Exploring Supply Chain Collaborative Innovation: Evidence from China

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ABSTRACT

Innovation is a critical source of competitive advantage. With increasing competition, globalisation and improved communications technology, organisations are, to a large extent, operating and competing on the supply chain (SC) level. Similarly, an organisation's technology innovation is also presenting boundary-spanning features. The SC itself is a kind of network structure. In such a network structure, technology innovation, co-influenced by various interdependent elements, shows itself as a complex non-linear system, which comprises multiple feedbacks. However, the relationships among these elements are complex and unclear. Further investigation is needed so as to develop a model of continuous SC collaborative innovation.

This paper embraces the system dynamics methodology and explores how elements internal and external to the SC interact with each other and contribute to SC collaborative technology innovation. The model serves as an exploratory tool for analysing the interaction and interdependence among network actors and evaluates possible alternatives to promote innovation.

Key Words: Supply chain; collaborative innovation; system dynamics model

INTRODUCTION

Today, the fact that innovation is a key to competitive advantage has been widely accepted (Hult, 2004). With increasing competition, globalisation and improved communications technology, organisations are, to a large extent, operating and competing on the supply chain (SC) level. SC research has also become an area of great interest to scholars. Greater SC collaboration is crucial to firms because they need to utilise the resources and knowledge of their partners (Fawcett and Magnan, 2004; Cao and Zhang, 2011). The focus of SC

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research has shifted also from narrow efficiency considerations to effective resources or capabilities development, and most recently to SC network management, which emphasises knowledge sharing and application (Miles and Snow, 2007).

Similarly, an organisation's technology innovation is also presenting boundary-spanning features. Inter-organisational collaboration and interaction permeate various aspects and stages of innovation. The complexity of technology innovation entails building ties and collaboration between the focal company and other organisations, so as to exchange knowledge and information, gain access to resources and enhance capabilities. Correspondingly, recent years have witnessed an increasing emphasis on the importance of innovation networks (Chesbrough and Prencipe, 2008; Dittrich and Duysters, 2007; Enkel, 2010), the aggregation of formal and informal collaborative research and development (R&D) relationships formed around firms during technology innovation processes (Liu and Chen, 2004). While some literature has investigated the influence exerted by a specific type of collaboration on innovation (e.g. Kaufman et al., 2000; Takeishi, 2002; Song and di Benedetto, 2008; van Echtelt et al., 2008), others consider various types of SC collaborations' influence on innovation or take an SC as a whole (Vickery et al., 2003; Vereecke and Muylle, 2006; Cao and Zhang, 2011). Firms, generally, are influenced by various collaborative relationships simultaneously, and different relationships interact with each other (Belderbos et al., 2006; Un et al., 2010). The complexity of the relationship between SC collaboration and innovation calls for further investigation.

Moreover, the SC itself is a kind of network system or network structure. In such a network structure, technology innovation, co-influenced by various interdependent elements, shows itself as a complex non-linear system, which comprises multiple feedbacks. However, the relationships among these elements are complex and unclear. Further research is needed to develop a model of continuous SC collaborative innovation, which can serve as an exploratory tool for analysing the interaction and interdependence among network actors and assess possible alternatives to promote innovation. It is argued that simulation modelling nearly always adds value, even in the face of significant uncertainties about data and the formulation of soft variables, which makes it suitable for dynamic analysis (Homer and Oliva, 2001). System dynamics offers the ability to bring a model to life, to see the consequences of structural assumptions, and to challenge managerial intuition (Vennix and Gubbels, 1994: 139). Some researchers have adopted a system dynamics approach in related fields. For example, King and Burgess (2006) analysed enterprise system innovation based on the system dynamics simulation concept, but the model still needs to be validated. Wu, Zeng and Chen (2010) built a system dynamics model describing the development of high-tech enterprises' innovation networks, in which R&D cooperation, standardisation and knowledge transfer are demonstrated as the key factors. Wu, Kefan, Hua, Shi and Olson (2010) used the system dynamics method to investigate the problem of technological innovation risk-based decision making. Drawing on the same method, Kamath et al. (2009) found that innovation requires extensive knowledge sharing and learning, and knowledge management is the prime driver of innovation. Based on these studies, as well as taking account of the complex and dynamic features of technology innovation, this paper embraces the system dynamics methodology and explores how SC network elements interact with each other and contribute to SC collaborative technology innovation. This gives a dynamic description and understanding of the process around innovation resources and capabilities that lead to knowledge and market outcomes.

TECHNOLOGY INNOVATION IN CHINA

At present, China aims to upgrade from a simple manufacturing-oriented economy to an innovation-oriented one. The Chinese government has set 'enhance innovation capability and building innovative country' (*People's Daily*, 2006) as the kernel of its development strategy. The SC provides a unique perspective for investigating the evolution of innovation capability as the driving force for the Chinese economy. Generally, large and medium-sized industrial enterprises in China are the focal players in the SC and have a crucial impact on industrial chain upgrading and regional economic development. As focal companies, their technology innovation activities not only influence SC members or related organisations in the outside environment, but also need collaboration from those organisations. Surveys from the National Bureau of Statistics of China have demonstrated that it is inevitable that focal companies make use of external resources to conduct innovation activities, such as collaboration with other firms or research institutes and universities (RU). This study aims to explore the factors that influence SC technology innovation and how they impact innovation performance. The insights from this study can be beneficial to China's policy-making in regard to conducting effective and efficient innovation.

COLLABORATIVE INNOVATION IN SC NETWORKS

Theory Foundation

Resource-Based View

The resource-based view (RBV) suggests that competitive advantage derives from the scarce and valuable resources which an organisation possesses. When heterogeneous resources complement each other, the potential to create competitive advantage will be generated (Barney, 1991). The scarcity and dispersal of innovation resources make it necessary for innovators to depend on other sources. An individual firm can integrate external resources by collaborating with other organisations to reduce the cost and risk of innovation (Gulati, 1999). The RBV was extended to focus on a special type of resource – knowledge. The knowledge-based view (KBV) argues that organisations exist to create, transfer and transform knowledge into competitive advantage (Kogut and Zander, 1992). SC technology innovation involves a large amount of tacit knowledge and a wide range of stakeholders, which entails capacity development, collaboration and resources integration of various SC members. This will create an interactive network of information and knowledge exchange (Vachon and Klassen, 2008).

Relational View

The relational view suggests that a firm's critical resources may span firm boundaries and may be embedded in inter-firm routines and processes. Collaborating firms can generate relational rents through relation-specific assets, knowledge-sharing routines, complementary resource endowments and effective governance (Dyer and Singh, 1998). SC network members' investment in relation-specific assets have the potential to generate relational rents within the relationship and create collaborative advantage (Kanter, 1994). SC knowledge-sharing routines as a mode of inter-firm interactions that permits the transfer, recombination or creation of specialised knowledge will increase partner-specific absorptive capacity and contribute to SC innovation (Dyer and Singh, 1998; Grant, 1996). Thus, innovation performed within an SC network is largely influenced by a variety of relationships in the network.

Organisational Learning Theory

Inter-organisational learning in the SC network is regarded as behaviour seeking to discover knowledge on the network level (Dyer and Nobeoka, 2000). Contemporary forms of competition increasingly raise the importance of distributed knowledge (Nonaka and Takeuchi, 1995) and companies need to expand external sources of knowledge (Katila and Ahuja, 2002) while enhancing their absorptive capacity. It has been argued that absorptive capacity would affect the learning process and co-evolve with organisational learning (Van den Bosch et al., 1999). The value of SC collaboration stems from the possibility of inter-organisational learning, which is one of the most important resources that can be developed in the SC. It entails a problem-solving routine involving supplier and/or customers (Schroeder et al., 2002), and the integration of SC knowledge, resources and capabilities (Vachon and Klassen, 2008) so as to enhance the innovation capacity of both the focal company and the SC.

Innovation Networks

Recent years have witnessed an increasing emphasis on the importance of innovation networks (Chesbrough and Prencipe, 2008; Dittrich and Duysters, 2007; Enkel, 2010). Some researchers define innovation networks as the linkages between organisations (e.g. firms, universities and government agencies) that create, acquire and integrate the diverse knowledge and skills required to create complex technologies and bring them into the market. Innovation networks are organised around constant learning (Rycroft and Kash, 2004). Others argue that innovation networks, as collaborative R&D relationships develop and deepen, are the aggregation of formal and informal collaborative R&D relationships formed around firms during the technology innovation processes (Liu and Chen, 2004).

Innovation cannot solely depend on the resources of a single firm, and needs to utilise resources and knowledge within the SC network. It is argued that when the knowledge base of an industry is both complex and expanding, and the sources of expertise are widely dispersed, the locus of innovation will be found in networks of learning, rather than in individual firms (Hacklin et al., 2004). In order to develop new technologies more efficiently, companies generally require extensive use of resources. This can be achieved by the development and utilisation of knowledge and technology outside the company or through the outflow of unexploited knowledge and technology. Meanwhile, firms themselves should have absorptive capacity to acquire, assimilate, transform and exploit external knowledge (Zahra and George, 2002).

SC Collaboration

Collaboration, in the context of the SC, is to share joint goals; have commitment, trust and respect; exchange skills and knowledge; and work jointly to plan and execute SC operations (Simatupang and Sridharan, 2002; Barratt, 2004). Collaboration has been referred to as the driving force behind effective SC management (Horvath, 2001; Min et al., 2005). Firms strengthen their competitive advantage through collaboration (Simatupang and Sridharan, 2004). There are many empirical studies indicating that companies with higher levels of collaboration show higher performance improvement. Firms need to collaborate with SC partners to achieve performance improvement (Fynes et al., 2005; Vereecke and Muylle, 2006; Cao and Zhang, 2011). The benefits of collaboration include knowledge sharing and production resources sharing (Björnfot and Torjussen, 2012), which are crucial to the innovation process.

SC Collaborative Innovation

SC themselves are an important kind of network system or network structure. Sustainable SC management involves the inter-connection between components and interfaces across the SC (Svensson, 2007). Exchanging knowledge and exchanging human resources have been identified as key activities in managing collaborative technological innovation (Johnsen and Ford, 2000). The complexity of the SC innovation process also promotes building ties and collaboration between focal firms and other organisations, so as to exchange knowledge and information, gain access to resources and enhance relevant skills.

Focal firms' innovation processes and activities normally involve interaction and collaboration with other SC members, such as knowledge sharing among SC partners and collaboration with suppliers to develop new products based on feedback from users. Collaborative innovation in SC networks involves joint asset investment, relational capital building and knowledge transfer; having collaborative willingness and commitment; and planning jointly to develop new products or processes. This reflects an organisation's capacities to effectively integrate the internal and external knowledge and technology resources, which are difficult to replicate, and thus brings competitive advantage. In fact, a range of research shows that innovation collaboration with upstream and downstream actors in the SC has many potential benefits, such as ideas generation, costs reduction, increasing flexibility, improving development, testing and diffusion, and shortening the time-to-market (Johnsen and Ford, 2000; Vereecke and Muylle, 2006). Besides the industrial SC, government and RUs are also key players in the environment of SC innovation. RUs are a major supplier of new ideas, knowledge and intelligent resources. Government can boost the development of collaborative innovation networks by implementing favourable policies and providing financial support.

A SYSTEM DYNAMICS MODEL OF SC COLLABORATIVE INNOVATION

A System Dynamics View

System dynamics was developed by J.W. Forrester to consider complex non-linear systems with several feedback loops of information (Sterman, 2001). The system dynamics model, combining qualitative and quantitative methods, simulates the system functions. The principal concept of this methodology is the feedback. Only by observing the whole feedback system can the system dynamics behaviour be comprehended (Sterman, 2002).

Technology innovation in the SC network, with various interdependent resources, actors or activities being involved, shows itself as a complex non-linear system, comprising multiple feedbacks. Not only does it necessitate the efficient utilisation and allocation of a firm's internal resources, but it also calls for consistent and sufficient information and material exchanges with network actors and environment. For example, Garcia et al. (2003) present a system dynamics model to investigate innovation policy decisions. Likewise, this paper considers the interdependence among network actors, embraces the system dynamics methodology and studies SC technology innovation from a system perspective.

Model Description

Innovation is increasingly recognised as being the result of the combination of resources and knowledge from different organisations (Freeman, 1991; Hagedoorn, 1995; Johnsen and Ford, 2000) because firms use their SC's knowledge stocks to innovate. In order to understand the dynamic behaviour of this complex system, a system dynamics simulation model is developed and tested. Using this model, we create a dynamic collaboration and learning environment to explore the effects of investment decision, collaboration strategy and inter-organisational learning on the innovation output and profits of the SC.

Based on this approach, elements internal and external to the SC are considered (e.g. financial capital, intellectual capital and innovation outputs) and four key actors are identified: focal company, other SC members, government, and RUs. Various elements in the systems interact with each other and synthetically influence innovation. Among the basic elements, investment from the focal company, government and RUs act as the main sources of financial capital input. The focal companies, RUs and other SC members, through inter-organisational learning and collaboration, provide intellectual capital. Innovation patent output and new product sales represent innovation outputs.

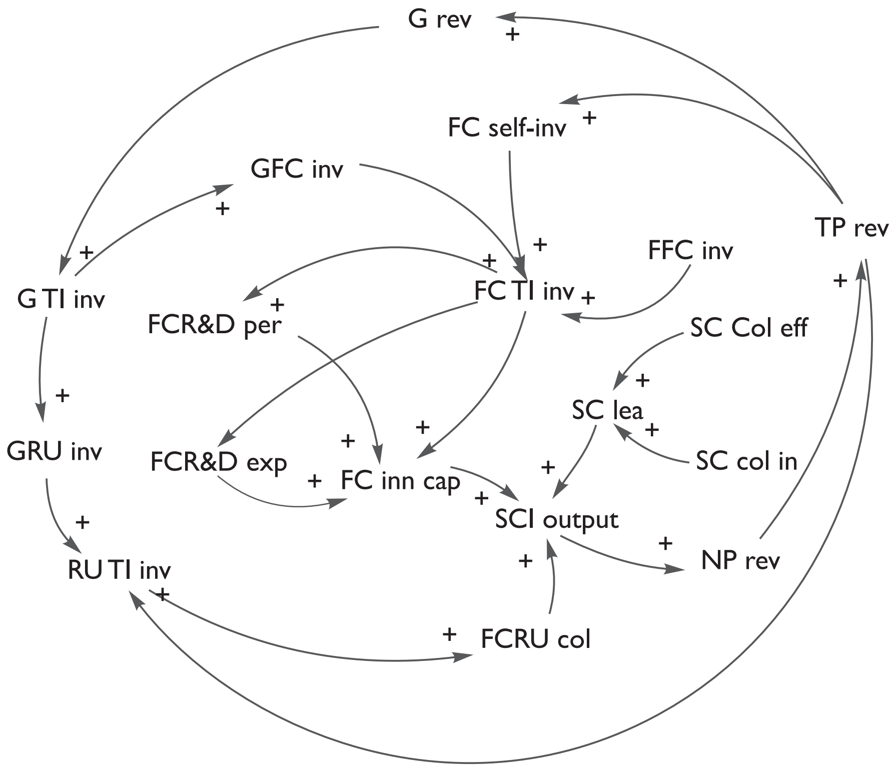
Causal Loop Diagram of SC Collaborative Innovation

Based on the systemic features of the SC innovation network, it seems that the growth of the SC innovation network is dependent on collaboration and learning among SC members; focal companies' innovation investment and capability development; and collaboration with RUs as well as government.

Above all, SC innovation outputs depend on the innovation capability of the SC or focal companies. The increase of focal companies' total investment in innovation, comprising investment from government, focal companies and financial institutions, directly increases R&D expenditure and the human resources of focal companies. This contributes to the building of innovation capability, but it also has long-term positive influence on the accumulation of innovation capability.

In addition, the outputs of SC innovation are largely influenced by inter-firm knowledge transfer and learning within the SC network, which entails efficient and strong collaboration among SC members. Similarly, the collaboration with RUs is also crucial to innovation outputs. Collaborations between firms and RUs not only give the firm a window on emerging technologies and fields, but also improve RUs' research and teaching (Lee, 1996; Webster, 1994; George et al., 2002). Larger amounts of knowledge can be transferred with stronger collaboration within the network. Through collaboration and learning, new capabilities, resources and knowledge can be identified, acquired, integrated or shared among network participants (Rycroft and Kash, 2004). This will facilitate continuous innovation and generate competitive advantage for the SC network.

Figure 1: Causal Loop Diagram of Supply Chain Collaborative Innovation



In a word, the development of an SC innovation network delivers greater innovation patent outputs and financial incomes, which in turn contribute to the growth of the SC innovation network by strengthening collaboration and investment from actors within the network. Based on the above analysis, a causal loop diagram of SC collaborative innovation can be drawn as in Figure 1. The variables used in the model in Figures 1 and 2 are listed and explained in Table 1.

Table 1: Variables and Explanations

Variable	Unit	Explanation
FC TI inv	100 million yuan	Focal company technology innovation investment (total science and technology (S&T) investment)
Inv inf	100 million yuan	Technology innovation investment inflow
FC self-inv	100 million yuan	Focal company self-investment in S&T
GFC inv	100 million yuan	Government S&T investment in focal company
FFC inv	100 million yuan	Financial institutions S&T investment in focal company
FC inv in	N/A	Focal company S&T investment intensity (percentage of total sales revenue of products)
G TI inv	100 million yuan	Government technology innovation investment (total S&T investment)
GFC inv in	N/A	Government S&T investment intensity in focal company (percentage of G TI inv)
FCR&D per	10,000 man-years	Focal company R&D personnel
FCR&D exp	100 million yuan	Focal company R&D expenditure
FC inn cap	N/A	Focal company innovation capacity (firm's ability and willingness to innovate at the product and process level)
FCRU col	100 million yuan	Focal company and RU collaboration (focal company S&T investment in RUs)
SC lea	N/A	SC learning (the accumulation and development of a knowledge base through interaction with members in the SC network (Bessant et al., 2003))
SC col eff	N/A	SC collaboration efficiency (effective knowledge transfer linkages within SC members)
SC col in	N/A	SC collaboration intensity (the degree of SC members' involvement in the focal company's routines)
Output rate	N/A	Technology innovation output rate (patent applied rate)

(*Continued*)

Table 1: (*Continued*)

Variable	Unit	Explanation
Output inf	patent	Technology innovation output inflow
SCI output	patent	SC innovation output (numbers of patent applied)
NP rev	100 million yuan	Revenue from the sale of new products
TP rev	100 million yuan	Total sales revenue of products
G rev	100 million yuan	Government revenue
GRU inv	100 million yuan	Government S&T investment in RUs
RU TI inv	100 million yuan	RU technology innovation investment (RU S&T investment)

System Flow Chart of SC Collaborative Innovation

Based on the causal loop in Figure 1, certain variables of the innovation network were introduced, and the system flow chart of SC collaborative innovation is structured for simulation in a Vensim modelling environment (see Figure 2).

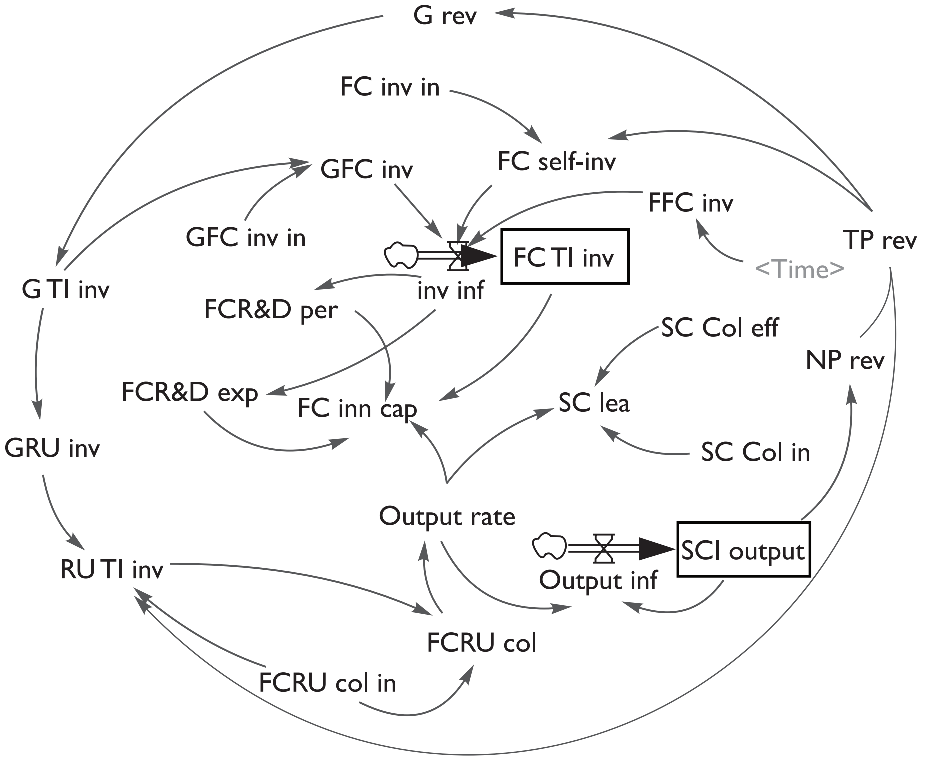
The equations depicting the relationships between different variables in the model are deduced from related data using SPSS (Statistical Product and Service Solutions) and Excel. The data are collected from the website of the National Bureau of Statistics of China (http://www.stats.gov.cn/) and the *China Statistical Yearbooks on Science and Technology* 1996–2008 (published yearly by China's statistical publishing house), which is edited by the National Bureau of Statistics and Ministry of Science and Technology. The yearbook covers basic statistics on large and medium-sized industrial enterprises, government expenditure for science and technology, basic statistics on R&D institutions, basic statistics on institutions of higher education, and similar statistics. It is an accessible and reasonable data source for this study.

Focal companies' total investment in innovation (*FC TI inv*), as the primary driving force for technology innovation within SC networks, is set as a stock variable. It is the aggregation of investment from focal companies, financial institutions and the government.

This model uses SC innovation outputs represented by the number of patents applied for by focal companies and new product revenue to reflect the performance of the SC collaborative innovation system. SC innovation outputs is a stock variable, mainly correlated with focal companies' SC learning, innovation capability and RU collaboration.

First, SC learning is determined by SC collaboration efficiency and SC collaboration intensity, both of which are constant. Based on previous research, SC collaboration efficiency suggests effective knowledge transfer linkages within SC members (Tang and Xi, 2006). SC collaboration intensity reflects the degree of SC members' involvement in the focal company's routines. The innovation capability of focal companies is dependent on the input of R&D expenditures, R&D personnel and delayed influence of accumulated science and technology (S&T) investment. Academic collaboration – the collaboration between focal companies and research institutes and universities (FCRU) – is influenced

Figure 2: System Flow Chart of Supply Chain Collaborative Innovation



by the innovation investment of RU and FCRU collaboration intensity (*FCRU col in*), and it is set as a constant value.

Despite the dynamic nature of system models in general, the model has some constants, which reflect the assumptions made (Kamath et al., 2009). Key variables that have important influences on technology innovation in SC networks were identified to conduct further simulation (see Table 2). The current values for these variables in the base run are determined based on history data, multiple experimentation and analysis.

Table 2: Variables and Constants Used for Simulation

Variable Names	Base Run	Trial 1	Trial 2
SC col eff	0.4	0.5 (run 1)	0.3 (run 2)
SC col in	0.05	0.06 (run 3)	0.04 (run 4)
FCRU col in	0.025	0.035 (run 5)	0.015 (run 6)
FC inv in	0.013	0.04 (run 7)	0.006 (run 8)

SIMULATION AND ANALYSIS

Model Validity Check

A model validity check is necessary before running the simulation. There are two testing methods: the theory test and the history test. The theory test is mainly based on the rationality of the model boundaries, the authenticity of the relationship between model variables, dimension consistency and the rationality of the exogenous variables and parameters. The history test compares the model results with historical data in order to test the degree of goodness between the model and the objective system (Wu, Kefan, Hua, Shi and Olson, 2010). Theoretical rationality of the model is analysed in the previous section. This paper used history data from the *China Statistical Yearbook on Science and Technology 2008* to conduct the history test. Using 2003 as the starting point, government revenue from 2004 to 2007 was simulated and compared with the actual value of history data (see Table 3). Overall, the predicted value and actual value are fitting well, confirming the validity of the model.

Table 3: History Test

	Time (Year)	Predicted Value (100 million yuan)	Actual Value (100 million yuan)	Error
Government Revenue (100 million yuan)	2003	21,571.23	21,715.25	-0.663%
	2004	25,125.6	26,396.47	-4.815%
	2005	30,397.36	31,649.29	-3.956%
	2006	38,888.59	3,8760.2	0.331%
	2007	54,321.98	51,321.78	5.846%

Parameter Sensitivity Analysis

Through multiple testing and theoretical analysis it can be identified that focal company S&T investment intensity (*FC inv in*) is a sensitive element, so it is used to test the sensitivity of this model. After changing '*FC inv in*' from a constant variable (current) to a lookup variable (current 2), the results for SC innovation output (*SCI output*) and new products' sales revenue (*NP rev*) reveal little difference and the trend is still the same (see Figure 3), so the parameter is insensitive and the model is not demanding on the parameters, which will benefit the application of this model.

Simulation Results

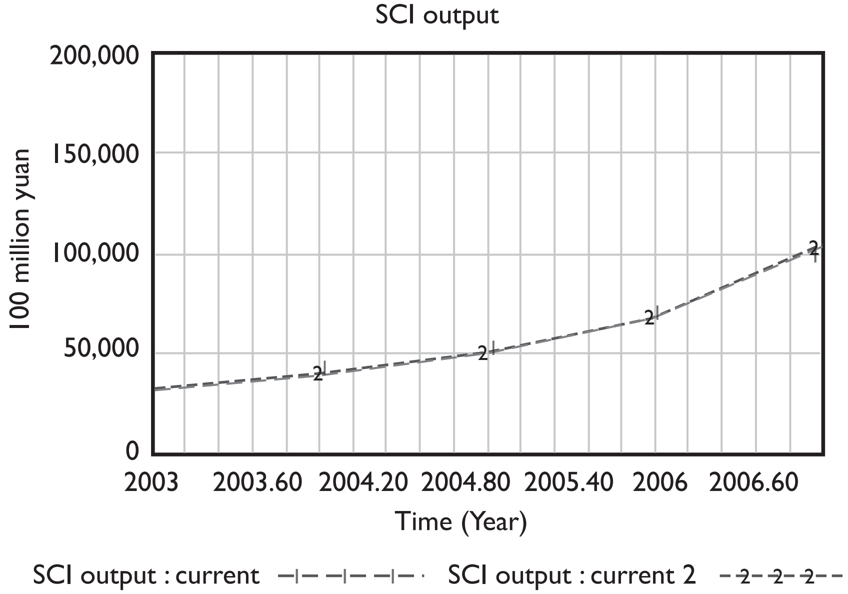
Improve Organisational Learning and Knowledge Transfer

As can be seen from Figure 4, when SC collaboration efficiency (*SC col eff*) is increased from 0.4 (current) to 0.5 (run 1), the SC innovation output (*SCI output*) and new products' sales revenue (*NP rev*) both ascend correspondingly, and vice versa.

Meanwhile, as can be seen in Figure 5, *SCI output* and *NP rev* also rise with the enhancement of SC collaboration intensity (*SC col in*), from 0.05 (current) to 0.06 (run 3).

The increase in *SC col eff* and *SC col in* will enhance SC technology innovation output and the focal company's new product sales revenue. This can be achieved by augmenting

Figure 3: Parameter Sensitivity Analysis



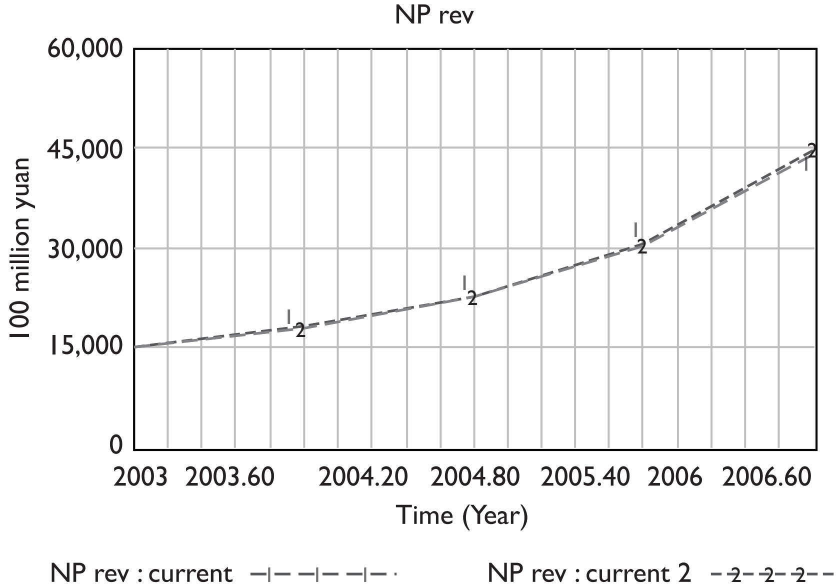
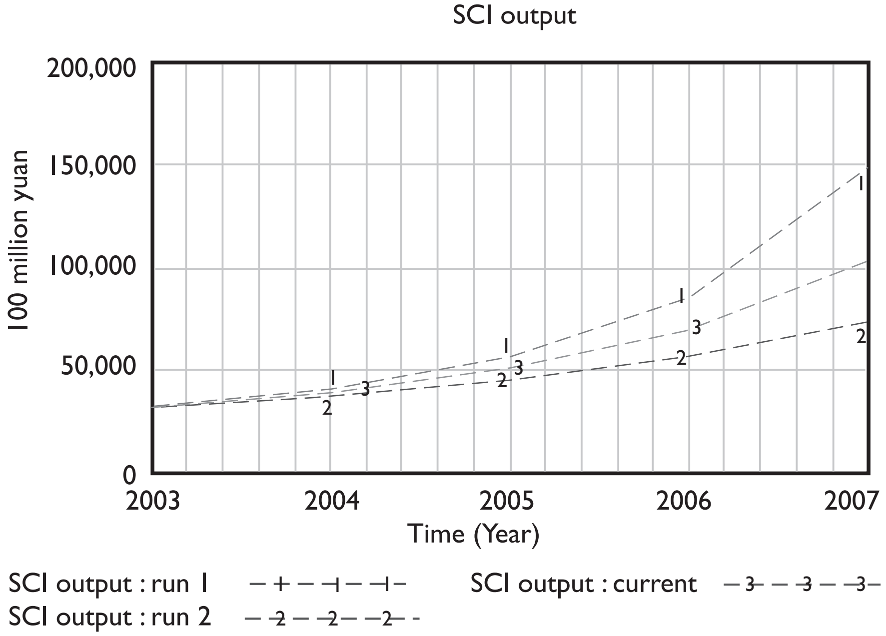


Figure 4: Supply Chain Collaboration Efficiency under Trial



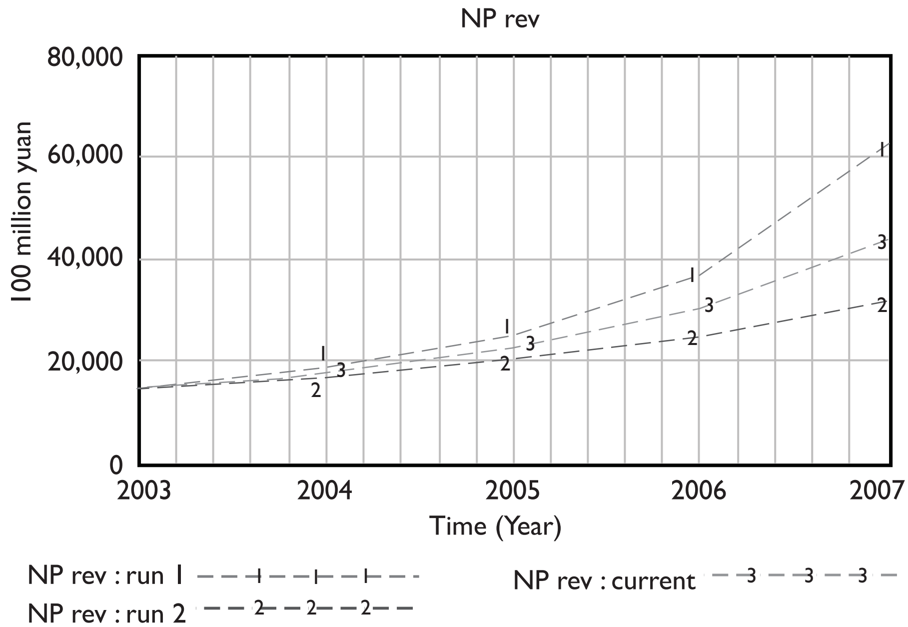


Figure 5: Supply Chain Collaboration Intensity under Trial

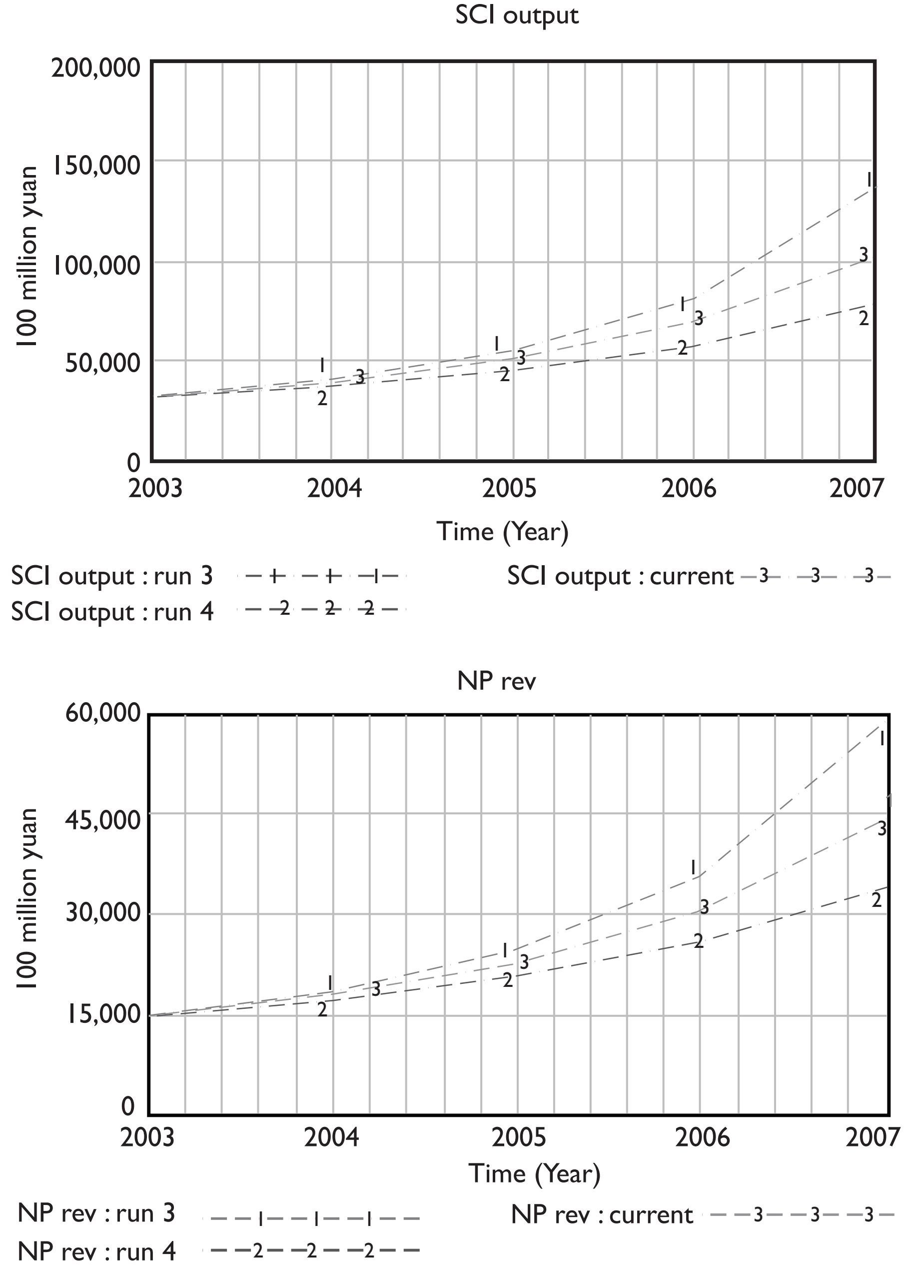


Figure 6: Focal Company and Research Institute and University Collaboration Intensity under Trial

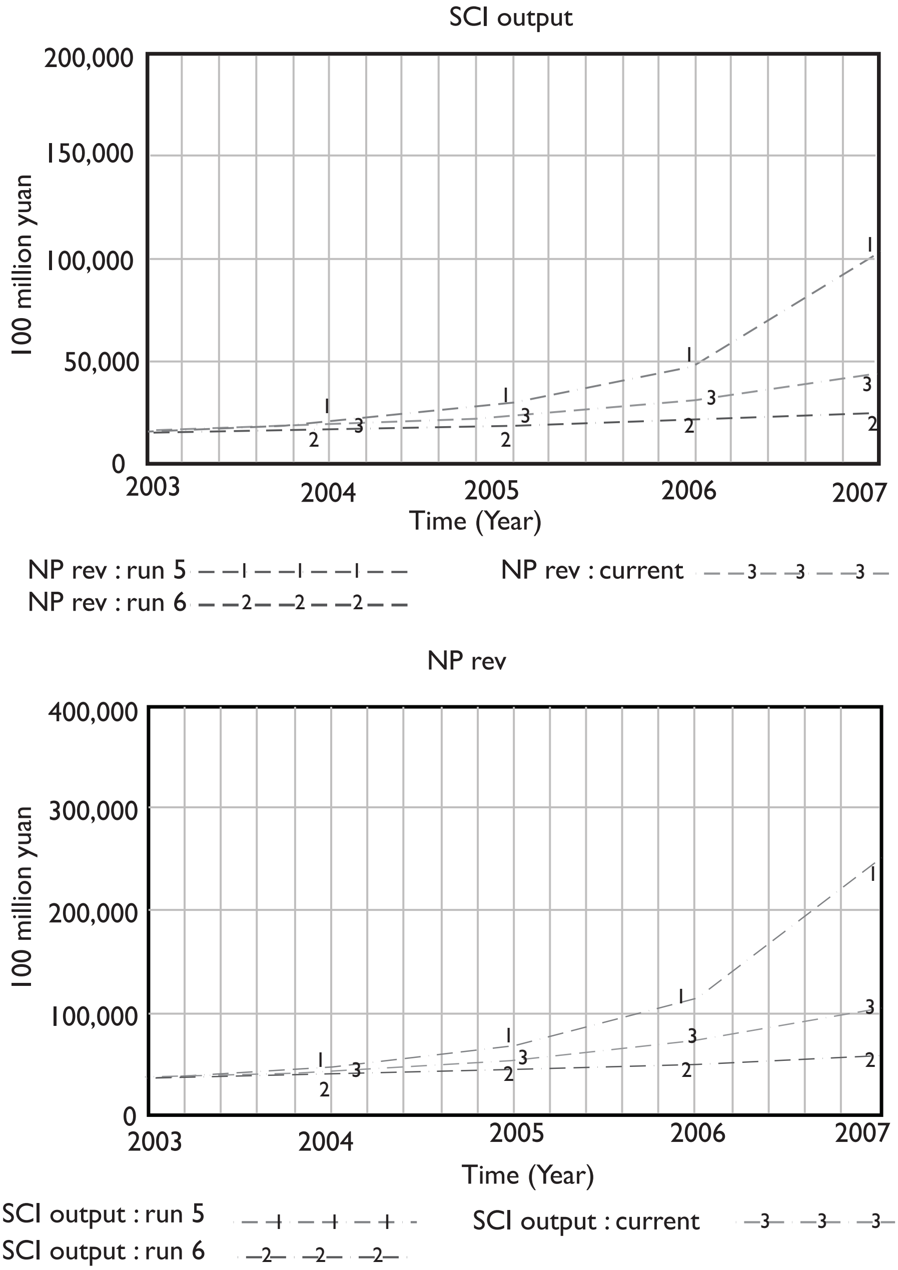
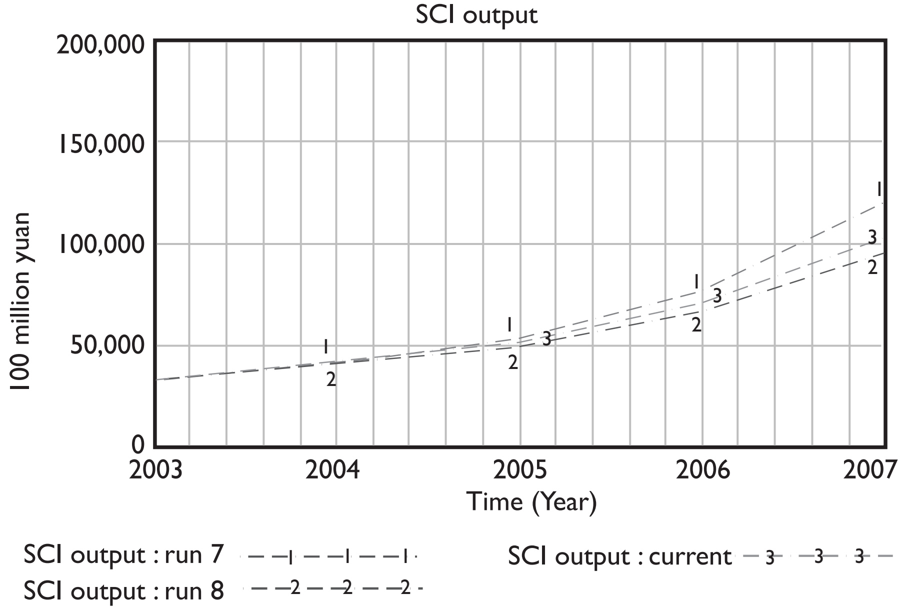
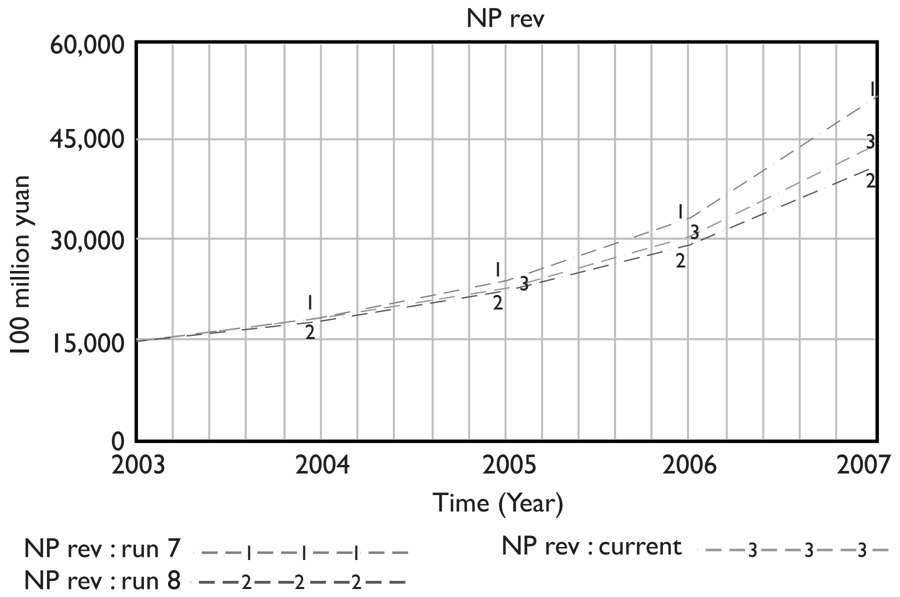


Figure 7: Focal Company's Science and Technology Investment Intensity under Trial





efficient linkages among SC members and the focal company, which mainly include trust building, fine-grained information exchange and joint problem-solving arrangements (McEvily and Marcus, 2005; Uzzi, 1997). Furthermore, it is necessary to strengthen focal companies' collaboration with upstream or downstream partners in the SC, so as to improve the efficiency of SC learning and knowledge transfer.

Scan and Acquire Knowledge and Recourses from SC Environment

As is shown in Figure 6, when collaboration intensity between focal companies and RU (*FCRU col in*) increases from 0.025 (current) to 0.035 (run 5), *SCI output* and *NP rev* also increase, and vice versa.

The up-rise of *FCRU col in* will increase SC technology innovation output and the focal company's new product sales revenue. Collaboration with RUs can bring in valuable knowledge and resources, and reduce the R&D cost and innovation cycle of the firm.

The SC Core Actors' Commitment to Innovation

As presented in Figure 7, the *SCI output* and *NP rev* vary with the change of focal companies' self-investment in S&T. When *FC inv in* rise from 0.013 (current) to 0.04 (run 7), *SCI output* and *NP rev* also increase, and vice versa.

Augmenting companies' self-investment in S&T activities can facilitate focal companies' investment in R&D both financially and intellectually, which are the key drivers of SC innovation capability. Moreover, the accumulation of S&T investment and R&D activities could have long-term effects on the focal company's innovation capability.

DISCUSSION AND CONCLUSIONS

The complexities of technology innovation and competitive environment suggest that effective technology innovation and management must be extended to the SC networks. Collaborative innovation in the SC network is becoming an important source of competitive advantage to the SC. Developing collaborative innovation is a relatively new concept among key actors in the SC network, and requires new studies to reveal how firms can use their SC networks to their advantage in technology innovation.

This paper uses the system dynamics approach to build a model of SC collaborative innovation that depicts the interdependence between various elements in the system, and explains the roles played by SC collaboration efficiency, SC collaboration intensity, FCRU collaboration intensity and focal company S&T investment intensity in the SC innovation network. This will help organisations and SCs better allocate their resources and manage the relationship between collaborative partners, so as to contribute to SC collaborative technology innovation.

Following the test of the model, a series of simulations was conducted. It is shown by the results that the increase in SC collaboration efficiency, SC collaboration intensity, FCRU collaboration intensity and FC self-investment intensity will improve SC innovation capability, increase innovation output and contribute to the sustainable development of the SC collaborative innovation network. To be more specific, what's implicit in the

SC collaborative innovation process is the need for knowledge and technology transfer between such partners. It is indispensable to enhance organisational learning and knowledge transfer through establishing efficient and close linkages among SC members. Furthermore, the results demonstrate that collaboration with RUs is beneficial to technology innovation and SC performance. This is consistent with the conclusions of former studies (e.g. George et al., 2002). University–industry collaboration can bring in valuable knowledge and resources to help build or sustain new technology capabilities, reduce R&D costs and lessen the innovation cycle of a firm. Effective supporting routines and interfaces should be established to strengthen the collaboration (Dooley and Kirk, 2007). Last but not least, focal companies' investment in innovation is also crucial. It will facilitate focal companies' investment in R&D both financially and intellectually, which are the key drivers of SC innovation capability. Moreover, the accumulation of S&T investment and R&D activities could have long-term effects on a company's innovation capability. Firms require absorptive capacity to leverage the resources within the SC networks and to deal with the challenges associated with managing cross-boundary partnerships and interactions. Simply put, the company should make the best use of the network resources and build trust, information exchange mechanisms and joint problem-solving arrangements while enhancing the SC and focal companies' learning ability so as to improve knowledge transfer and innovation performance. If China is to attain its goal of becoming an innovation-oriented economy, SC collaboration and academic collaboration should be encouraged and promoted by local and central government.

This paper uses the data of large and medium-sized enterprises to reflect the innovation activities of SC focal companies and patent applications as the SC innovation output. The data still have certain limitations. Given these limitations, future studies should adopt in-depth case studies on specific focal companies and SC networks. Moreover, future studies could investigate the influence of SC collaboration on different forms of innovation (e.g. product and process innovation). Finally, it may be instructive to delve into the process of SC knowledge transfer between different SC members.

APPENDIX 1: RELATED MODEL EQUATIONS AND EXPLANATIONS

- FC TI inv = INTEG(Inv inf, 1588.6)
  (The initial value of focal company total innovation investment is 1588.6, and FC TI inv = ΣInv inf)
- Inv inf = FC self-inv+GFC inv+FFC inv
  (Technology innovation investment inflow is composed of the investment from focal companies, government and financial institutions)
- FC self-inv = FC inv in*TP rev
  (Focal companies' self-investment is dependent on focal company innovation investment intensity and total sales revenue of products)

- GFC inv = G TI inv*GFC inv in
  (Government innovation investment in focal company is dependent on government technology innovation investment and government innovation investment intensity in the focal company)
- FFC inv = WITH LOOKUP (Time, ([(1996,89.2)-(2007,267.6)], (1996,89.2), (1999,84), (2000,97.3), (2002,99.9), (2005,169.4), (2006,253.7), (2007,267.6))
  (Financial institutions' innovation investment in focal company is set as a lookup variable)
- FCR&D per = 21.87+0.015*Inv inf; FCR&D exp = 0.521*Inv inf-97.314
  (Focal company R&D personnel and expenditure are both correlated with Inv inf)
- FC inn cap = 0.5*LN(FCR&D exp)+0.4*LN(FCR&D per)+0.1*LN(DELAY1(FC TI inv,3))
  (Focal companies' innovation capability depends on R&D expenditures, R&D personnel and the delayed influence of accumulated S&T investment)
- FCRU col = FCRU col in*RU TI inv; FCRU col in= 0.0025
  (Academic collaboration is influenced by the innovation investment of RU and FCRU collaboration intensity. FCRU col in is set as a constant value)
- SC lea = SC col eff*SC col in; SC col eff = 0.4; SC col in = 0.05
  (SC learning is determined by SC collaboration efficiency and SC collaboration intensity)
- Output rate = FCRU col*FC inn cap*SC lea
  (SC innovation output rate depends on FCRU collaboration, focal companies' innovation capability and SC learning)
- Output inf = Output rate*SCI output
  (Innovation output inflow is decided by output rate and SCI output)
- SCI output = INTEG (Output inf, 31382)
  (The initial value of SCI output is 31382, and SCI output = ΣOutput inf)
- NP rev = 1961.4+0.412*SCI output
  (New products' sale revenue is correlated with SCI output)
- TP rev = 8638.17+6.256*NP rev
  (Total sales revenue of products is correlated with new products' sale revenue)
- G rev = 3451.73+0.178*TP rev
  (Government revenue is correlated with total sales revenue of products)
- G TI inv = 47.723+0.041*G rev
  (Government technology innovation investment is correlated with government revenue)

- GRU inv = 42+0.64*G TI inv
  (Government innovation investment in RU is correlated with government total technology innovation investment)
- RU TI inv = FCRU col in*TP rev+GRU inv
  (RU technology innovation investment is composed of the investment from focal company and government)

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REFERENCES

Barney, J. (1991) 'Firm Resources and Sustained Competitive Advantage', *Journal of Management*, 17, pp. 99–120.

Barratt, M. (2004) 'Understanding the Meaning of Collaboration in the Supply Chain', *Supply Chain Management: An International Journal*, 9, pp. 30–42.

Belderbos, R., Carree, M. and Lokshin, B. (2006) 'Complementarity in R&D Cooperation Strategies', *Review of Industrial Organization*, 28, pp. 401–26.

Bessant, J., Kaplinsky, R. and Lamming, R. (2003) 'Putting Supply Chain Learning into Practice', *International Journal of Operations and Production Management*, 23, pp. 167–84.

Björnfot, A. and Torjussen, L. (2012) 'Extent and Effect of Horizontal Supply Chain Collaboration among Construction SMEs', *Journal of Engineering, Project, and Production Management*, 2, pp. 47–55.

Cao, M. and Zhang, Q.Y. (2011) 'Supply Chain Collaboration: Impact on Collaborative Advantage and Firm Performance', *Journal of Operations Management*, 29, pp.163–80.

Chesbrough, H. and Prencipe, A. (2008) 'Networks of Innovation and Modularity: A Dynamic Perspective', *International Journal of Technology Management*, 42, pp. 414–25.

Dittrich, K. and Duysters, G. (2007) 'Networking as a Means to Strategy Change: The Case of Open Innovation in Mobile Telephony', *Journal of Product Innovation Management*, 24, pp. 510–21.

Dooley, L. and Kirk, D. (2007) 'University–Industry Collaboration: Grafting the Entrepreneurial Paradigm onto Academic Structures', *European Journal of Innovation Management*, 10, pp. 316–32.

Dyer, J.H. and Nobeoka, K. (2000) 'Creating and Managing a High-Performance Knowledge-Sharing Network: The Toyota Case', *Strategic Management Journal*, 21, pp. 345–67.

Dyer, J.H. and Singh, H. (1998) 'The Relational View: Cooperative Strategy and Sources of Interorganizational Competitive Advantage', *Academy of Management Review*, 23, pp. 660–79.

Enkel, E. (2010) 'Attributes Required for Profiting from Open Innovation in Networks', *International Journal of Technology Management*, 52, pp. 344–71.

Fawcett, S.E. and Magnan, G.M. (2004) 'Ten Guiding Principles for High-Impact SCM', *Business Horizons*, 47, pp. 67–74.

Freeman, C. (1991) 'Networks of Innovators: A Synthesis of Research Issues', *Research Policy*, 20, pp. 499–514.

Fynes, B., Voss, C. and Búrca, S.D. (2005) 'The Impact of Supply Chain Relationship Dynamics on Manufacturing Performance', *International Journal of Operations and Production Management*, 25, pp. 6–19.

Garcia, R., Calantone, R. and Levine, R. (2003) 'The Role of Knowledge in Resource Allocation to Exploration versus Exploitation in Technologically Oriented Organizations', *Decision Sciences*, 34, pp. 323–49.

George, G., Zahra, S.A. and Wood, R.D. (2002) 'The Effects of Business–University Alliances on Innovative Output and Financial Performance: A Study of Publicly Traded Biotechnology Companies', *Journal of Business Venturing*, 17, pp. 577–609.

Grant, R. (1996) 'Toward a Knowledge-Based Theory of the Firm', *Strategic Management Journal*, 17, pp. 109–22.

Gulati, R. (1999) 'Network Location and Learning: The Influence of Network Resources and Firm Capabilities on Alliance Formation', *Strategic Management Journal*, 20, pp. 397–420.

Hacklin, F., Lopperi, K., Bergman, J.P. and Marxt, C. (2004) 'Toward an Integrated Knowledge Management Cycle in Cumulative Open Innovation', paper presented at the R&D Management Conference, Sesimbra, Portugal.

Hagedoorn, J. (1995) 'Strategic Technology Partnering During the 1980s: Trends, Networks and Corporate Patterns in Non-Core Technologies', *Research Policy*, 24, pp. 207–31.

Homer, J. and Oliva, R. (2001) 'Maps and Models in System Dynamics: A Response to Coyle', *System Dynamics Review*, 17, pp. 347–55.

Horvath, L. (2001) 'Collaboration: The Key to Value Creation in Supply Chain Management', *Supply Chain Management: An International Journal*, 6, pp. 205–7.

Hult, G. (2004) 'Innovativeness: Its Antecedents and Impact on Business Performance', *Industrial Marketing Management*, 33, pp. 429–38.

Johnsen, T.E. and Ford, I.D. (2000) 'Managing Collaborative Innovation in Complex Networks: Findings from Exploratory Interviews', paper presented at the Sixteenth Annual Industrial Marketing and Purchasing Conference, 7–9 September, Bath.

Kamath, V., Rodrigues, L.L.R. and Desai, P.V. (2009) 'The Effect of a Good HR in Promoting KM & Innovation in a Manufacturing Sector: A System Dynamics Approach', *Proceedings of the 2009 Third UKSim European Symposium on Computer Modeling and Simulation*, pp. 281–6.

Kanter, R.M. (1994) 'Collaborative Advantage: The Art of Alliances', *Harvard Business Review*, 72, pp. 96–108.

Katila, R. and Ahuja, G. (2002) 'Something Old, Something New: A Longitudinal Study of Search Behavior and New Product Introduction', *Academy of Management Journal*, 45, pp. 1183–94.

Kaufman, A., Wood, C. and Theyel, G. (2000) 'Collaboration and Technology Linkages: A Strategic Supplier Typology', *Strategic Management Journal*, 21, pp. 649–63.

King, S.F. and Burgess, T.F. (2006) 'Beyond Critical Success Factors: A Dynamic Model of Enterprise System Innovation', *International Journal of Information Management*, 26, pp. 59–69.

Kogut, B. and Zander, U. (1992) 'Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology', *Organization Science*, 3, pp. 383–97.

Lee, Y.S. (1996) 'Technology Transfer and the Research University: A Search for the Boundaries of University–Industry Collaboration', *Research Policy*, 25, pp. 843–63.

Liu, W.M. and Chen, J.X. (2004) 'A Study on Innovation Network, Complex Technology and Its Policy', *Forum on Science and Technology in China*, 5, pp. 56–9.

McEvily, B. and Marcus, A. (2005) 'Embedded Ties and the Acquisition of Competitive Capabilities', *Strategic Management Journal*, 26, pp. 1033–55.

Miles, R. and Snow, C. (2007) 'Organization Theory and Supply Chain Management: An Evolving Research Perspective', *Journal of Operations Management*, 25, pp. 459–63.

Min, S.H., Roath, A.S., Daugherty, P.J., Genchev, S.E., Chen, H. and Arndt, A.D. (2005) 'Supply Chain Collaboration: What's Happening?', *International Journal of Logistics Management*, 16, pp. 237–56.

Nonaka, I. and Takeuchi, H. (1995) *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*, London: Oxford University Press.

People's Daily (2006) 'Strive to Build an Innovative Country', *People's Daily*, 9 January.

Rycroft, R.W. and Kash, D.E. (2004) 'Self-Organizing Innovation Networks: Implications for Globalization', *Technovation*, 24, pp. 187–97.

Schroeder, R.G., Bates, K.A. and Junttila, M.A. (2002) 'A Resource-Based View of Manufacturing Strategy and the Relationship to Manufacturing Performance', *Strategic Management Journal*, 23, pp. 105–17.

Simatupang, T.M. and Sridharan, R. (2002) 'The Collaborative Supply Chain', *International Journal of Logistics Management*, 13, pp. 15–30.

Simatupang, T.M. and Sridharan, R. (2004) 'A Benchmarking Scheme for Supply Chain Collaboration', *Benchmarking: An International Journal*, 11, pp. 9–30.

Song, M. and di Benedetto, A.C. (2008) 'Supplier's Involvement and Success of Radical New Product Development in New Ventures', *Journal of Operations Management*, 26, pp. 1–22.

Sterman, J.D. (2001) 'System Dynamics Modeling: Tools for Learning in a Complex World', *California Management Review*, 43, pp. 8–25.

Sterman, J. (2002) 'All Models Are Wrong: Reflections on Becoming a Systems Scientist', *System Dynamics Review*, 18, pp. 501–31.

Svensson, G. (2007) 'Aspects of Sustainable Supply Chain Management (SSCM): Conceptual Framework and Empirical Example', *Supply Chain Management: An International Journal*, 12, pp. 262–6.

Takeishi, A. (2002) 'Knowledge Partitioning in the Interfirm Division of Labor: The Case of Automotive Product Development', *Organization Science*, 13, pp. 321–38.

Tang, F.C. and Xi, Y.M. (2006) 'Knowledge Transfer and Dynamics Behavior Pattern of Network Organization', *Systems Engineering: Theory & Practice*, 26, pp. 122–7.

Un, C.A., Cuervo-Cazurra, A. and Asakawa, K. (2010) 'R&D Collaborations and Product Innovation', *Journal of Product Innovation Management*, 27, pp. 673–89.
Uzzi, B. (1997) 'Social Structure and Competition in Interfirm Networks: The Paradox of Embeddedness', *Administrative Science Quarterly*, 42, pp. 35–67.
Vachon, S. and Klassen, R. (2008) 'Environmental Management and Manufacturing Performance: The Role of Collaboration in the Supply Chain', *International Journal of Production Economics*, 111, pp. 299–315.
Van den Bosch, F.A.J., Volberda, H.W. and de Boer, M. (1999) 'Coevolution of Firm Absorptive Capacity and Knowledge Environment: Organizational Forms and Combinative Capabilities', *Organization Science*, 10, pp. 551–68.
van Echtelt, F.E.A., Wynstra, F., van Weele, A.J. and Duysters, G. (2008) 'Managing Supplier Involvement in New Product Development: A Multiple-Case Study', *Journal of Product Innovation Management*, 25, pp. 180–201.
Vennix, J.A.M. and Gubbels, J.W. (1994) 'Knowledge Elicitation in Conceptual Model Building: A Case Study in Modelling a Regional Dutch Health Care System', in J.D.W. Morecroft and J.D. Sterman (eds.), *Modeling for Learning Organizations*, New York: Productivity Press.
Vereecke, A. and Muylle, S. (2006) 'Performance Improvement through Supply Chain Collaboration in Europe', *International Journal of Operations & Production Management*, 26, pp. 1176–98.
Vickery, S.K., Jayaram, J., Droge, C. and Calantone, R. (2003) 'The Effects of an Integrative Supply Chain Strategy on Customer Service and Fnancial Performance: An Analysis of Direct versus Indirect Relationships', *Journal of Operations Management*, 21, pp. 523–39.
Webster, A. (1994) 'University–Corporate Ties and the Construction of Research Agendas', *Sociology*, 28, pp. 123–42.
Wu, D.D., Kefan, X., Hua, L., Shi, Z. and Olson, D.L. (2010) 'Modeling Technological Innovation Risks of an Entrepreneurial Team Using System Dynamics: An Agent-Based Perspective', *Technological Forecasting and Social Change*, 77, pp. 857–69.
Wu, C.R., Zeng, D.M., Chen, Y.W. (2010) 'Modeling and Simulation of High-Tech Enterprises Innovation Networks Using System Dynamics', *Systems Engineering – Theory & Practice*, 30, pp. 587–93.
Zahra, S.A. and George, G. (2002) 'Absorptive Capacity: A Review, Reconceptualization, and Extension', *Academy of Management Review*, 27, pp. 185–203.