International Journal of Technology Management

ISSN online: 1741-5276 - ISSN print: 0267-5730
https://www.inderscience.com/ijtm

How does product innovation affect the performance of university-industry collaboration? A dynamic knowledge transfer perspective

Huiyong Yi, Qian Zhang

DOI: 10.1504/IJTM.2024.10062293

Article History:

Received:	09 June 2022
Last revised:	18 November 2022
Accepted:	16 February 2023
Published online:	01 March 2024

How does product innovation affect the performance of university-industry collaboration? A dynamic knowledge transfer perspective

Huiyong Yi and Qian Zhang*

School of Economics and Management,
Chongqing Jiaotong University,
Chongqing, 400074, China
Email: yihuiyong1977@126.com
Email: 18302863074@163.com
*Corresponding author

Abstract: Product innovation is gradually being noticed in university-industry collaboration (UIC), yet research on its impact on performance is scarce. A dynamic knowledge transfer perspective is presented in our paper, which is an integration of the dynamic nature of knowledge transfer and dynamic strategies, exploring R&D effort strategies in UIC. Further, we apply a Stackelberg differential game to portray the knowledge transfer process and investigate how product innovation affects UIC performance. The results indicate that in the scenario where the leadership positions of the two participants can be interchanged, stronger performance occurs in the case of university leadership. Equilibrium strategies that maximise the revenues always exist no matter who is the game leader, and revenues are U-shaped correlated with product innovativeness. Intriguingly, our research shows that enterprises' revenue-sharing ratios do not always lead to higher profits. Our study provides several insights for both universities and firms.

Keywords: university-industry collaboration; UIC; performance; knowledge transfer; Stackelberg differential game.

Reference to this paper should be made as follows: Yi, H. and Zhang, Q. (2024) 'How does product innovation affect the performance of university-industry collaboration? A dynamic knowledge transfer perspective', *Int. J. Technology Management*, Vol. 95, Nos. 1/2, pp.55–89.

Biographical notes: Huiyong Yi received his PhD in Technology Economy and Management from the Chongqing University, Chongqing, China, in 2008. He has authored over 30 articles and a monograph. These articles and monography were supported by the National Natural Science Foundation of China, one Postdoctoral Foundation, one Ministry of Industry and Information Technology Foundation, and three provincial and ministerial projects as the main research. The resulting projects and topics were highly evaluated. His research interests include green technology innovation, product innovation, and innovation performance. He has long been committed to corporate strategic planning, investment and financing, and marketing research, especially familiar with the manufacturing and financial industry.

Qian Zhang is currently pursuing his Master's degree in the Department of Business Administration at Chongqing Jiaotong University. Her research interests include innovation management, university-industry collaboration, and knowledge transfer.

1 Introduction

In the era of great changes in knowledge and technology, open innovation is the key to enhancing the core competitiveness of enterprises in the longer term (Bagherzadeh et al., 2021; Lyu et al., 2019). As a practical organisation of open innovation (Perkmann and Walsh, 2007), the university-industry (U-I) alliance has heterogeneous resources (Chang, 2017), which the external knowledge provided by universities can technological advancements in companies (Arvanitis et al., 2008). Innovation in modern society is increasingly based on knowledge derived from universities that is available and beneficial to companies (Cassiman et al., 2008; Liefner and Schiller, 2008). Many scholars have emphasised knowledge transfer in U-I due to the need for sustainable innovation (Alexander et al., 2020; Muscio et al., 2012; Weerasinghe and Dedunu, 2021).

A number of prior studies have been devoted to finding the relationship between university-industry collaboration (UIC) and innovation performance, and several scholars (Bstieler et al., 2015; Cassiman and Veugelers, 2006; Wirsich et al., 2016) believed that UIC would enhance innovation performance and shorten the time to commercialisation. Conversely, other scholars have shown that innovation does not affect economic performance, but they claim it is only a matter of time (Robin and Schubert, 2013). Therefore, there is a controversy about whether UIC promotes firms' innovation performance.

Generally, UIC performance is measured in terms of academic, educational, and commercial outputs. Meanwhile, Kobarg et al. (2018) believed that the innovative performance of UIC is best demonstrated by the degree to which it achieved commercial success through developing and selling novel products. R&D product is a significant form of achieving collaborative innovation between businesses and academics. Examples of U-I co-production are especially demonstrated in the high-tech industry and are widely accessible to us (Petruzzelli and Murgia, 2020; Robertson et al., 2019), such as medical and biotechnology (e.g., Abbott Lab's COVID-19 test, Boyer-Cohen 'gene-splicing' rDNA technique). Increasingly, product innovation in UIC breaks through internal capabilities and resources, sustaining companies' survival and competitive advantage (Zhang et al., 2022). Regarding the relationship between product innovation and UIC performance, thus far, several scholars have found that radical innovation contributes more effectively than incremental innovation in improving the innovation performance of UIC (Tang et al., 2020).

Whereas extant studies on UIC and research on product innovation have chiefly focused on the investigation of case studies (Jussila et al., 2020; Kunttu and Neuvo, 2020; Kuys et al., 2021; Paay et al., 2021), factors influencing innovation performance (Kobarg et al., 2018; Melnychuk et al., 2021), public policies (Song et al., 2022), and product innovation processes (Prabhu, 1999). However, there has been little exploitation of the relationship between the degree of product innovation and the performance of UIC and the use of underlying mechanisms at a deeper level to improve UIC, even though this is advantageous for economic performance (Robin and Schubert, 2013).

Van Wijk et al. (2008) define the concept of knowledge transfer as a process in which organisations communicate, accept, and be influenced by the experience and knowledge of others. Knowledge transfer is strongly connected with technology development, strengthening the innovation performance in U-I (Hobbs et al., 2017). Knowledge is the link between business and university collaboration (Ahrweiler et al., 2011; Hermans and Castiaux, 2017), and U-I partnerships emphasise the process of transforming knowledge transferred by universities into commercially exploitable products through the efforts of firms (Robertson et al., 2019). Meanwhile, the empirical literature on knowledge management revealed that knowledge transfer enhances the knowledge level of products in a dynamic interactive process; demonstrating knowledge transfer is a dynamic process with high risks, which aggravates the research difficulty (Ozkan-Seely et al., 2015). Product innovation achieved through U-I knowledge transfer plays a critical role in its performance, and thus successful knowledge transfer strategies can be conducive to enhancing UIC performance. Equilibrium can be achieved by continuously adjusting subjects' effort strategies in dynamic game theory (Ma et al., 2020); yet such dynamic knowledge transfer strategies in UIC have rarely been discussed.

The purpose of our paper is to demonstrate how product innovation affects U-I economic performance by exploring the following problems:

1 How does product innovation affect the economic performance of UIC?

2 Which structure is more effective in improving the performance of UIC in product innovation, enterprise leaders or university leaders?

3 How should we control the micro variables in the product innovation process to maximise the benefits for both an enterprise and a university?

Therefore, given the above questions, we add to the dynamic knowledge transfer perspective by portraying the time-varying process of knowledge transfer to enterprises resulting in product innovation and then investigate the impact of the rights and autonomy of UIC on economic performance. Our paper establishes a Stackelberg differential game wherein the leadership positions of the two participants can be interchanged. It is essential to understand that innovation is a dynamic process (Dosi, 1988) in which the knowledge movement process is also complex and uncertain (Gao and Sun, 2020). Nevertheless, differential game theory can better simulate the dynamic time-varying process and has been applied in the field of knowledge management by Ma et al. (2020) and Lin and Wang (2019). Besides, the Stackelberg game model is often used to explore game problems under different decision orders (He et al., 2020; Mukherjee and Carvalho, 2021) means that leadership positions are exchangeable. Consequently, this study considers two scenarios: the enterprise Stackelberg (ES) game, which implies that the enterprise is the game leader in UIC, and the university Stackelberg (US) game, which means that the university leads innovation.

Some intriguing findings were obtained by our analysis in combination with the problems posed above. First, our findings explain why some scholars (Robin and Schubert, 2013) have done experiments to prove that product innovation does not affect economic performance. In contrast, we found a U-shaped relationship between product innovativeness and the benefits of enterprises and universities. Furthermore, we find that the revenue of firms and universities will always increase with product innovativeness as long as the marginal contribution of product innovation is higher. Second, when the university is the game leader, this means that the university has more power and autonomy, and product innovativeness will increase dramatically, leading to a remarkable enhancement in economic performance in U-I. Contrary to the consensus, a higher distribution rate of the enterprise does not always lead to more substantial earnings. Besides, we found that low price sensitivity and high marginal contribution of innovative products can greatly promote consumer demand, resulting in increased revenue for enterprises and universities. Therefore, the top priority for enhancing economic performance lies in improving the consumer perception of innovative products.

This paper includes seven sections. Section 2 presents the literature review. Section 3 proposes the Stackelberg differential model and makes some basic assumptions. The model analysis is demonstrated in Section 4. Numerical analysis is performed in Section 5. Discussions and conclusions are provided in Section 6.

2 Literature review

This paper uses game theory to depict the time-varying process of knowledge transfer of universities to firms to form innovative products and then investigates the impact of product innovation on UIC performance. Consequently, we assembled three key themes in this article: product innovation in UIC, the impact of product innovation on UIC performance, and a dynamic knowledge transfer perspective.

2.1 Product innovation in UIC

Product innovation is crucial to gaining a competitive advantage and achieving standing business success (Paay et al., 2021). Since seminal work such as Prabhu (1999) revealed the comprehensive progress of product innovation projects, special attention has been given to product innovation. Industrial innovation depends heavily on the knowledge interaction of companies and universities, whereas few studies have focused on the whole process of UIC product innovation (Maietta, 2015). Two mainstream approaches are used to explore product innovation in UIC: one is the case study, and the other is the empirical experiment.

Case studies are usually employed to demonstrate the importance of UIC for product innovation (Jussila et al., 2020; Kunttu and Neuvo, 2020). According to the study of Kuys et al. (2021), wherein a joint product innovation project between the Malaysian government and a University in Mexico provides advice on the sustainable development of such products. Further, Paay et al. (2021) demonstrate the value of collaborative output for increasing university knowledge and company outputs through a case study of innovative design skylights.

In essence, case studies describe a systematic process of product innovation in UIC, but this approach cannot be generalised, nor do they provide comprehensive guidance on UIC. Thus, empirical experiments gradually appear in the research literature, usually employed to investigate the factors influencing product innovation in UIC. A panel data of 56 global pharmaceutical firms were measured by Melnychuk et al. (2021) to testify that the stronger R&D intensity and the greater R&D performance. Using moderated multiple regressions based on a sample of 2061 German firms; Kobarg et al. (2018) considered the effects of two moderating variables, absorptive capacity and innovation capacity, on product innovation in UIC. Their results show that absorptive and innovation capacity impact innovation performance but are not the only effects.

Although case studies and empirical studies have yielded some contributions on the importance of UIC and the influencing factors of product innovation, the establishment of a theoretical framework to encompass both the product innovation process and the influencing factors are lacking. Only this area has been focused on by Song et al. (2022), who applied a three-stage game to investigate how government subsidies affect the sustainability of product innovation in UIC. The conclusion indicates that government subsidies to firms and universities can generate greater benefits and social welfare. Hence, the above discussion demonstrates that in the case of outlining the product innovation process and influencing factors, the impact of product innovation on economic performance has not yet been attended.

2.2 The impact of product innovation on UIC performance

As the debate over the determinants of innovation has unfolded, UIC has played a critical role in shaping universities' and firms' innovative performances (Barbolla and Corredera, 2009). A large majority of scholars have extensively focused on the link between UIC and businesses' innovative performance (Kobarg et al., 2018). Yet, insufficient attention has been paid to innovation performance at the level of the overall framework of U-I alliances. Regarding the measurement of UIC performance, Huang et al. (2019) believed that it could be considered in terms of the number of publications, the number of patents, the number of commercial collaborations, and commercial products. A large part of UIC consists of cooperative R&D products, which are considered to be the best indicators of performance (Kobarg et al., 2018). In addition, compared with non-product-development firms, Kodama (2008) found that product-development companies benefit more from partnering with universities. We thus focus on measuring product innovation performance in UIC.

Since collaborations between businesses and academics enable them to maintain stronger performance, several scholars have endeavoured to find those factors that enhance the innovative performance of UIC (Lee and Huang, 2012). There is considerable divergence in the extant literature on whether the degree of innovation affects the economic performance of UIC. Tang et al. (2020) believed that innovation improves the performance of U-I partnerships, where radical innovation is more effective than incremental innovation. Conversely, Robin and Schubert (2013) have experimentally demonstrated that innovation does not affect the economic performance of the U-I.

As a result of this divergence mentioned above, it is imperative to establish a systematic research framework to examine the impact of product innovation on UIC economic performance and identify additional influencing factors so that some measures can be proposed in order to enhance UIC economic performance.

2.3 A dynamic knowledge transfer perspective

Knowledge can be shared anywhere and anytime thanks to a variety of communication media, proving knowledge transfer is a dynamic process. Thus, a number of scholars believe that a dynamic framework is required to examine knowledge transfer (Lawson and Potter, 2012). Studying knowledge transfer in a dynamic framework can better capture the dynamic interplay between firms and universities over time (Ozkan-Seely et al., 2015). This framework responds to the characteristic of phased product innovation development, creating an opportunity for cooperative R&D products embedded in the constantly changing market demands (Dangelico et al., 2017).

Lately, universities have gradually enhanced their efforts to transfer knowledge to firms, for example, by signing business contracts or setting up research platforms, given that these firms have a strong need for industrial innovation and improvement of their competitiveness (Wang et al., 2021). Although appropriate knowledge transfer strategies can help them develop professional knowledge and achieve technological advantages in UIC, they seem to be neglected.

Previous literature has used game theory to explore knowledge transfer strategies, which are essential to knowledge management. Employing Bayesian games, Koessler (2004) first considers the problem of direct, public, and strategic knowledge sharing. To find the collaborative strategies between organisations, Samaddar and Kadiyala (2006) established a Stackelberg game to explore the cooperative conditions in two situations where organisations only spend current efforts and spend related prior efforts. The exploration of such strategies is a gradual process. Dynamic strategies can be further discovered along with the shift from static to dynamic games.

As the research pointed out by Lin and Wang (2019) has found, a dynamic game model framework can incentive knowledge-sharing behaviours in construction project teams, which is the first time to establish a dynamic game model to explore knowledge management strategies. Based on this article, Ma et al. (2020) designed a dynamic incentive model added venture to explore the knowledge-sharing behaviour under three scenarios: no cost-sharing, cost-sharing, and centralised decision-making. Additionally, since firms and universities have different interests, dynamic knowledge management strategies should also be considered in their cooperation. In this regard, considering the funding needs in UIC, Yi and Zhang (2022) employed a dynamic game model to investigate knowledge-sharing strategies.

Dynamic game theory has proven effective for interacting with game subjects in complex and constantly changing environments (Srinivasan et al., 2017). In this work, we expect to gain a new interpretation of how product innovation affects UIC performance by adopting a dynamic knowledge transfer perspective, which combines the dynamic characteristics of knowledge sharing with the dynamic strategic needs of knowledge management.

3 Model

One of the essential forms of UIC is corporates develop the knowledge transferred from universities into commercial products, which is the product innovation process (Bramwell and Wolfe, 2008; D'Este and Patel, 2007; Robertson et al., 2019). In the product innovation process through UIC, universities contribute knowledge, and enterprises transform knowledge into products. Therefore, enterprises bear the production cost, while universities bear the knowledge transfer cost. In fact, both the company and the university jointly determine the price of the innovative product for two reasons. One is that both parties are involved in the process of UIC, and the other is that the cost of the product consists of two parts. Technology dynamics and market dynamics are two crucial environmental dimensions of high-technology industries (Yang et al., 2022). Firms are market inductors (Xiao et al., 2011), while universities transfer knowledge that evolves into technology (Wang and Lu, 2021). Consequently, the price of innovative products in this paper is dichotomised into those market-driven and technology-driven. This article proposed a new decision-making model to discuss the impact of product innovation on collaborative performance when universities and enterprises jointly determine the prices of innovative products.

The Stackelberg game is a dynamic information game with strict time order. One side of the game decides its optimal strategies based on the other side's possible strategies for achieving Nash equilibrium. Usually, there is a leader and a follower in the Stackelberg game, and they have the decision order (Liu et al., 2012). This article studies the effect of rights and autonomy on UIC in product innovation. We thus discuss the order of precedence of the game. Innovation is a process of randomness and uncertainty accompanied by high risk (Boudreau et al., 2011), in which transforming knowledge into products is chronical and arduous with high contribution (Robertson et al., 2019). This is an essential reason we need to explore the knowledge transfer and innovation process over a long period. However, differential games build a continuous-time model that takes into account changes in time (Ma et al., 2020). Therefore, in conjunction with the research objectives of this paper, we attempt to develop the Stackelberg differential game model in UIC. Two rational players try their best to maximise revenues, consisting of one enterprise and one university. Both subjects are risk-neutral and morally neutral. For convenience, Table 1 shows the main parameters we set in the model.

Table 1 Notations of main parameters

Notation	*Description*
k	The knowledge transfer cost coefficient of the university
λ	The ability of product innovation of the U-I
c	The coefficient of production cost of the enterprise
a	The potential demand market
b	The coefficient of price effect on the innovative product demand
δ	The decay rate of product innovation
φ	The marginal contribution of innovation
θ	The revenue-sharing ratio of the enterprise
$P'(t)$	The price of innovative products
$p(t)$	The market-driven price of products
$m(t)$	The technology-driven price of products
$q(t)$	The amount of knowledge transferred by the university
$I(t)$	The product innovativeness
$D(t)$	The demand for innovative products

Most scholars (D'Este and Patel, 2007; Robertson et al., 2019; Ryan et al., 2018) believe that firms and universities collaborate to achieve innovation by transferring knowledge or technology from universities to firms, which can be used by firms to create innovative products. Previous literature has attempted to employ game theory to incorporate knowledge development process control into management activities. Regarding the process of knowledge transfer, Terwiesch and Loch (1999) have shown that it is a function of the transfer amount and time. Therefore, an effective way to represent such a process is to include the knowledge development process as a state variable contributing to knowledge transfer, knowledge absorption, and knowledge transformation. For example, Lin and Wang (2019) and Ma et al. (2020) portrayed this process of knowledge interaction as a state variable using dynamic game theory.

We regard knowledge development as a product innovation process, consistent with Ozkan-Seely et al. (2015). To capture how knowledge transfer affects the level of product innovation over time, we use the Nerlove and Arrow (1962) equation to incorporate the product innovation caused by the university's knowledge transfer. The degree of product innovation is closely related to the ability of the company to absorb and transform knowledge, which is often expressed by the parameter of innovation efficiency. This parameter is used by Lu et al. (2019). Additionally, the constant change in demand leads to a replacement process of innovation (Haefner et al., 2021), so the level of product innovation will have a natural decay process. Based on the above discussion, supposing that $I(t)$ denotes the degree of product innovation of the U-I, (i.e., product innovativeness) and is determined by the amount of knowledge transfer of the university. We can obtain the following differential equation:

$$\begin{cases} \dot{I}(t) = \lambda q(t) - \delta I(t) \\ I(0) = I_0 \geq 0 \end{cases} \tag{1}$$

where $\lambda > 0$ represents the innovative effectiveness of the U-I (i.e., the ability of product innovation of the U-I). δ is the ratio referring to depreciation in the progress of product innovation with $\delta > 0$. $I(0) = I_0$ denotes the initial level of product innovation of the U-I. Due to the background, reputation, and experience of firms and universities, the initial level of product innovation of the U-I is known (Carrillo and Gaimon, 2004; Epple et al., 1996).

There are two types of costs associated with achieving collaborative innovation between the enterprise and the university: knowledge transfer investment and the increasing unit production cost regarding the degree of knowledge innovation. First, the amount of knowledge transferred by the university, (i.e., the willingness of the university to transfer knowledge) is $q(t)$ with $q(t) \geq 0$. Conveniently, the amount of knowledge transfer is measurable, and unit knowledge is deemed the unit measurement. Ozkan-Seely et al. (2015) pointed out that the cost increases with the amount of knowledge pursued. In this work, we suppose that the relation between the knowledge transfer cost and the amount of knowledge transfer is simply inverse linear. Consistent with Lin and Wang (2019) and Ma et al. (2020), the cost is supposed as a quadratic cost function $C(q(t), t) = kq^2(t)/2$, where $k > 0$ denotes the knowledge transfer cost coefficient of the university. Second, co-production with high innovativeness may require high-quality talents, high-tech equipment, and advanced technology, proving that innovation input is highly correlated with product innovativeness (Bzhalava and Cantner, 2018). For simplicity, it is assumed that production cost has a simple linear correlation with product innovation level. Therefore, we suppose the production costs of the enterprise are as follows:

$$C = cI(t) \tag{2}$$

where c denotes the coefficient of production cost of the enterprise. The idea of equation (2) is drawn from Ozkan-Seely et al. (2015), who presented that the production cost of firms' increases with the level of knowledge innovation.

Based on the driving factors of product price determination and the key factors influencing consumers, we extended the demand function of He et al. (2020), Zhang et al. (2016), and Song et al. (2022). First, for driving factors of product price determination, the price of products is affected by different dynamic factors when the U-I decides to co-production. According to Yang et al. (2022), this paper assumes that the price of innovative products produced by U-I is determined by technology and market dynamics. Thus the price $P'(t)$ of the innovative product is composed of two parts, the price $P'(t)$ driven by market dynamic is determined by the enterprise, and the price $(m(t))$ driven by technology dynamic is determined by the university, so $P'(t) = p(t) + m(t)$. Second, empirical studies have shown that the degree of product innovation is a crucial factor influencing consumer purchases (Kshetri, 2017). The demand for innovative products by the price as well as product innovativeness, and we thus assume the demand function $D(t)$ as follows:

$$D(t) = a - b(p + m) + \varphi I(t) \tag{3}$$

where a represents the potential market demand for innovative products. The parameter b denotes the coefficient of price effect on the innovative product demand. $\varphi > 0$ is the marginal contribution of innovation to product demand.

This article designs a revenue-sharing contract in which the revenue-sharing ratio of the enterprise is θ and the revenue-sharing ratio of the university is $1 - \theta$ with $\theta \in (0, 1)$. In the infinite period, the same discount ratio ρ is owned by two players, and $\rho > 0$. Both players try to achieve their maximum benefits during the unlimited period. On account of these assumptions, the revenues of product innovation between the enterprise and the university are represented in the objective functions in the period's time as follows:

$$J_e = \int_0^\infty e^{-\rho t} \left\{[p + \theta m - cI(t)][a - b(p + m) + \varphi I(t)]\right\} dt \tag{4}$$

$$J_u = \int_0^\infty e^{-\rho t} \left\{[(1-\theta)m][a - b(p + m) + \varphi I(t)] - \frac{k}{2} q^2(t)\right\} dt \tag{5}$$

It is well known that the differential game model established in this paper has three control variables $p(t)$, $m(t)$, $q(t)$ and one state variable $I(t)$.

4 Model analysis

In this section, our assumptions include the ES game, (i.e., the enterprise is the game leader) and the US game (i.e., the university is the game leader). This paper analyses the equilibrium strategies the enterprise and the university made in collaborative innovation under two different decision sequences: who has more rights and autonomy? From the perspective of maximising benefits, the U-I alliance hopes to increase product innovation through cooperation and maximise the innovation benefits for both parties.

4.1 The ES game

In this scenario, we consider a two-stage model in which the firm first determines the market-driven price of products $p(t)$, which is the basis for the next stage. Following that, the university submits to determine the technology-driven price of products $m(t)$ and the amount of knowledge transfer of the university $q(t)$. This paper focuses on deriving the optimal amount of knowledge transferred and the product price to maximise the economic performance of the two players. The objective equations of the enterprise and the university are respectively represented as (denoted by superscript ES):

$$\max_{p(\cdot)} J_e^{ES} = \int_0^{\infty} e^{-\rho t} \{[p+\theta m - cI][a - b(p+m) + \varphi I]\} dt \tag{6}$$

$$\max_{m(\cdot),q(\cdot)} J_u^{ES} = \int_0^{\infty} e^{-\rho t} \left\{[(1-\theta)m][a - b(p+m) + \varphi I] - \frac{k}{2} q^2\right\} dt \tag{7}$$

Proposition 1. In the ES game, the optimal equilibrium strategies for the product price, the amount of knowledge transfer, and product innovativeness are:

$$q^{ES}(t) = \frac{kb(\rho+2\delta)(2-\theta) - \Delta_1}{2\lambda kb(2-\theta)} I + \frac{\lambda a(1-\theta)(\varphi - bc)}{(2-\theta)\Delta_2} \tag{8}$$

$$P'^{ES}(t) = \frac{a(3-2\theta) + [\varphi(3-2\theta) + bc]I}{2b(2-\theta)} \tag{9}$$

$$I^{ES} = I_\infty^{ES} + \left(I_0 - I_\infty^{ES}\right) e^{-\tau_1 t} \tag{10}$$

where $I_\infty^{ES} = \frac{\lambda^2 a(1-\theta)(\varphi - bc)}{2kb\delta(\rho+\delta)(2-\theta)^2 - \lambda^2(1-\theta)(\varphi - bc)^2}$, $\tau_1 = \frac{\Delta_1 - \rho kb(2-\theta)}{2kb(2-\theta)}$. I_∞^{ES} represents the steady-state product innovativeness when $t \to +\infty$ in ES.

The equilibrium price, knowledge transfer strategies, and profit functions are shown in Table 2. The proofs of these strategies, profit functions, and expressions of Δ_1, Δ_2, and are Δ_3 presented in Appendix.

Corollary 1. In the ES game.

a $\partial q^{ES}/\partial I > 0$; $\partial P'^{ES}/\partial I > 0$.

b $\partial^2(V_e^{ES})/\partial I^2 > 0$; $\partial^2(V_u^{ES})/\partial I^2 > 0$. When $\varphi > bc$, $\partial V_e^{ES}/\partial I > 0$ and $\partial V_u^{ES}/\partial I > 0$.

c When $\rho + \delta > 2(1-\theta)/(2-\theta)$, $\partial I_\infty^{ES}/\partial(1-\theta) > 0$, otherwise, $\partial I_\infty^{ES}/\partial(1-\theta) < 0$.

The first part of Corollary 1 indicates that the amount of knowledge transfer q^{ES} and the prices of innovative products P'^{ES} increase in product innovativeness I. The reason is straightforward with more knowledge contributed, the higher product innovation, and the innovative product can attract more customers, eventually leading to more expensive products. As per Corollary 1(b), it is easy to verify that the benefits of the enterprise V_e^{ES} and the university V_u^{ES} are U-shaped functions of product innovativeness I. Contrary to the consensus, revenues do not always grow with product innovation. This is why innovation is a long-term and complex process requiring continuous efforts from enterprises and universities. Furthermore, V_e^{ES} and V_u^{ES} are monotonic increasing in I when $\varphi > bc$, contrarily, it is decreasing in I once $\varphi > bc$. This means that we need to increase the marginal contribution of innovation while controlling consumers' price sensitivity and firms' production costs. The last part of Corollary 1 implies that firms must allocate sufficient profits to universities if they want to maintain a high degree of product innovation when the depreciation rate of the product is large enough ($\rho + \delta > 2$

(1 – θ)/ (2 – θ)), which means that the rapid replacement of the product will lead to less profit for companies.

Table 2 Equilibrium results

	ES	*US*
	Feedback equilibria	
$q(I)$	$\frac{kb(\rho+2\delta)(2-\theta)-\Delta_1}{2\lambda kb(2-\theta)}I+\frac{\lambda a(1-\theta)(\varphi-bc)}{(2-\theta)-\Delta_2}$	$\frac{kb(\rho+2\delta)-\Delta_4}{2\lambda kb}I+\frac{\lambda a(\varphi-bc)}{2(\rho kb+\Delta_4)}$
$p(I)$	$\frac{a(1-\theta)+[\varphi(1-\theta)+bc]I}{b(2-\theta)}$	$\frac{a(1-3\theta)+[(1-3\theta)\varphi(3-\theta)+bc]I}{4b(1-\theta)}$
$m(I)$	$\frac{a+(\varphi-bc)I}{2b(2-\theta)}$	$\frac{a+(\varphi-bc)I}{2b(1-\theta)}$
$P'(I)$	$\frac{a(3-2\theta)+[\varphi(3-2\theta)]+bc]I}{2b(2-\theta)}$	$\frac{3a+(3\varphi+bc)I}{4b}$
	Time path	
$I(t)$	$I_\infty^{ES}+(I_0-I_\infty^{ES})e^{-\tau_1 t}$	$I_\infty^{US}+(I_0-I_\infty^{US})e^{-\tau_2 t}$
	Steady states	
I_∞	$\frac{\lambda^2 a(1-\theta)(\varphi-bc)}{2kb\delta(\rho+\delta)(2-\theta)^2-\lambda^2(1-\theta)(\varphi-bc)^2}$	$\frac{\lambda^2 a(\varphi-bc)}{4(\rho+\delta)-\lambda^2(\varphi-bc)^2}$
	Value functions	
V_e	$v_1I^2+v_2I+v_3$	$v_4I^2+v_5I+v_6$
V_u	$n_1I^2+n_2I+n_3$	$n_4I^2+n_5I+n_6$

4.2 The US game

In this case, we study a two-stage game where the university is the leader while the enterprise is the follower. To maintain the vitality of innovation, the university first sets the technology-driven price of products $m(t)$ and the amount of knowledge transferred by the university $q(t)$. After that, the enterprise determines the market-driven price of products $p(t)$. Our main objective is to derive the optimal amount of knowledge transfer and product price, maximising the benefits for both parties. For ease of description, this paper indexes this scenario by superscription US. The corresponding objective equations for the enterprise and the university are given by:

$$\max_{p(\cdot)} J_e^{US}=\int_0^\infty e^{-\rho t}\{[p+\theta m-cI][a-b(p+m)+\varphi I]\}dt \tag{11}$$

$$\max_{m(\cdot),q(\cdot)} J_u^{US}=\int_0^\infty e^{-\rho t}\left\{[(1-\theta)m][a-b(p+m)+\varphi I]-\frac{k}{2}q^2\right\}dt \tag{12}$$

Proposition 2. In the US game, the optimal equilibrium strategies for the product price, the amount of knowledge transfer, and product innovativeness are

$$q^{US}(t)=\frac{kb(\rho+2\delta)-\Delta_4}{2\lambda kb}I+\frac{\lambda a(\varphi-bc)}{2\left(\rho kb+\Delta_4\right)} \tag{13}$$

$$P'^{US}(t)=\frac{3a+(3\varphi+bc]I}{4b} \tag{14}$$

$$I^{US}=I_\infty^{US}+\left(I_0-I_\infty^{US}\right)e^{-\tau_2 t} \tag{15}$$

where $I_\infty^{US}=\dfrac{\lambda^2 a(\varphi-bc)}{4\delta(\rho+\delta)-\lambda^2(\varphi-bc)^2}$, $\tau_2=\dfrac{\Delta_4-\rho kb}{2kb}$. I_∞^{US} represents the steady-state product innovativeness when $t\to+\infty$ in the US.

The equilibrium price, knowledge transfer strategies, and profit functions are shown in Table 2. The proofs of these strategies and profit functions and expression of Δ_4 are presented in Appendix.

Corollary 2. In the US game

a $\partial q^{US}/\partial I>0$; $\partial P'^{US}/\partial I>0$.

b $\partial^2(V_e^{US})/\partial I^2>0$; $\partial^2(V_u^{US})/\partial I^2>0$. When $\varphi>bc$, $\partial V_e^{US}/\partial I>0$ and $\partial V_u^{US}/\partial I>0$.

c $\partial(q^{US})/\partial\theta=0$, $\partial(P'^{US})/\partial\theta=0$.

d $\partial(I_\infty^{US})/\partial\theta=0$.

Corollary 2 indicates that in the US game, the amount of knowledge transfer q^{US} and the products price P'^{US} increase in product innovativeness I, which means that regardless of the game case, the amount of knowledge transferred by universities increases, the degree of product innovation increases, and thus the products price will increase. From Corollary 2(b), the benefits of the enterprise V_e^{ES} and the university V_u^{ES} are U-shaped functions of product innovativeness I. This finding indicates that the profits of the enterprise and the university will first decrease and then increase with product innovativeness. Furthermore, V_e^{ES} and V_u^{ES} increase in I when φ is sufficiently big ($\varphi>bc$), but they decrease in I once $\varphi>bc$. In general, these findings give us practical enlightenment that the marginal contribution of innovation is the critical variable affecting the increase or decrease of revenues. Accordingly, it is significant to guide consumers to accept innovative products. Inconsistent with the ES, it is clear find that under the US, the amount of knowledge transfer q^{US}, the product price P'^{US}, and the steady-state product innovativeness I_∞^{US} are both independent of the revenue-sharing ratio θ. As the game leader, this is why the university can provide participants with more innovative vitality and motivation. When the university is the leader in collaborative innovation activities, the willingness to contribute knowledge is not influenced by the benefits distributed by firms. Meanwhile, it will actively participate in innovation activities, significantly increasing product innovativeness and benefits.

5 Numerical analysis

Although the expressions of the amount of knowledge transfer and the profits functions of the two players are definite, they are so complex that it is impossible to clearly see the relationship between the parameters. Therefore, in this section, we will use numerical simulations to analyse the effects of parameters on the amount of knowledge transfer of the university, the product price, the degree of product innovation, and the profits of the two players. Changing the parameter values allows for simulating different contract mechanisms and finding effective incentives so that we can draw illuminating conclusions from these comparative analyses.

5.1 Case study

In this section, we choose a case that fits the research situation of this paper, which serves the specific parameter settings. Case studies are often used in theoretical studies to explain the current situation better and then simulate numerical experiments (Yang et al., 2019, 2021). From what we know, case studies should only be selected based on their research requirements. Since our paper examines the collaborative form of the U-I for joint R&D products, the case studies chosen should be in accord with this scenario, which includes firms and universities. In summary, the selected case comes from a collaborative project between industry, academia, and research in Chongqing, China.

Focusing on a UIC case between Nanjing Yunhai Special Metals Co., Ltd. and Chongqing University to develop high-performance magnesium alloy materials for die-casting of body-integrated structural parts, using body-integrated structural parts to achieve batch production. Due to the significant cost reduction advantage of integrated casting, new power and traditional car manufacturers are utilising integrated die-casting processes. Developing materials for integrated structural parts die-casting has become an essential prerequisite with the accelerated penetration of integrated die-casting technology. One of the new materials suitable for die-casting integrated structural components is magnesium alloy, which has good die-casting performance. Both parties combine their advantages to develop high-performance magnesium alloy materials for die-casting of integrated body structure parts. The company is the leading manufacturer of magnesium alloy, while Chongqing University has been researching magnesium alloy materials for many years. The collaboration between the two parties aligns with the long-term strategic development plan of the company, which is conducive to enhancing the company's sustainable development capabilities.

Parameters can be set based on this UIC. First, since this company and university have already established a sufficient basis for cooperation, the initial number of knowledge transfers is not zero. Second, Chongqing University has a strong R&D base for such products, making it highly efficient for knowledge transfer. As a result of their efforts, the knowledge transfer efficiency, (i.e., the innovative efficiency) can be improved and enhanced, which indicates that it can be a change parameter. Third, the contractual agreement to determine the distribution plan based on mutual agreement indicates uncertainty regarding the distribution coefficient of product profits. Further, other parameter values are set with reference to expert opinion and previous literature (Lin and Wang, 2019; Ma et al., 2020). Thus, the values of the parameters we set are shown as follows.

- Fixed parameters

  $k = 1, c = 0.1, a = 1, \rho = 0.8, I_0 = 5.$

- Varying parameters

  $\theta \in \{0.2, 0.4, 0.6, 0.8\}, b \in \{0.4, 0.5, 0.6, 0.7\}, \varphi \in \{0.2, 0.25, 0.3, 0.35\},$
  $\lambda \in \{2, 2.2, 2.4, 2.6\}, \delta \in \{0.15, 0.2, 0.25, 0.3\}$

5.2 Comparison of equilibrium results

Analysis based on the values of the parameters we set above, the variation trend of the degree of product innovation, (i.e., product innovativeness), the amount of knowledge transfer, the products price in ES, the products price in the US, and the revenues of two players are shown as follows.

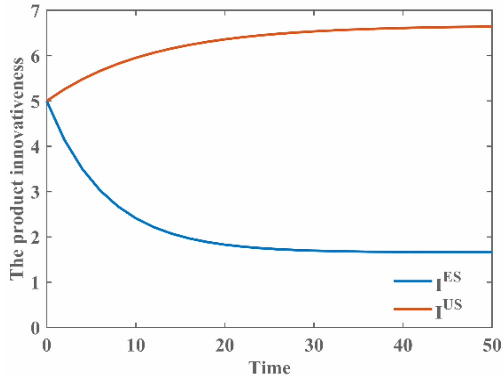
From Figure 1(a), we notice that product innovativeness first decreases and then stabilises when the enterprise is the game leader, yet it increases and then stabilises along with the time when the university is the game leader. What's more, product innovativeness in the US is much greater than in the ES. The above phenomenon shows that the innovation activities in UIC led by the university will significantly increase product innovativeness.

The amount of knowledge transfer in ES firstly decreases and finally stabilises while it increases and then stabilises when the university is the game leader. In addition, the amount of knowledge transfer in the US is higher. All of the above information is displayed in Figure 1(b). This indicates that the university will be more active in contributing knowledge to promote collaborative innovation in the US. When the efficiency of knowledge absorption and knowledge transfer is not considered, product innovativeness naturally improves as long as the amount of knowledge transfer increases. This also explains the phenomenon in Figure 1(a).

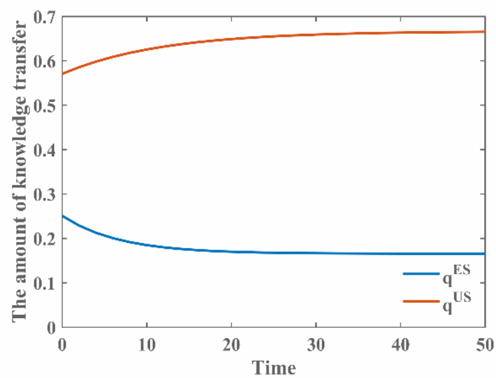
Combining Figures 1(c) and 1(d) demonstrate that in the ES, the product price is driven more by market dynamics. In contrast, in the US, technological advancements drive product prices more than market advancements. The product price in the US is higher than in the ES because of product innovativeness. When the enterprise leads the game, the product is less innovative as well as the price of the product is low. Thus, the price is a weapon for innovative products to reduce competition. When the university leads the game, product innovativeness and price are also higher. Therefore, enterprises and universities should try to change consumers' consumption concepts to make them accept new things.

Figure 1(e) shows how the revenues of two players in the ES both first decrease and then stabilise. Moreover, the enterprise revenues are higher than the university revenues. While the revenues of the two players in the US both increase and stabilise finally, the university revenues are higher than the enterprise revenues. In addition, within a reasonable range, the revenues of the enterprise and the university in the US are always higher than their revenues in the ES.

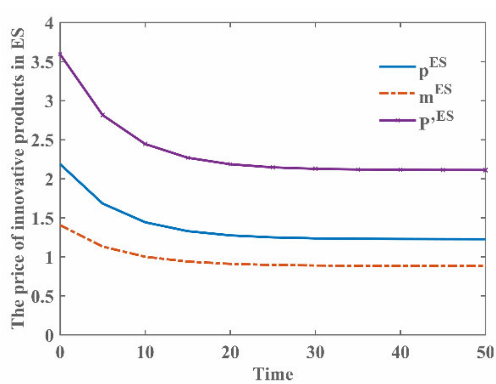
Figure 1 Equilibrium results, (a) the product innovativeness, (b) the amount of knowledge transfer, (c) the product price in ES, (d) the product in US, (e) the revenues of two layers (see online version for colours)



(a)

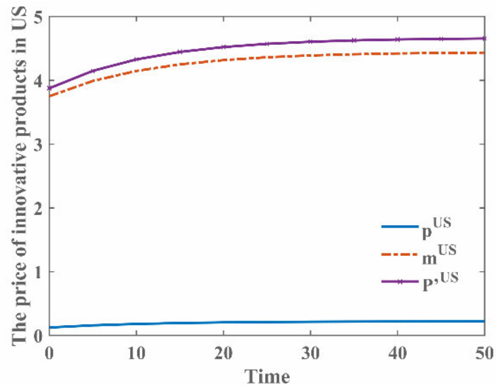


(b)

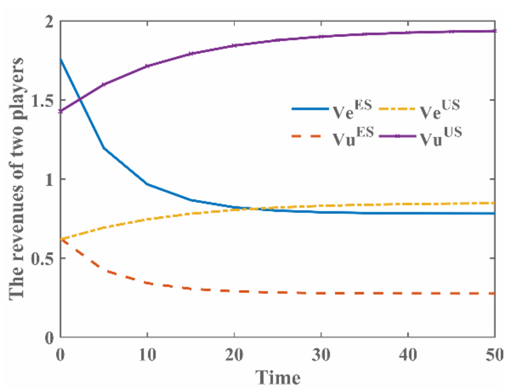


(c)

Figure 1 Equilibrium results, (a) the product innovativeness, (b) the amount of knowledge transfer, (c) the product price in ES, (d) the product in US, (e) the revenues of two layers (continued) (see online version for colours)



(d)



(e)

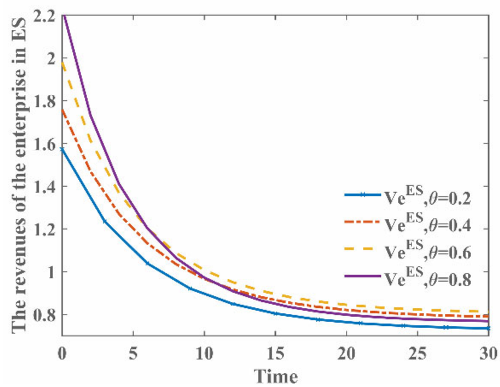
5.3 *Revenues analysis*

Due to the complexity of the parameters in the revenues, the effect of these parameters on the revenues cannot be seen directly. Therefore, we will explore the time course in which the revenues of both parties are affected by the following three aspects: revenue-sharing, consumer demands for products, and product innovativeness.

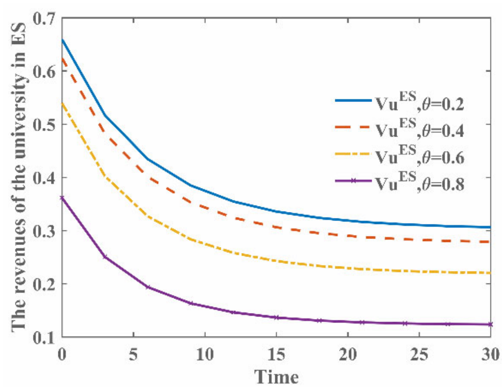
5.3.1 *Impact of the revenue-sharing ratio*

Both companies and universities are interested individuals who try to maximise their profits. Discussing the revenue-sharing ratio in the context of cooperative R&D products in the U-I is essential since both sides generate income from the product profits. Holding other parameter values constant, we set $\theta = 0.2, 0.4, 0.6, 0.8$ to investigate the effect of θ on the revenues of two players.

Figure 2 Revenues sensitivity to θ, (a) the enterprise revenues in ES, (b) the university revenues in ES (see online version for colours)



(a)



(b)

Observation 1. The impact of the revenue-sharing ratio on the revenues of the enterprise and the university is as follows:

a $V_e^{ES}(\theta = 0.6) > V_e^{ES}(\theta = 0.4) > V_e^{ES}(\theta = 0.8) > V_e^{ES}(\theta = 0.2)$

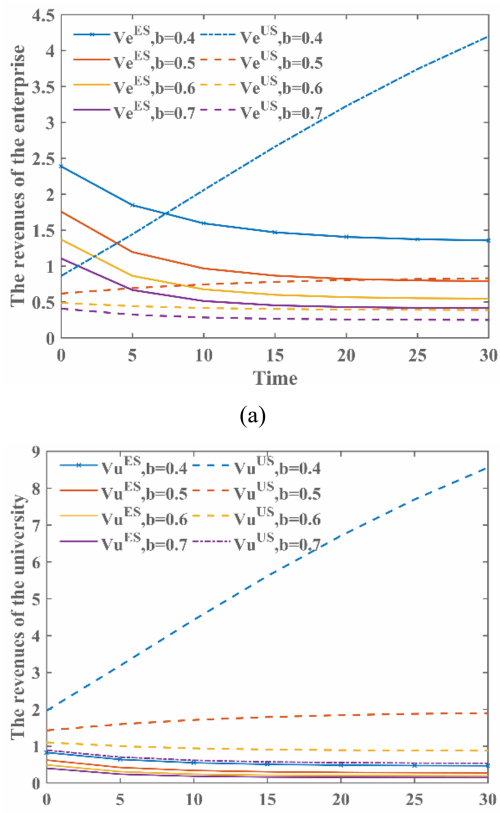
b $V_u^{ES}(\theta = 0.2) > V_u^{ES}(\theta = 0.4) > V_u^{ES}(\theta = 0.6) > V_u^{ES}(\theta = 0.8)$.

From Figure 2, we can find that within the steady state, a revenue-sharing ratio of 0.6 is a reasonable value for a company. When the revenue-sharing ratio exceeds 0.6, both parties' revenues will drop significantly. Thus, firms increasing their earnings distribution do not continually improve their earnings. A plausible interpretation is that as the enterprise gains a higher percentage of revenues, the amount of knowledge transfer and product innovativeness is accompanied by lower motivation from universities, resulting in lower firms' earnings. As $1 - \theta$ decreases, the university revenues will be reduced. This phenomenon is well explained by Corollary 6, which states that the lower the enterprise's revenue-sharing ratio is, the higher the university's revenues will be. Meanwhile, the university will contribute more knowledge to increase product innovativeness, raise the product price, and increase revenues.

5.3.2 Impact of the consumer demand for innovative products

It is known that the main factors affecting consumer demand for innovative products are the price sensitivity coefficient of products and the marginal contribution of innovation to consumer demand. Therefore, under the conditions of the parameter values set above, we vary the value of the parameters b and φ to analyse the influence of consumer demand on revenues.

Figure 3 Revenues sensitivity to b, (a) the enterprise revenue, (b) the university revenue (see online version for colours)



(b)

Observation 2. The impact of price sensitivity of innovative products on the revenues of firms and universities is as follows:

a $V_e^{ES}(b=0.4) > V_e^{ES}(b=0.5) > V_e^{ES}(b=0.6) > V_e^{ES}(b=0.7)$

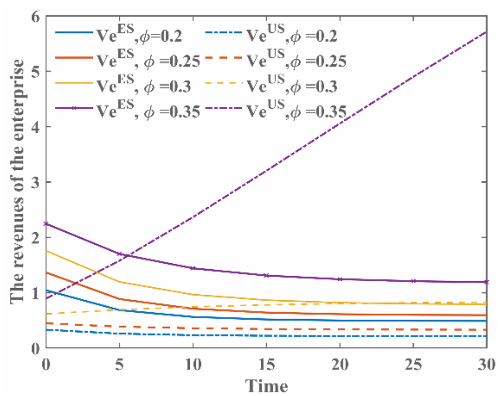
b $V_e^{US}(b=0.4) > V_e^{US}(b=0.5) > V_e^{US}(b=0.6) > V_e^{US}(b=0.7)$

c $V_u^{ES}(b=0.4) > V_u^{ES}(b=0.5) > V_u^{ES}(b=0.6) > V_u^{ES}(b=0.7)$

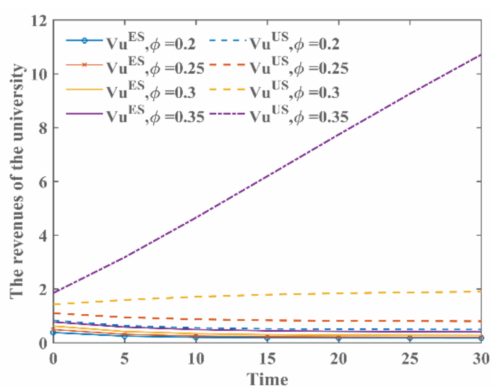
d $V_u^{US}(b=0.4) > V_u^{US}(b=0.5) > V_u^{US}(b=0.6) > V_u^{US}(b=0.7)$

It can be found from Figure 3 that regardless of the game situation, the less sensitive the market is to the product price, the higher the returns of the enterprise and the university. In the case where cooperation enters a steady state, (i.e., after a while), a value of b below 0.5 allows the firm's gain to be consistently higher in the US than the ES. Furthermore, the revenues of two players in ES increase more equilibrium with the decrease of the value of b in the US. Once the value of b falls below 0.4, the two players' revenues increase steeply. This implies that when the university is the game leader, there will not be a steady state of the enterprises and the university's returns for values of b below 0.4, but always be in a condition of rapid growth. Furthermore, universities and enterprises should guide consumers to focus on product innovation and reduce price sensitivity in addition to producing more innovative products. Yet this kind of guidance for consumer perception is long-term and continuous.

Figure 4 Revenues sensitivity to φ, (a) the enterprise revenue, (b) the university revenue (see online version for colours)



(a)



(b)

Observation 3. The impact of the marginal contribution of innovation to consumer demand on the revenues of firms and universities is as follows:

a $V_e^{ES}(\varphi = 0.35) > V_e^{ES}(\varphi = 0.3) > V_e^{ES}(\varphi = 0.25) > V_e^{ES}(\varphi = 0.2)$

b $V_e^{US}(\varphi = 0.35) > V_e^{US}(\varphi = 0.3) > V_e^{US}(\varphi = 0.25) > V_e^{US}(\varphi = 0.2)$

c $V_u^{ES}(\varphi = 0.35) > V_u^{ES}(\varphi = 0.3) > V_u^{ES}(\varphi = 0.25) > V_u^{ES}(\varphi = 0.2)$

d $V_u^{US}(\varphi = 0.35) > V_u^{US}(\varphi = 0.3) > V_u^{US}(\varphi = 0.25) > V_u^{US}(\varphi = 0.2)$

From Figure 4, we expect a higher marginal contribution of innovation to increase customer demand. Obviously, a slight increase in the marginal contribution will significantly increase the benefits of the enterprise and the university. In the steady state, a value of φ exceeding 0.3 gives higher firm returns in the ES than in the US. Once the value of φ exceeds 0.35, there will be no steady state in the US, but always be a high growth rate in the earnings of the firm and the university. To sustainably improve marginal contribution, consumers should be the first step. The U-I should rebuild consumers' consumption concept and increase product publicity to enhance market demand for innovative products. In general, if firms and universities want to increase consumer demand for innovative products, they need to reduce price sensitivity and increase the marginal contribution of innovation, preferably by keeping the value of b within 0.4 and expanding the value of b to 0.35.

5.3.3 Impact of product innovativeness

Product innovativeness is the key to U-I co-production, which significantly influences the development of collaboration and profitability of both parties. According to Melnychuk et al. (2021) and Kobarg et al. (2018), improving innovation performance requires accelerating knowledge absorption and transformation. Measuring the decay rate of product innovation is necessary because of the rapid turnover of current technologies and innovative products. The decay rate δ is a particular parameter that exists only with dynamic games. Consequently, we next investigate the impact of λ and δ in product innovation on the firm's and university's revenues.

Observation 4. The impact of the ability of product innovation on the revenues of enterprises and universities is as follows:

a $V_e^{ES}(\lambda = 2.6) > V_e^{ES}(\lambda = 2.4) > V_e^{ES}(\lambda = 2.2) > V_e^{ES}(\lambda = 2)$

b $V_e^{US}(\lambda = 2.6) > V_e^{US}(\lambda = 2.4) > V_e^{US}(\lambda = 2.2) > V_e^{US}(\lambda = 2)$

c $V_u^{ES}(\lambda = 2.6) > V_u^{ES}(\lambda = 2.4) > V_u^{ES}(\lambda = 2.2) > V_u^{ES}(\lambda = 2)$

d $V_u^{US}(\lambda = 2.6) > V_u^{US}(\lambda = 2.4) > V_u^{US}(\lambda = 2.2) > V_u^{US}(\lambda = 2)$

The revenues of the enterprise and the university increase with the ability of product innovation can be seen in Figure 5. In the case of ES, for each 0.2 increase in the parameter λ, the enterprise and the university have approximately equal increases in revenues. In the case of the US, as long as the value of the parameter λ reaches 2.6, the returns to the two players grow exponentially. The ability of innovative products depends on the quality of knowledge transferred by universities and the ability of firms to absorb and transform knowledge. Both sides need to work together to improve such ability. With regard to select partners, they should fully consider each other's ability to meet the innovation needs.

Observation 5. The impact of the decay rate of product innovation on the revenues of firms and universities is as follows:

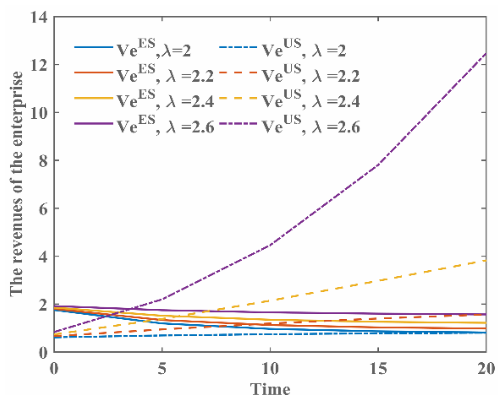
a $V_e^{ES}(\delta = 0.15) > V_e^{ES}(\delta = 0.2) > V_e^{ES}(\delta = 0.25) > V_e^{ES}(\delta = 0.3)$

b $V_e^{US}(\delta = 0.15) > V_e^{US}(\delta = 0.2) > V_e^{US}(\delta = 0.25) > V_e^{US}(\delta = 0.3)$

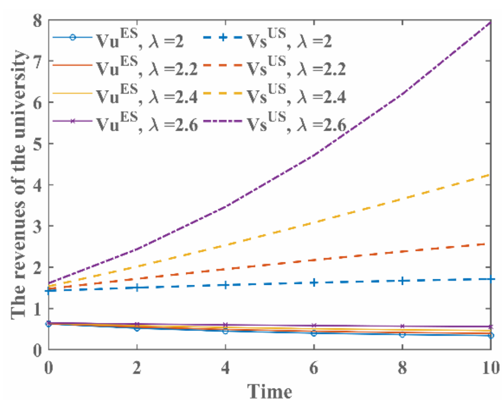
c $V_e^{ES}(\delta = 0.15) > V_e^{ES}(\delta = 0.2) > V_e^{ES}(\delta = 0.25) > V_e^{ES}(\delta = 0.3)$

d $V_u^{US}(\delta = 0.15) > V_u^{US}(\delta = 0.2) > V_u^{US}(\delta = 0.25) > V_u^{US}(\delta = 0.3)$

Figure 5 Revenues sensitivity to λ, (a) the enterprise revenue, (b) the university revenue (see online version for colours)



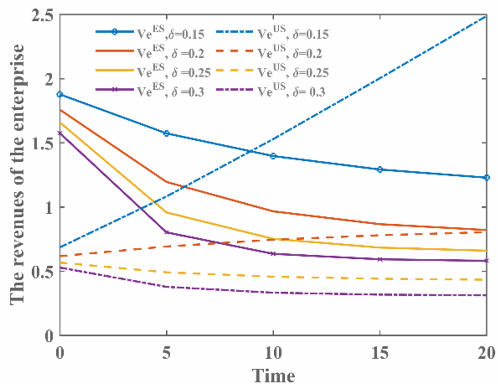
(a)



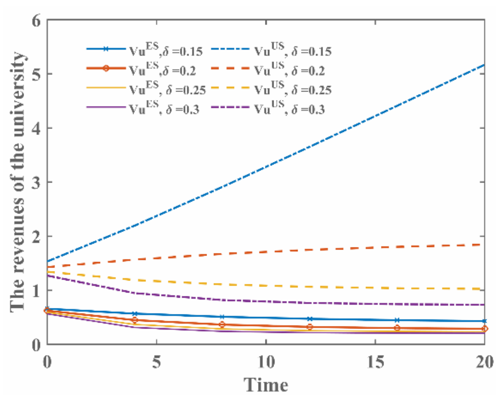
(b)

As Figure 6 shows, we can find that the revenues increase with the parameter δ, decreases. This is because a lower decay rate means that innovative products can be used for more extended periods, which directly impacts revenues. Interestingly, in the context of university leadership, when the decay rate is as low as 0.15, there is a tremendous increase in revenues for both parties. In fact, the decay rate of innovative products is determined by industry, and different categories of innovative products differ. To control the decline rate of innovative products at a low level, companies and universities need to have an excellent degree of market awareness and understand the market outlook and consumer needs. Hence, we suggest that enterprises and universities should conduct sufficient market research before co-production. As a result, with respect to product innovativeness, what we need to do is to improve product innovation capacity and reduce the decay rate of innovative products, preferably rise λ to more than 2.6 and reduce δ to 0.15. In doing so, the overall product innovativeness increases along with it.

Figure 6 Revenues sensitivity to δ, (a) the enterprise revenue, (b) the university revenue (see online version for colours)



(a)



(b)

6 Discussion and conclusions

Existing literature on UIC has investigated the impact of product innovation on firm performance. Several studies have found that innovation enhances UIC performance, while others believe that innovation has a weak association with UIC performance (Robin and Schubert, 2013; Tang et al., 2020). Nevertheless, these studies do not examine the economic performance of U-I alliances when both parties jointly develop products as a whole systematically and dynamically. Employing a Stackelberg game wherein the enterprise or the university is the game leader, in this work, we explore the effect of product innovation on the economic performance of UIC. In our paper, factors influencing the UIC performance in the product innovation process have been examined, strategies for knowledge transfer efforts have been decided, and relationships between product innovation and UIC performance have been identified. To sum up, our research makes some distinctive contributions.

First, one of the most significant contributions of our study is the discovery of a U-shaped relationship between product innovativeness and UIC performance rather than a simple increase or decrease. We extend the results of Robin and Schubert (2013), who argued that the impact of innovation on UIC performance is ambiguous. As a result, the current divergence about whether innovation improves UIC performance is resolved. With a sufficient investment of time and cost, the theoretical model we derive finds that the innovation can enhance the UIC performance, ensuring the investment's effectiveness. Furthermore, in response to the situation that an increase in innovation input leads to a decrease in UIC performance during the early stages of the project, we provide an explicit solution to address this dilemma in the numerical experiment.

Second, we consider dynamic solutions for university knowledge transfer to be driven by complex dynamic relationships among many parameters, including the ability of UIC to transform knowledge and create products, as well as market demand outside of the product. Following that, we analyse how knowledge transfer works, how market demand is composed, and how profit maximisation is achieved. In spite of the fact that knowledge transfer is enhancing the innovativeness of products in UIC, they may naturally decay once products are finally produced since developing products is a long-term and arduous process. And this is the dynamic knowledge transfer process. In this context, we find two ways to sustainably improve UIC economic performance by discussing the interaction of parameters. One is to adjust the appropriate revenue-sharing ratio, which can promote the incentive of firms and universities to participate in product innovation. The other is maintaining low price sensitivity and high marginal contribution, which can stimulate consumer demand for the product.

Third, we establish a Stackelberg wherein the leadership order of game subjects can be exchanged, which gives us the possibility to explore the governance structure in the U-I. In our results, no matter the enterprise or the university, the benefits under the university leadership are always greater than those under the enterprise leadership in cases where the collaboration is well developed. Compared with the enterprise as the game leader, the university in the game leader position can fully exert the vitality of UIC, which has a tremendous increase in product innovativeness and revenues.

6.1 Managerial insights

In the early stages of U-I collaborative R&D, managers of firms and universities need to realise that there is a payoff and reward mismatch. Whereas high investments are accompanied by high profits, representing a U-shaped relationship. Numerical experiments reveal that increasing the marginal contribution of innovation can resolve the dilemma of too low benefits for both parties at the beginning of UIC. This analysis is particularly relevant since managers can influence the marginal contribution of innovation. The inability of firms to absorb knowledge transferred from universities may affect the timely effectiveness of product innovation. Collaboration software, for example, helps document information and defines procedures for codifying knowledge, which increases return on investment. Furthermore, increasing both partners' confidence can be achieved by modelling the threshold at which benefits begin to grow.

Additionally, compared to previous literature, our study offers guidance on dynamic strategies for knowledge transferred by universities. An appropriate revenue-sharing ratio and high consumer demands can achieve a more effective knowledge transfer strategy. It is generally believed that in UIC, more profits allocated to the university will cause a decrease in the firm's profits. Interestingly, our study found that when a firm's revenue-sharing ratio exceeds the limit, a higher revenue-sharing ratio makes the firm's earnings fall. It is therefore possible to simulate an appropriate revenue-sharing ratio in numerical experiments to maximise the incentive for knowledge transfer in universities. However, when formulating the revenue-sharing ratio, the enterprise will need to consider the common interests of both parties separately. Moreover, promoting consumer demands as an external incentive measure can boost product innovation inputs for both parties. For example, disclosing product design highlights and processes and increasing publicity can be important ways to enhance consumer demand.

Lastly, we suggest that more authority be delegated to universities in the U-I governance structure. This is because our results show that the game under university leadership maximises the benefits to both firms and universities, just as Zalewska-Kurek and Harms (2020) argues that universities should maintain a high degree of autonomy in the collaboration process, which is in line with our conclusion.

6.2 Future research

Despite these outstanding findings, our study still has some limitations because our model lacks some of the key variables that facilitate or hinder UIC (Atta-Owusu et al., 2021; Cheng et al., 2022). What's more, our study only discusses UIC in product development, but there are many other ways of UIC (Turk-Bicakci and Brint, 2005). Future studies can be developed based on our model, adding intermediate variables affecting UIC or subdividing the ways of UIC.

Acknowledgements

The authors would like to acknowledge the financial support from the National Social Science Foundation of China (No. 20XGL030).

References

Ahrweiler, P., Pyka, A. and Gilbert, N. (2011) 'A new model for university-industry links in knowledge-based economies', *Journal of Product Innovation Management*, Vol. 28, No. 2, pp.218–235.

Alexander, A., Martin, D.P., Manolchev, C. and Miller, K. (2020) 'University-industry collaboration: using meta-rules to overcome barriers to knowledge transfer', *Journal of Technology Transfer*, Vol. 45, No. 2, pp.371–392.

Arvanitis, S., Kubli, U. and Woerter, M. (2008) 'University-industry knowledge and technology transfer in Switzerland: what university scientists think about co-operation with private enterprises', *Research Policy*, Vol. 37, No. 10, pp.1865–1883.

Atta-Owusu, K., Fitjar, R.D. and Rodriguez-Pose, A. (2021) 'What drives university-industry collaboration? Research excellence or firm collaboration strategy?', *Technological Forecasting and Social Change*, Vol. 173, p.121084.

Bagherzadeh, M., Markovic, S. and Bogers, M. (2021) 'Managing open innovation: a project-level perspective', *IEEE Transactions on Engineering Management*, Vol. 68, No. 1, pp.301–316.

Barbolla, A.M.B. and Corredera, J.R.C. (2009) 'Critical factors for success in university-industry research projects', *Technology Analysis & Strategic Management*, Vol. 21, No. 5, pp.599–616.

Boudreau, K.J., Lacetera, N. and Lakhani, K.R. (2011) 'Incentives and problem uncertainty in innovation contests: an empirical analysis', *Management Science*, Vol. 57, No. 5, pp.843–863.

Bramwell, A. and Wolfe, D.A. (2008) 'Universities and regional economic development: the entrepreneurial University of Waterloo', *Research Policy*, Vol. 37, No. 8, pp.1175–1187.

Bstieler, L., Hemmert, M. and Barczak, G. (2015) 'Trust formation in university-industry collaborations in the US biotechnology industry: IP policies, shared governance, and champions', *Journal of Product Innovation Management*, Vol. 32, No. 1, pp.111–121.

Bzhalava, L. and Cantner, U. (2018) 'The journey towards open innovation: why do firms choose different routes?', *Eurasian Business Review*, Vol. 8, No. 3, pp.245–265.

Carrillo, J.E. and Gaimon, C. (2004) 'Managing knowledge-based resource capabilities under uncertainty', *Management Science*, Vol. 50, No. 11, pp.1504–1518.

Cassiman, B. and Veugelers, R. (2006) 'In search of complementarity in innovation strategy: internal R&D and external knowledge acquisition', *Management Science*, Vol. 52, No. 1, pp.68–82.

Cassiman, B., Veugelers, R. and Zuniga, P. (2008) 'In search of performance effects of (in)direct industry science links', *Industrial and Corporate Change*, Vol. 17, No. 4, pp.611–646.

Chang, S.H. (2017) 'The technology networks and development trends of university-industry collaborative patents', *Technological Forecasting and Social Change*, Vol. 118, pp.107–113.

Cheng, H., Huang, S.Q., Yu, Y.H., Zhang, Z.Y. and Jiang, M.F. (2022) 'The 2011 collaborative innovation plan, university-industry collaboration and achievement transformation of universities: evidence from China', *Journal of the Knowledge Economy*, Vol. 26.

D'Este, P. and Patel, P. (2007) 'University–industry linkages in the UK: What are the factors underlying the variety of interactions with industry?', *Research Policy*, Vol. 36, No. 9, pp.1295–1313, https://doi.org/10.1016/j.respol.2007.05.002.

Dangelico, R.M., Pujari, D. and Pontrandolfo, P. (2017) 'Green product innovation in manufacturing firms: a sustainability-oriented dynamic capability perspective', *Business Strategy and the Environment*, Vol. 26, No. 4, pp.490–506.

Dosi, G. (1988) 'Sources, procedures, and microeconomic effects of innovation', *Journal of Economic Literature*, Vol. 26, No. 3, pp.1120–1171.

Epple, D., Argote, L. and Murphy, K. (1996) 'An empirical investigation of the microstructure of knowledge acquisition and transfer through learning by doing', *Operations Research*, Vol. 44, No. 1, pp.77–86.

Gao, Y.X. and Sun, B.Z. (2020) 'The large-small group-based evolutionary game on knowledge sharing in uncertain environment under the background of telemedicine service', *Complexity*, Vol. 2020, pp.1–13.

Haefner, N., Wincent, J., Parida, V. and Gassmann, O. (2021) 'Artificial intelligence and innovation management: a review, framework, and research agenda', *Technological Forecasting and Social Change*, Vol. 162, p.120392.

He, P., He, Y., Shi, C.M., Xu, H. and Zhou, L. (2020) 'Cost-sharing contract design in a low-carbon service supply chain', *Computers & Industrial Engineering*, Vol. 139, p.17, 106160.

Hermans, J. and Castiaux, A. (2017) 'Contingent knowledge transfers in university-industry R&D projects', *Knowledge Management Research & Practice*, Vol. 15, No. 1, pp.68–77.

Hobbs, K.G., Link, A.N. and Scott, J.T. (2017) 'Science and technology parks: an annotated and analytical literature review', *The Journal of Technology Transfer*, Vol. 42, No. 4, pp.957–976.

Huang, C.Y., Yang, C.W. and Fang, S.C. (2019) 'The contrasting interaction effects of university-industry collaboration motivation with demographic characteristics on university-industry collaboration performance in Taiwan', *Technology Analysis & Strategic Management*, Vol. 31, No. 9, pp.1048–1062.

Jussila, J., Raitanen, J., Partanen, A., Tuomela, V., Siipola, V. and Kunnari, I. (2020) 'Rapid product development in university-industry collaboration: case study of a smart design project', *Technology Innovation Management Review*, Vol. 10, No. 3, pp.48–58.

Kobarg, S., Stumpf-Wollersheim, J. and Welpe, I.M. (2018) 'University-industry collaborations and product innovation performance: the moderating effects of absorptive capacity and innovation competencies', *Journal of Technology Transfer*, Vol. 43, No. 6, pp.1696–1724.

Kodama, T. (2008) 'The role of intermediation and absorptive capacity in facilitating university-industry linkages – an empirical study of TAMA in Japan', *Research Policy*, Vol. 37, No. 8, pp.1224–1240.

Koessler, F. (2004) 'Strategic knowledge sharing in Bayesian games', *Games and Economic Behavior*, Vol. 48, No. 2, pp.292–320.

Kshetri, N. (2017) 'The evolution of the internet of things industry and market in China: an interplay of institutions, demands and supply', *Telecommunications Policy*, Vol. 41, No. 1, pp.49–67.

Kunttu, L. and Neuvo, Y. (2020) 'The role of academics, users, and customers in industrial product development', *Technology Innovation Management Review*, Vol. 10, No. 3, pp.59–68, https://urn.fi/URN:NBN:fi-fe2020061543326.

Kuys, J., Al Mahmud, A. and Kuys, B. (2021) 'A case study of university-industry collaboration for sustainable furniture design', *Sustainability*, Vol. 13, No. 10915, p.18.

Lawson, B. and Potter, A. (2012) 'Determinants of knowledge transfer in inter-firm new product development projects', *International Journal of Operations & Production Management*, Vol. 32, No. 10, pp.1228–1247.

Lee, C.Y. and Huang, Y.C. (2012) 'Knowledge stock, ambidextrous learning, and firm performance evidence from technologically intensive industries', *Management Decision*, Vol. 50, No. 6, pp.1096–1116.

Liefner, I. and Schiller, D. (2008) 'Academic capabilities in developing countries – a conceptual framework with empirical illustrations from Thailand', *Research Policy*, Vol. 37, No. 2, pp.276–293.

Lin, L. and Wang, H. (2019) 'Dynamic incentive model of knowledge sharing in construction project team based on differential game', *Journal of the Operational Research Society*, Vol. 70, No. 12, pp.2084–2096, https://doi.org/10.1080/01605682.2018.1516177.

Liu, Z.G., Anderson, T.D. and Cruz, J.M. (2012) 'Consumer environmental awareness and competition in two-stage supply chains', *European Journal of Operational Research*, Vol. 218, No. 3, pp.602–613.

Lu, L.J., Marin-Solano, J. and Navas, J. (2019) 'An analysis of efficiency of time-consistent coordination mechanisms in a model of supply chain management', *European Journal of Operational Research*, Vol. 279, No. 1, pp.211–224.

Lyu, Y.B., He, B.Y., Zhu, Y.Q. and Li, L. (2019) 'Network embeddedness and inbound open innovation practice: the moderating role of technology cluster', *Technological Forecasting and Social Change*, Vol. 144, pp.12–24.

Ma, G.F., Jia, J.Y., Jiang, S. and Wu, Z.J. (2020) 'Incentives and contract design for knowledge sharing in construction joint ventures', *Automation in Construction*, Vol. 119, p.103343.

Maietta, O.W. (2015) 'Determinants of university-firm R&D collaboration and its impact on innovation: a perspective from a low-tech industry', *Research Policy*, Vol. 44, No. 7, pp.1341–1359.

Melnychuk, T., Schultz, C. and Wirsich, A. (2021) 'The effects of university-industry collaboration in preclinical research on pharmaceutical firms' R&D performance: absorptive capacity's role', *Journal of Product Innovation Management*, Vol. 38, No. 3, pp.355–378.

Mukherjee, A. and Carvalho, M. (2021) 'Dynamic decision making in a mixed market under cooperation: towards sustainability', *International Journal of Production Economics*, Vol. 241, p.108270.

Muscio, A., Quaglione, D. and Scarpinato, M. (2012) 'The effects of universities' proximity to industrial districts on university-industry collaboration', *China Economic Review*, Vol. 23, No. 3, pp.639–650.

Nerlove, M. and Arrow, K.J. (1962) 'Optimal advertising policy under dynamic conditions', *Economica*, Vol. 29, No. 114, pp.129–142.

Ozkan-Seely, G.F., Gaimon, C. and Kavadias, S. (2015) 'Dynamic knowledge transfer and knowledge development for product and process design teams', *M&Som-Manufacturing & Service Operations Management*, Vol. 17, No. 2, pp.177–190.

Paay, J., Kuys, B. and Taffe, S. (2021) 'Innovating product design through university-industry collaboration: codesigning a bushfire rated skylight', *Design Studies*, Vol. 76, p.101093.

Perkmann, M. and Walsh, K. (2007) 'University-industry relationships and open innovation: towards a research agenda', *International Journal of Management* Reviews, Vol. 9, No. 4, pp.259–280.

Petruzzelli, A.M. and Murgia, G. (2020) 'University-industry collaborations and international knowledge spillovers: a joint-patent investigation', *Journal of Technology Transfer*, Vol. 45, No. 4, pp.958–983.

Prabhu, G.N. (1999) 'Implementing university-industry joint product innovation projects', *Technovation*, Vol. 19, No. 8, pp.495–505.

Robertson, J., McCarthy, I.P. and Pitt, L. (2019) 'Leveraging social capital in university-industry knowledge transfer strategies: a comparative positioning framework', *Knowledge Management Research & Practice*, Vol. 17, No. 4, pp.461–472.

Robin, S. and Schubert, T. (2013) 'Cooperation with public research institutions and success in innovation: evidence from France and Germany', *Research Policy*, Vol. 42, No. 1, pp.149–166, https://doi.org/10.1016/j.respol.2012.06.002.

Ryan, P., Geoghegan, W. and Hilliard, R. (2018) 'The microfoundations of firms' explorative innovation capabilities within the triple helix framework', *Technovation*, Vol. 76, pp.15–27.

Samaddar, S. and Kadiyala, S.S. (2006) 'An analysis of interorganizational resource sharing decisions in collaborative knowledge creation', *European Journal of Operational Research*, Vol. 170, No. 1, pp.192–210.

Song, Y., Sahut, J.., Zhang, Z.Y., Tian, Y.F. and Hikkerova, L. (2022) 'The effects of government subsidies on the sustainable innovation of university-industry collaboration', *Technological Forecasting and Social Change*, Vol. 174, p.121233.

Srinivasan, D., Rajgarhia, S., Radhakrishnan, B.M., Sharma, A. and Khincha, H.P. (2017) 'Game-theory based dynamic pricing strategies for demand side management in smart grids', *Energy*, Vol. 126, pp.132–143.

Tang, Y.L., Motohashi, K., Hu, X.Y. and Montoro-Sanchez, A. (2020) 'University-industry interaction and product innovation performance of Guangdong manufacturing firms: the roles of regional proximity and research quality of universities', *Journal of Technology Transfer*, Vol. 45, No. 2, pp.578–618.

Terwiesch, C. and Loch, C.H. (1999) 'Measuring the effectiveness of overlapping development activities', *Management Science*, Vol. 45, No. 4, pp.455–465.

Turk-Bicakci, L. and Brint, S. (2005) 'University-industry collaboration: patterns of growth for low-and middle-level performers', *Higher Education*, Vol. 49, Nos. 1–2, pp.61–89.

Van Wijk, R., Jansen, J.J.P. and Lyles, M.A. (2008) 'Inter-and intra-organizational knowledge transfer: a meta-analytic review and assessment of its antecedents and consequences', *Journal of Management Studies*, Vol. 45, No. 4, pp.830–853.

Wang, W.J. and Lu, S. (2021) 'University-industry innovation community dynamics and knowledge transfer: evidence from China', *Technovation*, Vol. 106, p.102305.

Wang, Y.Y., Yuan, C.H., Zhang, S.M. and Wang, R.Q. (2021) 'Moderation in all things: industry-university-research alliance portfolio configuration and SMEs' innovation performance in China', *Journal of Small Business Management*, Vol. 60, No. 6, pp.1516–1544.

Weerasinghe, I.M.S. and Dedunu, H.H. (2021) 'Do demographic factors matter in university-industry knowledge exchange? A study based on Sri Lankan university system', *Journal of Knowledge Management*, Vol. 25, No. 5, pp.973–988.

Wirsich, A., Kock, A., Strumann, C. and Schultz, C. (2016) 'Effects of university-industry collaboration on technological newness of firms', *Journal of Product Innovation Management*, Vol. 33, No. 6, pp.708–725.

Xiao, P., Tang, C.S. and Wirtz, J. (2011) 'Optimizing referral reward programs under impression management considerations', *European Journal of Operational Research*, Vol. 215, No. 3, pp.730–739.

Yang, J., Zhang, J. and Zeng, D.M. (2022) 'Scientific collaboration networks and firm innovation: the contingent impact of a dynamic environment', *Management Decision*, Vol. 60, No. 1, pp.278–296.

Yang, X., Zhang, J., Shen, G.Q. and Yan, Y. (2019) 'Incentives for green retrofits: an evolutionary game analysis on public-private-partnership reconstruction of buildings', *Journal of Cleaner Production*, Vol. 232, pp.1076–1092.

Yang, Z., Chen, H., Du, L., Lin, C.R. and Lu, W. (2021) 'How does alliance-based government-university-industry foster cleantech innovation in a green innovation ecosystem?', *Journal of Cleaner Production*, Vol. 283, p.124559.

Yi, H.Y. and Zhang, Q. (2022) 'Knowledge-sharing strategies of university-industry alliances promoting green technology innovation in ecosystems: based on the utility of multichannel funding', *IEEE Access*, Vol. 10, pp.65728–65743.

Zalewska-Kurek, K. and Harms, R. (2020) 'Managing autonomy in university-industry research: a case of collaborative Ph.D. projects in the Netherlands', *Review of Managerial Science*, Vol. 14, No. 2, pp.393–416.

Zhang, Q., Tang, W.S. and Zhang, J.X. (2016) 'Green supply chain performance with cost learning and operational inefficiency effects', *Journal of Cleaner Production*, Vol. 112, pp.3267–3284.

Zhang, S.M., Chen, C. and Deng, C. (2022) 'University-industry collaboration portfolio concentration and focal firms' innovation performance: evidence from China', *Technology Analysis & Strategic Management*, pp.1–14.

Appendix

Proof of Proposition 1. According to the solution method of the Stackelberg game (the enterprise is in the leading position and the university is the follower), the optimal strategies for the university will be sought first. Define the profit functions of the enterprise and the university under the ES game as V_e^{ES} and V_u^{ES}, respectively. The optimal benefits function of the follower satisfying the HJB equation is

$$\rho V_u^{ES}(I) = \max_{m\geq 0, q\geq 0}\left\{[m-\theta m][a-b(p+m)+\varphi I]-\frac{k}{2}q^2+\frac{\partial V_u}{\partial I}(\lambda q-\delta I)\right\} \tag{A.1}$$

To maximise the result of the equation (A.1), based on the first-order condition of m and q (necessary condition), respectively, we have

$$m=\frac{a-bp+\varphi I}{2b} \tag{A.2}$$

$$q=\frac{\frac{\partial V_s}{\partial I}\lambda}{k} \tag{A.3}$$

At the same time, the enterprise is also aware that the university will determine the technology-driven price of products and the amount of knowledge transferred by equations (A.2) and (A.3). Thus, the optimal benefits function of the enterprise satisfying the HJB equation is

$$\rho V_e^{ES}(I)=\max_{p\geq 0}\left\{[p+\theta m-cI][a-b(p+m)+\varphi I]+\frac{\partial V_e}{\partial I}(\lambda q-\delta I)\right\} \tag{A.4}$$

Substituting the equations (A.2) and (A.3) into (A.4), maximising the equation (A.4), and finding the first-order derivative of p yields

$$p=\frac{a(1-\theta)+[\varphi(1-\theta)+bc]I}{b(2-\theta)} \tag{A.5}$$

Substituting the equation (A.5) into (A.2), we have

$$m=\frac{a+(\varphi-bc)I}{2b(2-\theta)} \tag{A.6}$$

Learning from differential equations (A.1) and (A.4), $V_i^{ES}(I)$, $i \in (e, s)$ are quadratic functions of I. Generally, we suppose

$$V_e^{ES}(I)=v_1I^2+v_2I+v_3 \tag{A.7}$$

$$V_u^{ES}(I)=n_1I^2+n_2I+n_3 \tag{A.8}$$

where v_1, v_2, v_3, n_1, n_2 and n_3 are unknown constants. From equations (A.7) and (A.8), the partial derivatives of the profits functions are given by

$$\frac{\partial V_e}{\partial I} = 2v_1 I + v_2 \tag{A.9}$$

$$\frac{\partial V_u}{\partial I} = 2n_1 I + n_2 \tag{A.10}$$

Substituting equations (A.9) and (A.10) into (A.4) and (A.1), respectively, results in

$$\rho V_e^{ES}(I) = \left\{ \begin{array}{l} \left[\frac{(\varphi - bc)^2}{4b(2-\theta)} + \frac{4\lambda^2 v_1 n_1}{k} - 2\delta v_1 \right] I^2 + \left[\frac{a(\varphi - bc)}{2b(2-\theta)} + \right. \\ \left. \frac{2\lambda^2 (v_1 n_2 + v_2 n_1)}{k} - \delta v_2 \right] I + \left[\frac{a^2}{4b(2-\theta)} + \frac{\lambda^2 v_2 n_2}{k} \right] \end{array} \right\} \tag{A.11}$$

$$\rho V_u^{ES}(I) = \left\{ \begin{array}{l} \left[\frac{(1-\theta)(\varphi - bc)^2}{4b(2-\theta)^2} + \frac{2\lambda^2 n_1^2}{k} - 2\delta n_1 \right] I^2 + \left[\frac{a(1-\theta)(\varphi - bc)}{2b(2-\theta)^2} \right. \\ \left. + \frac{2\lambda^2 n_1 n_2}{k} - \delta n_2 \right] I + \left[\frac{(1-\theta)a^2}{4b(2-\theta)^2} + \frac{\lambda^2 n_2^2}{2k} \right] \end{array} \right\} \tag{A.12}$$

Substituting equations (A.7)–(A.10) into equations (A.11) and (A.12), we can obtain the solutions of six nonlinear equations with respect to the coefficients v_i and n_i (i = 1, 2, 3).

$$\rho v_1 = \frac{(\varphi - bc)^2}{4b(2-\theta)} + \frac{4\lambda^2 v_1 n_1}{k} - 2\delta v_1 \tag{A.13}$$

$$\rho v_2 = \frac{a(\varphi - bc)}{2b(2-\theta)} + \frac{2\lambda^2 (v_1 n_2 + v_2 n_1)}{k} - \delta v_2 \tag{A.14}$$

$$\rho v_3 = \frac{a^2}{4b(2-\theta)} + \frac{\lambda^2 v_2 n_2}{k} \tag{A.15}$$

$$\rho n_1 = \frac{(1-\theta)(\varphi - bc)^2}{4b(2-\theta)^2} + \frac{2\lambda^2 n_1^2}{k} - 2\delta n_1 \tag{A.16}$$

$$\rho n_2 = \frac{a(1-\theta)(\varphi - bc)}{2b(2-\theta)^2} + \frac{2\lambda^2 n_1 n_2}{k} - \delta n_2 \tag{A.17}$$

$$\rho n_3 = \frac{(1-\theta)a^2}{4b(2-\theta)^2} + \frac{\lambda^2 n_2^2}{2k} \tag{A.18}$$

Solving for the above six equations (A.13)–(A.17) yields

$$n_1 = \frac{kb(\rho + 2\delta)(2-\theta) \pm \Delta_1}{4\lambda^2 b(2-\theta)} \tag{A.19}$$

where $\Delta_1 = \sqrt{k^2 b^2 (2-\theta)^2 (\rho + 2\delta)^2 - 2\lambda^2 kb(1-\theta)(\varphi - bc)^2}$. After making calculations, the larger value means that the dynamic of product innovativeness does not converge to a steady-state value. Therefore, the larger value is omitted.

$$n_1 = \frac{kb(\rho + 2\delta)(2-\theta) - \Delta_1}{4\lambda^2 b(2-\theta)} \tag{A.20}$$

$$v_1 = \frac{k(\varphi - bc)^2}{4\Delta_1} \tag{A.21}$$

$$n_2 = \frac{ak(1-\theta)(\varphi - bc)}{(2-\theta)\Delta_2} \tag{A.22}$$

$$v_2 = \frac{ak(\varphi - bc)\left(\Delta_1\Delta_2 + k\Delta_3\right)}{\Delta_1\Delta_2^2} \tag{A.23}$$

where $\Delta_2 = \rho kb(2 - \theta) + \Delta_1$, $\Delta_3 = \lambda^2 b(1 - \theta)(\varphi - bc)^2$.

$$n_3 = \frac{a^2(1-\theta)\left(\Delta_2^2 + 2k\Delta_3\right)}{4\rho b(2-\theta)^2\Delta_2^2} \tag{A.24}$$

$$v_3 = \frac{a^2\left[\Delta_1\Delta_2^3 + 4k\Delta_3\left(\Delta_1\Delta_2 + k\Delta_3\right)\right]}{4\rho b(2-\theta)\Delta_1\Delta_2^3} \tag{A.25}$$

Substituting v_1, v_2, v_3, n_1, n_2 and n_3 into V_e^{ES} and V_u^{ES}, we can obtain optimal benefits equations of the enterprise and the university.

Proof of Proposition 2. According to the solution method of the Stackelberg game (the university is the game leader, and the enterprise is in the following position), the optimal strategy for the enterprise will be sought first. Define the profits functions of the enterprise and the university under the US game as V_e^{US} and V_u^{US}, respectively. The optimal profits function of the enterprise satisfying the HJB equation is

$$\rho V_e^{US}(I) = \max_{p\ge 0}\left\{[p + \theta m - cI][a - b(p+m) + \varphi I] + \frac{\partial V_e}{\partial I}(\lambda q - \delta I)\right\} \tag{A.26}$$

To maximise the result of the equation (A.26), based on the first-order condition of p (necessary condition), we have

$$p = \frac{a - b(1+\theta)m + (\varphi + bc)I}{2b} \tag{A.27}$$

At the same time, the university also realises that the enterprise will decide the technology-driven price of products and the amount of knowledge transferred by the equation (A.27). Hence the optimal benefits function of the university satisfying the HJB equation is

$$\rho V_u^{US}(I) = \max_{m\ge 0, q\ge 0}\left\{[m - \theta m][a - b(p+m) + \varphi I] - \frac{k}{2}q^2 + \frac{\partial V_u}{\partial I}(\lambda q - \delta I)\right\} \tag{A.28}$$

Substituting the equation (A.27) into (A.28), we have

$$m = \frac{a + (\varphi - bc)I}{2b(1-\theta)} \tag{A.29}$$

$$q = \frac{\frac{\partial V_s}{\partial I}\lambda}{k} \tag{A.30}$$

Substituting the equation (A.30) into (A.28), we have

$$p = \frac{a(1-3\theta)+[(1-3\theta)\varphi+(3-\theta)bc]I}{4b(1-\theta)} \tag{A.31}$$

Learning from differential equations (A.26) and (A.28), $V_i^{US}(I)$, $i \in (e, s)$ are quadratic functions of I. Generally, we suppose

$$V_e(I) = v_4 I^2 + v_5 I + v_6 \tag{A.32}$$

$$V_s(I) = n_4 I^2 + n_5 I + n_6 \tag{A.33}$$

where v_4, v_5, v_6, n_4, n_5 and n_6 are unknown constants. From equations (A.32) and (A.33), the partial derivatives of the profits functions are given by

$$\frac{\partial V_e}{\partial I} = 2v_4 I + v_5 \tag{A.34}$$

$$\frac{\partial V_s}{\partial I} = 2n_4 I + n_5 \tag{A.35}$$

Substituting equations (A.34) and (A.35) into (A.25) and (A.27), respectively, resulting in

$$\rho V_e^{US}(I) = \begin{Bmatrix} \left[\frac{(\varphi-bc)^2}{16b} + \frac{4\lambda^2 v_4 n_4}{k} - 2\delta v_4\right] I^2 + \left[\frac{2a(\varphi-bc)}{16} + \right. \\ \left. \frac{2\lambda^2(v_4 n_5 + v_5 n_4)}{k} - \delta v_5\right] I + \left[\frac{a^2}{16b} + \frac{\lambda^2 v_5 n_5}{k}\right] \end{Bmatrix} \tag{A.36}$$

$$\rho V_u^{US}(I) = \begin{Bmatrix} \left[\frac{(\varphi-bc)^2}{8b} + \frac{2\lambda^2 n_4^2}{k} - 2\delta n_4\right] I^2 + \left[\frac{a(\varphi-bc)}{4b} \right. \\ \left. + \frac{2\lambda^2 n_4 n_5}{k} - \delta n_5\right] I + \left[\frac{a^2}{8b} + \frac{\lambda^2 n_5^2}{2k}\right] \end{Bmatrix} \tag{A.37}$$

Substituting equations (A.31)–(A.35) into equations (A.36) and (A.37), we can obtain the solutions of six nonlinear equations concerning the coefficients v_i and $n_i (i = 4, 5, 6)$.

$$\rho v_4 = \frac{(\varphi-bc)^2}{16b} + \frac{4\lambda^2 v_4 n_4}{k} - 2\delta v_4 \tag{A.38}$$

$$\rho v_5 = \frac{2a(\varphi-bc)}{16} + \frac{2\lambda^2(v_4 n_5 + v_5 n_4)}{k} - \delta v_5 \tag{A.39}$$

$$\rho v_6 = \frac{a^2}{16b} + \frac{\lambda^2 v_5 n_5}{k} \tag{A.40}$$

$$\rho n_4 = \frac{(\varphi - bc)^2}{8b} + \frac{2\lambda^2 n_4^2}{k} - 2\delta n_4 \tag{A.41}$$

$$\rho n_5 = \frac{a(\varphi - bc)}{4b} + \frac{2\lambda^2 n_4 n_5}{k} - \delta n_5 \tag{A.42}$$

$$\rho n_6 = \frac{a^2}{8b} + \frac{\lambda^2 n_5^2}{2k} \tag{A.43}$$

Solving for the above six equations (A.38)–(A.42), we can obtain

$$n_4 = \frac{kb(\rho + 2\delta) \pm \Delta_4}{4\lambda^2 b} \tag{A.44}$$

where $\Delta_4 = \sqrt{b^2 k^2 (\rho + 2\delta)^2 - \lambda^2 bk(\varphi - bc)^2}$. After making calculations, the larger value means that the dynamic of product innovativeness does not converge to a steady-state value. Thus, the larger value is omitted.

$$n_4 = \frac{kb(\rho + 2\delta) - \Delta_4}{4\lambda^2 b} \tag{A.45}$$

$$v_4 = \frac{k(\varphi - bc)^2}{16\Delta_4} \tag{A.46}$$

$$n_5 = \frac{ak(\varphi - bc)}{2(\rho kb + \Delta_4)} \tag{A.47}$$

$$v_5 = \frac{akb(\varphi - bc)\left[2(\rho kb + \Delta_4)\Delta_4 + \lambda^2 k(\varphi - bc)^2\right]}{8\Delta_4(\Delta_4 + \rho kb)^2} \tag{A.48}$$

$$n_6 = \frac{a^2\left[(\rho kb + \Delta_4)^2 + \lambda^2 kb(\varphi - bc)^2\right]}{8\rho b(\rho kb + \Delta_4)^2} \tag{A.49}$$

$$v_6 = \frac{a^2}{16\rho b} + \frac{\lambda^2 a^2 kb(\varphi - bc)^2\left[2\Delta_4(\rho kb + \Delta_4) + \lambda^2 k(\varphi - bc)^2\right]}{16\rho\Delta_4(\Delta_4 + \rho kb)^3} \tag{A.50}$$

Substituting v_4, v_5, v_6, n_4, n_5 and n_6 into V_e^{US} and V_u^{US}, we can have optimal benefits equations of the enterprise and the university.

According to the dynamic equation, the amount of knowledge innovation is as follows:

$$\begin{cases} \dot{I}(t) = \lambda q(t) - \delta I(t) \\ I(0) = I_0 \geq 0 \end{cases} \tag{A.51}$$

Table A1 A summary of the parameter calculations

Summary	
$\Delta_1=\sqrt{k^2b^2(2-\theta)^2(\rho+2\delta)^2-2\lambda^2kb(1-\theta)(\varphi-bc)^2}$	$\Delta_2=\rho kb(2-\theta)+\Delta_1$
$\Delta_3=\lambda^2b(1-\theta)(\varphi-bc)^2$	$\Delta_4=\sqrt{b^2k^2(\rho+2\delta)^2-\lambda^2bk(\varphi-bc)^2}$
$\tau_1=\dfrac{\Delta_1-\rho kb(2-\theta)}{2kb(2-\theta)}$	$\tau_2=\dfrac{\Delta_4-\rho kb}{2kb}$
$v_1=\dfrac{k(\varphi-bc)^2}{4\Delta_1}$	$v_2=\dfrac{ak(\varphi-bc)\left(\Delta_1\Delta_2+k\Delta_3\right)}{\Delta_1\Delta_2^2}$
$v_3=\dfrac{a^2\left[\Delta_1\Delta_2^3+4k\Delta_3\left(\Delta_1\Delta_2+k\Delta_3\right)\right]}{4\rho b(2-\theta)\Delta_1\Delta_2^3}$	$n_1=\dfrac{kb(\rho+2\delta)(2-\theta)-\Delta_1}{4\lambda^2b(2-\theta)}$
$n_2=\dfrac{ak(1-\theta)(\varphi-bc)}{(2-\theta)\Delta_2}$	$n_3=\dfrac{a^2(1-\theta)\left(\Delta_2^2+2k\Delta_3\right)}{4\rho b(2-\theta)^2\Delta_2^2}$
$v_4=\dfrac{k(\varphi-bc)^2}{16\Delta_4}$	$v_5=\dfrac{akb(\varphi-bc)\left[2\left(\rho kb+\Delta_4\right)\Delta_4+\lambda^2k(\varphi-bc)^2\right]}{8\Delta_4\left(\Delta_4+\rho kb\right)^2}$
$v_6=\dfrac{a^2}{16\rho b}+\dfrac{\lambda^2a^2kb(\varphi-bc)^2\left[2\Delta_4\left(\rho kb+\Delta_4\right)+\lambda^2k(\varphi-bc)^2\right]}{16\rho\Delta_4\left(\Delta_4+\rho kb\right)^3}$	$n_4=\dfrac{kb(\rho+2\delta)-\Delta_4}{4\lambda^2b}$
$n_5=\dfrac{ak(\varphi-bc)}{2\left(\rho kb+\Delta_4\right)}$	$n_6=\dfrac{a^2\left[\left(\rho kb+\Delta_4\right)^2+\lambda^2kb(\varphi-bc)^2\right]}{8\rho b\left(\rho kb+\Delta_4\right)^2}$

In the case of ES, substituting the optimal equilibrium strategy of knowledge transferred into the equation (A.51) and then solving the differential equation, we can obtain

$$I^{ES}(t)=I_\infty^{ES}+\left(I_0-I_\infty^{ES}\right)e^{-\tau_1t} \tag{A.52}$$

where $I_\infty^{ES}=\dfrac{\lambda^2a(1-\theta)(\varphi-bc)}{2kb\delta(\rho+\delta)(2-\theta)^2-\lambda^2(1-\theta)(\varphi-bc)^2}$, $\tau_1=\dfrac{\Delta_1-\rho kb(2-\theta)}{2kb(2-\theta)}$.

In the case of US, substituting the optimal equilibrium strategy of knowledge transferred into the equation (A.51), and then solving the differential equation, we can obtain

$$I^{US}(t)=I_\infty^{US}+\left(I_0-I_\infty^{ES}\right)e^{-\tau_2t} \tag{A.53}$$

where $I_\infty^{US}=\dfrac{\lambda^2a(\varphi-bc)}{4\delta(\rho+\delta)-\lambda^2(\varphi-bc)^2}$, $\tau_2=\dfrac{\Delta_4-\rho kb}{2kb}$.

The first-order partial derivative I_∞^{ES} with respect θ to is

$$\frac{\partial\left(\dfrac{1}{I_\infty^{ES}}\right)}{\partial\theta}=\frac{2\lambda^2kab\delta(\varphi-bc)(2-\theta)\xi}{[\lambda^2a(1-\theta)(\varphi-bc)^2} \tag{A.54}$$

where $\xi = (\rho + \delta)(2 - \theta) - 2(1 - \theta)$.

The first-order partial derivative ξ concerning the θ is

$$\frac{\partial \xi}{\partial \theta} = 2 - (\rho + \delta) \tag{A.55}$$

Because of $\rho \in (0, 1)$ and $\delta \in (0, 1)$, we can know that $\frac{\partial \xi}{\partial \theta} > 0$. Let $\xi \in (0, 1)$, we get $\rho + \delta = 1 - \frac{\theta}{2 - \theta}$. When $\rho + \delta > 1 - \frac{\theta}{2 - \theta}$, we can conclude that I_{∞}^{ES} is decreasing with respect to θ. On the contrary, when $\rho + \delta < 1 - \frac{\theta}{2 - \theta}$, I_{∞}^{ES} increases with θ.