Dynamics of Costs and Revenue Sharing Schemes in Open Innovation: an Evolutionary Game Approach

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***Abstract* — The concept of open innovation has recently gained widespread attention. It is particularly relevant now because many firms are required to implement it. In order to investigate the incentives of open innovation, this article analyzed companies' choice to open innovation in an evolutionary game setting using replicator dynamics. It discussed how costs and revenue allocation schemes affect the final equilibrium. Evolutionary game analysis shows that participants' choices are related to schemes of cost sharing. The probability of choosing open innovation is positively related to excess benefits, and negatively related to total costs. There exists an optimal excess benefits allocation, so that firms tend to adopt open innovation strongest. The probability of both firms adopting open innovation is greater in punishment case. This article shed some light on how to promote companies to choose open innovation.**

Keywords - Open innovation; Evolutionary game theory; Replicator dynamics

I. INTRODUCTION

Traditionally, industrial firms have developed new technologies for their own products internally [1, 2]. Thus, most companies have pursued relatively "closed" innovation strategies, and had limited interactions for the purpose of developing new technologies. In recent decades, the innovation strategies have begun to change as firms across different types of industries have increasingly acquired external technologies to complement their internal knowledge bases [3]. In light of these developments, Professor Henry Chesbrough coined the term "open innovation" to describe innovation processes in which firms interact extensively with outsiders for ideas and methodology [4]. With the growing importance of open innovation, some pioneering companies, such as Procter & Gamble and Eli Lilly, have achieved great benefits from the new technologies that have developed from these interactions [5, 6].

Open innovation is vital for companies whose products have short life cycles (for example software and consumer electronics). An example of a typical product that has utilized open innovation is Android, which uses Open Source software, whose source code has been partially or completely released [7]. A policy of Open Innovation policy allows companies to obtain external technologies and have control over the release of its own knowledge with outside partners [8,9]. Through the use of external expertise, Open Innovation stimulates advances by sharing the cost and risk associated with developing new technologies, offering access to new contact networks through "intermediaries" and information pools [10]. A few recent studies examine the underlying factors affecting the degree of openness of a firm from a strategic point of view [11,12]. These authors identify "sourcing and acquiring" as the typical inbound processes and "revealing and selling" as the typical outbound processes, and investigate the advantages and disadvantages of each form of openness.

Open innovation helps company to share external technologies and absorb outside knowledge with other partners, it has been examined to play a role on value co-creation, wealth spillover and competitive advantage [13,14,15]. Open innovation can be seen as an innovation in itself, because it evokes new issues on distributing the cost and risk, offering access to new contact networks [16]. It finds out open innovation in small and medium-sized firms (SMEs) is attractive when initiating a risk and revenue-sharing agreement with partners sharing cost of open innovation sometimes induces new cost such as transaction costs as collaborating partners may free-ride [17]. External resources of outbound open innovation can be perceived as a public good, so innovating partners can free-ride on collaborated activities [18].

Since Open Innovation has been studied theoretically and empirically in recent decades, a few models have already appeared in economic literature. The most common frameworks have been the static games. It has investigated aspects of technology transfers and differentiated Cournot duopolies, which lead to asymmetric equilibrium structures [19,20,21]. One of the few studies to work with a dynamic model of Open Innovation has been established [22]. In this work, the authors determine the optimal strategy of a firm when it has to choose between proprietary and Open Source software. Technically, their model is an optimal control problem for a firm in the market subject to the quality of its product as it evolves. Their analysis focuses on the essential role of research and development costs, and works to determine when it is convenient to open the source code for the firm. However, these studies all think about single choice, neglect interaction in long period. Evolutionary games promise richer prediction than orthodox game models, evolutionary game analysis of open innovation may turns out new outcomes [23,24].

What leads a firm to choose a policy of Open Innovation? The establishment of partnerships is an essential issue. The question is whether outside partners will alter their choices. In this paper, we will take into consideration costs sharing and excess benefits between firms and their outside partners, Since the reviewed literature either builds on the static game theory, or on optimal control, without strategic interaction among firms, we adopted a differential game. This article establishes an evolutionary game model. It analyzes different equilibrium results, and explores optimal incentive and punishment schemes between firms and outside partners.

Our study contributes to the open innovation literature by providing new insights on collaboration league form, introducing evolutionary game analysis makes out different outcomes. Additionally, we also contribute to game theory by adding to the body on knowledge on how companies can benefit from utilizing open innovation activities. From a overall perspective, our study provides new insights to mangers in companies and governors about how they can allocate limited resources for practicing open innovation and share innovation spillovers to achieve and sustain collaborated innovation.

The rest of article is organized as follows. Next, we will outline the setup of our model. In the third section, the analytical study of equilibrium are described. Section 4 subsequently presents the results and discussions on punishment case. Conclusions, limitations and suggestion for future studies are offered in the final section.

II. THE SETUP

Whether or not firms implement Open Innovation could be considered as the results of mutual games between firms and outside partners. They can adopt strategic alliance, joint ventures, technology transfer or outsourcing research in form of Open Innovation. They can also stick to the traditional closed innovation by their own resources. Given incomplete information and limited rationality of game players, it's difficult for players to ensure that their choice of strategies is the best. In the innovation process, the players need to repeat games to look for better strategy by learning.

Based on the nature of the issue, we have two assumptions to simplify the situation:

1) Consider the market is only composed by two firms, denoted as firm 1 and firm 2. Each firm has two strategies to choose from open innovation and closed innovation. If the firm chooses closed innovation, it have to bare R&D cost by itself and get product wholly. If the firm chooses open innovation, it will share product as well as costs.

2) Revenue and costs vary by firms' choice. If both firms choose closed innovation, they get benefits from different new products, denoted as π_1 and π_2. If both firms choose open innovation, they can get excess benefits $\Delta\pi$, besides π_1 and π_2. The firm can get $\alpha\Delta\pi$, the outside partner will get $(1-\alpha)\Delta\pi$, α represents excess benefits allocation ratio; the costs c will shared by ratio β, the firm bares costs $(1-\beta)c$, the outside partner bares . If they choose different strategies, the player who adopts open innovation will share costs without excess revenue, the player of choosing closed innovation can get additional benefits r for technique spillover from other side.

All above is common knowledge. The costs and benefits matrix is shown in table 1.

TABLE 1. THE PAYOFF MATRIX OF TWO FIRMS

		Firm 2	
		Open innovation	Closed innovation
Firm 1	Open innovation	$\pi_1+\alpha\Delta\pi-\beta c$, $\pi_2+(1-\alpha)\Delta\pi-(1-\beta)c$	$\pi_1-\beta c$, π_2+r
	Closed innovation	π_1+r, $\pi_2-(1-\beta)c$	π_1,π_2

III. EQUILIBRIUM ANALYSES

1. The basic concept of the evolutionary game theory

The evolutionary game theory is the combination of game theory and dynamic evolution. It differs from game theory to focus on the static equilibrium and comparative static equilibrium, but to emphasize the dynamic equilibrium [25]. Currently, evolutionary game theory has been widely applied in cooperative behavior and strategy selection problem [26,27]. The core content of the evolutionary game model is the evolutionary stable strategy(ESS), it characterizes the dynamic convergence process to the steady state. The replicator dynamic equations describe the steady state of the evolutionary game. The dynamic pace of change is expressed as $dx(t)/dt = x(U_s-\overline{U})$, x is the proportion of the individuals who choose the policy s, U_s is the expected revenue of the choose the strategy s, $dx(t)/dt$ is the average benefit of all strategies for the player, shows the change of ratio that select the strategy s over time.

2 Evolutionary game analysis of open innovation of simplified case

In order to simplify the problem, we assume that firm 1 adopting open innovation accounts for x , while firm 1 adopting closed innovation accounts for $1-x$. Firm 2 adopting open innovation accounts for y , while firm 1 adopting closed innovation accounts for $1-y$. The respective expectation values of "open innovation" and "closed innovation" strategy for firm 1 are u_{1o} and u_{1c} . Governments' average value is $\overline{u_1}$.

$$u_{1o} = y\alpha\Delta\pi + \pi_1 - \beta c \qquad (1)$$

$$u_{1c} = yr + \pi_1 \qquad (2)$$

$$\overline{u_1} = x[y(\alpha\Delta\pi - r) - \beta c] + yr + \pi_1 \qquad (3)$$

In the same way, The respective expectation values of "open innovation" and "closed innovation" strategy for firm 2 are u_{2o} and u_{2c} . Governments' average value is $\overline{u_2}$.

$$u_{2o} = x(1-\alpha)\Delta\pi + \pi_2 - (1-\beta)c \qquad (4)$$

$$u_{2c} = xr + \pi_2 \qquad (5)$$

$$\overline{u_2} = y\{x[(1-\alpha)\Delta\pi - r] - (1-\beta)c\} + xr + \pi_2 \qquad (6)$$

Further, the replicator dynamics equation to choose open innovation are as follows.

$$\frac{dx}{dt} = x(u_{1o} - \overline{u_1}) = x(1-x)[y(\alpha\Delta\pi - r) - \beta c] \qquad (7)$$

$$\frac{dy}{dt} = y(u_{2o} - \overline{u_2}) = y(1-y)\{x[(1-\alpha)\Delta\pi - r] - (1-\beta)c\} \qquad (8)$$

According to state of ESS, when $\alpha\Delta\pi - r > 0$ and $(1-\alpha)\Delta\pi - r > 0$,we get conclusions as follows:

① If $y = \frac{\beta c}{\alpha\Delta\pi - r}$,then $\frac{dx}{dt} \equiv 0$,which means that all games are stable;

If $y > \frac{\beta c}{\alpha\Delta\pi - r}$, then $x = 1$,which means that all games are stable;

If $y < \frac{\beta c}{\alpha\Delta\pi - r}$,then $x = 0$,which means that all games are stable.

② If $x = \frac{(1-\beta)c}{(1-\alpha)\Delta\pi - r}$,then $\frac{dy}{dt} \equiv 0$,which means that all games are stable;

If $x > \frac{(1-\beta)c}{(1-\alpha)\Delta\pi - r}$,then $y = 1$,which means that all games are stable;

If $x < \frac{(1-\beta)c}{(1-\alpha)\Delta\pi - r}$,then $y = 0$,which means that all games are stable. the dynamic tendency and stability of firms population are shown in Figure1. The game has five equilibrium points: A(0,0), B(1,0),C(0,1), D(1,1), E($\frac{(1-\beta)c}{(1-\alpha)\Delta\pi - r}$, $\frac{\beta c}{\alpha\Delta\pi - r}$). E is saddle point.

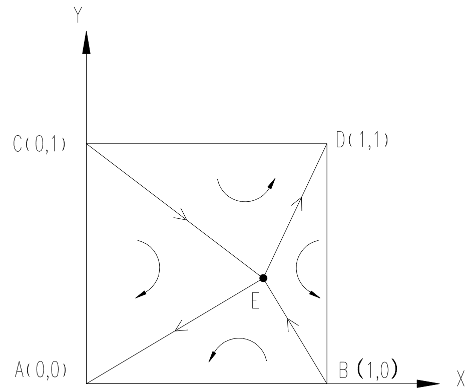

Figure 1. Populations evolutionary game route 1

According to Figure 1, if initial statement is located in area ABEC, the evolution system will converge to point A(0,0), it means firm 1 and firm 2 will both adopt closed innovation; if initial statement is located in area CDBE, the evolution system will converge to point D(1,1), it means firm 1 and firm 2 will both adopt open innovation.

3 Analysis of costs sharing and benefits allocation effect on open innovation

According to analysis of evolution equilibrium, although the optimal strategy is (open innovation, open innovation), stable strategies for firm 1 and firm 2 are (open innovation, open innovation) and (closed innovation, closed innovation). The tendency of evolution result is determined by size of region ABEC and region CDBE. If $S_{ABEC}<S_{CDBE}$, the probability of both firms adopting open innovation is bigger than that of closed innovation, if $S_{ABEC}>S_{CDBE}$, otherwise. If $S_{ABEC}=S_{CDBE}$, probability will be equal. According to Figure 1 , S_{ABEC} can be described as follows.

$$S_{ABEC} = \frac{1}{2}[\frac{\beta c}{\alpha\Delta\pi - s} + \frac{(1-\beta)c}{(1-\alpha)\Delta\pi - s}] \qquad (9)$$

According to equation (9), there are five variables influencing the area. We can get results by mathematical analysis.

Proposition 1: With the increase of R&D costs, the probability of both firms adopting open innovation is smaller.

Proof: according to equation (9),

$$\frac{\partial S_{ABEC}}{\partial c} = \frac{1}{2}[\frac{\beta}{\alpha\Delta\pi - s} + \frac{(1-\beta)}{(1-\alpha)\Delta\pi - s}] > 0$$. So is a monotonically increasing function of c. It means that with the increase of open innovation costs of both firms,

size of S_{ABEC} is bigger, the probability of system evolving to point A(0,0) gets bigger, the probability of both firms adopting open innovation is smaller.

Proposition 2: With the increase of excess benefits of open innovation, the probability of both firms adopting open innovation is bigger.

Proof: according to equation (9),

$$\frac{\partial S_{ABEC}}{\partial \Delta\pi} = -\frac{1}{2}\{\frac{\alpha\beta c}{(\alpha\Delta\pi - r)^2} + \frac{(1-\alpha)(1-\beta)c}{[(1-\alpha)\Delta\pi - r]^2}\} < 0$$

So S_{ABEC} is a monotonically decreasing function of . It means that with the increase of open innovation excess benefits, size of S_{ABEC} is smaller, the probability of system evolving to point D(1,1) gets bigger, both firms have stronger intention to adopt open innovation .

Proposition 3: With the increase of benefits of technique spillovers, the probability of both firms adopting open innovation is smaller.

Proof: according to equation (9),

$$\frac{\partial S_{ABEC}}{\partial s} = \frac{1}{2}\{\frac{\beta c}{(\alpha\Delta\pi - r)^2} + \frac{(1-\beta)c}{[(1-\alpha)\Delta\pi - r]^2}\} > 0$$

So S_{ABEC} is a monotonically increasing function of c. It means that with the increase of open innovation costs of both firms, size of S_{ABEC} is bigger, the probability of system evolving to point A(0,0) gets bigger, both firms lack motivation to adopt open innovation .

Proposition 4: There is a optimal ratio of excess benefits allocation, for the probability of both firms adopting open innovation is biggest.

Proof: according to equation (9),

$$\frac{\partial S_{ABEC}}{\partial \alpha} = \frac{1}{2}\{\frac{(1-\beta)c\Delta\pi}{[(1-\alpha)\Delta\pi - r]^2} - \frac{\beta c\Delta\pi}{(\alpha\Delta\pi - r)^2}\}$$

So impact is not monotonically. According to second derivative equation

$$\frac{\partial^2 S_{ABEC}}{\partial \alpha^2} = \frac{\beta c\Delta\pi^2}{(\alpha\Delta\pi - r)^3} + \frac{(1-\beta)c\Delta\pi^2}{[(1-\alpha)\Delta\pi - r]^3}\} > 0 \quad .$$

So it exists smallest value for S_{ABEC} . Let

$\frac{\partial S_{ABEC}}{\partial \alpha} = 0$,then $\alpha = \frac{r\sqrt{1-\beta} + \sqrt{\beta}(\Delta\pi - r)}{\Delta\pi(\sqrt{1-\beta} + \sqrt{\beta})}$, size of S_{ABEC} is smallest, the probability of system evolving to point D(1,1) gets biggest, both firms lack motivation to adopt open innovation .

Proposition 5: costs sharing ratio matching to excess benefits allocation ratio will help to firms adopting open innovation.

Proof: according to equation (9),

$$\frac{\partial S_{ABEC}}{\partial \beta} = \frac{1}{2}[\frac{c}{\alpha\Delta\pi - r} - \frac{c}{(1-\alpha)\Delta\pi - r}]$$

. So if $\alpha > \frac{1}{2}$,then $\frac{\partial S_{ABEC}}{\partial \beta} < 0$. S_{ABEC} is a monotonically decreasing function of costs sharing ratio . It means that only when firm 1 gets more excess benefits than firm 2, with the increase of sharing costs of firm 1, size of is smaller, the probability of system evolving to point D(1,1) gets bigger, both firms have stronger intention to adopt open innovation; if $\alpha < \frac{1}{2}$,the situation is quite opposite, with the decrease of open innovation costs of firm 1, system will more likely evolve to point D(1,1).

IV. Discussing the Punishment Scheme of Closed Innovation

In order to encourage enterprisers to take part in open innovation and avoid free-riding behavior, it will be helpful to design punishment scheme. we assume that before the cooperation firm 1 and firm 2 have signed contract to clarify each one's commitment to open innovation. when innovation activities is over, the firm which didn't choose open innovation will get punishment of paying P to the other firm, the other assumption is the same as basic model. All above is common knowledge. The costs and benefits matrix is shown in table II.

TABLE II. THE PAYOFF MATRIX OF PUNISHMENT SCHEME

		Firm 2	
		Open innovation	Closed innovation
Firm 1	Open innovation	$\pi_1 + \alpha\Delta\pi - \beta c$, $\pi_2 + (1-\alpha)\Delta\pi - (1-\beta)c$	$\pi_1 - \beta c + P$, $\pi_2 + r - P$
	Closed innovation	$\pi_1 + r - P$, $\pi_2 - (1-\beta)c + P$	π_1, π_2

we assume that firm 1 adopting open innovation accounts for x , while firm 1 adopting closed innovation accounts for $1-x$. Firm 2 adopting open innovation accounts for y , while firm 1 adopting closed innovation accounts for $1-y$. The respective expectation values of "open innovation" and "closed innovation" strategy for firm 1 are u_{1o} and u_{1c} . Governments' average value is $\overline{u_1}$.

$$u'_{1o} = y(\alpha\Delta\pi - P) + \pi_1 - \beta c + P \quad (10)$$

$$u'_{1c} = y(r - P) + \pi_1 \quad (11)$$

$$\overline{u'_1} = x[y(\alpha\Delta\pi - r) - \beta c + P] + y(r - P) + \pi_1 \quad (12)$$

In the same way, The respective expectation values of "open innovation" and "closed innovation" strategy for firm 2 are u_{2o} and u_{2c} . Governments' average value is $\overline{u_2}$.

$$u'_{2o} = x[(1-\alpha)\Delta\pi - P] + \pi_2 - (1-\beta)c + P \quad (13)$$

$$u'_{2c} = x(r - P) + \pi_2 \quad (14)$$

$$\overline{u'_2} = y\{x[(1-\alpha)\Delta\pi - r] - (1-\beta)c + P\} + x(r - P) + \pi_2 \quad (15)$$

Further, the replicator dynamics equation to choose open innovation are as follows.

$$\frac{dx}{dt} = x(u'_{1o} - \overline{u'_1}) = x(1-x)[y(\alpha\Delta\pi - r) - \beta c + P] \quad (16)$$

$$\frac{dy}{dt} = y(u'_{2o} - \overline{u'_2}) = y(1-y)\{x[(1-\alpha)\Delta\pi - r] - (1-\beta)c + P\} \quad (17)$$

As in the above analysis, we only discuss situation when , .According to state of ESS, we have to explore two situation.

① when $P > \beta c$ and $P > (1-\beta)c$, the game has four equilibrium points: A(0,0), B(1,0), C(0, 1), D(1,1). The dynamic tendency and stability of firms population are shown in Figure2, according to the figure, point D is saddle point.

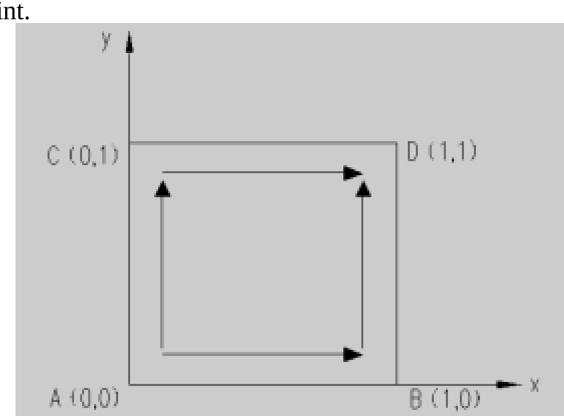

Figure 2. Populations evolutionary game route 2

Proposition 6: when taking count into punishment scheme, only the punishment is enough to miss the cooperator's loss, $P > \max\{\beta c, (1-\beta)c\}$ in the long terms the game's evolutional outcome will converge to {open innovation, open innovation}

In the initial situation both firms don't choose open innovation, the market competition impels firms to open innovation gaining extra revenue by designing new product in shorter time, then firms will both alter their choice to open innovation. When one firm chooses closed innovation while the other choose the opposite innovation mode, the one opting closed innovation choice will get server loss because of high punishment, so it will turn to open innovation in the next time, at the same time, the one choosing open innovation will get excess revenue from punishment, which impetus it to insist on open innovation in the later game. So in the long term, both firms will choose open innovation in the game, and they will share the excess revenue from the right choices.

② when $P < \beta c$ and $P < (1-\beta)c$, the game has four equilibrium points: A(0,0), B(1,0), C(0, 1), D(1,1), E($\frac{(1-\beta)c - P}{(1-\alpha)\Delta\pi - r}$, $\frac{\beta c - P}{\alpha\Delta\pi - r}$). E is saddle point.

The dynamic tendency and stability of firms population are shown in Figure3, according to the figure, point E is saddle point.

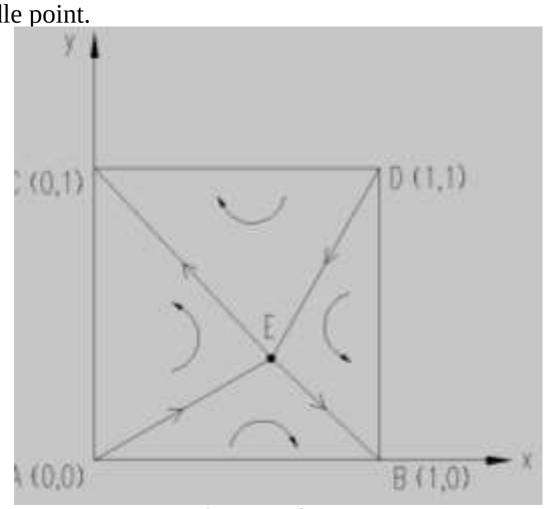

Figure 3. Populations evolutionary game route

According to Figure 3, if initial statement is located in area ABEC, the evolution system will converge to point A(0,0), it means firm 1 and firm 2 will both adopt closed innovation; if initial statement is located in area CDBE, the evolution system will converge to point D(1,1), it means firm 1 and firm 2 will both adopt open innovation. According to analysis of evolution equilibrium, although the optimal strategy is (open innovation, open innovation), stable strategies for firm 1 and firm 2 are (open innovation, open innovation) and (closed innovation, closed innovation). The tendency of evolution result is determined by size of region ABEC and region CDBE. If $S_{ABEC}<S_{CDBE}$, the probability of both firms adopting open innovation is bigger

than that of closed innovation, if $S_{ABEC}>S_{CDBE}$, otherwise. If $S_{ABEC}=S_{CDBE}$, probability will be equal. According to Figure 1 , S_{ABEC} are as follows.

$$S_{ABEC}=\frac{1}{2}[\frac{\beta c-P}{\alpha\Delta\pi-s}+\frac{(1-\beta)c-P}{(1-\alpha)\Delta\pi-s}] \tag{18}$$

According to equation (18), there are five variables influencing the area. We can get results by mathematical analysis.

Proposition 7: With the increase of punishment P, the probability of both firms adopting open innovation is greater.

Proof: according to equation (18),

$$\frac{\partial S_{ABEC}}{\partial c}=-\frac{1}{2}[\frac{1}{\alpha\Delta\pi-s}+\frac{1}{(1-\alpha)\Delta\pi-s}]<0 \quad .$$

So is a monotonically increasing function of c. It means that with the increase of open innovation costs of both firms, size of S_{ABEC} is smaller, the probability of system evolving to point D(1,1) gets bigger, the probability of both firms adopting open innovation is greater.

From Proposition 6 and Proposition 7, we get breakpoint of punishment, which is $\max\{\beta c,(1-\beta)c\}$, when the punishment don't reach this threshold, it should be greater to promote popularity of open innovation, once it passes the threshold, there is no need to set greater punishment, for in this situation open innovation is the last evolutional equilibrium.

V. CONCLUSION

In this paper, we analyzed costs and benefits effect on innovation behavior of firms based on evolutionary game theory. Through the research on organization which composed by two companies, we found that decrease total costs of innovation cooperation would promote open innovation strategies become the ultimate evolutionary stable strategy, as well as that improve excess benefits of innovation cooperation. And decreasing technique spillover or controlling ride-off behavior is essential to boot open innovation. Then we consider there exists an optimal excess benefits allocation, so that firms tend to adopt open innovation strongest. With the increase of punishment, the probability of both firms adopting open innovation is greater.

Our research extends and contributes to the literature in three main ways. First we extend the findings of open innovation by accounting for the cost and revenue sharing scheme of open innovation versus closed innovation. We find that firms prefer to open innovation in the long term in some situations. Second, we introduce evolutionary game to open innovation analysis, and makes out meaningful outcomes. Third, we enrich game theory by adding to the body on knowledge on how companies can benefit from utilizing open innovation activities. It's helpful for mangers in companies and governors to allocate limited resources for practicing open innovation and share innovation spillovers to achieve and sustain collaborated innovation.

Nevertheless, we leave ample opportunities for further research. Our article assumed that the enterprises are homogeneous and ignore the difference between them. If fact , the status of each firm is not consistent. Because of different absorbing capacity, firms will get different revenues from same technique spillover. We suggest that the future research takes more explicit account of heterogeneity of firms. It will, however, be challenging to find suitable measures in the game.

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