the production capacity, we summarize the insights as follows. First, adopting clean technology could improve the company green image, and the product is produced in a sustainable manner. This is consistent with the existing literature that developing clean technology may benefit the outcome of firm in market (Dong et al., 2014; Nguyen et al., 2015). Second, implementation of clean technology in the textile supply chain incurs heavy financial investment from supply chain members. This investment can be mortgaged into several periods but is still a financial burden from the manufacturer’s perspective. Thus, it is important to investigate how financial resource allocation significantly influences the practice of low carbon supply chain. Last but not the least, we find that the manufacturers desire the retailers or external organization to provide the financial support and technology assistance. However, it is under-studied that what kind of cooperating scheme that the manufacturer should work with.

4. Analytical model
Based on the practices of textile supply chains we observed from two investigated companies (i.e. manufacturer), we find that the textile manufacturers trade their buyers (i.e. retailers) with energy consumption constraint, as the Chinese government requires companies to adopt a low carbon supply chain practice[4]. Thus, we consider a two-echelon textile supply chain with one single manufacturer (he) and one single retailer (she) that the manufacturer has an energy consumption constraint in production. In other words, the manufacturer is responsible for producing the textile products, but his production capacity is limited due to the energy consumption enforcement, whereas the retailer is responsible for selling the products to market. We consider that the manufacturer can invest in the choice of clean technology $e$ (e.g. the SWH or HER systems) to increase energy efficiency and production capacity. If the used clean technology is greener (i.e. able to generate higher energy efficiency), the product is produced in a more sustainable manner; as a result, consumers may perceive that the product is safer and more environmental friendly, and, hence, the market demand would be higher. This assumption is consistent with the industrial practice and has been widely adopted in literature (Swami and Shah, 2013; Dong et al., 2014). We consider that the market demand is sensitive to both price $p$ and choice of clean technology $e$, with the demand function $q = a - bp + e$, where $b$ and $e$ are the coefficients, and all the coefficients satisfy the conditions of $a > 0$, $b > 0$ and $e > 0$. This consideration follows the classic economic assumption and the industrial practices in the textile and apparel industry that market demand is lower when the retail price of the product is higher (Chen et al., 2010, Xu et al., 2013; Wang et al., 2015; Shen et al., 2012). Besides, we also consider that there is an enforcement of the carbon emission level and the energy consumption constraint of the manufacturer is $K$, which is determined by the government. Based on the energy consumption constraint, the manufacturer could determine the production capacity and implement the clean technology to increase production capacity. This assumption is consistent with the real practices we observed in textile supply chain that technology investment can increase total production capacity such as Drake et al. (2016). In this supply chain, we assume the retail price is $p$ per unit and the production cost is $k$ per unit. According to the real practices, the manufacturer is trading with the retailer via the WS contract, where the WS is denoted as $w$ per unit and determined by the manufacturer.

The game sequence is as follows. First, the manufacturer decides the WS $w$ and the choice of clean technology $e$, where $0 \leq e < 1$. If $e$ closes to 1, that means the manufacturer adopts a clean technology with high energy efficiency; if $e$ closes to 0, that means the manufacturer adopts a clean technology with lower energy efficiency; if $e = 0$, that means no clean technology is adopted. We assume that the $K$ and $e$ are in the same scale. Next, based on the determined $w$ and $e$, the retailer decides the retail price $p$. We conduct this game sequence by backward induction. Similar to Savaskan and Van Wassenhove (2006), Gurmani and Erkoc (2008) and Swami and Shah (2013), we assume that the clean technology investment cost $C(e)$ of the manufacturer is a quadratic function, i.e. $\eta e^2/2$, where $\eta$ is the sustainability investment coefficient. The subscripts $M$, $R$, $SC$ denote manufacturer, retailer and supply chain, respectively.

By considering that the manufacturer implements the clean technology to increase the efficiency of energy consumption...
and production capacity, the profit functions of the retailer and the manufacturer are as follows:

\[
\pi_R(p) = (p - w)q, \quad \text{and} \quad \pi_M(p, e) = (w - k)q - C(e) \tag{1}
\]

Scenario 1: \( q \leq K + e \):

If \( q \leq K + e \), we have \( a - \beta p - (1 - \theta) e \leq K \). Thus, the profit functions of the retailer and the manufacturer are revised as follows:

\[
\pi'_R(p) = (p - w)(a - \beta p + \theta e), \quad \text{and} \quad \pi'_M(p, e) = (w - k)(a - \beta p + \theta e) - C(e) \tag{2}
\]

Taking the first and second differentiations of \( \pi'_R(p) \), with respect to \( p \), we can find \( d^2 \pi'_R(p)/dp^2 < 0 \) and \( p'(w) \). Substituting \( p'(w) \) into the manufacturer’s profit function and taking the first and second differentiations of \( \pi'_M(p, e) \), we can find that when \( 4\beta \eta - \theta^2 > 0 \), \( w^*_1 = [2\eta(a - \beta K)/(4\beta \eta - \theta^2)] + k \), and \( e^*_1 = (a - \beta k)/(4\beta \eta - \theta^2) \), where the subscript 1 represents the Scenario 1.

Scenario 2: \( q > K + e \):

If \( q > K + e \), the maximum amount of manufacturer’s production quantity is \( K + e \), and we have \( a - \beta p - (1 - \theta) e > K \). The profit functions of the retailer and the manufacturer are revised as follows:

\[
\pi_R(p) = (p - w)(K + e), \quad \text{and} \quad \pi_M(p, e) = (w - k)(K + e) - C(e) \tag{3}
\]

Taking the first differentiation of \( \pi'_R(p) \), we can find that the profit function is increasing in \( p \). Thus, the optimal retail price we can get is \( p^*(e) = a - K - (1 - \theta) e/\beta \). Substituting \( p^*(e) \) into \( \pi'_M(w, e) \), and taking the differentiation of \( \pi'_M(w, e) \) with respect to \( e \), we can find that \( e'(w) = (w - k)/\eta \). For the retailer, there is a reservation WS that he is willing to accept the contract, and we denote the reservation WS as \( w_o \). Thus, the optimal retail price, WS and choice of clean technology are

\[
\rho_{SC2} = \eta(a - \beta K - 2K + \theta K)/(2(1 - \theta) + \eta \beta) + k
\]

and

\[
e^*_{SC2} = \eta(a - \beta K - 2K + \theta K)/(2(1 - \theta) + \eta \beta).
\]

\( P1 \). When \( q \leq K + e \), supply chain is not able to achieve coordination; when \( q > K + e \), supply chain is coordinated if:

\[
\omega_{o2} = \eta(a - \beta K - 2K + \theta K)/(2(1 - \theta) + \eta \beta) + k
\]

\( P1 \) implies that supply chain is not able to achieve channel coordination under the WS contract when the manufacturer has sufficient production capacity to fulfill all the market demand. This is because both the manufacturer and retailer determine the parameters in their optimal levels (i.e. WS \( w_o \), the choice of clean technology \( e \) and the retail price \( p \)) based on their own profit functions, and, hence, the optimal production quantity of the manufacturer (i.e. the demand of the decentralized system) is different from that of the whole supply chain. This phenomenon is called double marginalization. However, supply chain coordination could be achieved under the WS contract for the Case 1 when there is a rigid energy consumption constraint (i.e. a significantly small \( K \)) such that the manufacturer can only satisfy the demand partially and Case 2 when the reservation WS is set appropriately (i.e. \( w_{o2} = w_{o2}^* \)). With such parameter setting on the optimal reservation WS, it will affect the manufacturer’s optimal decision of the choice of the technology, as well as the retailer’s optimal decision on the retail price, and eventually result in a same demand quantity under the decentralized and centralized supply chain system.

According to the case studies indicated in Section 3, we observe that manufacturers desire to cooperate with their business partners to jointly develop the clean technology to share the investment cost. The implementation of the clean technology not only helps the manufacturer to increase the production capacity but also improves the brand image of the retail company (Faisal, 2010). Thus, we consider the CS contract in this textile supply chain. We assume the retailer shares \( (1 - \lambda) \) of clean technology investment with the manufacturer, and the remaining \( \lambda \) is responsible by the manufacturer, where \( 0 < \lambda < 1 \). Under the CS contract, the profit functions of retailer and manufacturer are as follows:

\[
\pi_R(p) = (p - w)q - (1 - \lambda)C(e), \quad \text{and} \quad \pi_M(p, e) = (w - k)q - \lambda C(e) \tag{7}
\]

Using the similar approach as above, we can find that when \( q \leq K + e \), the optimal retail price, WS and choice of clean technology are:

\[
\rho_{CS} = \frac{3\lambda \eta(a - \beta k)}{4 \lambda \eta \beta - \theta^2} + k, \quad w_{CS} = \frac{2 \lambda \eta(a - \beta k)}{4 \lambda \eta \beta - \theta^2} + k,
\]

and

\[
e^*_{CS} = \frac{(a - \beta k)\theta}{4 \lambda \eta \beta - \theta^2}, \quad \text{for} \quad 4 \lambda \eta \beta - \theta^2 > 0
\]

On the other hand, when \( q > K + e \), the optimal retail price, WS and choice of clean technology become:
To achieve supply chain coordination, we should let $\rho_{i, CS} = \rho_{SC}$ and $\epsilon_{i, CS} = \epsilon_{SC}$ if $i \in \{1, 2\}$.

$P2$. Under the CS contract, when $q \leq K + \varepsilon$, supply chain is not able to achieve coordination; when $q \geq K + \varepsilon$, supply chain is coordinated if:

$$w_{i, CS} = \frac{\lambda \eta (a - K) - (1 - \theta)(w^c - k)}{\lambda \eta \beta},$$

and

$$\epsilon_{i, CS} = \frac{(w^c - k)}{\lambda \eta}.$$  

$P2$ shows that the supply chain is inefficient for the case when the manufacturer’s production capacity with clean technology adoption under the energy consumption constraint is equal to or larger than that of the demand quantity. Similar to $P1$, a coordinated supply chain can be achieved when the manufacturer is able to properly set the reservation $WS$ even under the rigid energy consumption constraint.

$P3$. Under the CS contract with the consideration of $q \leq K + \varepsilon$, when $(i)$ $0 < \lambda < 0.5$, we have $\epsilon_{1, CS} > \epsilon_{SC}$; $(ii)$ $0.5 \leq \lambda < 1$, we have $\epsilon_{1, CS} \leq \epsilon_{SC}$.

$P3$ reveals that when the manufacturer can fulfill all the demand requirement and the retailer is willing to share half of the clean technology investment cost under the CS contract, it will motivate the manufacturer to adopt the clean technology which has the same decision on the energy efficiency as in the centralized system (even though the optimal production quantity of the manufacturer is still smaller than that of the centralized system’s decision). It is initiative to observe that the degree of financial support from the retailer or the government (i.e. the proportion of clean technology investment cost sharing) will affect the choice of the clean technology that the manufacturer is adopted for producing the garments. In other word, the more the capital support from the retailer for the clean technology implementation (i.e. $\lambda$ is smaller), the cleaner the technology the manufacturer will use.

According to the existing literature, the CS contract is able to achieve channel coordination in supply chain (Leng and Parlar, 2010). However, under our model, supply chain might not be able to achieve coordination via the CS contract. Suppose that the international fashion buyers (i.e. retailers) are willing to provide the financial assistance to the Chinese manufacturers for pursuit of profitable energy-efficiency investment in supply chain (Plambeck et al., 2012), the CS contract can only induce the manufacturer to implement cleaner technology, which is equal to the optimal choice of clean technology in supply chain, rather than achieving channel coordination. This implies that the provision of CS contract is able to enhance the choice of clean technology. This result is consistent with the practices in the investigated company FH, where financial support was distributed and the clean technology is enhanced. This result can provide the managerial insights for the large buyers such as H&M, who should be more willing to help their suppliers and invest in clean energy technology adoption at the individual supplier sites.

$P4$. When $q > K + \varepsilon$ and the manufacturer considers the supply chain coordination achievement under the WS contract and CS contract, it will result in $w_{i, 2} > w_{i, 2, CS}$ for $\lambda \neq 1$; $\epsilon_{2} = \epsilon_{2, CS} = \epsilon_{SC2}$ and $\rho_{2} = \rho_{2, CS} = \rho_{SC2}$.

$P4$ evaluates the relative values of each decision parameters under the WS contract and CS contract. To be specific, when the government imposes a strict enforcement on the energy consumption level, the optimal reservation $WS$ under the WS contract is larger than that under the CS contract. In addition, it is also observed that the optimal choice on the clean technology and the optimal retail price under the WS contract (or the CS contract) is the same as in the centralized system. Thus, no matter how much the retailer involves in supporting the clean technology adoption, there is no difference in terms of the manufacturer’s optimal choice of the clean technology adoption and the retailer’s optimal retail price under the WS or CS contracts when the supply chain is coordinated.

5. Conclusion, insights and future research opportunities

Low carbon supply chain management takes environmental elements into consideration. Low carbon supply chain practices among textile manufacturers have been widely promoted by the Chinese government. The Chinese government has launched the regulation regarding the cap of energy consumption (i.e. energy consumption constraint) at corporate level to ensure a low carbon emission. In China, energy is mainly generated by coal in which large amount of carbon is emitted. Therefore, one of the measures to control carbon emission is to significantly reduce the energy consumption from burning the coal. In this paper, we examine a low carbon supply chain from energy consumption constraints perspective. We first conduct two case studies of adopting low carbon production practices in textile supply chain in China. The observation results from the investigated companies indicate some of the challenges and opportunities in developing low carbon supply chain with energy consumption constraints. We show that there is a trade-off between the clean technology and technology investment. To balance this trade-off, different textile companies react differently according to the company’s position and resource. Effective allocation of resource and maximization of energy efficiency have become a critical problem for the development of China’s textile industry. Based on the practices of low carbon supply chain from case studies, we develop a two-echelon supply chain. We identify the optimal decision of retailer and manufacturers in pricing and choice of clean technology. Our analytical results generate the following insights:

- **Double marginalization effect:** Double marginalization effect exists when there is an energy consumption restriction, but the manufacturer still has sufficient production capacity to fulfill all the market demand under the WS contract (or CS contract).
Low carbon supply chain with energy consumption

Bin Shen, Xuemei Ding, Lizhu Chen and Hau Ling Chan

Supply chain coordination: When the government imposes a strict enforcement on the energy consumption level and the manufacturer can fulfill partial market demand, supply chain coordination can be achieved if the manufacturer properly sets the reservation WS as \( w_{2_1} \) (or \( w_{2_3, CS} \)) under the WS contract (or the CS contract).

Clean technology investment cost sharing: Under the CS contract with sufficient production capacity (i.e. \( q \leq K + e \)), the proportion of clean technology investment cost that the retailer is willing to share will affect the degree of energy efficiency selection of the clean technology. Specially, when the retailer shares half of the investment cost, the energy efficiency level selection of the manufacturer will be the same as the centralized supply chain’s decision.

Reservation WS: By comparing the WS and CS contracts with insufficient production capacity (i.e. \( q > K + e \)), it is found that the optimal reservation WS under the WS contract is larger than that under the CS contract (while there is no difference in terms of the optimal choice of the clean technology selection and the optimal retail price under both contracts) when the supply chain is coordinated.

This study generates important insights to the low carbon supply chain management. However, our study is subjected to three main limitations that point toward fruitful directions for future research. First, in our analytical model, we study the impact of energy consumption constraint without considering the carbon tax and cap-and-trade regulation (e.g. European carbon emission cap). Under this setting (with the exclusion of carbon tax and cap-and-trade regulation), the impact of energy consumption constraint on supply chain performance could be examined thoroughly. In the future, this study could be extended to examine how the European carbon emission cap affects firms’ operations and decisions. Second, we consider the low carbon supply chain practices in Chinese textile industry only. Due to the various culture backgrounds, in the future research, it would be interesting to expand our study into other countries such as India and Bangladesh through the case study and analytical analysis. Third, our model is developed for the textile and apparel industry based on the practical evidence. It would be interesting to extend our models to the general contexts in the future research.

References


Further reading


Appendix

Proof of P1

As \( e_1^* = (a - \beta k)\theta/4\beta \eta - \theta^2 \), \( e_{CS1}^* = (a - \beta k)\theta/2\eta \beta - \theta^2 \), \( p_1^* = 3\eta(a - \beta k)/4\beta \eta - \theta^2 + k \), and \( p_{CS1}^* = \gamma(a - \beta k)/2\eta \beta - \theta^2 + k \), we can easily find that \( e_1^* \neq e_{CS1}^* \) and \( p_1^* \neq p_{CS1}^* \), thus when \( a - \beta p + \theta e \leq K + e \), the supply chain is not able to achieve channel coordination. When \( a - \beta p + \theta e > K + e \), we find that if \( w_o = \gamma(a - k\beta - 2K + 0K)/2(1 - \theta) + \eta \beta + k \), then \( e_2^* = e_{SC2}^* \) and \( p_2^* = p_{SC2}^* \).

Proof of P2

As \( e_{CS1}^* = (a - \beta k)\theta/4\eta \beta - \theta^2 \) and \( p_{CS1}^* = 3\lambda\eta(a - \beta k)/4\lambda \eta \beta - \theta^2 + k \), we can easily find that under the CS contract, when \( a - \beta p + \theta e \leq K + e \), \( e_{CS1}^* \neq e_{SC1}^* \) and \( p_{CS1}^* \neq p_{SC1}^* \). When \( a - \beta p + \theta e > K + e \), we can find that if \( w_o = \lambda \eta(a - k\beta - 2K - 0K)/2(1 - \theta) + \eta \beta + k \), both \( e_{CS1}^* = e_{SC1}^* \) and \( p_{CS1}^* = p_{SC1}^* \) could be obtained simultaneously.

Proof of P3

Under the CS contract with \( q \leq K + e \), (i) when \( 0 < \lambda < 0.5 \), we have \( e_{CS1}^* < e_{SC1}^* \) because \( 4\lambda \beta \eta - \theta^2 < 2\beta \eta - \theta^2 \); (ii) \( 1 > \lambda \geq 0.5 \), we can find that \( e_{CS1}^* \leq e_{SC1}^* \) because \( 4\lambda \beta \eta - \theta^2 < 2\beta \eta - \theta^2 \).

Proof of P4

By comparing \( w_o = \gamma(a - k\beta - 2K + 0K)/2(1 - \theta) + \eta \beta + k \) and \( w_{CS1}^* = \gamma(a - k\beta - 2K - 0K)/2(1 - \theta) + \eta \beta + k \), we can easily find that \( w_o \preceq w_{CS1}^* \) and \( \lambda \neq 1 \).

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Contract and incentive mechanism in low-carbon R&D cooperation

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Abstract
Purpose – This paper focuses on how the producer inspires his cooperative research partner to reduce carbon emission, by developing a menu of incentive contracts both in research and development (R&D) stage and recycling stage.

Design/methodology/approach – The proposed mechanism combines the researcher with the producer in a two-staged closed-loop system. Based on the concept that the producer takes the environmental responsibility, this paper designs a dynamically updating contract for the producer to encourage low-carbon efforts. Meanwhile, the producer offers a menu of contracts against the asymmetric information, that is, the R&D partner owns private information on his low-carbon R&D capability. According to incentive mechanism, the researcher decides whether to tell the truth and how much effort she would exert in R&D and recycling stages.

Findings – Discriminating between different types of researchers hurts the producer’s profit. But the updated screening contract can inspire researchers to tell the truth and is beneficial in reducing carbon emissions in the two stages. The results give the optimal solutions of the incentive mechanism. The low-type researcher only obtains reservation profit, whereas the high-type is given more to induce the information.

Originality/value – This paper proposes a strategy of updating the contract factors for avoiding adverse selection and moral hazard. Considering the environmental responsibility of waste products, the producer would like to encourage low-carbon designs among the R&D partners in a closed-loop supply chain.

Keywords Contracts, Closed loop supply chains, Carbon emission, Asymmetric information, Game theory, Low carbon, R&D cooperation, Recycling, Outsourcing risks, Incentive mechanism, Screening contract

Paper type Research paper

1. Introduction

With the rise in public environmental awareness on green consumption, some innovative products with low carbon become more and more attractive for the consumers. In a product’s life cycle, from research and development (R&D) to manufacturing, storing, transportation and recycling, each process directly or indirectly contributes to carbon emissions. Therefore, how to reduce carbon emissions and who should take the responsibility for the emissions is critical to achieve the low-carbon objective. In terms of the first issue, a carbon emissions trading mechanism is considered to be an effective method to reduce carbon emissions (Fischer et al., 2003). In addition, tax rebate and low-carbon subsidy are also economic tools to attain the low-carbon goal (Lee et al., 2008; Fankhauser and Hepburn, 2010). In terms of the second issue, the basic principle is the one who (the producer) makes it and takes the responsibility (Jacobs and Subramanian, 2012; Sunar and Plambeck, 2016).

Nowadays, the policy of extended producer responsibility (EPR) is implemented in most western countries. EPR requires companies to take responsibilities for the impacts of their products: from the materials used in manufacturing to product recycling. This has been enacted from automotive and packaging industries, to batteries and electrical and electronic waste (e-waste) (Atasu and Subramanian, 2012). The Waste Electrical and Electronic Equipment (WEEE) Directive in Europe and The Specified Household Appliance Recycling Law enacted in Japan in 2001 (Tojo, 2004) are early examples of such legislation. Since 2004, 24 states in the USA adopted EPR policy to handle the waste product, especially e-waste (Electronics Take Back Coalition, 2014). The object of EPR laws is to lower the environmental impact by reducing the amount of waste sent to landfills and to encourage the producer to design greener products (Mayers et al., 2005). However, because of the large population, there are 0.4 billion wasted mobile phones junked...
every year in China, which causes serious concerns to Chinese government and enterprises.

The main drivers of low-carbon R&D are sustainable cooperation for R&D alliance and consumer awareness of environmental issues. Product innovation will be affected by the greenness of upstream suppliers. Lisa Jackson, the vice president of Apple’s Environment Policy and Social Initiatives, said that carbon emissions of the new generation iPhone 6s and iPhone 6s plus were reduced by 16 and 14 per cent, respectively. That is because one supplier in China has improved the compression molding process and used clearer hydroelectric power when they developed the aluminum shell of the newest iPhone (Apple Inc., 2016). Owing to consumer’s consciousness on low-carbon preference, the brand influence of green products can make the producer a stronger competitor. Usually, the realization of green products depends on all supply chain partners’ efforts. Therefore, the cooperation and involvement are the critical factors to supply chain partners for the low-carbon innovative product.

To improve inter-organizational coordination and greenness of product, the producer often requires the R&D researcher (she) to share more information about new material and technology information. Once the researcher designs component for recycling and disassembly, the producer will pay less in the recovery process (Song and Lee, 2010). Usually the producer does not know the real information about researcher’s low-carbon skill. Even if the researcher promises a specific carbon emission level, it is hard to verify it after she delivers the component (e.g. Volkswagen automobile emission scandal). Hence, an issue for the core enterprise in the supply chain is how to urge researchers to commit themselves to making low-carbon products under asymmetric information scenarios.

Motivated by the low-carbon concept in practice, a low-carbon supply chain is investigated in this paper. The assembly producer adopts an incentive mechanism to encourage the R&D researcher to exert more effort in a closed-loop supply chain (CLSC). The main contribution of this paper is to achieve the following multifold objectives:

- First, showing the optimal solution of the updated model and the original model.
- Second, giving the producer suggestions about when and how to revise the contract factors.
- Third, inducing the researchers to provide authentic low-carbon technology information.
- Fourth, finding how much effort the researcher would like to take in the two stages and the impact on emissions.

The remainder of the paper is organized as follows. In Section 2, we provide a literature review. In Section 3, we introduce the research problem and related model assumptions. In Section 4, a menu of screening contracts and the updated incentive mechanism are proposed for the producer. Following the optimal contract structure, we analyze the effects on profit and environment in Section 5. Managerial insights are concluded in Section 6.

2. Related literature

Our paper is most relevant to the literature on contract design in supply chain coordination. The types of contracts are well explored, including wholesale price, two-part tariff, revenue sharing, sales rebate and return policy contracts (Wei and Choi, 2010; Taylor, 2002; Govindan et al., 2012; Nandi, 2016). For example, Cachon (2003) shows that a simple wholesale price contract cannot coordinate a supply chain with price-independent demand, but a two-part tariff contract can. Then, Bernstein and Federgruen (2005) show that the same linear price discount scheme coordinates the chain when dealing with noncompeting retailers. Chiu et al. (2011) examine a price-rebate-return policy to coordinate a two-echelon supply chain with price-dependent demand, and obtain an upper bound for the manufacturer to implement the policy. Then, the studies extend to risk attitudes of the manufacturer or different retailers (Choi et al., 2008; Chiu et al., 2015).

For the revenue-sharing contract we used in our study, Cachon and Lariviere (2005) address the strengths and limitations of the revenue-sharing contract in the price-setting newsvendor case by comparing with other contracts. In a supply chain structure with one manufacturer and one retailer, Koulamas (2006) studies the effect of the revenue-sharing policy on the allocation of channel profit and finds that the revenue-sharing policy always benefits the retailer. Gerchak et al. (2006) also show that the revenue-sharing contract with license fee could coordinate the whole channel under individual rationality constraint. Later, a more complex structure with competing retailers or suppliers is extended (Yao et al., 2008; Gerchak and Wang, 2004). Wang et al. (2004) observe that the retailer is the Stackelberg leader to offer the revenue-sharing rule, whereas the supplier decides the retail price and production quantity as the follower. Xiao et al. (2011) focus on the product quality and service quality decisions in a two-stage supply chain via a revenue-sharing contract. Some literature use profit sharing models in supply chain alliances (Nagarajan and Sošić, 2008).

The operation literature on contracts investigate the design of optimal R&D contract to coordinate investments and resolve agency problems under asymmetric information. Papers about innovation R&D contract typically include a combination of upfront payment, milestone payment and royalties and study the impact of the contract elements (Dechenaux et al., 2009). When product innovation is perceived as the source of competitive advantage, product design strategy becomes a central issue in supply chain (Halldorsson et al., 2007). Taylor and Plambeck (2007) study a supplier-manufacturer relationship and consider the moral hazard in supplier’s investment decision. Crama et al. (2008) study how innovators can optimally design licensing contracts and show that moral hazard may create an additional value loss when combined with adverse selection. Xiao and Xu (2012) study a royalty revision contract in a multi-stage R&D with information asymmetry about the innovator’s capability, based on the technical performance of the innovative product. Bhattacharya et al. (2014) find that milestone-based options contracts always attain the first-best outcome for client when the provider has some bargaining power in renegotiation. As for asymmetric information, Armstrong and Rochet (1999) use a screening model and show that multidimensionality may require the introduction of upward incentive constraints, because a low-type agent may pretend to be the high type. A number of recent papers study cost information asymmetry (Kaya and Özer, 2014).
2009), Iyer et al. (2005) is related to our study. They use the screening contract in the context of product development, and focus on how collaboration incentives are influenced by various types of procurement contracts. However, these papers focus on traditional supply chain problems but do not discuss product recovery issues. We study the screening contracts with asymmetric information and give a renegotiation chance to revise the contract.

Our work is also related to CLSC management. For an overview of this research field, we refer the readers to Guide and Van Wassenhove (2009) and Govindan et al. (2015). Some interesting research has emerged in either the competitive strategy or the channel leadership in the closed-loop context (Miemczyk et al., 2016). The theme of CLSC with competitive behavior has received much attention in the last few years (Govindan et al., 2013). Atasu et al. (2008) think remanufacturing can be used as an effective marketing strategy that allows an integrated manufacturer to defend its market share via price discrimination. Therefore, the manufacturer has the incentive to organize the CLSC. The other stream of channel leadership in reverse logistics is well explored. It commonly assumed that the manufacturer or retailer is the leader (Savaskan et al., 2004; Cakanyildirim et al., 2012). Choi et al. (2013) examine the performance of three different leaderships in the CLSC with a price-dependent demand, and find that the retailer-led model is more effective. Zhang et al. (2014) design a two-part nonlinear contract and a collection effort requirement contract in a CLSC when the cost of collection effort is the retailer’s private information. Hong et al. (2017) find that royalty licensing is dominated by fixed fee licensing from the viewpoints of both the consumer surplus and environmental protection in a remanufacturing context. However, this paper focuses on the relationship of the researcher and the producer, because we assume that the producer owns the distribution channels and also uses them to take back waste products.

Another relevant stream is the economics and management literature of low-carbon designing and environment. Firms develop their strategies not only for short-term gains in revenues and expense controls, but also for product design innovation to make recapture and remanufacture of their products more viable (Maslennikova and Foley, 2000; Clifford DeFeo et al., 2009). Lee et al. (2009) introduce a model to select and determine green suppliers for the sustainability of the manufacturer in the long term. Diabat et al. (2013) find that the three most relevant green supply chain management practices in the automotive industry are design for environment, collaboration with clients and reverse logistics. The recent operation management literature study how the principle of EPR can be effectively implemented to e-waste products (Toyasaki et al., 2011; Atasu and Subramanian, 2012; Gui et al., 2015). All the studies above confirm the view that the producer should take responsibility for the carbon emissions of the product, even in its use and recycling processes. To the best of our knowledge, there are few papers involving the supplier when the operation performance of CLSC is analyzed (Porteous et al., 2015). Jacobs and Subramanian (2012) examine the effects of sharing product recovery responsibility between a supplier and a non-integrated manufacturer with no competition. Xiong et al. (2013) extend the scenario to that where the non-integrated manufacturer is not only a buyer but a rival to the supplier. They find the non-integrated manufacturer may be worse off with a lower remanufacturing cost.

Most of the researches focus on either traditional R&D or recovery process but ignore the carbon emissions in the life cycle of the product. In this paper, we incorporate low-carbon recycling into the R&D stage, and induce the researchers to show their information by updating contracts. Table I presents a summary of the comparison based on several aspects.

### 3. Model description

As described in the introduction, our analysis focuses on how to reduce carbon emissions during the life cycle of the product. This paper considers a leading electronic innovation-oriented producer (e.g. Apple Inc.), which assembles electronics such as tablet, mobile phone or other innovative products. To pursue low carbon emissions, the producer outsources a critical component to a researcher, who can develop a new screen with a lighter, recyclable and free of harmful chemical material to satisfy the market demand. Once the contract is signed, the researcher will exert efforts for a low-carbon component, considering the life cycle assessment and the waste generation with low cost. After launching to the market, the producer will be responsible for calling back the e-waste and sending them into the recycling process (e.g. disassembling, shredding or reusing). However, the researcher’s technology level of low-carbon R&D is

<table>
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Notes:  
- aClosed-loop supply chain; bSupplier-manufacturer; cmanufacturer-retailers; dAsymmetric Information; eEnvironment responsibility; fContract types; gWholesale price; hRevenue sharing

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private information. It is hard for the assembling producer to identify the real level from many researchers before signing cooperation contract.

This situation can be formulated as a principal-agent issue, in which the producer acts as the principal, and the low-carbon R&D supplier acts as the agent. In addition to asymmetric information on the level of researcher’s low-carbon skills, the efforts of both parties are also unobservable. Figure 1 details the timeline of the model. There are two negotiation stages in our model. First, at the R&D stage, the producer offers a menu of contracts to the researcher, which contains an upfront payment \( e_i \) and a revenue sharing ratio \( \alpha_i \), with \( i \in \{l, h\} \). The researcher chooses one of the contracts and exerts effort \( e_1 \) to research and develop the component, based on her low-carbon technology. The R&D effort is private action that could not be contracted. Next, in the marketing and recycling stage, the producer assembles and launches the innovative product to the market, and the researcher would exert recycling effort \( e_2 \) for the waste product.

After verifying the real carbon emission level of the component, the producer will update his belief of the researcher’s type, and propose a revised contract, which contains a milestone payment \( \gamma \) and a revenue share rate \( \beta_i \), with \( i \in \{l, h\} \). If the researcher rejects the revision contract, she will still get the original revenue ratio \( \alpha_i \), where \( \alpha \geq 0 \) and \( \beta \geq 0 \). The producer gives promotion and return policy with the effort \( e_m \). The cost function of producer is \( c_p(e_m) = e_m^2 / 2 \).

It is assumed that cost function of the researcher’s effort is increasing and convex. The cost of exerting green R&D effort is \( c_i(e_i) = e_i^2 / 2g \), and the cost of handling the recycling product in the second stage is \( c_d(e_i) = e_l^2 / 2g \). The coefficient \( g \) presents the researcher’s low-carbon R&D technology level, which is private information. To facilitate tractability, we assume two different types of researchers depending on whether they have a better technology in low-carbon production process, which are labeled \( g_l \) and \( g_h \) with \( 0 < g_l < g_h \). In this expression, \( g_h \) means more advanced technology or optimized equipment to reduce carbon emissions. The higher \( g \) is, the lower the cost the contractor will afford under the same effort. The producer just knows the probability distribution: \( g \), with probability \( \varphi \), \( g_h \) with probability \( 1 - \varphi \).

One important issue is to reduce carbon emissions during the whole life cycle of the product. Like EPA policy in USA and WEEE directive in European Union, producers are financially responsible for the post-use collection, transportation, and recycling processes (Gui et al., 2015). In this paper, the researcher is assumed to pay the environmental expenses. The emission reduction in the returning process depends on the efforts of researcher in two stages, as well as the effort of producer in marketing stage (e.g. assembling, packaging, returning policy).

Thus, \( T = t_0 - t_c \) is defined as the cost of the carbon emissions for the producer, where \( t_0 \) denotes the carbon expense for a common product, and \( t_c \) represents the reward of emission reduction during production and recycling.

The reduced emissions during the production and recycling relies on the efforts of the R&D alliances in the two stages. Thus, the reward of emission reduction can be written as:

\[
t_c = p(e_1 + \sigma e_2 + v e_m)
\]

where \( \sigma \geq 0 \) and \( \nu \geq 0 \) mean the effectiveness of the researcher’s effort and the producer’s effort to reduce the carbon emissions, respectively. The parameter \( p \) represents the reward coefficient, with \( p > 0 \).

The low-carbon product has a great impact on consumer purchase decisions. The total revenue collected from selling the product is determined by the following form:

\[
R = e_1 + \theta e_2 + \lambda e_m + \nu
\]

where \( \theta \geq 0 \) is the effective coefficient of researcher’s effort in the recycling stage, and \( \lambda \geq 0 \) is the effective coefficient of the producer’s effort to increase sales revenue. If \( \theta \) is higher than \( \lambda \), the researcher’s effort (i.e. disassembly and recycling) has a larger impact on the sales revenue than that of the producer’s effort (i.e. promotion and marketing channels) in the second stage, which implies consumers are more concerned about environmentally sensitive products, and vice versa. The total revenue of the product is influenced by a random noise \( \nu \) with mean 0 (e.g. competition strategy).

4. Updating mechanism under asymmetric information

The producer and the researcher are engaged in a multistage game with incomplete information. The solution of the two-stage game is the perfect Bayesian equilibrium. In this mechanism, the producer would use the separating contracts to maximize his expected profit, and the optimal solution can be obtained by the backward induction method.

4.1 Updated contracts in the second stage

In the marketing stage, if the researcher chooses the new contract, she will obtain the milestone payment \( \gamma \) and the updated sharing rate \( \beta_i \). Otherwise, the researcher still gets the sharing revenue with \( \alpha_i \). Thus, there are two scenarios:

4.1.1 Rejection

If the researcher rejects the revision, her expected profit in the second stage is:

\[
\pi_{R(i)} = \alpha_i(e_1 + \theta e_2 + \lambda e_m) - c_p(e_m)
\]

4.1.2 Acceptance

The researcher in two stages, as well as the effort of producer in recycling stage (e.g. assembling, packaging, returning policy).

Figure 1 Timeline of the green R&D cooperation

![Figure 1](image-url)
Given $\frac{\partial \pi_{R(i)}}{\partial e_2} = 0$, the expected profit is maximized at $e_2^* = \alpha_2 g_i$. The expected profit of the producer with the revised contract is:

$$\pi_{P(i)} = (1 - \alpha)(e_1 + \theta e_2 + \lambda e_m) - c_m(e_2) - (t_o - t_x)$$

To have an analytically tractable model and gain sharper insights into the problem, we assume $t_o = 0$. Thus, $\pi_{P(i)}$ can be written as:

$$\pi_{P(i)} = (1 - \alpha)(e_1 + \theta e_2 + \lambda e_m) - e_2^*/2 + p(e_1 + \sigma e_2 + v e_m)$$

(2)

The optimal effort for the producer is $e_2^* = (1 - \alpha)\lambda + pv$.

4.1.2 Acceptation

If the researcher accepts the revised contract, her expected profit in the second stage is:

$$\pi_{R(i)} = \beta_i(e_1 + \theta e_2 + \lambda e_m) - c_2(e_2) + \gamma_i$$

(3)

The expected profit of the producer is:

$$\pi_{P(i)} = (1 - \beta_i)(e_1 + \theta e_2 + \lambda e_m) - e_2^*/2 - \gamma_i + p(e_1 + \sigma e_2 + v e_m)$$

(4)

The optimal efforts are $e_1 = \beta_i g_i, e_2^* = (1 - \beta_i)\lambda + pv$. To ensure the researcher accepts the updated contract, the revised contract for type $i$ should be Pareto improving. The optimal issue in the second stage can be written as:

$$\max_{\alpha_i = \beta_i > 1, \gamma_i} \pi_{P(i)} \{\beta_i, \gamma_i | e_i\}$$

s.t. $\pi_{R(i)}(i) \geq \pi_{P(i)}(r) \geq 0, i \in \{1, h\}$

(5)

The objective function (5) is to maximize the producer's expected profit for each type of researcher when the updated contract is in the second stage. The issue can be solved for each $i$ separately. $\pi_{R(i)}(r | i)$ (or $\pi_{R(i)}(r | i)$) means the expected profit of the $i$-type researcher when she chooses the $i$-type original contract and accepts (or rejects) the updated contract. Constraint (6) ensures that the researcher could obtain the reservation utility, and get more profit if telling truth and accepting updated contract. Without loss of generality, it is supposed that the researcher is risk neutral with a reservation utility of zero. To induce the researcher accepting the updated contract, the expected profit of the researcher under the updated contract will be no less than that under the original one.

PI. After observing the researcher’s effort in the R&D stage, the producer will update the contract with the milestone payment $\gamma_i$ and the new revenue sharing rate $\beta_i^*$, where:

$$\gamma_i = \alpha_i [e_1 + \frac{\theta^2 g_i}{2} + \lambda^2(1 - \alpha_i) + p e_2 \lambda] - \beta_i^*[e_1 + \frac{\theta^2 g_i}{2} + \lambda^2(1 - \beta_i) + p e_2 \lambda]$$

$$\beta_i^* = \frac{\alpha_i g_i + \theta^2 g_i}{\lambda^2 + \theta^2 g_i}$$

(7)

(8)

The proof is provided in Appendix.

Equation (8) can be written as $\beta_i^* = p(\sigma/\theta) + 1/(\lambda/\theta^2) (1/g_i) + 1$. Thus, we have the following lemma:

**Lemma 1.** $\beta_i^*$ increases with $g_i$ and $\sigma$, whereas it decreases with $\lambda$. If other variables are constant, the optimal ratio $\beta_i^*$ reaches its maximum when $\theta_i = \lambda^2 + \lambda \sqrt{\lambda^2 + p^2 \sigma^2 g_i}/ \psi g_i$, and reaches its minimum $\beta_i^* = 0$ when $\theta_i = 0$.

Three findings can be concluded from Lemma 1:

1. Researcher with a better low-carbon research capability will be given a higher revenue sharing, that is, $\beta_i^* > \beta_j^*$.

2. When the researcher plays a more important role in low-carbon recycling process, the producer will raise the sharing ratio. When the producer’s effort has more impact on market sales, the producer would reduce the profit ratio with the researcher. If consumers completely do not care about the recycling of the e-waste, there will be no any revenue profit to the researcher.

3. The coefficient $\theta_i$ does not always play a positive role to raise the revenue sharing ratio. Because low-carbon recycling of the innovative product can attract more customers, the researcher has a stronger bargaining power to get a higher sharing ratio with $\theta_i$ increasing in interval $\theta_i \leq \theta_0$. However, the producer would reduce the updated sharing ratio to avoid risks and control the supply chain if $\theta_i$ further increases ($\theta_i > \theta_0$). Then the sharing ratio will return to $\beta_i^* = 1$ when $\theta_i$ is large enough.

4.2 Original contract in the R&D stage

Based on Lemma 1 (i.e. $\beta_i^* > \beta_j^*$), the low-type researcher has the motivation to pretend to be the high type. Assuming that the researcher of type $i$ chooses the contract $[\alpha_i, \omega_i]$ to hide her real type, she would accept or reject the updated contract $[\beta_i, \gamma_i]$ after the R&D stage. There are two scenarios at the start of the second stage:

1. **Rejection:** if $i$ type of researcher pretends to be $j$ and rejects the updated contract, she will keep the contract $[\alpha_j, \omega_j]$ and her expected profit at the beginning of R&D stage would be:

$$\pi_{R(i)}(i) = \alpha_j(e_1 + \theta e_2 + \lambda e_m) - c_{12}(e_1) - c_{22}(e_2) + \omega_j$$

(9)

In this case, the researcher would decide the optimal effort in the two stages:

$$e_1^*(i) = \alpha_j g_j, e_2^*(i) = \alpha_j g_j$$

The producer's expected profit is:

$$\pi_{R(i)} = (1 - \alpha_j)(e_1 + \theta e_2 + \lambda e_m) - c_{12}(e_2) - \omega_j + t_o$$

(10)

Although the producer will update his belief to the researcher’s type, he would not change his optimal effort in the marketing stage. We can get:

$$e_2^*(i) = (1 - \alpha_j)\lambda + pv$$

2. **Acceptation:** if $i$ type of researcher pretends to be $j$ type and accepts the revised contract $[\beta_j, \gamma_j]$. The researcher’s expected profit at the beginning would be:
Substituting the best efforts of  
\[ e_i'(a) = \frac{e_i'^2 + 1}{(1 - \beta_i)\lambda + \rho v \gamma_i + \lambda^2 - \omega_i} \]
into equation (11), the researcher's optimal decision on effort in the first stage can be obtained as  
\[ e_i'(a) = \frac{e_i'^2 + 1}{(1 - \beta_i)\lambda + \rho v \gamma_i + \lambda^2 - \omega_i} \]
The researcher makes the optimal effort in the first stage based on the original sharing ratio. However, both the producer and the researcher will change the effort decisions once accepting the new contract at the second stage.

4.3 Screening contract under information asymmetry
Generally speaking, the R&D researcher can choose a wide range of contract menus. However, the direct revelation principle (Mas-Colell et al., 1995) restricts the category of contract menus by showing that the optimal mechanism could induce the researcher revealing her true type. The screening model is to induce the researcher telling the true type and then accepting the Pareto improving contract. Once the researcher chooses one of the contracts, she will decide the equilibrium effort level  
\[ e_i' \]
under that contract. In this case, the expected profit of the producer is:
\[
\pi_p(a | l, l) = (1 - \beta_i ')(e_i' + \theta e_i' + \lambda e_i' - \frac{e_i'^2}{2} - r_i - \omega_i) + p(e_i' + \sigma e_i' + \nu e_i')
\]
Under asymmetric low-carbon production information, the optimal mechanism can be formulated as follows:
\[
P(0) \max_{\pi_p, \pi_h, \pi_l} \pi_p = \varphi \pi_p(a | l, l) + (1 - \varphi) \pi_p(a | h, h)
\]
s.t.
\[
\pi_p(a | l) \geq \pi_p(a | h)
\]
\[
\pi_h(a | l) \geq \pi_h(r | h)
\]
\[
\pi_h(a | h) \geq \pi_h(a | l)
\]
\[
\pi_h(a | h) \geq \pi_h(r | l)
\]
\[
\pi_h(a | h) \geq 0
\]
\[
\pi_h(a | l) \geq 0
\]
Equation (13) is the producer’s expected profit for the two types, taking into account the R&D researcher's optimal contract and action decision. Different from the traditional adverse selection problem that has one incentive compatibility (IC) constraint for each type, the proposed model has two IC constraints. In constraint (6) of the second stage problem, the Pareto improving condition ensures that the researcher will accept the revision contract if she tells a truth. Thus, the next step is to consider whether the researcher will accept the updated contract when she tells a lie in the first stage.
Constraints (14) and (15) are both the IC constraints for the low-type researcher, which ensure that the low-type researcher can get more profit when she tells the truth at the beginning, whether accepting or rejecting the updated contract. Similarly, the IC constraints (16) and (17) are designed for the high type. Under this mechanism, the only action of the researcher is to reveal her type truthfully and make the optimal effort  
\[ e_i' \]. The individual rationality (IR) constraints (18) and (19) guarantee that the researcher receives her reservation utility.

4.4 Optimal contract structure
This is a bi-level programming problem with six constraints. First, let us simplify the problem and see the character of this model.

Lemma 2. This screening model guarantees:
- the high-type researcher obtains positive expected profit; and
- the low-type researcher can only obtain the reservation utility, and we can solve the optimal upfront payment  
\[ \omega^*_i \]
Because the margin cost of the high type is lower with the effective low-carbon production line, the high-type researcher will get more profit if she chooses the low-type contract, that is,  
\[ \pi_{Rh} (a | l) \geq \pi_{Rh} (a | h) \]. Combined with constraint (16) (i.e.  
\[ \pi_{Rh} (a | h) \geq \pi_{Rh} (a | l) \]), it is easy to know that if constraint (19) is satisfied, the IR constraint (18) for the high type can be ignored. In Lemma 2 (2), the producer will design the contract to squeeze more profit from the researcher and keep them joining the contracts. Therefore, the IR constraint for the low type should be binding in the optimal solution. When  
\[ \pi_{Rh} (a | h) = 0 \], the upfront payment  
\[ \omega^*_i \] can be obtained:
\[
\omega^*_i = -\alpha_i \left[ \frac{\alpha g_i}{2} + \frac{\theta^2 \alpha g_i}{2} + \lambda^2 (1 - \alpha_i) + \rho v \lambda \right]
\]
At the same time, we need to determine which one of constraints (16) and (17) should be binding. From (11), we have:
\[
\pi_{Rh} (a | l) = \alpha_i \left[ \frac{\alpha g_i}{2} + \frac{\theta^2 \alpha g_i}{2} + \lambda^2 (1 - \alpha_i) + \rho v \lambda \right]
\]
\[
+ \frac{\beta_i ^2 (g_h - g)}{2} + \omega_i
\]
\[
\pi_{Rh} (r | l) = \alpha_i \left[ \frac{\alpha g_i}{2} + \frac{\theta^2 \alpha g_i}{2} + \lambda^2 (1 - \alpha_i) + \rho v \lambda \right] + \omega_i
\]
Further, we get:
\[
\pi_{Rh} (a | l) - \pi_{Rh} (r | l) = \frac{\theta^2 (g_h - g) (\beta_i ^2 - \alpha_i ^2)}{2}
\]
When  
\[ \alpha_i \leq \beta_i \], there is  
\[ \pi_{Rh} (a | l) \geq \pi_{Rh} (r | l) \], the high-type researcher would like to accept the revised contract in the marketing stage, even if she pretends to be low. Constraint (16) should be binding. Similarly, when  
\[ \alpha_i \geq \beta_i \], there is  
\[ \pi_{Rh} (a | l) \leq \pi_{Rh} (r | l) \], the producer just ensures constraint (17) should be binding. The high-type researcher will reject the updated contract designed for the low type.
P2. Given the revision contract \( \{ \beta_i \}, \gamma_i \) for each type of the researchers, the producer gives the upfront payment \( w_i \) in the original contract, as follows:

- **Case 1:** if \( \alpha_i \geq \beta_i \), the pretended researcher would like to reject the revision contract, the binding constraint is \( \pi_{Rh} (a | h) = \pi_{Ro} (r | l) \):

\[
\begin{align*}
\omega_i^* &= -\alpha_i \left[ \frac{\alpha_i g_i}{2} + \frac{\beta_i \alpha_i g_i}{2} + \lambda_i^2 (1 - \alpha_i) + p \nu \lambda \right] \\
\omega_h^* &= -\alpha_h \left[ \frac{\alpha_h g_h}{2} + \frac{\beta_h \alpha_h g_h}{2} + \lambda_h^2 (1 - \alpha_h) + p \nu \lambda \right] \\
&+ \frac{1}{2} \alpha_h (g_h - g)(1 + \theta^2)
\end{align*}
\]

- **Case 2:** if \( \alpha_i \leq \beta_i \), the pretended researcher would like to accept the revised contract, the binding constraint is \( \pi_{Rh} (a | h) = \pi_{Ro} (r | l) \):

\[
\begin{align*}
\omega_i^* &= -\alpha_i \left[ \frac{\alpha_i g_i}{2} + \frac{\beta_i \alpha_i g_i}{2} + \lambda_i^2 (1 - \alpha_i) + p \nu \lambda \right] \\
\omega_h^* &= -\alpha_h \left[ \frac{\alpha_h g_h}{2} + \frac{\beta_h \alpha_h g_h}{2} + \lambda_h^2 (1 - \alpha_h) + p \nu \lambda \right] \\
&+ \frac{1}{2} \alpha_i (g_i - g)(1 + \theta^2)
\end{align*}
\]

In Case 1, because \( \pi_{Rh} (a | h) = \pi_{Ro} (r | l) \), we get:

\[
\begin{align*}
\omega_i^* &= \omega_i^* - \alpha_i \left[ \frac{\alpha_i g_i}{2} + \frac{\beta_i \alpha_i g_i}{2} + \lambda_i^2 (1 - \alpha_i) + p \nu \lambda \right] \\
&+ \frac{1}{2} \alpha_i (g_i - g)(1 + \theta^2)
\end{align*}
\]

Substituting \( \omega_i^* \), \( \omega_h^* \), \( \beta_i \) into the objective function, the expected profit of the producer facing to two types of researchers can be written as:

\[
\pi_p(a | l, l) = \alpha g_i (1 + p) + p \nu \lambda + \frac{\lambda_i^2}{2} \left( \frac{(\alpha_i g_i + \theta^2 g_i)^2}{2(\lambda_i^2 + \theta^2 g_i)} \right) \]

\[
\pi_p(a | h, h) = \alpha g_i (1 + p) + p \nu \lambda + \frac{\lambda_i^2}{2} \left( \frac{(\alpha_h g_h + \theta^2 g_h)^2}{2(\lambda_h^2 + \theta^2 g_h)} \right)
\]

In Case 2, because let \( \pi_{Rh} (a | h) = \pi_{Ro} (a | l) \), we get:

\[
\begin{align*}
\omega_i^* &= -\alpha_i \left[ \frac{\alpha_i g_i}{2} + \frac{\beta_i \alpha_i g_i}{2} + \lambda_i^2 (1 - \alpha_i) + p \nu \lambda \right] \\
&+ \frac{1}{2} \alpha_i (g_i - g)(1 + \theta^2)
\end{align*}
\]

Substituting \( \omega_i^* \), \( \omega_h^* \), \( \beta_i \) into the objective function, we have the producer’s expected profit in different types:

\[
\pi_p(a | l, l) = \alpha g_i (1 + p) + p \nu \lambda + \frac{1}{2} \frac{2 \theta_i^2 g_i}{2(\lambda_i^2 + \theta_i^2 g_i)}
\]

\[
\pi_p(a | h, h) = \alpha g_i (1 + p) + p \nu \lambda + \frac{1}{2} \frac{2 \theta_i^2 g_i}{2(\lambda_i^2 + \theta_i^2 g_i)}
\]

After determining the optimal values of \( \omega_i^* \) and \( \omega_h^* \), we need to find the optimal values of \( \alpha_i^* \) and \( \alpha_h^* \). Although the incentive compatibility constraint designed for the low type is proved to be redundant in previous studies, in this study, the researcher has an opportunity to get the updated contract; thus, the two IC constraints (14) and (15) for the low type should be considered.

Following the analysis of P2, we can divide the primal optimization problem P0 into two sub-problems:

\[
P(1) \max_{\alpha, \beta} \pi_{p1} = \varphi \pi_{p1}(a | l, l) + (1 - \varphi) \pi_{p2}(a | h, h)
\]

s.t. \( \alpha_i \geq \beta_i \)

\[
\alpha_i^2 + \beta_i^2 \theta^2 \geq \alpha_i^2 (1 + \theta^2)
\]

\[
\alpha_i \geq \alpha_i^*
\]

\[
P(2) \max_{\alpha, \beta} \pi_{p2} = \varphi \pi_{p1}(a | l, l) + (1 - \varphi) \pi_{p2}(a | h, h)
\]

s.t. \( \alpha_i \leq \beta_i \)

\[
\alpha_i^2 + \beta_i^2 \theta^2 \geq \alpha_i^2 + \beta_i^2 \theta^2
\]

\[
\alpha_i^2 + \alpha_i \theta^2 \geq \alpha_i^2 + \beta_i^2 \theta^2
\]

**Lemma 3.** In the original contract, there is \( \alpha_i^* > \alpha_i^* \). The sharing ratio \( \alpha \) has positive correlation with the low-carbon reward coefficient \( p \).

Let \( \partial \pi_p / \partial \alpha = 0 \), \( \partial \pi_p / \partial \alpha_i = 0 \), in P1, we have:

\[
\alpha_i^* = 1 + p, \ \alpha_i^* = \frac{g_i (1 + p)}{(g_i - g)(1 + \theta^2)(1 - \varphi) + g_i}
\]

In P2, we have:

\[
\alpha_i^* = 1 + p, \ \alpha_i^* = \frac{g_i (1 + p)}{(g_i - g)(1 - \varphi) + g_i}
\]

It is easy to find \( \alpha_i^* > \alpha_i^* \). The revenue sharing ratio for the high-type researcher is always higher than that of the low type. The original revenue sharing ratio \( \alpha_i^* \) is influenced by \( p \), whereas \( \beta_i^* \) is not. For \( p > 0 \), \( \alpha_i^* = 1 + p \) means that the high-type researcher will not only obtain the whole revenue but also benefit from the contribution to reduce emissions.
P3. Given the optimal upfront payment $\omega_i$, the optimal revenue sharing ratio $\alpha_i^*$, $i \in \{l, h\}$, can be characterized as follows:

- \((I1)\): when $\beta_i^l < u_i$, solving $P1$, we have $\alpha_i^l < \alpha_i$ and $\alpha_i^l > \alpha_i$. The constraint for the low type to accept the updated ratio should be binding.
- \((I2)\): when $\beta_i^l \geq u_i$ and $\beta_i^l \leq \alpha_i$, solving $P1$, we have $\alpha_i^l = \alpha_i$ and $\alpha_i^l = \alpha_i$. The constraints in $P1$ are satisfied, no binding.
- \((I3)\): when $\alpha_i^l < \beta_i^l \leq \alpha_i$, the optimal solution can be solved from both $P1$ and $P2$. From $P1$, we have $\alpha_i^l = \beta_i^l$ and $\alpha_i^l = \alpha_i$.
- \((I4)\): when $\alpha_i^l < \beta_i^l \leq u_{i2}$ solving $P2$, we have the optimal solution $\alpha_i^l = \alpha_i^l$ and $\alpha_i^l = \alpha_i$.
- \((I5)\): when $\beta_i^l > u_{i2}$, solving $P2$, the optimal solution will be $\alpha_i^l > \alpha_i$ and $\alpha_i^l < \alpha_i$.

The proof can be found in Appendix.

5. Contracts analysis and discussion

5.1 The optimal contract structure

From the optimal contract in the two stages, the producer can get some suggestions about how to update the contract parameters. The intuitions behind these results are as follows:

- \((II)\): From $P1$, the third constraint condition infers $u_i = (\alpha_i^l(1 + \theta^l) - \alpha_i^l)^2 / \theta^l$. When $\beta_i^l < u_i$, the optimal solution will be $\alpha_i^l < \alpha_i$ and $\alpha_i^l > \alpha_i$. In this case, the sharing ratio of the revision contract is very small, that is, $\beta_i^l < \beta_i^l < \sqrt{u_i}$. The理工大学 will make different choices in the second stage: if the high-type researcher pretends and chooses $[\alpha_i, \alpha_i^l]$, she would reject the updated contract with a smaller ratio $\beta_i^l$; if the low-type researcher pretends, interestingly, she would accept the new ratio $\beta_i^l$. This observation is different from the previous studies, where the IC constraint will never be binding. With the probability of the low-type researcher increasing, $\alpha_i^l$ will be raised and $\alpha_i^l$ will be distorted down.

- \((I2)\): In this interval, although $\beta_i^l$ may be larger than the solution in \((I1)\), it is still small ($\beta_i^l < \alpha_i$). The high-type researcher would reject the updated contract. All the constraints for the low type in $P1$ are satisfied, no binding conditions. Therefore, the low-type researcher would not accept the updated ratio and her optimal strategy is telling the truth at the beginning.

- \((I3)\): In this interval, constraints \((16)\) and \((17)\) in $P0$ should be binding. That means if the high-type researcher pretends, there is no difference for her to reject or accept the updated ratio, that is, $\beta_i^l = \alpha_i^l$. Thus, the producer cannot judge the researcher’s real type. Similarly, the low-type researcher has no motivation to pretend the high type.

- \((I4)\): To solve $P2$, we define that $u_i = \sqrt{(\alpha_i^l(1 + \theta^l) - \alpha_i^l)^2 / \theta^l}$, $u_i = \sqrt{(\alpha_i^l + \beta_i^l)^2 / \theta^l}$. From the proof, $\pi_{Ri}(l, h) \geq \pi_{Ri}(a, h)$ in $P0$ is always satisfied. $\beta_i^l \leq u_i$ can guarantee the IC constraint $\pi_{Ri}(l, h) \geq \pi_{Ri}(a, h)$ satisfaction. Therefore, the low type would not tell a lie. Based on $P2$(Case 2), the constraint for the high type to accept the updated sharing ratio is binding, that is, $\pi_{Ri}(a, h) = \pi_{Ri}(a, h)$ in $P2$. In this case, the high-type researcher can pretend to be the low type and accept the new ratio $\beta_i^l$.

However, the disguise does not bring any benefits for the high type, so a rational researcher will tell the truth.

- \((I5)\): In this interval, $\beta_i^l$ increases. The rejection IC constraint should be binding, but the acceptance IC constraint is not. Thus, the best strategy of the low-type researcher is telling the truth. Unlike the previous result that $\alpha_i^l$ is constant, it is distorted down for the low type and up for the high type in this case.

According to the above analysis, we can get the relationship of $\alpha^l$ and $\beta^l$, as depicted in Figure 2. $\alpha_i^l$ in the original contract is offered with a fixed value (i.e. $\alpha_i^l = \alpha_i^l$), whereas $\alpha_i^l$ will increase from $\alpha_i$ to $\alpha_i^l$. The revised ratio $\beta_i^l$ is the same with the original ratio $\alpha_i^l$ when $\alpha_i < \beta_i < \alpha_i^l$, which is different with the changes of $\beta_i^l$ in this case. From Figure 2, we can find that the change of $\alpha_i^l$ is more flexible than $\alpha_i$ to separate the two types of researchers.

Corollary 1. If $l > k_1$ or $\sigma < s_1$, the producer should offer a lower $\beta_i^l$ than $\alpha_i^l$; if $k_1 \leq l \leq k_2$ or $s_1 \leq \sigma \leq s_2$, $\beta_i^l$ should be the same with the initial one $\alpha_i^l$; if $l < k_2$ or $\sigma > s_2$, the producer will offer a higher $\beta_i^l$ than $\alpha_i^l$.

The proof can be seen in Appendix. Under information asymmetry, the producer can inspire the researcher to give more effort in the recycling stage using the revised contract. If the low-type researcher contributes a lot in the low-carbon recycling process (i.e. $\sigma > \varphi(1 + p)(\lambda^2 + \theta g)|p\theta_{Ri}(g_5 - g_1(1 - \varphi) + g\varphi) - \varphi/p = s_1$), the producer will raise $\beta_i^l$. Contrarily, if the impact to low-carbon recycling is inconspicuous (i.e. $\sigma < \varphi(1 + p)(\lambda^2 + \theta g)|p\theta_{Ri}(g_5 - g_1(1 + \theta))/(1 - \varphi) + g\varphi) - \varphi/p = s_2$), the sharing ratio will be reduced. Considering the updating strategy of the producer, the researcher should pay much attention to her contribution to the recycling process.

Corollary 2. If $\sigma > s_3$, $\beta_i^l$ is larger than $\alpha_i^l$. If $s_1 \leq s_3$, $\beta_i^l$ is smaller than $\alpha_i^l$. The proof can be found in Appendix. The conclusion for the high type depends on $\sigma, \lambda, \theta, \rho, g_5$ and $g_0$ but has no relationship with $\varphi$, based on $s_1 = (1 + p)(\lambda^2 + \theta g)|p\theta_{Ri}(g_5 - g_1(1 + \theta))/(1 - \varphi) + g\varphi) - \varphi/p$. Thus, unlike $\beta_i^l$, the producer will not concern with the probability of the two types when he decides the time to change $\beta_i^l$. If the high-type researcher gives more contribution in recycling, the producer will offer a revising-up ratio to her.

**Figure 2** The relationship of $\alpha_i^l$ and $\beta_i^l$
5.2 The effect on profits with asymmetric information
A numerical study is presented to analyze the optimal expected profit of the producer. With the probability of low-type researcher changing from 0 to 1, we choose $g_l = 0.6$, $g_h = 0.8$, $\lambda = 1$, $\sigma = 3$, $v = 1$, $p = 0.5$. From the result of Lemma 1, the researcher’s effort coefficient $\theta$ during the second stage will affect the updated ratio $\beta$ according to a certain rule. For example, when $\theta = 1.5$, Figure 3 illustrates that the optimal solution goes across three regions from $I_2$ to $I_4$. In the regions of $I_4$ and $I_3$, the optimal expected profit goes down with $\varphi$ increasing. However, in the region of $I_2$, the producer’s expected profit first falls down and then rises with $\varphi$ increasing. It is because that the producer will pay some information rent to encourage the R&D researcher to join the contract and exert more effort. If the researcher were more likely to be the low type (i.e. $\varphi$ is close to 1), the producer will reduce incentives to the low-type researcher.

Given by Lemma 2, the low-type researcher can only obtain the reserved profit, whereas the high type can yield more than the reserved profit (Figure 4). One interesting finding is that the probability of the two types of researchers cannot affect the expected profit of the high-type researcher in the third optimal solution region ($I_3$). When the probability of the high type is very small, the optimal ratio locates in $I_2$ solution region, and the high-type researcher will obtain a rapid-growing profit.

![Figure 3](image3.png) The change of producer’s expected profit with $\varphi$

![Figure 4](image4.png) The changes of the high-type researcher’s expected profit with $\varphi$

5.3 Effect on carbon emissions
According to the assumption, the emission reduction during the production and recycling relies on the efforts of the R&D alliances in the two stages. $V$ means the emission reduction caused by the incentive mechanism in CLSC. It can be written as $V = e_1 + \sigma e_2 + \varphi e_m$. The efforts of the researcher and the producer with asymmetric information can be obtained under different values of $g_l$ where $\varphi$ changes from 0 to 1. The comparison results can be seen in Table II.

From Table II, we can conclude:
- The effort of the lower type ($e_1$) in the low-carbon R&D stage can be affected by the asymmetric information, but the other efforts ($e_2$ and $e_m$) cannot be (e.g. $e_1$ changes within $[0, 0.9]$ or $[0, 0.45]$, whereas the others are constant).
- The efforts of the producer ($e_m$) and the researcher ($e_2$) in the recycling stage have complementary relation. The more efforts the researcher makes in the disassembling and recycling, the less investment the producer puts in channel promotion and returning policy (e.g. when $e_2 = 1.029$, $e_m = 0.214$; when $e_2 = 0.698$, $e_m = 0.351$; when $e_2 = 0.242$, $e_m = 0.694$).

In Figure 6, $V_l$ and $V_h$ mean emission reductions coordinating with the low and the high types of the researchers respectively. The results indicate that:
- $V_l$ remains the same with $\varphi$ increasing, and the effort of the high type researcher has been inspired to the most.
- An interesting finding is that the reduced emission by the low-type researcher ($V_l$) increases with the probability of the low type ($\varphi$).

Traditionally, the more the low type of the researchers the less effort they will make, which is like “Lemon market”. However, the low-type researcher should have a better performance in the R&D stage if she wants to join the cooperation. One reason is that the producer would update the menu of contracts in the second stage depending on the researcher’s R&D effort. The other reason is that the researcher should bear the recycling cost of the waste component developed by herself in the CLSC.

6. Conclusion
6.1 Implications for theory
This paper contributes to the field of R&D innovation cooperation by integrating the researcher into the recycling process in the CLSC. Although existing studies on the CLSC explored the structure of manufacturer and retailer (Hong et al., 2017; Wang et al., 2016), it cannot essentially solve the carbon emission problem if ignoring R&D partner. More specifically, the producer could share the environmental responsibility with outsourcing researcher.
(or supplier) and also give the researcher rewards of reducing emissions to exert more effort in the R&D and recycling process.

This paper also adds to the literature focusing on asymmetric information (Iyer et al., 2005; Xiao and Xu, 2012). When a producer outsources the R&D process to a researcher, the real low-carbon technology level seems to be private information, which may cause adverse selection. While the researcher is also involved in the recycling process, she should take the consequence of the component’s carbon emission, which may avoid the problem of moral hazard. Therefore, we propose an updated screening contract for the producer to induce researchers to reveal the true green development level. Actually, the producer gives the researcher

![Figure 5](image)

**Figure 5** The high-type researcher’s expected profit with $\theta$ and $\phi$

<table>
<thead>
<tr>
<th>Table II Low-carbon efforts in the two stages with $\varphi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_l = 0.6, g_h = 0.8$ $g_l = 0.3, g_h = 0.8$</td>
</tr>
<tr>
<td>Low-carbon efforts</td>
</tr>
<tr>
<td>$e_1$</td>
</tr>
<tr>
<td>$e_2$</td>
</tr>
<tr>
<td>$e_m$</td>
</tr>
</tbody>
</table>

**Notes:** $R_l$ = the low-type of researcher; $R_h$ = the high-type of researcher

![Figure 6](image)

**Figure 6** The impact on emission reductions with $\varphi$

![Table II](image)
a chance for renegotiation based on the research results, though he aims to squeeze more profit.

Our results reveal that the optimal screening contracts can help to separate the different types of researchers in asymmetric information. The producer should pay attention to the technology level and the probability of the low-type researcher, because a more sensitive and flexible original contract may be offered to her. Meanwhile, useful suggestions are also given to the producer when and how to update the contract to different types of researchers. There are many factors (e.g. contributions to reducing emission or to the sales revenue, reward coefficient) that need to be considered when designing the incentive mechanism.

6.2 Managerial implications

From the perspective of the producer, he needs to pay information rent to the researcher and his expected profit may be distorted. But when a researcher is most likely to be a low type, the producer would not like to pay her more information rent. Instead, the producer would let the researcher make the best investment balance between the R&D and the recycling stages. Actually, the marginal expected profit of the producer increases at this time, because the low-type researcher makes more contribution to the rewards of emission reduction.

From the perspective of the R&D researcher, she should tell the truth if she would like to join the innovation R&D project with the updated screening model. The low-type researcher only obtains reservation profit, whereas the high type is given more profit to induce the information. Our study is different from existing studies that say the screening model only offers incentives the high type; here, the low-type researcher is also inspired in low-carbon investment. If the researcher gets a Pareto improving contract, she should put more investment in R&D stage. Then, this innovative product can attract more customers and is beneficial for waste recycling. Unlike the “Lemon market”, the analysis indicates that the more the low-type researchers are in the supplier market, the more emissions can be reduced.

In some cases, if the researcher has a high-level technology of low-carbon R&D, the producer would ask her for a deposit at the beginning of R&D stage, and promise to give her all of the sales revenue and some other rewards in the end. Actually, the researcher greatly reduces and shares the producer’s investment risk. This happens when the customer focuses more on low-carbon recycling process of the waste product, especially in pharmaceutical industry or new energy industry.

Finally, an effective low-carbon innovation R&D program can bring more benefit to the producer both in attracting customers and waste disposal. To ensure the low-carbon production and recycling, information revealing may damage the producer’s interest, but that is good for emission reduction and environment. The updated contract is a double-edged sword for the producer. Therefore, the Chinese government should implement mandatory rules to push circle economy, and encourage the ecological design and recycling management mode in the whole supply chain.

6.3 Limitations and future research

This paper has taken a perspective of R&D innovation but offers limited insights into the remanufacturing process and the returning rate. These issues need to be taken into account in future research, because they may have effects on the profits of the alliance members. For example, First Solar, a global leader in photovoltaic solar energy solutions, commits to collecting and recycling its modules, and paying insurance premiums to his customers to guarantee the recycling, because of the raw material cost of tellurium rose from below $29/kg in 2004 to above $360/kg in early 2012 (Plambeck, 2013).

Second, we study this issue in a monopolistic market, and it would be interesting to extend this problem into a duopoly model. Under the competition of price or quantity of the heterogeneous products, the R&D innovation alliance may change their incentive mechanism and decisions.

Another extension is letting the R&D researcher be the leader of the game, for example Phytopharm, a biotechnology company based in Cambridge shire, England, looked for a partner to develop the product and launched it in the market (Crama et al., 2013). The screening game in this paper will be changed to the signal game. We could investigate what happens when new information is revealed at the end of each stage.

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Appendix

Proof to P1
In the marketing and recycling stage, if the producer wishes the researcher to accept the revised contract, he should ensure that the expected profit of the researcher would not decrease under the revised contract than the original one. We use to constraint (6) to guarantee that the optimal ratio is Pareto improving for the researcher. Therefore, both types of researchers would prefer accepting the new contracts. The constraint (6) should be binding. We can get , and put into the target equation (5). To find the optimal ratio, let , then . Substituting , we can get the value of .

Proof to Lemma 1
From P1, we have . The first order condition about is . Letting the first order condition equal to zero , we can get . The negative solution of is . Therefore, there is one stagnation point when . Meanwhile, it is easy to know that reaches the minimum value when .

Proof to P2
The original programing problem P0 can be divided into two sub-problems according to constraints (16) and (17). Which one should be binding is based on the value of and . When , we get , we obtain the optimal in this situation. Substituting and into the primal problem, we get the new problem about the original ratio . The similar analysis can yield the other solution of when .

Proof of P3
From P2, we know that the producer would maximize his profit by choosing the larger values of and in P1 and P2.

When , we solve the problem that the high-type researcher rejects the revision contract in the second stage. Then we need to analyze the low type researcher’s contract plan. From Lemma 3, to maximize , we get the optimal revenue sharing ratio in P1:

where .
So the constraint $\alpha_{h} \geq \alpha_{i}$ is always satisfied. We just verify the other constraint:

- If $\beta_{i}^* < \sqrt{\alpha_{h}^2(1+\theta^2) - \alpha_{i}^2 / \theta^2} = u_{1i}$, to preserve constraint (24), the optimal $\alpha_{i}^*$ should be smaller than $\alpha_{i}$, and the optimal $\alpha_{h}^*$ should be larger than $\alpha_{h}$.

- If $\beta_{h}^* \geq \sqrt{\alpha_{h}^2(1+\theta^2) - \alpha_{h}^2 / \theta^2} = u_{1h}$, all the constraints are satisfied. The ratio will be the first-order optimal solution, there are $\alpha_{i}^* = \alpha_{i}$, $\alpha_{h}^* = \alpha_{h}$.

When $\pi_{p2} > \pi_{p1}$, the high type would reject the revision contract in the second stage. To maximize $\pi_{p2}$, we get the optimal revenue sharing ratio in $P2$:

$$\alpha_{h} = 1 + \rho, \quad \alpha_{i}^* = \frac{g(1 + \rho)}{(h - g)(1 - \varphi) / \varphi + g}$$

The constraints in $P2$ can be written as:

$$\begin{align*}
\beta_{i}^* & \leq \frac{(\alpha_{i}^2 - \alpha_{i}^2)}{\theta^2} \\
\beta_{h}^* & \leq \frac{(\alpha_{h}^2 - \alpha_{h}^2)}{\theta^2}
\end{align*}$$

According to Lemma 1, there is $\beta_{h}^* \geq \beta_{i}^*$. So the second constraint above is always satisfied, which means the high-type researcher would never accept the revised contract if she pretended to be a low type.

- If $\alpha_{i}^* < \beta_{i}^* < \sqrt{(\alpha_{h}^2 + (\alpha_{h}^2 - \alpha_{h}^2) / \theta^2} = u_{2i}$, the ratio will be the first-order optimal solution, that is $\alpha_{i}^* = \alpha_{i}$, $\alpha_{h}^* = \alpha_{h}$. All the constraints in $P2$ are satisfied.

- If $\beta_{h}^* > \sqrt{(\alpha_{h}^2 + (\alpha_{h}^2 - \alpha_{h}^2) / \theta^2} = u_{2h}$, to ensure constraint (27) satisfaction, the optimal solution will be $\alpha_{i}^* > \alpha_{i}$, $\alpha_{h}^* > \alpha_{h}$.

- When $\pi_{p1} = \pi_{p2}$, the producer obtains the same profit under $P1$ and $P2$, which means $\pi(h_i) = \pi(h_j) = \pi(h_k)$. Hence, we get the solution in this case:

- In this situation, the revenue sharing ratio of the low type is the same with the original ratio in the first stage, $\alpha_{i}^* = \beta_{i}^*$. The revised ratio to the high type is the same in both $P1$ and $P2$, $\alpha_{h}^* = \alpha_{h}$.

**Proof to Corollary 1**

To find the turning point, we have the solution $\alpha_{i}^* = \alpha_{i}$ under the condition of $\beta_{h}^* \leq \beta_{i}^*$ from P3-I2. Thus, when $\beta_{i}^* < \alpha_{i}$, it infers that:

$$\lambda > \frac{\theta(1 + \sigma p)(g - g)(1 + \theta)(1 - \varphi) + g\varphi)}{(1 + \rho)\varphi} - \theta^2 g_i = \gamma$$

or written as:

$$\sigma > \frac{\theta (1 + \rho)(\alpha_{i}^2 + \theta^2 g_i)}{\rho [(g - g)(1 + \theta)(1 - \varphi) + g\varphi]} - \frac{\varphi}{\rho} = \lambda$$

From P3-I4, we have $\alpha_{i} = \alpha_{i}^* < \beta_{i}^*$, which infers that:

$$\lambda < \frac{\theta(1 + \sigma p)(g - g)(1 - \varphi) + g\varphi)}{(1 + \rho)\varphi} - \theta^2 g_i = k_2$$

or written as:

$$\sigma > \frac{\theta (1 + \rho)(\alpha_{i}^2 + \theta^2 g_i)}{\rho [(g - g)(1 - \varphi) + g\varphi]} - \frac{\varphi}{\rho} = \lambda$$

And from P3-I3, there is $\alpha_{i}^* = \beta_{i}^*$ when $k_2 \leq \lambda \leq k_1$ or $s_1 \leq \sigma \leq s_2$.

**Proof of Corollary 2**

To get the crossing, we have the following characters:

- From $\alpha_{i}^* = (1 + \rho)(1 - \varphi)(g - g)/((\varphi g) + 1) < 1 + \rho = \alpha_{i}$, we have $\alpha_{i}^* < \alpha_{i}$.

- Because of $\alpha_{i}^* = (1 + \rho)(1 - \varphi)(g - g)/((\varphi g) + 1) < \alpha_{i}$, we have $\alpha_{i}^* < \alpha_{i} < \alpha_{i}$.

- $u_{2} = \sqrt{(\alpha_{i}^2 + (\alpha_{i}^2 - \alpha_{i}^2) / \theta^2} > \alpha_{i}$, From P3, we have $u_{2} < u_{3}$.

The above characters are solved from $P2$. Let $\delta$ present the crossing point when $\beta_{i}^* = \alpha_{i}$, so we can get the location on $x$-axis $\delta = (1 + \rho)(\alpha_{i}^2 + \theta) / (1 + \theta)$. If $\delta < \beta_{i}$, the revenue sharing ratio of the high type should be raised, which means $\beta_{i}^* < \alpha_{i}$; otherwise, the ratio for the high-type contract should be turned down. To solve $\delta < \beta_{i}$, we can get $\sigma > (1 + \rho)(\lambda^2 + \theta^2 g_k) / (\rho \theta g_h (\lambda^2 + \theta g_k)) = \gamma$.

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On green market segmentation under subsidy regulation

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Abstract
Purpose – This study aims to provide a better understanding of the market balance between regular (high-carbon) and green (low-carbon) products. Further, this study analyses the role of government subsidy policy, based on the results of the government’s optimal green subsidy decision and its implication for green market segmentation and social welfare.

Design/methodology/approach – This study adopts a Stackelberg game framework to study the interaction between the government’s subsidy regulations and the firms’ marketing regimes. When considering government subsidy decision, we use multi-objective programming theory and turn the problem into weighted single-objective optimisation programming.

Findings – This study explores three marketing regimes and identifies the conditions under which each regime should be adopted by a firm. Further, investigating the optimal subsidy decision problem for the government reveals three subsidy regimes corresponding to the three marketing regimes. The government may be stuck in a regime of useless subsidy and the reason for this phenomenon is analysed as well.

Research limitations/implications – Developing the model into a more complex supply chain situation will enhance the applicability of the framework. Incorporating other environmental regulations, such as carbon tax, can be interesting research extensions of this study.

Practical implications – This study provides a quantitative framework, which can help the regulator gain a deeper understanding of green subsidy policies and assist focal companies in acquiring a better appreciation of green marketing segmentation.

Originality/value – The study is one of the first few works to explore the optimal design of green subsidy regulation for the government and its impact on market segmentations of high- and low-carbon products by using quantitative modelling approaches and deriving vital managerial insights.

Keywords Green supply chains, Carbon emission, Market segmentation, Low carbon, Subsidy, Green product, Carbon management

1. Introduction

During the past decades, environmental concern has transformed from just a trendy topic to a realistic priority of human existence and development. Emissions of primary greenhouse-gas (GHG) CO₂ are now over 50 per cent higher than 1990 levels (the reference year for the Kyoto Protocol) and the rate is still growing rapidly, which makes it “a mission almost impossible” to hold global temperature increase below 4°C before 2050 (Peters et al., 2012). Thus, governments around the world have made GHG emission one of the highest priorities in their respective agendas and put forward various environmental regulations. For example, many European countries have introduced carbon or energy-related taxation to control emission volume. Carbon trading markets in the European Union have stepped into the third stage according to the plan in 2013, with total annual trading volumes of 10.3 billion tons and US$52.8 bn.

Apart from tax and cap-and-trade, green subsidy is also a commonly used regulation, especially in developing countries with relatively immature market and subordinate development statuses. For example, South Africa established a renewable energy subsidy scheme in 2010, which aims at prompting manufacturers, including state-owned enterprise ESKOM and independent production firms, to fight pollution and boost energy efficiency across the country. In 2012, China embarked on a subsidy plan of 26.5 billion RMB for energy-saving home appliances, offering 5-10 per cent price discount to consumers purchasing them. Similar subsidy policies can be found worldwide in some specific industries, such as automotive, with a variety of monetary incentives adopted to promote electric vehicles (EVs) that are regarded “greener” than gasoline-run vehicles. In the USA, a federal subsidy programme for EVs allows for a one-time bonus of up to a maximum of US$7,500 upon the purchase of an EV.
Meanwhile, China has rolled out a series of subsidy policies to increase sales of EVs since 2010, and recently announced the extension of its policies to 2020. European countries, such as Norway and The Netherlands, have also provided bonuses to EV consumers by various tax credit schemes which are tied to production and marketing actions from enterprises as means of boosting environmental benefits. While providing incentives for socially desirable behaviour to achieve legislative goals has intuitive appeal, the broader economic consequences have not been fully understood. The underlying rationale remains unclear on the use of market-based subsidies associated with the desired behaviour from industry, and the corresponding research are of imminent need for governments implementing green regulations and firms adopting green practices. For example, despite the use of similar subsidy policies, why do the market shares of electric cars substantially differ among different countries, as shown by Figure 1? What are the major influencing factors and how should the regulator accordingly make monetary policy and take complementary measures as well? As Mock and Yang (2014, p. 3):

[... ] fiscal incentives matter, but are clearly not the only factor that influences today’s electric vehicle market growth [...]. A more comprehensive study is needed of the full portfolio of policy actions taken to accelerate the early electric vehicle market and their impact on the effective total cost of ownership.

In the current study, we seek to answer the above questions by establishing and solving a quantitative model in consideration of green market segmentation under subsidy regulation. A monopoly firm produces both regular and green products which differ in their carbon emission volumes during their life cycle. Meanwhile, the government proposes a subsidy to the consumer who purchases a green product. We use a consumer willingness-to-pay (WTP) model to depict the market end of green and green products and identify three marketing regimes for the firms. The effects of the subsidy are studied while considering the differences in consumers’ WTP and in the production costs between green and regular products. We further explore the optimal subsidy regulation of the government, with the objective of maximising the entire social welfare. Three subsidy regimes are revealed as useless subsidy, effective subsidy and full subsidy. In addition, a unique optimal subsidy is characterised from one of these three regimes based on system parameters. Specifically, when the production cost difference is large but emission reduction of green product is low, the regime of useless subsidy can occur and thus the government fails to increase green market segmentation by raising subsidy. Conversely, when the production cost difference is small but emission reduction of green product is high, an utmost subsidy can be applied to cover the production cost difference between green and regular products. The regime of effective subsidy is adopted when system parameters are within the medium ranges. The implications of obtained results can help regulators to more deeply understand the strategic ramifications of green subsidy incentives for the marketplaces in which firms operate. They are also instructive to focal companies in acquiring a better apprehension of green marketing segmentation resulting from their pricing decisions.

Our study is relevant to the literature regarding the effects of environmental regulations on firms’ behaviour and on social welfare, including Carraro and Soubeyran (1996), Amacher and Malik (2002), Fischer et al. (2003), Drake et al. (2010), Krass et al. (2013), Atasu et al. (2013), Lao (2014) and Wan et al. (2015), etc. For instance, Carraro and Soubeyran (1996) assumed that a firm possesses both “dirty” and “clean” technologies and found that emission taxes induce firms to clean production technology, which reduces output, raises prices and hampers consumers’ surplus. Amacher and Malik (2002) established a game model to study two styles of interactions between the environment tax regulator and the firm choosing dirty and clean technologies, and found that the regulator may be better able to achieve the first-best outcome when the firm moves first. Fischer et al. (2003) compared the welfare effects of emission taxes as well as auctioned emission permits and free permits when technological innovation is endogenously exerted, and observed that there is no unambiguous case for preferring any of these policy instruments. Drake et al. (2010) considered tax and cap-and-trade regulatory regimes in a setting similar to that reported in Carraro and Soubeyran (1996) without explicitly considering regulator problems; they found that expected profits are greater and expected emissions are less under cap-and-trade, whereas expected production is greater under an emissions tax, indicating competing welfare effects. Krass et al. (2013) investigated the role of environmental taxes in motivating the choice of innovative and green emission-reducing technologies, and they found that a pure environmental taxation policy may lead to the choice of dirty technology and significant welfare losses whereas supplementing it with fixed cost subsidies and consumer rebates can eliminate this effect. Gil-Moltó and Varvarigos (2013) assumed that consumers are environmentally conscious and demonstrated that increasing the tax rate on emissions does not necessarily lead to adoption of clean technologies. If we extend the scope of environmental regulation to the field of product take-back legislation, our paper is also related to Atasu et al. (2009) and Atasu et al. (2013). Atasu et al. (2009) explored the economic and environmental impacts of product take-back legislation and found that its efficiency is driven by environmental classification of products, industry structure and end-user willingness. Atasu et al. (2013) further compared the legislation implementations between manufacturer- and

**Figure 1** Market share of electric passenger cars for the years 2012 (lighter colours) and 2013 (darker colours), in comparison to total sale

*Source: Mock and Yang (2014)*
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China has carried out several subsidy projects that compensate the firms for investing in green technologies in accordance with the actual amount of energy saving or emission reduction achieved. In our model, we assume giving subsidy to consumers and will demonstrate its equivalent effects to giving subsidy to the firm.

On the market side, we assume that a consumer values product $G$ more than product $R$ because of environmental consciousness. In a survey conducted by Accenture (2009), 80 per cent of the respondents expressed concern for products’ carbon footprints during the production process; their perceived utility will increase as the carbon footprint of products they purchase reduces. Other empirical research have shown that low-carbon products generate greater market share (Ibanez and Grolleau, 2008), higher added value (Conrad; 2005), and stronger competitive edge (Lu et al., 2007). Another example is energy-saving products with low carbon emission during usage, which is preferable to consumers for its green image and energy usage expense savings. Specifically, we assume that when a consumer values product $R$ at $\theta$, she values product $G$ at $\delta\theta$, where $\delta > 1$ measures the scale of consumers’ WTP for green products compared to regular ones. Hence, a consumer achieves utility $U_R = \theta - p_R$ from purchasing product $R$ and utility $U_G = \delta\theta + s - p_G$ from purchasing product $G$, where $p_G$ and $p_R$ are the market prices of products $R$ and $G$, respectively, and $s$ is the subsidy given by the government. The consumer purchases product $G$ if $U_G > U_R$ and $U_G > 0$ whereas she purchases product $R$ if $U_R > U_G$ and $U_R > 0$. The market base is normalised to 1. Customers are heterogeneous with respect to their WTP $\theta$ for product $R$, which are supposed uniformly distributed over the interval $[0,1]$. The unit production costs $c_p$ and $c_G$ satisfy $c_R < c_G < 1$, because manufacturing product $G$ is costlier.

Based on the above assumptions, we obtain the market demands of products $R$ and $G$, denoted as $d_R$ and $d_G$, with the following three pricing options for the firm:

1. Price product $G$ low, that is, $p_G \leq \delta p_R + s$. Consequently, product $R$ is wiped out and only product $G$ is sold in the market, with demands as:

$$
\begin{align*}
  d_R &= 0 \\
  d_G &= \frac{\delta - p_G + s}{\delta}
\end{align*}
$$

2. Give product $G$ a medium price range, that is, $\delta p_R + s < p_G < p_R < \delta - 1 + s$. Consequently, both products are sold in the market with positive demands given by:

$$
\begin{align*}
  d_R &= \frac{p_G - \delta p_R - s}{\delta - 1} \\
  d_G &= \frac{\delta - 1 - p_G + p_R + s}{\delta - 1}
\end{align*}
$$

3. Price product $G$ high, that is, $p_G \geq p_R + \delta - 1 + s$. In consequence, product $G$ is wiped out and only product $R$ is sold in market, with demands as:

$$
\begin{align*}
  d_R &= 1 - p_R \\
  d_G &= 0
\end{align*}
$$

state-operated systems, and showed that their impacts on different stakeholders can be significantly different and stakeholder preferences for these models vary depending on the operating environments.

Similar to the above literature, we also consider the impact of environmental regulation on the firm and social welfare. Especially, we adopt a Stackelberg game framework to formulate the policy-making problem of the regulator and responsive marketing decision of a firm, the methodology of which is similar to Amacher and Malik (2002), Krass et al. (2013), Atasu et al. (2009) and Atasu et al. (2013). However, our paper contributes in considering market segmentation of green and non-green products and their potential cannibalization effects. By doing so, we reveal the effects of the regulators’ subsidy policy on the marketing regimes and their relation to consumers’ WTP for green products. Our results underscore that incentives put in place to meet broader societal objectives have notable ramifications for firms and consumers in markets with green and non-green products complementary to each other. To the best of our knowledge, these topics have not yet been discussed in the existing literature.

The rest of the study is organised into sections. In Section 2, we describe the model. In Section 3, we analyse the firm’s problem of balancing two market segments given subsidy regulation. In Section 4, we analyse the government’s problem of determining optimal subsidy to maximise the entire social welfare. Finally, Section 5 concludes the study and presents future research directions.

2. Model description

Consider that a monopoly firm offers to market two products: a regular product referred to as product “$R$” and a green product referred to as product “$G$”. These two products have similar functions but differ in their environmental impacts, which are measured in our paper by evoked carbon emissions. We normalise the emission volume from unit product $R$ as 1 and that from unit product $G$ as $e \in (0,1)$. Note that the emission reduction for product $G$ can stem from different stages of its life cycle, including manufacturing and usage. Hence, one implication of the greenness of product $G$ is its adopted manufacturing technology that leads to relatively low emission in the production process. For example, emissions with carbon capture and storage technology in cement industry is projected to be 0.54 tonnes per tonne of clinker, as compared with 2.34 (gas) – 4.4 (coal) tonnes without (WBCSD 2009). On the other hand, product $G$ may also demonstrate its environmental superiority in the process of consumer usage. A typical example is the automotive industry, in which the carbon emissions for electric and hybrid-electric vehicles are around 125 g/km whereas that for a gasoline-run one is over 200 g/km, which manifests a 15-ton carbon emission reduction in consumer usage stage on average[1]. This green conception can also be applied to broader areas such as lessening resource usage or power consumption, which transfers to the measurement of a lower carbon emission after all.

The government offers a subsidy $s$ to the consumers of product $G$. In reality, this subsidy can also be given to firms producing green products instead of consumers. For example,
The sequence of events for our problem is that the government first prescribes the subsidy regulation, then the firm makes the pricing decisions for regular and green products and finally the consumers choose to purchase. Figure 2 shows the decision-making process of our model.

3. Firm’s problem: balancing two market segmentations

The firm’s objective is to determine the prices for products R and G to maximise profit. The problem is formulated as:

\[
\max_{p_R, \phi_G} \pi = (p_R - c_R)d_R + (p_G - c_G)d_G
\]

where \((d_R, d_G)\) is given by equations (1)-(3).

Denote the optimal solution as \((p^*_R, p^*_G)\) and the corresponding demand as \((d^*_R, d^*_G)\). We have the results given below.

Theorem 1.

When \(s \geq c_G - \delta c_R\), we have:

\[
\begin{align*}
    p^*_R &= \text{any value} \geq \frac{\delta + c_G - s}{2\delta} \\
    p^*_G &= \frac{\delta + c_G + s}{2} \\
    d^*_R &= 0 \\
    d^*_G &= \frac{\delta + c_G + s}{2\delta}
\end{align*}
\]

When \(c_G - c_R - (\delta - 1) < s < c_G - \delta c_R\), we have:

\[
\begin{align*}
    p^*_R &= \frac{c_G + 1}{2} \\
    p^*_G &= \frac{\delta + c_G + s}{2} \\
    d^*_R &= \frac{c_G - \delta c_R - s}{2(\delta - 1)} \\
    d^*_G &= \frac{\delta - 1 - c_G + c_R + s}{2(\delta - 1)}
\end{align*}
\]

When \(s \leq c_G - c_R - (\delta - 1)\), we have:

\[
\begin{align*}
    p^*_R &= \frac{1 + c_R}{2} \\
    p^*_G &= \text{any value} \geq \delta - 1 + s + \frac{1 + c_R}{2} \\
    d^*_R &= \frac{1 - c_R}{2} \\
    d^*_G &= 0
\end{align*}
\]

All proofs can be found in the Appendix.

Theorem 1 provides the optimal pricing decision for the firm. Specifically, three marketing regimes can be identified as follows:

1. **Monopolising G**: Give up the market share of product R by making an extremely high price (any price above \(\delta + c_G - s/2\delta\)), but use an optimal monopoly pricing strategy for product G (which is \(\delta + c_G + s/2\)). In consequence, product R is squeezed out of the market while product G is given a monopoly market segment under optimality (which is \(\delta + c_G + s/2\)).

2. **Sharing between R and G**: Use optimal monopoly pricing strategy for both product R (price it as \(c_R + 1/2\)) and product G (price it as \(\delta + c_G + s/2\)), so that each product shares a certain segment of the market and no product can be totally squeezed out.

3. **Monopolising R**: give up the market share of product G by making an extremely high price (any price above \(\delta - 1 + s + 1 + c_G/2\)), while using an optimal monopoly pricing strategy for product R (which is \(c_R + 1/2\)). In consequence, product G is squeezed out of the market while product R is given a monopoly market segment under optimality (which is \(1 - c_R^2\)).

Figure 3 depicts the above marketing regimes corresponding to the subsidy and cost difference between producing products R and G. Note that the cost difference is measured relative to the WTP difference, \(\delta\), between products R and G among consumers. The cost difference becomes smaller as the consumer utility for product G increases.

**Figure 3** Marketing regimes for the production costs of \(c_R\) and \(c_G\)

- **Region A**: Monopolise G
  - Share between G and R (if \(s < c_G - \delta c_R\))
  - Monopolise R (if \(s \geq c_G - \delta c_R\))

- **Region B**: Monopolise G (if \(s \geq c_G - \delta c_R\))
  - Share between G and R (if \(c_G - c_R - (\delta - 1) < s < c_G - \delta c_R\))
  - Monopolise R (if \(s \geq c_G - \delta c_R\))

- **Region C**: Monopolise G (if \(s \geq c_G - \delta c_R\))
  - Share between G and R (if \(s \geq c_G - \delta c_R\))
  - Monopolise R (if \(s \geq c_G - \delta c_R\))
If the cost difference between producing products R and G is very small \((c_G \approx \delta c_R)\) or the green subsidy is very high \((s \geq c_G - c_R)\), then monopolizing G regime should be adopted. In this regime, a small production cost difference or a high green subsidy makes manufacturing product G profitable; thus, product R should not be supplied any more.

If the cost difference between producing products G and R is medium or high \((c_R > \delta c_G)\) and green subsidy is medium \((c_R - c_G - (\delta - 1)) < s < c_G - c_R\), then sharing between R and G regime should be adopted. In this regime, a medium value of high green subsidy makes manufacturing products R and G profitable, and an appropriate market share between these two products should be kept based on the optimal pricing scheme.

If the cost difference between producing products R and G is high \((c_G > \delta c_R)\) and the green subsidy is small \((s < c_G - c_R - (\delta - 1))\), then monopolizing R regime should be adopted. In this regime, a high production cost difference together with small green subsidy, makes producing product G non-profitable; hence, product R dominates the market with its optimal monopoly price.

**Corollary 1.** \(p_R\) is irrelevant to \(\delta\), and \(p_G\) is increasing with \(\delta\). \(d_R\) is decreasing with \(\delta\), and \(d_G\) is increasing with \(\delta\) if \(s < c_G\).

Corollary 1 shows that the price of product R is not related to the WTP of product G, whereas the price of product G is increasing with its WTP. In addition, the demand of product R decreases with the WTP of product G, whereas the demand of product G increases with the WTP of green product as long as the subsidy is not extremely large. In other words, the marketing competitive effect between products R and G is closely linked by consumers’ WTP for the green product. The obtained result is once again supported by the practice of the automotive industry. For example, it is found that California has higher market share and growth rate for battery electric vehicles (BEVs) compared to other markets in the USA with the same level of subsidy incentives. One reason is the use of high-occupancy vehicle lanes for BEVs and plug-in hybrid electric vehicle (PHEVs) in California. This provides a significant incentive for consumers in California, particularly in the Los Angeles and San Francisco metropolitan areas, where many EVs are registered. As listed by Mock and Yang (2014), other influencing factors that contribute to the growth rate include well-developed EV action plans, infrastructure policy, electric utility engagement and consumer awareness programmes, all which will result in a rise in the level of consumers’ WTP for EVs.

Figures 4 and 5 further illustrate how the prices and demands of the two products evolve as the subsidy increases, respectively. The price of product R is equal to its optimal monopoly price \(1 + c_R / 2\) (as long as product R is not squeezed out of the market) and the price of product G is equal to its optimal monopoly price \(\delta + c_G + s / 2\) (as long as product G is not squeezed out of the market). Specifically, the price of product R is irrelevant to \(s\) and the price of product G is increasing with \(s\) at slope 1/2 (when they are not squeezed out of the market). Hence, a half of the subsidy given to the consumers who purchase product G will finally be extracted by the firm, consequently raising the market price of product G. Moreover, the demand for product R is first independent of \(s\) and then decreases with it (when product R is not squeezed out of the market), whereas the demand for product G is increasing with \(s\) (when product G is not squeezed out of the market). This observation shows that the effect of subsidy trims the market share of product R and expands that of product G.

Our finding suggests a positive link between the provision of subsidy incentives and the uptake of green products in a market, which is confirmed by the observed practice in the automotive industry. Clear examples are Norway and The Netherlands, where high EV fiscal incentives result in high EV market growth rate and market share. Specifically, only BEVs are excluded from value-added tax and registration tax in Norway, whereas in The Netherlands the corresponding incentives apply to both vehicle types. Consequently, in The Netherlands the market share of PHEVs increases much more rapidly and dominates that of BEVs whereas in Norway exactly the opposite occurs, as shown in Figure 1.

Now we turn our attention to the environmental impact of the two products, which is characterised by the total carbon emission and measured by \(TE = d_R \times 1 + d_G \times e\). We have the following result.

**Corollary 2.** \(TE\) is irrelevant to \(s\) when \(s \leq c_G - c_R - (\delta - 1)\), decreases with \(s\) when \(c_G - c_R - (\delta - 1) < s < c_G - \delta c_R\), and increases with \(s\) when \(s \geq c_G - \delta c_R\). \(TE\) is
irrelevant to $\delta$ when $s \leq c_G - c_R - (\delta - 1)$, decreases with $\delta$ when $c_G - c_R - (\delta - 1) < s < c_G - \delta c_R$, and increases with $\delta$ when $c_G > s \geq c_G - \delta c_R$. 

Corollary 2 shows the relationships between total carbon emission and the related parameters such as subsidy and consumers’ WTP for green products. Raising the green subsidy brings about a positive environmental impact in the market regime of share with $R$ and $G$. Specifically, a higher subsidy lowers the production quantity of product $R$ but raises that of product $G$, which leads to a reduction in the total emission. The sensitivity result on consumers’ WTP for product $G$ is very similar. That is, a rise in the WTP for product $G$ lowers the total emission in the market regime of share with $R$ and $G$ and thus offers an environmental benefit.

In the following section, we examine the policy of providing subsidy to the firm and show its equivalence to providing subsidy to consumers. Suppose that subsidy $\tilde{m}$ is given to the firm for unit emission reduction, which is equal to an award of $\tilde{c} = \tilde{m}(1 - c)$ for manufacturing each product $G$. The result below applies as a complement to Theorem 1.

**Corollary 3.** When $\tilde{c} \geq c_G - \delta c_R$, we have:

$$
\begin{align*}
\tilde{p}_R &= \text{any value} \geq \frac{\delta + c_G - \tilde{c}}{2}\delta \\
\tilde{p}_G &= \frac{\delta + c_G - \tilde{c}}{2} \\
\tilde{d}_R &= 0 \\
\tilde{d}_G &= \frac{\delta - c_G + \tilde{c}}{2}\delta
\end{align*}
$$

(8)

When $c_G - c_R - (\delta - 1) < \tilde{c} < c_G - \delta c_R$, we have:

$$
\begin{align*}
\tilde{p}_R &= \frac{c_R + 1}{2} \\
\tilde{p}_G &= \frac{\delta + c_G - \tilde{c}}{2} \\
\tilde{d}_R &= \frac{c_G - \delta c_R - \tilde{c}}{2(\delta - 1)} \\
\tilde{d}_G &= \frac{\delta - 1 - c_G + c_R + \tilde{c}}{2(\delta - 1)}
\end{align*}
$$

(9)

When $\tilde{c} \leq c_G - c_R - (\delta - 1)$, we have:

$$
\begin{align*}
\tilde{p}_R &= \frac{1 + c_R}{2} \\
\tilde{p}_G &= \text{any value} \geq \frac{\delta - 1 + 1 + c_R}{2} \\
\tilde{d}_R &= \frac{1 - c_R}{2} \\
\tilde{d}_G &= 0
\end{align*}
$$

(10)

Corollary 3 indicates that the demands for products $R$ and $G$ and the corresponding ranges for the subsidy to the firm, $\tilde{c}$, are exactly the same as those in Theorem 1. Hence, market regimes under subsidy to the firm coincide with those under subsidy to consumers. The only difference is the price of product $G$, which decreases with $\tilde{c} / 2$ under this policy but increases with $s / 2$ under subsidy to consumers. This result implies that the firm will transfer half of the subsidy to the consumer by deducting $\tilde{c} / 2$ from the price of product $G$ under the policy of subsidy to the firm. However, under subsidy to consumers, the firm will raise the price by $s / 2$ to extract half of the subsidy as a part of net profit. Under either policy, the benefit for the consumer of product $G$ is also half of the subsidy. In conclusion, the effect of subsidy to the firm is equivalent to that to consumers.

**4. Government’s problem: maximising entire social welfare**

In this section, we turn to the government’s problem, which focuses on entire social welfare when determining the subsidy policy. Entire social welfare has two major elements: monetary welfare and environmental welfare. First, monetary welfare consists of three terms:

1. Firm’s profit $\pi$, which is given as equation (4);
2. Consumers’ surplus, which is the total utility of consumers in the market and calculated as

$$
CS = \int_{\tilde{c}}^{c_G} (\theta - p_d) d\theta \quad \text{when } s \leq c_G - c_R - (\delta - 1)
$$

(11)

3. Minus total subsidy, which is calculated as $GE = -sd_G$.

Hence, one of the goals of the government is to maximise monetary welfare:

$$
\max_{s} MW = \pi + CS + GE
$$

(12)

On the other hand, the element of environmental welfare aims at minimising total emission and given by:

$$
\min_{s} TE = d_R + ed_G
$$

(13)

Therefore, the government faces a dual-objective optimisation problem of maximising monetary welfare and minimising total emission at the same time. It can be formulated as a single-objective problem of choosing subsidy $s$ to maximise the entire social welfare characterised by:

$$
\max_{s} SW = MW - kTE
$$

(14)

Here, $k$ is a weight that measures how much environmental impact is valued by the government compared with monetary welfare.

In the following, we solve Problem (14). We exclude two extreme cases:

1. very small cost difference between producing products $G$ and $R$, that is, $c_G \leq \delta c_R$; and
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very large subsidy to the consumer purchasing product G, that is, \( s > c_G - \delta C_R \). These two trivial cases can directly lead to marketing regimes of monopolize G, which seldom occurs in real practice. Hence, we assume \( c_G > \delta C_R \) and \( s \in [0, c_G - \delta C_R] \), which is relevant to both practical industry and theoretical analysis. We also denote \( \Delta = 1 - \varepsilon > 0 \) as the emission reduction from product G compared to product R.

**Theorem 2.** We have:

\[
\begin{align*}
\delta &= \begin{cases} 
\frac{1 - c_G}{2}, & \text{when } k \Delta 
\leq [c_G - c_R - (\delta - 1)]^+ \\
\frac{2c_G - (\delta + 1)c_R - (\delta - 1) - 2k \Delta}{\delta - 1}, & \text{when } [c_G - c_R - (\delta - 1)]^+ \\
\frac{2c_G - (\delta + 1)c_R - (\delta - 1) - 2k \Delta}{\delta - 1}, & \text{when } [c_G - c_R - (\delta - 1)]^+ \\
\frac{1 - c_R}{2}, & \text{when } k \Delta \geq c_G - \frac{(\delta + 1)c_R + (\delta - 1)}{2} \\
\end{cases}
\end{align*}
\]

with the corresponding market outcome:

\[
\begin{align*}
\delta, \delta' &= \begin{cases} 
\frac{1 - c_G}{2}, & \text{when } k \Delta
\leq [c_G - c_R - (\delta - 1)]^+ \\
\frac{2c_G - (\delta + 1)c_R - (\delta - 1) - 2k \Delta}{\delta - 1}, & \text{when } [c_G - c_R - (\delta - 1)]^+ \\
\frac{2c_G - (\delta + 1)c_R - (\delta - 1) - 2k \Delta}{\delta - 1}, & \text{when } [c_G - c_R - (\delta - 1)]^+ \\
\frac{1 - c_R}{2}, & \text{when } k \Delta \geq c_G - \frac{(\delta + 1)c_R + (\delta - 1)}{2} \\
\end{cases}
\end{align*}
\]

(15)

Theorem 2 shows that optimal subsidy regulation is closely related to the production costs \( c_G \) and \( c_R \), the consumer WTP difference \( \delta \) and weight of environmental welfare for the government multiplied by the emission reduction of product G, \( \Delta \). The following three subsidy regimes can be identified:

1. **Full subsidy**: When the weight of environmental welfare multiplied by emission reduction of product G is larger than a threshold related to the production cost difference and consumer WTP difference between the two products, that is, \( k \Delta \geq c_G - (\delta + 1)c_R + (\delta - 1)/2 \), then an utmost subsidy should be provided so that product R is totally squeezed out of the market. This phenomenon occurs only when the government is significantly environmentally concerned and the firm’s green technology is superb, that is, green product entails a low carbon emission at an economical cost.

2. **Effective subsidy**: When the weight of environmental welfare multiplied by the emission reduction of product G falls into a medium range of two thresholds related to production cost difference and consumer WTP difference between the two products, that is, \( [c_G - c_R - (\delta - 1)]^+ < k \Delta < c_G - (\delta + 1)c_R + (\delta - 1)/2 \), then the ensuing unique optimal subsidy from the government leads to the maximisation of social welfare with the coexistence of products R and G in the market. Hence, optimal subsidy is increasing with weight \( k \); thus, subsidy should be raised if the government focuses more on environmental welfare. This subsidy increases with consumers’ WTP and emission reduction for product G, but decreases with production cost difference. In other words, generous subsidies should be provided to the product or industry with more advanced green technology (which incurs less emission and lower production cost) and for consumers with greater environmental consciousness.

3. **Useless subsidy**: When the weight of environmental welfare multiplied by the emission reduction of product G is less than a threshold related to the production cost difference and the consumer WTP difference between two products, that is, \( k \Delta \leq [c_G - c_R - (\delta - 1)]^+ \), then any subsidy in interval \( [0, [c_G - c_R - (\delta - 1)]^+] \) is optimal. However, such subsidy is useless in promoting green product sales, because the resulting marketing regime is monopolise R in which all green products are wiped out of the market. Hence, no green product will be sold no matter how hard the government tries to raise the subsidy to stimulate the consumers.

Note whether the occurrence of full subsidy is related to the cost difference between producing products G and R relative to the difference of consumer WTPs between products R and G. If the cost difference is larger than the WTP difference \( (c_G - c_R) \geq R \), then all three subsidy regimes can occur depending on the product of weight of environmental concerns and the emission reduction of product G, \( k \Delta \). On the other hand, if the cost difference is no larger than the WTP difference \( (c_G - c_R) \leq R \), then only the regimes of effective subsidy and full subsidy can be involved.

Figure 6 further illustrates how subsidy regimes correspond to the production costs of products R and G. The regime of useless subsidy is applied under high production cost of product R and low production cost of product G, with large cost differences between them, and that of effective subsidy is applied under medium-high production cost of product R and low-to-medium production cost of product G with medium cost difference. In addition, full subsidy is utilized when the production cost difference is low. This result is instructive to regulators when making the optimal subsidy policy. Figure 6 also shows that the threshold in the regime of useless subsidy is increasing with the production cost difference and emission reduction for product G.
decising with the consumers’ WTP difference between products $G$ and $R$. Hence, lowering the production cost and raising the consumers’ WTP for green products are effective approaches for regulators to secede from the regime of useless subsidy. In addition, the threshold for useless subsidy is also increasing with the weight of environmental welfare in the objective for the government and the emission reduction from green product. Hence, enhancing environmental concerns from the government and expanding environmental advantages of green products also help evade the occurrence of useless subsidy.

Corollary 4. Under the regime of effective subsidy, $d_G$ is decreasing with $c_R$ and increasing with $c_G$, whereas $d_R$ is decreasing with $c_G$ and increasing with $c_R$. $d_G$ is decreasing with $\delta$ whereas $d_R$ is increasing with $\delta$. Under the regime of effective subsidy, $d_G$ is decreasing with $k\Delta$ whereas $d_R$ is increasing with $k\Delta$.

Corollary 4 shows the parameter sensitivity of market segmentations. Generally speaking, the demand of a product is decreasing with its production cost and increasing with the production cost of the opponent product. The only exception is the demand of product $G$ under the regime of full subsidy, which is also decreasing with the production cost of product $R$. In addition, raising consumers’ WTP for green products will increase the market share of product $G$ but will decrease that of product $R$ when both products are sold. Finally, the demands under the regime of effective subsidy are also related to the weight of environmental welfare for government and the emission reduction for product $G$. Government focusing more on the environmental welfare and firms lowering the carbon emission for green products will raise the market share of product $G$ and tailor that of product $R$.

Corollary 5. $TE^*$ is increasing with $c_G$ and decreasing with $c_R$. $TE^*$ is decreasing with $k$ under the regime of effective subsidy. $TE^*$ is decreasing with $\delta$.

Corollary 5 shows that total carbon emission increases with the production cost of product $G$, but decreases with that of product $R$. Focusing more on environmental welfare will make the government provide higher subsidy and thus lower total emission. Raising consumers’ WTP for product $G$ reduces total emission, and this can be achieved by implementing measures, such as increased publicity for green consciousness and greater technology advancement to make green products more consumer friendly.

Finally, we explore the scenario when a subsidy $\tilde{s}$ is provided to the firm, instead of consumers, for manufacturing and selling one unit of product $G$. The following result shows that the optimal subsidy to the firm is equal to that to consumers and leads to the same marketing regimes from the firm. Hence, these two subsidy policies are equivalent.

Corollary 6. We have:

$\tilde{s} = \begin{cases} 
\text{any value } \in [0, c_G - c_R - (\delta - 1)] & \text{when } k\Delta \leq [c_G - c_R - (\delta - 1)]^+
\delta - 1 + c_R - c_G + 2k\Delta & \text{when } k\Delta \geq [c_G - c_R - (\delta - 1)]^+
\end{cases}$

with the corresponding market outcome given by:

$\begin{align*}
(d_G, d_R) &= \begin{cases} 
\left( \frac{1 - c_G}{2}, 0 \right) & \text{when } k\Delta \leq [c_G - c_R - (\delta - 1)]^+
\frac{2c_G - (\delta + 1)c_R - (\delta - 1) - 2k\Delta}{\delta - 1 + c_R - c_G + k\Delta} & \text{when } [c_G - c_R - (\delta - 1)]^+ < k\Delta < c_G
\frac{(\delta + 1)c_R + (\delta - 1)}{2} & \text{when } k\Delta \geq c_G - \frac{[c_G - c_R - (\delta - 1)]^+}{2}
\end{cases} 
\end{align*}$

(18)

5. Conclusions

Issues concerning carbon emission, energy saving and green product production have received substantial attention from both practitioners and academics. However, the role of government intervention in such an environmentally concerned social system is not as clear. Industry has indicated the necessity of research in this field that helps better understand the relationship between green market segmentation and government financial regulations. In this study, we established a two-layer Stackelberg game to quantitatively explore this issue under a green subsidy policy of the government.

One layer is on how the firm balances between two market segments of regular products (product $R$) and green products (product $G$), under a given subsidy regulation. We find that one of three marketing regimes will occur depending on the green subsidy and production cost difference between the two products. If the production cost difference is very small or the green subsidy is very high, then the regime of monopolise $G$ is adopted and no product $R$ is produced. If the production cost difference and the green subsidy are in medium ranges, then producing products $R$ and $G$ are both profitable and the regime of share between $R$ and $G$ should be adopted. If the production cost difference is high and the green subsidy is small, then product $G$ is swept out of the market and the regime of monopolise $R$ should be adopted. A major instruction to the firm is the importance of carefully weighing between the green and regular markets linked to production costs, subsidy policy and consumers’ WTP, of which the latter is obviously in need of scientific marketing research. Another observation is that subsidy is indeed useful in raising the green market segment and promoting environment benefits as long as it is in the market segment of share between $R$ and $G$. In this case, it does not matter whether the subsidy is given to consumers or the firm.

The other layer has to do with the subsidy policy-making from the perspective of the government. We formulate this problem as a single-objective programming, which aims at maximising entire social welfare including a weighed environmental welfare. We identify three subsidy regimes, namely, useless subsidy, effective subsidy, and full subsidy. Which regime to adopt depends on three critical factors, including the production cost difference between the two products, the weight of environmental welfare and the emission reduction of product $G$. When the production cost difference is large and the weight of environmental welfare multiplied by emission reduction of product $G$ is low, the regime of useless subsidy can occur because the government will find it difficult to stimulate green product market by raising green
subsidy. On the contrary, when the production cost difference is small and the weight of environmental welfare multiplied by the emission reduction of unit product $G$ is high, the regime of full subsidy can be adopted to sweep product $R$ out of the market. In addition, the regime of effective subsidy is applied when the production cost difference and weight of environmental welfare multiplied by emission reduction are in medium ranges, which leads to positive market shares for both products. Hence, an important insight is that promoting a more advanced green technology and raising consumers’ green consciousness helps to rid the regulator of useless subsidies; the government should also emphasize more on the objective of environmental welfare when making subsidy policies.

To the best of our knowledge, our study is among the first to explore green subsidy regulation design and its impact on market segments of high- and low- carbon products based on a quantitative modelling approach. From the perspective of government regulation, a limitation of this study is that we focus only on green subsidy. Other mechanisms, such as total and intensity caps, tax, cap-and-trade, etc., have also been adopted, especially in developed countries. Therefore, future research can compare these environmental policies or study the comprehensive usage of multiple policies in a country. From the perspective of market segmentation, this study only focuses on a monopoly firm. Future studies can expand the model into a more complex supply chain environment under the interaction between producers and distributors. Adding such factors as demand uncertainty and information asymmetry can also make the problem more interesting.

Note

1 These data are calculated based on sample vehicle of 1,400 kg weight, displacement 2 L, engine power 100 kw and 200,000 km driving range.

References


Further reading


Appendix

Proof of Theorem 1

The problem is equivalent to solving:

$$\max_{R, G} \pi = (p_R - c_R)d_R + (p_G - c_G)d_G.$$  (19)

We first solve $p_G$ given $p_R$ is constant and then solve $p_R$:

When $p_G \leq \delta p_R + s$, we have:
and it is easy to derive the local maximiser of \( p_G \) as \( 1/2(c_G + \delta + s - 1) \):

When \( \delta_p R < s < p_G < \delta - 1 + p_R + s \) we have:

\[
\pi = \frac{1}{\delta - 1} [(p_R - c_R)(p_G - \delta - p_R - s) + (p_G - c_G)(\delta - 1 - p_G + p_R + s)]
\]

and it is easy to derive the local maximiser of \( p_G \) as \( p_R + 1/2 (c_G - c_R + \delta + s - 1) \):

When \( p_G \geq \delta - 1 + p_R + s \) we have:

\[
\pi = (1 - p_R)(p_R - c_R)
\]

which is not related to \( p_G \).

Hence, we should compare three cases: \( p_R + 1/2(c_G - c_R + \delta + s - 1) \), \( \delta_p R + s, \delta - 1 + p_R + s \), and \( 1/2(c_G + \delta + s) \).

According to the above discussion, we have:

(A) When \( s \leq c_G - c_R - (\delta - 1) \):

1. If \( 1/2(c_G + \delta + s) \leq \delta_p R + s \) and \( p_R + 1/2(c_G - c_R + \delta + s - 1) \), we yield \( p_G = p_R + 1/2(c_G - c_R + \delta + s - 1) \), and correspondingly, \( \pi = \pi(p_R) = 1/2(\delta - 1)[ - (p_R - c_R)(2/\delta - 1)p_R - (c_G - c_R + \delta + s - 1)] + (\delta + s - 1 - c_G + 2p_R + \delta + s - 1 - c_R - \delta - 1)] \).

2. If \( 1/2(c_G + \delta + s) \leq \delta_p R + s \) and \( p_R + 1/2(c_G - c_R + \delta + s - 1) \), we yield \( p_G = c_G + \delta + s/2 \).

3. If \( 1/2(c_G + \delta + s) \leq \delta_p R + s \) and \( p_R + 1/2(c_G - c_R + \delta + s - 1) \), we yield \( c_G = c_R + \delta + s/2 \).

(B) When \( s < c_G - c_R - (\delta - 1) \), we have \( s < c_G - c_R - (\delta - 1) \), and correspondingly, \( \pi = \pi_2(p_R) \leq (1 - p_R)(p_R - c_R) \).

Combining cases (1) and (2) in (B) we have that \( \pi = \pi_2(p_R) = (1 - p_R)(p_R - c_R) \).

\[
p_R = \frac{c_R + 1}{2}, \quad p_G = \frac{\delta + c_G + s}{2}
\]

and the demands are correspondingly obtained. We have proven that Eq. (6) holds for \( c_G - c_R - (\delta - 1) \leq s \leq c_G - \delta R \).

When \( s > c_G - \delta R \), we have \( c_G - c_R - s + \delta - 1/2(\delta - 1) \), and the maximiser of \( p_R \) is in case (2), which yields \( p_R \geq \delta - s + c_G/26 \). Meanwhile, we have \( p_G = c_G + \delta + s/2 \).

\[
p_R = \frac{\delta + c_G + s}{2}
\]

and the demands are correspondingly obtained. We have proven that equation (5) holds for \( s > c_G - \delta R \).

(B) When \( s < c_G - c_R - (\delta - 1) \), we have \( s < c_G - c_R - (\delta - 1) \), and correspondingly, \( \pi = \pi_2(p_R) \leq (1 - p_R)(p_R - c_R) \).

Combining cases (1) and (2) in (B) we have that \( \pi = \pi_2(p_R) = (1 - p_R)(p_R - c_R) \).

\[
p_R = \frac{\delta + c_G + s}{2}.
\]

and the demands are correspondingly obtained. We have proven that Eq. (7) holds under \( s \leq c_G - c_R - (\delta - 1) \). Therefore, the three parts of Theorem 1 have all been proven.

**Proof of Corollary 1**

It is obvious from Theorem 1 that \( p_R \) is not related to \( \delta \) and \( p_G \) is increasing with \( \delta \). Taking the first-order derivative of \( d_R \) with respect to \( \delta \) shows that \( d_R \) in equation (5) is decreasing with \( \delta \) is equivalent to \( c_G - c_R - s > 0 \). Noting that \( c_G - c_R - s \) is decreasing with \( \delta \). In addition, that \( d_G \) in equation (5) is increasing with
δ is also equivalent to \( c_G - c_R - s > 0 \), which is proven true. It is also easy to see that \( d_G' \) in equation (4) is increasing with \( δ \) if \( s < c_G \).

**Proof of Corollary 2**

When \( s + (\bar{δ} - δ) = c_G - δc_R \), TE = \((δ - c_G - et + s)/2δ \) is increasing with \( s \) and decreasing with \( t \). When \( s + (\bar{δ} - δ) = c_G - δc_R \), TE = \( (1 - e) c_G - (\bar{δ} - δ) c_R + (δ - 1) e δ + (e - 1) s + (2e - e^2 - δ) t^2(δ - 1) \) is decreasing with \( s \) and \( t \) because \( e < 1 \) and \( 2e - e^2 - δ = - (e - 1)^2 + (1 - δ) < 0 \). When \( s + (\bar{δ} - δ) ≤ c_G - δc_R \), TE = \( 1/2 + (c_G - c_R - s - (1 - e)t)(1 - e) ≥ (\bar{δ} - 1)(c_R + t) \) and decreases with \( δ \), because \( (c_G - c_R - s - (1 - e)t) \) is decreasing with \( \bar{δ} \).

The result of Corollary 3 is directly obtained by substituting \( s \) by 0 and \( c_G \) by \( c_G - \bar{δ} \).

**Proof of Theorem 2**

We have the following results after algebraic calculations:

\[
SW(\bar{d}) =
\begin{cases}
\frac{1}{2}(3 - 3c_R - 4\bar{d})(1 - \bar{c}) & \text{when } s \leq c_G - c_R - (\bar{δ} - 1) \\
\frac{1}{2}(\bar{d} - 1) - [x^2 + (\bar{d} - 1/2) + c_G - c_R] & \text{when } c_G - c_R - (\bar{d} - 1) \leq s \leq c_G - c_R - (\bar{δ} - 1) \\
+2(1 - e)t + M & \text{when } c_G - c_R - (\bar{d} - 1) \leq s \leq c_G - c_R - (\bar{δ} - 1)
\end{cases}
\]

(26)

Hence, when \( c_G - c_R - \bar{d} ≤ 1 \), we have that \( SW(\bar{d}) \) is a constant function in \([0, c_G - c_R - (\bar{d} - 1)]\) and is a concave function in \([c_G - c_R - (\bar{d} - 1), c_G - \bar{δ}c_R]\). It is also easy to verify that \( SW(\bar{d}) \) is a continuous function over \([0, c_G - \bar{δ}c_R]\). Therefore, if \( SW(\bar{d}) \mid_{c_G - c_R - (\bar{d} - 1)} \leq 0 \Leftrightarrow k\Delta \leq c_G - c_R - (\bar{d} - 1) \), \( s' \) can be any value in \([0, c_G - c_R - (\bar{d} - 1)]\). Otherwise, we only need to check \( SW(\bar{d}) \mid_{c_G - c_R - (\bar{d} - 1)} \geq 0 \Leftrightarrow k\Delta \geq c_G - c_R - (\bar{d} - 1) \) in interval \([c_G - c_R - (\bar{d} - 1), c_G - \bar{δ}c_R]\) with the optimal maximiser \( s' \) from solving \( SW(\bar{d}) = 0 \), which yields \( s' = \bar{d} - 1 + c_R - c_G + 2k\Delta \). If \( SW(\bar{d}) \mid_{c_G - c_R - (\bar{d} - 1)} \geq 0 \Leftrightarrow k\Delta \geq c_G - c_R - (\bar{d} - 1) \), then \( s' = c_G - \bar{δ}c_R \). The demands can be derived correspondingly by substituting \( s' \) into equations (5)-(7) in Theorem 1.

On the other hand, when \( c_G - c_R ≤ \bar{d} - 1 \), we have that \( SW(\bar{d}) \) is a globally concave function in \([0, c_G - \bar{δ}c_R]\). Therefore, if \( SW(\bar{d}) \mid_{c_G - c_R - (\bar{d} - 1)} < 0 \Leftrightarrow k\Delta < c_G - (\bar{d} + 1)c_R + (\bar{d} - 1)/2 \), then \( s' \) solves \( SW(\bar{d}) = 0 \), which yields \( s' = \bar{d} - 1 + c_R - c_G + 2k\Delta \). If \( SW(\bar{d}) \mid_{c_G - c_R - (\bar{d} - 1)} \geq 0 \Leftrightarrow k\Delta \geq c_G - (\bar{d} + 1)c_R + (\bar{d} - 1)/2 \), then \( s' = c_G - \bar{δ}c_R \). The demands can be derived correspondingly by substituting \( s' \) into equations (6) and (7) in Theorem 1.

**Proof of Corollary 4**

We have \( d_G'/\delta < 0 \Leftrightarrow k\Delta < c_G - c_R \Leftrightarrow d_G'/\delta > 0 \). Note that \( k\Delta < c_G - (\bar{d} + 1)c_R + (\bar{d} - 1)/2 < c_R - c_G \); therefore, \( d_G' \) is decreasing with \( \delta \) and \( d_G' \) is increasing with \( \delta \). The sensitivities to other parameters can be easily obtained in a similar pattern.

**Proof of Corollary 5**

It is easy to see that \( TE = 2(1 - e)c_G - (\bar{d} + 1 - 2\bar{d})c_R + (\bar{d} - 1)(2e - 1 - 2k(1 - e)/2(\bar{d} - 1) \) under the regime of effective subsidy is increasing with \( c_G \) while decreasing with \( c_R \) and \( k \). According to Corollary 2, we have that \( TE \) is decreasing with \( \delta \) because \( s \) Proof of Corollary \( \in [c_G - c_R - (\bar{d} - 1), c_G - \bar{δ}c_G] \). The results of \( TE \) under other subsidy regimes can be easily obtained in a similar pattern.

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