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Influencing factors in the application of RFID technology in the supply chain

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ABSTRACT
This article analyzes the obstacles in the application of the Internet of Things in the supply chain by means of evolutionary game theory. Through modeling, the game payoff matrix of core enterprises and suppliers as well as their replicator dynamic equations are obtained. Subsequently, an analysis of two populations that adopt the key technology of the Internet of Things, radio frequency identification (RFID), is conducted through replicator dynamics. The two populations achieve an evolutionarily stable strategy through continuous imitation and adjustment to the strategy. Furthermore, through the analysis of relevant parameters, the influence on the RFID application strategy selected by core enterprises and suppliers of factors such as implementation risk, tag cost, system cost, maintenance cost, compelling force of core enterprises, and expected return, among others, is verified.

Introduction

The Internet of Things refers to radio frequency identification (RFID) devices and other information sensing equipment in combination with the Internet. It is a network into which the "things" in life will be incorporated by exchanging information and communication to achieve intelligent identification, location, tracking, monitoring, and management. The application of RFID is the key technology of the Internet of Things. Such application has significantly improved the competitiveness of the supply chain. Local and international research on how the Internet of Things is used in the supply chain is mainly concentrated on the following aspects: the application of (1) RFID technology and (2) a variety of key technologies of Internet of Things in all links of the supply chain and other areas. Generally, RFID is used to automate the tracking of pallets, cases, and individual products, as well as reusable assets such as bins and containers throughout the supply chain (Tajima 2012). Results of a survey conducted by Cheng et al. (2014) indicate that the application of RFID systems on roads is very attractive and even essential for future transportation systems and can improve roadway safety and efficiency. Jones et al. (2007) demonstrated the cost-effectiveness of using an RFID system to track calibrated tools throughout a production facility. RFID technology can reduce the lead time of the supply chain (Chew et al. 2013). After adoption of RFID technology, the interval

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of the contract parameters will shrink, the retailer's optimal order quantity will be reduced, and the supplier's wholesale prices will rise (Fan et al. 2013). Aiming at information management in the pork supply chain, a warning information system based on the Internet of Things has been established. The system uses RFID and wireless sensor networks to realize the automatic sensing of pig growth and pork processing and marketing. The system also tracks the shipment environment and the geographical location of the pork in real time. Moreover, the system can reduce the logistics costs and improve circulation efficiency (Ma and Ni 2012). Supply chains are increasingly virtualized in response to market challenges and to opportunities offered by affordable new technologies. The process through which the Internet of Things concept can be used to enhance virtualization of supply chains in the floricultural sector is an interesting question (Verdouw et al. 2013). However, the popularization of RFID in the supply chain has been inconsistent. Leung et al. (2014) conducted a case study of 88 reported RFID applications and provided a clear view of the RFID implementation landscape. The authors suggested that organizations often mindlessly adopt RFID applications that are misaligned with their supply chain strategies. Zhu et al. (2012) cited a study by Eurostat, the statistical office of the European Union, which showed that only 3% of European Union companies have used RFID technology. Wei et al. (2015) showed that most Chinese firms have adopted RFID applications without fully utilizing its benefits. Based on these ideas, the current article presents the results of our analysis of the obstacles in the application of RFID in the supply chain. The results were derived through the use of evolutionary game theory with the aim of promoting the application of RFID in the supply chain. RFID has achieved widespread success in various domains, including animal identification, asset tracking, highway toll collection, smart home appliances, supply chain management, and surveillance systems (Zhang et al. 2015).

Applicability of evolutionary game theory

At present, classical game theory is the common model used when people apply game theory to analyze the influencing factors in the strategic decision between core enterprises and suppliers. Whang (2010) used a stylized game-theoretic model to study the incentives behind the adoption of RFID in a supply chain. Gaukler (2011) used the Stackelberg game framework to study a few of the operational benefits of item-level RFID and how these benefits may affect the dynamics of the retailer–manufacturer interaction. W. Xu et al. (2015) established a three-stage supply chain model that involves two suppliers performing Stackelberg games (i.e., manufacturer and retailer) to elaborate the effect of RFID investment on a complex product. However, the sufficient and necessary conditions of classical game theory require the game participants to be fully rational and the information to be complete and symmetrical. No supply chain satisfies the two aforementioned presumed conditions in the real society. Compared with classical game theory, evolutionary game theory is a game with bounded rationality that does not require fully rational game participants and complete and symmetrical information because of the intractability of natural decision problems and the finite computational resources available. Evolutionary game theory has been proven invaluable in helping to explain many complex and challenging aspects of social economics. Based on the discussion above, the significance of evolutionary game analysis under the condition of bounded rationality is not a prediction on a one-off game result or a short-term economic equilibrium but an analysis and prediction for the long-term, stable relations of economics and society. Additionally, evolutionary game theory can be a tool to predict the current situation of social and economic problems with a long history.

In natural populations, the fitness of an organism often depends both on its own strategy and on the strategies of other population members (McNamara 2013). Evolutionary game theory is a result of the application of game theory to biological evolutionary contexts. Evolutionary dynamics provide a powerful set of tools for investigating a range of issues in biology and the social sciences (Hodgson and Huang 2012; Rand and Nowak 2012). The theory has been utilized in other areas of social science, such as business, culture, and economics (Antocia et al. 2014; G. S. Cai and Ned 2009; Mattei 2014). In evolutionary game theory, evolution and natural selection replace the rationality of the actors appropriately (Hummert et al. 2014). The theory studies the evolution process of the whole system, strategy, and distribution characteristics when limited rational individuals of populations are repeating a game process (Young 2011). The dynamic process provides the coordination device that brings beliefs in line with behavior through the individual learning process. The process also provides the context for play that may be useful in assessing multiple equilibriums. Furthermore, the dynamic process views equilibrium as the outcome of an adjustment process and a realistic version of human interactions (Fudenberg and Levine 1997; Samuelson 1997). An attempt has been made to find a comprehensive mathematical framework to investigate the problems of well-posedness and asymptotic analysis for fully nonlinear evolutionary game theoretic models (Cleveland and Ackleh 2013; Veloz et al. 2014).

With the application of RFID, companies can learn from other companies' behaviors and adjust their own strategies constantly to achieve a stable state of evolution.

Model descriptions

Model assumption

With the development of RFID technology and the gradual deepening of information acquisition, the concept of Internet of Things is becoming gradually clear and the Internet of Things has become a new way to help improve business economics. However, the application of RFID is still developing slowly, which has become a typical industrial phenomenon. We construct a model to analyze the obstacles in the application of the Internet of Things. Based on literature research, implementation risk (Hellstrom et al. 2011; Lim and Chang 2009), tag cost (Gaukler 2011), system cost (Harder and Voss 2012), and expected return (Jonathan et al. 2008) are identified as the main obstacles. Additionally, we have completed field research and in-depth interviews with a number of enterprises that deal with agricultural products, automobiles, petrochemicals, and wine. Results indicate that the market control force, including the behavior of firms in the marketplace as determined by market rules, maintenance cost, and enterprise size, is an additional main factors.

First, we illustrate the model assumptions.

1. There are numerous supply chains having horizontal orientation, as well as core enterprise population and supplier population with vertical orientation in the supply chain community.
2. Markets are classified into two types. The first type pertains to markets whose core enterprise has a strong compelling force (e.g., Wal-Mart). The second one signifies markets whose core enterprise has a relatively general control force.
3. The core enterprises whose market compelling force is strong can force suppliers to apply RFID. Otherwise, these enterprises cancel the suppliers' qualification if the suppliers take a negative attitude.

Table 1. Symbolic variables involved in the model and their descriptions and units.

Symbols	Descriptions	Units
π_m	Total returns of core enterprises	$
π_s	Total returns of suppliers	$
C	Fixed investment cost of the RFID system; we suppose $C = C_0 + rp$	$
C_m	Maintenance cost of the RFID system	$
C_e	Other relevant costs (including business processes, services, and training and education)	$
C_r	Cost of RFID tags	$
C_0	Cost of RFID hardware, middleware, and software	$
α	Sizes of core enterprises	Constant
β	Sizes of suppliers	Constant
R	Average return of RFID in the supply chain	$
R_0	Annual average return of the daily cooperation of core enterprises and suppliers	$
r	Risk of RFID implementation, which is the possible loss caused by the use of RFID technology. rp is the cost of the implementation risk for the enterprise	Constant
p	Cost coefficient of the risk, which implies that the implementation risk is directly proportional to the fixed investment cost of the RFID system	$
m	Expected returns rate on RFID of core enterprises	$
n	Expected returns rate on RFID of suppliers	$
k	Proportion that the core enterprises share, where $k \in [0, 1]$. The cost of the tag is also distributed according to k and $(1 - k)$ ratios	Constant, $k \in [0, 1]$
x	Proportion of the core enterprise population adopting the implement strategy	Constant, $x \in [0, 1]$
y	Proportion adopting the implement strategy in the supplier population	Constant, $y \in [0, 1]$

4. When the compelling force of the core enterprise is relatively general, an evolutionary game exists between the core enterprise and the market suppliers, and the results are influenced by other factors.
5. When the enterprises and suppliers implement RFID systems simultaneously, the return on implementation and the cost of system construction are allocated in accordance with the scale of the enterprises.
6. Many RFID application cases, such as those of Wal-Mart, Metro Group, and Amazon (Ali 2012; Feng et al. 2014; Roberti 2012), are used. The model assumes that enterprises that do not implement RFID experience a specific potential loss, namely, $1 - a$ of each enterprise's expected return on RFID. If only one party implements RFID, the implementing party only gains a of the expected return, where $a \in (0, 1)$. The application of RFID will only benefit the implementing enterprises and their downstream enterprises. If only the suppliers implement RFID, the core enterprises still gain b of the income, where $b \in (0, 1)$ and $b < a$. In contrast, suppliers will gain nothing if only the core enterprises implement RFID.

Game revenue of core enterprises and RFID application of suppliers

There are two behavioral strategies used in applying RFID for two kinds of enterprises, namely, "implement" and "not implement." The symbolic variables involved in the model and their descriptions and units are shown in Table 1.

The RFID application's system consists of both the RFID network itself (hardware, software, tags, etc.) and everything that needs to accommodate the RFID network: personnel, information technology infrastructure, business processes, and the facilities in which the application will be installed.

Determining the cost of deploying and maintaining an RFID application is not a trivial matter, because the magnitude of your investment will depend on several factors that may or may not influence the cost of other components within the system.

Table 2. Game payoff matrix of core enterprises and suppliers.

		Suppliers	
		Implement	Not implement
Core enterprises	Implement	(π_{1m}, π_{1s})	(π_{2m}, π_{2s})
	Not implement	(π_{3m}, π_{3s})	(π_{4m}, π_{4s})

We consider the total cost of an RFID application from the following six aspects:

1. The cost of RFID hardware, middleware, and software.
2. The cost of RFID tags.
3. The cost of maintenance.
4. The cost of business processes.
5. The cost of services.
6. The cost of training and education.

In this model, the cost of business processes, the cost of services, and the cost of training and education are not sensitive factors. To simplify the model, we use C_e to symbolize the cost of business processes, services, and training and education.

Thus, we assume that $C_m = \lambda_1 C_0 + \lambda_2 C_r + C_e$, λ_1, λ_2 are the cost coefficients of the maintenance cost, which signifies that a large value of C_r, C_0 equals a large maintenance cost of the RFID system, where $\lambda_1, \lambda_2 \in (0, 1)$.

$C_r(i, f, t, q)$ is the cost of RFID tags, which depends on the type of tags t, the use of frequency, f, the volume of the order, q, and the amount of information, i, stored in it. Although a passive tag usually only contains a unique ID for the object on which it is affixed, some active read–write tags may contain more information. For example, in the food industry there are tags that include temperature sensors and can record the temperature of the product as it moves through the supply chain. In general, an increase in the cost of RFID tags is parallel with an increase in the value of t, f, i. In contrast, a high volume leads to lower cost of RFID tags.

The payoff matrix of the behavioral strategies portfolio of core enterprises and suppliers is shown in Table 2.

$$\begin{pmatrix} \pi_{1m} \\ \pi_{1s} \end{pmatrix} = \begin{pmatrix} (1-r)mR\dfrac{\alpha}{\alpha+\beta} - (C_0 + pr)\dfrac{\alpha}{\alpha+\beta} - kC_r(f, i, t, q) - C_m\dfrac{\alpha}{\alpha+\beta} \\ (1-r)nR\dfrac{\beta}{\alpha+\beta} - (C_0 + pr)\dfrac{\beta}{\alpha+\beta} - (1-k)C_r(f, i, t, q) - C_m\dfrac{\beta}{\alpha+\beta} \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} \pi_{2m} \\ \pi_{2s} \end{pmatrix} = \begin{pmatrix} a(1-r)mR\dfrac{\alpha}{\alpha+\beta} - (C_0 + rp)\dfrac{\alpha}{\alpha+\beta} - C_r(f, i, t, q) - C_m \\ -a(1-r)nR\dfrac{\beta}{\alpha+\beta} - R_0 \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} \pi_{3m} \\ \pi_{3s} \end{pmatrix} = \begin{pmatrix} -(a-b)(1-r)mR\dfrac{\alpha}{\alpha+\beta} \\ a(1-r)nR\dfrac{\beta}{\alpha+\beta} - (C_0 + rp)\dfrac{\beta}{\alpha+\beta} - C_r(f, i, t, q) - C_m \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} \pi_{4m} \\ \pi_{4s} \end{pmatrix} = \begin{pmatrix} -a(1-r)mR\dfrac{\alpha}{\alpha+\beta} \\ -a(1-r)nR\dfrac{\beta}{\alpha+\beta} \end{pmatrix}. \tag{4}$$

Core enterprise population and replicator dynamics of the supplier population

The proportion of the core enterprise population adopting the implement strategy is defined as x, and the proportion adopting the not implement strategy is $1-x$ (Weibull 1997). The proportion adopting the implement strategy in the supplier population is y, and the proportion adopting the not implement strategy is $1-y$, where $x, y \in [0,1]$. The expected return of adopting the implement and not implement strategies (U_{mY} and U_{mN}) in the core enterprise population and the average return of the entire population of core enterprises ($\bar{U}_m$) can be described as follows:

$$U_{mY} = y\pi_{1m} + (1-y)\pi_{2m} \tag{5}$$

$$U_{mN} = y\pi_{3m} + (1-y)\pi_{4m} \tag{6}$$

$$\bar{U}_m = xU_{mY} + (1-x)U_{mN}. \tag{7}$$

Similarly, the expected return of adopting the implement and not implement strategies (U_{sY} and U_{sN}) in the supplier population and the average return of the entire supplier population ($\bar{U}_s$) can be described as

$$U_{sY} = x\pi_{1s} + (1-x)\pi_{3s} \tag{8}$$

$$U_{sN} = x\pi_{2s} + (1-x)\pi_{4s} \tag{9}$$

$$\bar{U}_s = yU_{sY} + (1-y)U_{sN}. \tag{10}$$

The replicator dynamics equation (Cressman and Tao 2014) of the proportion of the application of the implement strategy in core enterprises is illustrated as

$$\frac{dx}{dt} = x(U_{mY} - \bar{U}_m) = x(1-x)\left\{y\left[b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m\right] + (1-r)mR\frac{\alpha}{\alpha+\beta} - (C_0+rp)\frac{\alpha}{\alpha+\beta} - C_r - C_m\right\}. \tag{11}$$

Likewise, the replicator dynamics equation of the proportion of the application of the implement strategy in suppliers is illustrated as

$$\frac{dy}{dt} = y(U_{sY} - \bar{U}_s) = y(1-y)\left\{x\left[a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + \frac{\alpha}{\alpha+\beta}C_m + R_0\right] + \left[(1-r)nR\frac{\beta}{\alpha+\beta} - (C_0+rp)\frac{\beta}{\alpha+\beta} - C_r - C_m\right]\right\}. \tag{12}$$

The replicator dynamics equation embodies the individual learning speed and direction. If the replicator dynamics is 0, then the rate of learning is 0, which indicates that the game has reached a relative status of stability and balance (D. S. Cai et al. 2013). According to the Friedman algorithm, if we let Equations (11) and (12) be 0 and then obtain the replicator dynamics Equation (13), the system's population dynamics can be constituted as

$$\begin{cases} \dfrac{dy}{dt} = 0 \\ \dfrac{dx}{dt} = 0 \end{cases}. \tag{13}$$

Solving the replicator dynamics Equation (13), we can obtain five equilibrium points of the evolutionary game, namely, (0, 0), (0, 1), (1, 0), (1, 1), and (x_0, y_0) in the plane $M = \{(x,y)|0$

$\leq x, y \leq 1\}$, where

$$x_0 = \frac{-(1-r)nR\frac{\beta}{\alpha+\beta} + (C_0 + rp)\frac{\beta}{\alpha+\beta} + C_r + C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + R_0 + \frac{\alpha}{\alpha+\beta}C_m} \tag{14}$$

$$y_0 = \frac{-(1-r)mR\frac{\alpha}{\alpha+\beta} + (C_0 + rp)\frac{\alpha}{\alpha+\beta} + C_r + C_m}{b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m}. \tag{15}$$

The question regarding whether all five equilibrium points are evolutionarily stable strategies (ESSs) is analyzed in the next section.

Model analyses

Analysis of the replicator dynamic equation of core enterprises

When $y = y_0$ in Equations (12) and (15), all games are stable (Graph (1), Figure 1) because $\frac{dx}{dt} = 0$. Core enterprises have no preference between implement or not implement.

When $y > y_0$, games are stable when $x = 0$ and $x = 1$. Suppose that $F(x) = \frac{dx}{dt}$; then according to the Lyapunov's first method (G. Z. Xu 2000), the game is in ESS if $\frac{dF(x)}{dx} < 0$. Given that $\frac{dF(x)}{dx} < 0$ at point $x = 1$ and $\frac{dF(x)}{dx} > 0$ at point $x = 0$, the ESSs are therefore achieved when $x = 1$. If the initial proportion of the supplier population who chooses the strategy of implement exceeds y_0, then the decision making of the core enterprise population is affected, driving the population to adopt the implement strategy gradually. As time goes by, x evolves into point $x = 1$, which indicates that all of the core enterprise populations adopt the implement strategy. This phenomenon affects the value of y_0, which is largely subject to the enterprise scale, implementation risk, fixed investment costs, tag cost, and other factors of the two populations (see Graph (2) of Figure 1).

Although games are also stable at both points $x = 0$ and $x = 1$ when $y < y_0$, $\frac{dF(x)}{dx} < 0$ at point $x = 0$, and $\frac{dF(x)}{dx} > 0$ at point $x = 1$. The ESSs are achieved when $x = 0$. Similarly, the game evolves into point $x = 0$; namely, if the initial proportion of the supplier population who chooses the strategy of implement is less than y_0, then the decision making of the core enterprise population is affected, driving the population to adopt the not implement strategy gradually. As time goes by, x evolves into point $x = 0$, which indicates that all of the core enterprise population adopts the not implement strategy. This phenomenon affects the value of y_0, which is largely subject to the enterprise scale, implementation risk, fixed investment costs, tag cost, and other factors of the two populations (see Graph (3) of Figure 1).

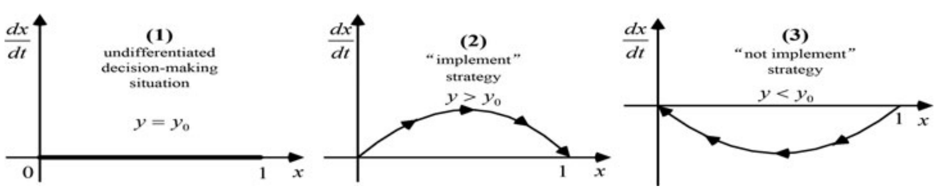

Figure 1. Replicator dynamics phase charts of core enterprises.

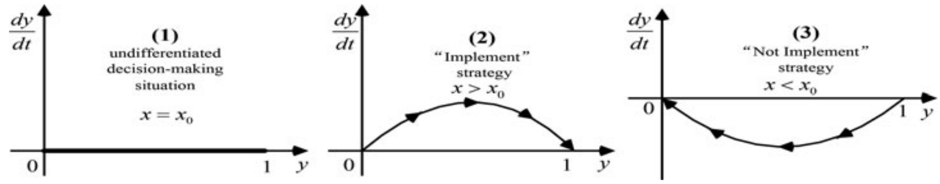

Figure 2. Replicator dynamics phase charts of suppliers.

Analysis of the replicator dynamic equation of suppliers

When $y = 1$ because $\frac{dy}{dt} = 0$ in Equations (12) and (14), all games are stable (Graph (1), Figure 2). Suppliers have no preference for either implement or not implement.

When $x > x_0$, games are stable if $y = 0$ and $y = 1$. Assume $G(y) = \frac{dy}{dt}$ when $x > x_0$, then $\frac{dG(y)}{dt} < 0$ at point $y = 1$, and $\frac{dG(y)}{dt} > 0$ at point $y = 0$. Therefore, the ESSs are achieved when $y = 1$. That is, if the initial proportion of the core enterprise population who chooses the strategy of implement exceeds x_0, then the decision making of the supplier population is affected, driving the population to adopt the implement strategy gradually. As time goes by, y evolves into point $y = 1$, which indicates that all of the supplier population will adopt the implement strategy. This phenomenon affects the value of x_0, which is largely subject to the enterprise scale, the implementation risk, fixed investment costs, tag cost, and other factors of the two populations (see Graph (2) of Figure 2).

When $x < x_0$, games are also stable if $y = 0$ and $y = 1$. However, $\frac{dG(y)}{dt} < 0$ at point $y = 0$, and $\frac{dG(y)}{dt} > 0$ at point $y = 1$. Therefore, the ESSs are achieved when $y = 0$. If the initial proportion of the core enterprise population who chooses the strategy of implement is less than x_0, then the decision making of the supplier population is affected, driving the population to adopt the not implement strategy gradually. As time goes by, y evolves into point $y = 0$, which indicates that all of the supplier population adopts the not implement strategy. This phenomenon affects the value of x_0, which is largely subject to the enterprise scale, implementation risk, fixed investment costs, tag cost, and other factors of the two populations (see Graph (3) of Figure 2).

Analysis of evolutionarily stable strategy of both sides in the game

Based on the above analysis of the replicator dynamics equations of core enterprise population and supplier population, both populations' replicator dynamic relationships in the same coordinate system are derived and shown in Figure 3.

Based on Figure 3 and the above analysis, point A(1, 1) and point C(0, 0), which represent the strategies (implement, implement) and (not implement, not implement), respectively, are the ESSs of the game. Both core enterprises and suppliers should choose implement or not implement at the same time. The final choice of the two players, whether (implement, implement) or (not implement, not implement), depends on the state of the system. If the primary state is in field I, the two players choose (implement, implement); if the primary state is in field III, the two players choose (not implement, not implement). This pattern indicates that the choice of strategy of the core enterprise population and the supplier population is highly dependent on the system's primary state.

The primary state game in field II or IV shown in Figure 3 is illustrated in Figure 4. When the primary state game is in field II_A or IV_A, the game enters field I. The process is easier

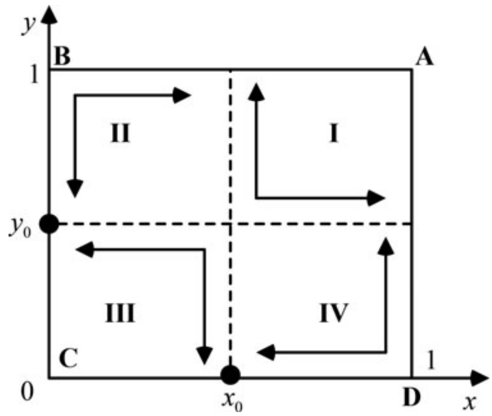

Figure 3. Replicator dynamics and stability of populations.

than when the primary state game enters field III from field II_A or IV_A. The ESS (not implement, not implement) can thus be achieved easily. Similarly, the primary state game in the fields II_C or IV_C enters field III. Consequently, the ESS (not implement, not implement) is achieved.

The strategy (implement, implement) is the desired state. In order to have as many enterprises as possible choose the implement strategy, the area of field I should be expanded as large as possible. Such expansion will cause x_0 and y_0 to be as small as possible. Therefore, the above goal can be achieved by adjusting the relevant parameters that compose x_0 and y_0. The influence of the relevant parameters on the state of the game is analyzed in the next section.

Factors affecting the evolution path and the simulation analysis

Factors affecting the evolution path

Influence of the proportion of tag cost allocation on the game strategy

In Equations (14) and (15), only k is set as variable. When k increases, x_0 decreases and y_0 increases. A decreasing x_0 indicates that the population eventually achieves the ESS of $y = 1$ (implement) in the case where the primary proportion selecting implement in the supplier

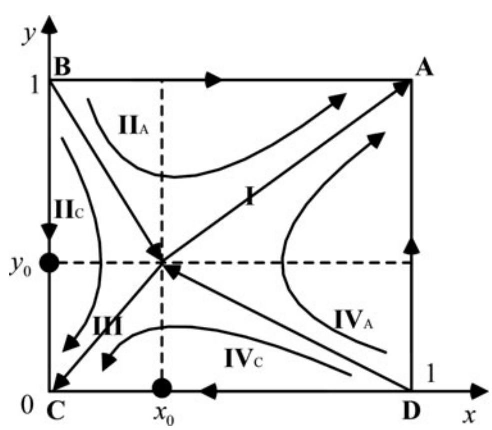

Figure 4. Strategy evolution of core enterprises and suppliers.

population is at a low level. An increasing y_0 indicates that the core enterprises cannot eventually achieve the evolutionarily stable strategy of $x = 1$ (implement) unless the primary proportion selecting implement in the core enterprises population is at a high level.

The above analysis illustrates that neither the core enterprises nor suppliers are willing to bear the cost of RFID tags. Any enterprise can apply RFID in the supply chain; thus, its downstream enterprises can enjoy the benefit of RFID at no cost.

Influence of the compelling force of core enterprises on game strategy

The compelling force of core enterprises comes from their dominant position and ability to decide whether to continue to cooperate with the suppliers who do not apply RFID, which will influence the return R_0 of suppliers. When R_0 increases, x_0 decreases accordingly and y_0 remains constant. The result shows that when the two populations' daily turnover increases, suppliers will choose to implement RFID, step by step. Such action is a result of the concern over losing the cooperation opportunity, even if the proportion of the primary adoption of the implement strategy is slight in the population. At this time, however, such a result does not have any effect on the strategy of the core enterprises.

Influence of implementation risk on the evolution of the population's game

According to Equations (14) and (15), we can obtain Equations (16) and (17), and x_0 and y_0 can be reformatted as

$$x_0 = -\frac{1}{a} + \frac{(C_0 + rp)\frac{\beta}{\alpha+\beta} + C_m\frac{\alpha}{a(\alpha+\beta)} + \frac{1}{a}R_0 + \frac{1}{a}kC_r + C_r + C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + R_0 + C_m\frac{\alpha}{\alpha+\beta}} \tag{16}$$

$$y_0 = -\frac{1}{b} + \frac{(C_0 + rp)\frac{\alpha}{\alpha+\beta} + \frac{1}{b}(1-k)C_r + \frac{\beta}{b(\alpha+\beta)}C_m + C_r + C_m}{b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + C_m\frac{\beta}{\alpha+\beta}} \tag{17}$$

In Equations (16) and (17), both x_0 and y_0 decrease, and the area of field I increases at the same time when the implementation risk r decreases. The population has a higher chance to achieve the ESS (implement, implement). Therefore, when the implementation risk decreases, core enterprises and suppliers are more likely to adopt the implement strategy.

Influence of expected return on the strategy of the population's game

In Equations (16) and (17), x_0 and y_0 will decrease accordingly, and the area of field I increases when the expected returns m and n increase. The chance of the game achieving the ESS (implement, implement) increases. Thus, when core enterprises and suppliers are more optimistic about an estimate for the expected return on RFID, their tendency will be to choose the implement strategy.

Influence of social average return on the strategy of the population's game

In Equations (16) and (17), x_0 and y_0 decrease simultaneously, and the area of field I increases when the population's average income level of the implementation of RFID R increases. The chance of the game achieving the ESS (implement, implement) increases. Therefore, the implementation return on RFID of the enterprises in the population that used RFID in the past will affect the individual choice of future strategy.

Influence of the cost of RFID system in the evolution of the population's game

In Equations (16) and (17), x_0 and y_0 decrease simultaneously, and the area of field I increases when the implementation cost of RFID system C decreases. The chance of the game achieving the ESS (implement, implement) increases. Therefore, reducing the implementation cost of the RFID system through a variety of ways is an effective way to expand the application scope of RFID.

Influence of the cost of RFID Tag on the evolution of the population's game

According to the Equations (14) and (15), we can obtain (18) and (19), and x_0 and y_0 can be reformatted as

$$x_0 = \frac{1}{k}\left[1 - \frac{(a+k)(1-r)nR\frac{\beta}{\alpha+\beta} - k(C_0+rp)\frac{\beta}{\alpha+\beta} + R_0 - (k-\frac{\alpha}{\alpha+\beta})C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + R_0 + \frac{\alpha}{\alpha+\beta}C_m}\right] \quad (18)$$

$$y_0 = \frac{1}{(1-k)}\left[1 - \frac{(1+b-k)(1-r)mR\frac{\alpha}{\alpha+\beta} - (1-\frac{\alpha}{\alpha+\beta}-k)C_m - (1-k)(C_0+rp)\frac{\alpha}{\alpha+\beta}}{b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m}\right] \quad (19)$$

When the cost of RFID tag C_r decreases, x_0 and y_0 decrease accordingly, and the area of field I increases, whereas the area of field III decreases. Achieving the ESS (implement, implement) is of small value for the primary proportions x and y of adopting the implement strategy in the core enterprises and suppliers. The reduction in the cost of tags improves the willingness of enterprises to utilize RFID.

Simulation analysis

This analysis determines the validity of implementing RFID. To describe the influence of parameters on the decision making between the core enterprise and the supplier populations effectively, we adopt a numerical simulation approach. The numbers are used for demonstration purpose only. We set the parameters as follows:

$$r = 0.3,\ R = 6000,\ R_0 = 5000,\ p = 1000,\ C_0 = 1200,\ \alpha = 0.8,\ \beta = 0.2,\ C_r = 700$$
$$C_m = 400,\ \lambda_1 = 0.2,\ \lambda_2 = 0.1,\ m = 0.6,\ n = 0.5,\ k = 0.3,\ a = 0.5,\ b = 0.25.$$

By changing the value of different parameters, we can obtain the simulation result of supply chain members in implementing RFID strategy changes and that of the quantitative analysis on the influence of various factors on the choice of enterprise strategy. Additionally, although the numerical value setting of these parameters has certain randomness, we run most of the different combinations of numerical values. We have determined that the change in the value of these parameters does not alter the changing trend of the simulation result and sensitivity analysis in this article.

Figure 5 shows the influence of the proportion k of tag cost allocation on the game strategy. The probability of achieving the ESS (implement, implement) decreases with an increase in the proportion k (see Figure 5).

Figure 6 shows the influence of implementation risk r on the evolution of the population's game. The probability of achieving the ESS (implement, implement) decreases with an increase in the implementation risk r (see Figure 6). However, the implementation risk r appears to have a larger influence on the decision making between the two populations than the proportion k. This observation indicates that the two populations are more sensitive to the implementation risk r than to the proportion k when they decide whether to implement RFID or not.

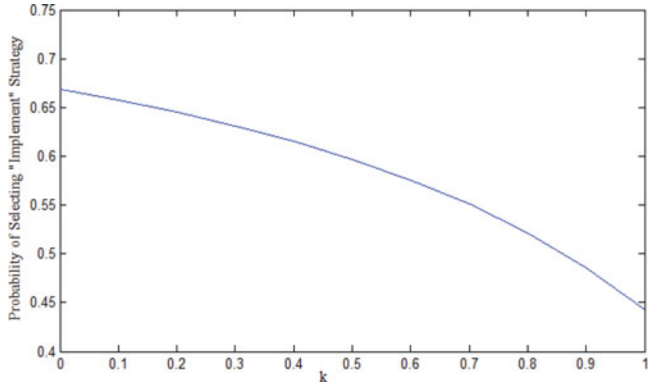

Figure 5. Influence of proportion *k*.

Figure 7 shows the influence of *a* and *b* on the evolution of the population's game. The probability of achieving the ESS (implement, implement) increases with the growing value of *a* and *b* (see Figure 7). We find that the value of *b* appears to have a larger influence on the decision making between the two populations than that of *a*. This observation indicates that when only the suppliers primarily implement RFID, the more income the core enterprises can benefit from it, the greater the probability of achieving the ESS (implement, implement) will be.

Subsequently, we study the influence of the expected returns rates *m* and *n* on the evolution of the population's game. An increase in the expected returns rate leads to an increasing probability of selecting the implement strategy (see Figure 8). Additionally, the expected returns rate *m* of the core enterprises tends to have a greater effect than the expected returns rate *n* of the suppliers. This observation implies that increasing the expected returns rate *m* of the core enterprises enables the two populations to achieve the ESS (implement, implement) easily.

The influence of the average return *R* of RFID and the annual average return R_0 on the evolution of the population's game is illustrated in Figure 9. An increase in the average return absolutely heightens the probability of selecting the implement strategy. The compelling force

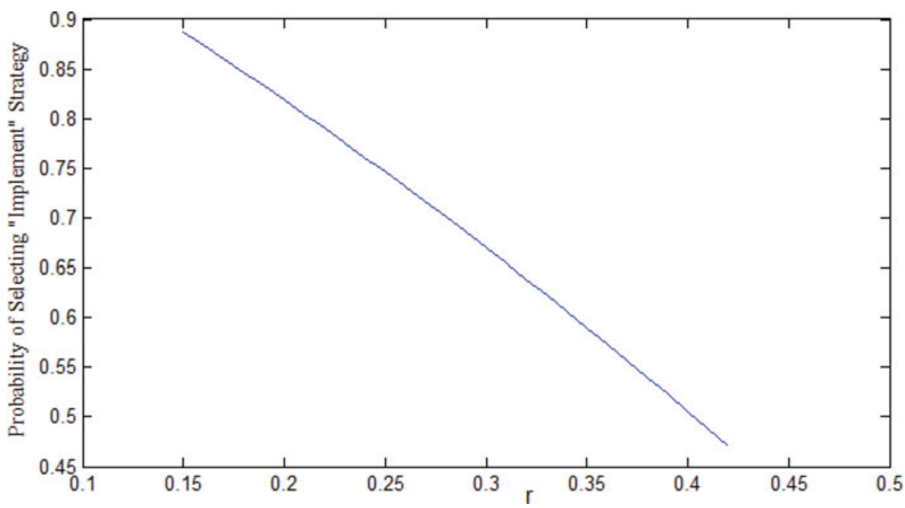

Figure 6. Influence of implementation risk *r*.

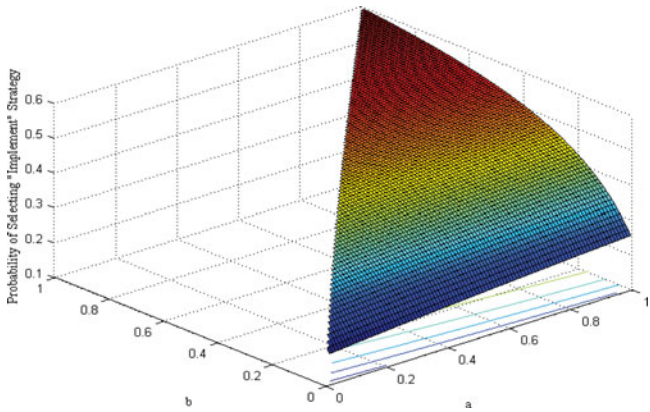

Figure 7. Influence of *a* and *b*.

of core enterprises emerges from their dominant position and ability to decide whether to continue cooperating with the suppliers who do not apply RFID, which influences the return R_0 of suppliers. Hence, the average return R_0 can represent the compelling force to a certain extent. Moreover, we note that the two populations are highly sensitive to the average return R of RFID. This observation signifies that although the core enterprises have a large compelling force, the best method to make the suppliers select the implement strategy is to improve the average return R of RFID. This situation is caused by the low growth rate of the probability of selecting the implement strategy with the average return R_0.

The sizes of core enterprises and suppliers can also affect the game strategy (see Figure 10). With a defined value of the size of core enterprises, we establish that the large size of the suppliers reduces the probability of achieving the ESS (implement, implement). In contrast, the probability increases as the size of core enterprises grows with a defined value of the size of the suppliers. Therefore, during the application of RFID technology, we have to break the "Domino trap." Only when more core enterprises join in the application of RFID technology will it be possible for the scale effect to form, which would allow thousands of core enterprises and suppliers to share costs. Changing several large-sized suppliers to small-sized suppliers also appears to be a good method to achieve the ESS (implement, implement).

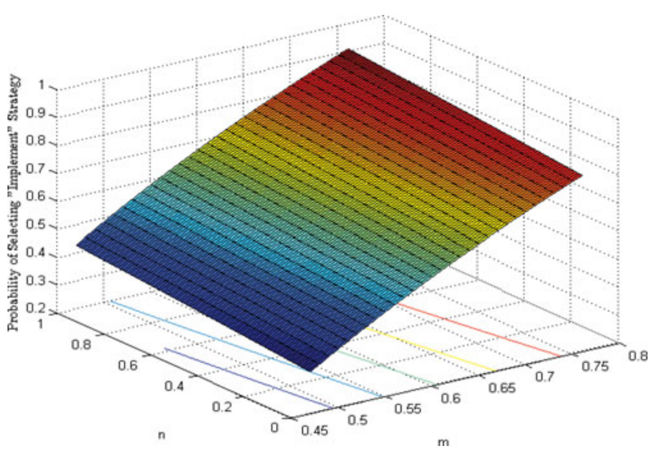

Figure 8. Influence of expected returns rate *m* and *n*.

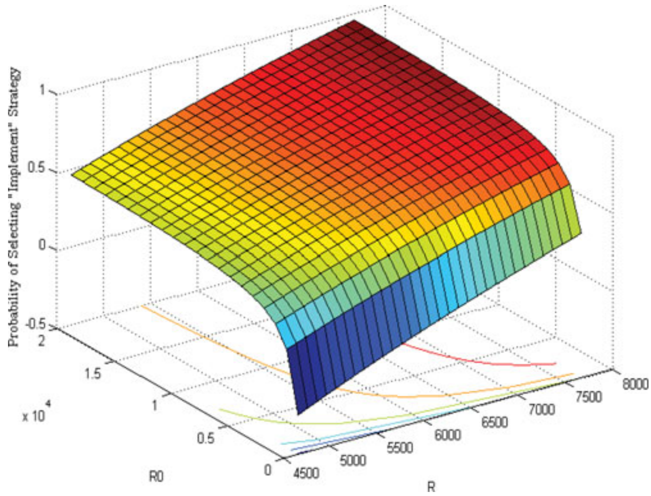

Figure 9. Influence of R and R_0.

Finally, we discuss the influence of the costs of RFID applications. Considering $C_m = \lambda_1 C_0 + \lambda_2 C_r + C_e$, we discuss the sensitivity of each parameter (C_0, C_r, C_m) on the decision making and their sensitivity analysis (see Figure 11). The relationship between these parameters is $C_m = \lambda_1 C_0 + \lambda_2 C_r + C_e$, and the parameters λ_1, λ_2 have a fixed value in this simulation. We can obtain different values of C_m by adjusting the value of C_e. The difference among the adjacent cross sections in Figure 10 is 300 units. Evidently, a low cost can encourage core enterprises and suppliers to apply RFID technology. Furthermore, a study on the contrast sensitivity of the costs (C_0, C_r, C_m) is exhibited in Figure 11 in which we note that the sensitivity ranking of the two populations is $C_r < C_0 < C_m$.

The sensitivity ranking indicates that the core enterprises and suppliers are more concerned with the maintenance cost than other costs. This signifies that reducing the maintenance cost is more effective than other cost reduction methods to achieve the ESS (implement, implement). Moreover, with an increase in the value of λ_1, λ_2, the maintenance cost has an extended effect on the decision making of the two populations. Considering $C_m = \lambda_1 C_0 + \lambda_2 C_r + C_e$, the maintenance cost can be reduced through the reduction of the RFID tag cost $C_r(i, f, t, q)$, C_0, or C_e.

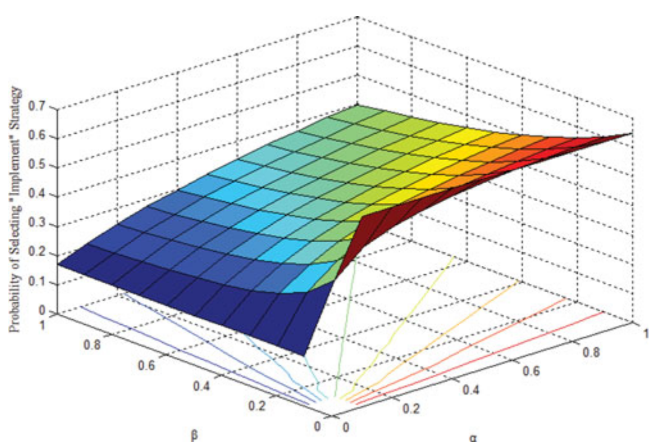

Figure 10. Influence of sizes of core enterprises and suppliers.

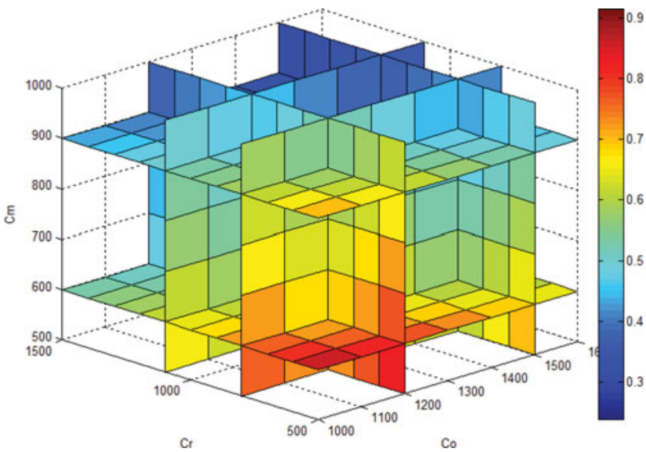

Figure 11. Influence of cost (C_0, C_r, C_m).

Conclusions

This article presented the results of a study on the use of the evolutionary game theory to analyze a replicator dynamics equation of the RFID application proportion of core enterprises and suppliers. The ESS was obtained and the relevant influencing parameters on population game state were analyzed. The following conclusions were derived:

1. The decreased cost of tags can improve the willingness of enterprises to employ RFID, but neither the core enterprises nor the suppliers are willing to bear the cost of RFID tag. Compared with the proportion k, the two populations are more sensitive to the implementation risk r, which is the possible loss caused by the implementation of RFID technology, than to the proportion k when they decide whether to implement RFID or not.
2. When core enterprises and suppliers are more optimistic about the estimate of the expected return on RFID, both players will tend to choose the implement strategy. The expected returns rate m of the core enterprises tends to have a greater effect than the expected returns rate n of the suppliers.
3. The implementation return of RFID of the enterprises in the population that have used RFID will affect the individual choice of future strategy and the compelling force of the core enterprises has a certain influence on the strategy of suppliers in relation to the application of RFID. Although the core enterprises have a large compelling force (according to R_0), the best method to make the suppliers select the implement strategy is to improve the average return R of RFID.
4. Only when more core enterprises join in the application of RFID technology will it be possible for the scale effect to form. Changing large-sized suppliers to several small-sized suppliers or the union of the core enterprises also appears to be a good method to achieve the ESS (implement, implement).
5. When only the suppliers implement RFID in a supply chain, the more income the core enterprises can benefit from RFID, the greater the probability of achieving the ESS (implement, implement) will be. This phenomenon indicates that if making the core enterprises select the implement strategy is difficult, we can start to implement the RFID policy from the supplier population and increase the probability of achieving the ESS (implement, implement).
6. Reducing the cost of an RFID system through a variety of ways is an effective way to broaden the application scope of the Internet of Things; for example, by changing the parameters λ_1,

λ_2. However, the core enterprises and suppliers are more concerned with the maintenance cost than other costs. Reducing the maintenance cost is an effective way to achieve the ESS (implement, implement).

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Appendix

Given Equations (1)–(10), we can get

$$\frac{dx}{dt} = x(U_{mY} - \bar{U}_m) = x(1-x)y\pi_{1m} + x(1-x)(1-y)\pi_{2m} - x(1-x)y\pi_{3m}$$
$$- x(1-x)(1-y)\pi_{4m} = x(1-x)\left\{y\left[b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m\right]\right.$$

$$+\ (1-r)mR\frac{\alpha}{\alpha+\beta}-(C_0+rp)\frac{\alpha}{\alpha+\beta}-C_r-C_m\Bigg\}$$

and

$$\frac{dy}{dt}=y(U_{sY}-\bar{U}_s)=y(1-y)\left\{x\left[a(1-r)nR\frac{\beta}{\alpha+\beta}+kC_r+\frac{\alpha}{\alpha+\beta}C_m+R_0\right]\right.$$
$$\left.+\left[(1-r)nR\frac{\beta}{\alpha+\beta}-(C_0+rp)\frac{\beta}{\alpha+\beta}-C_r-C_m\right]\right\}.$$

We can obtain the replicator dynamics equation when $\{\begin{smallmatrix}\frac{dy}{dt}=0\\ \frac{dx}{dt}=0\end{smallmatrix}$, and then we get the following equations:

$$\begin{cases} x(1-x)\left\{y\left[b(1-r)mR\frac{\alpha}{\alpha+\beta}+(1-k)C_r+\frac{\beta}{\alpha+\beta}C_m\right]\right.\\ \left.+\ (1-r)mR\frac{\alpha}{\alpha+\beta}-(C_0+rp)\frac{\alpha}{\alpha+\beta}-C_r-C_m\right\}=0\\ y(1-y)\left\{x\left[a(1-r)nR\frac{\beta}{\alpha+\beta}+kC_r+\frac{\alpha}{\alpha+\beta}C_m+R_0\right]\right.\\ \left.+\left[(1-r)nR\frac{\beta}{\alpha+\beta}-(C_0+rp)\frac{\beta}{\alpha+\beta}-C_r-C_m\right]\right\}=0 \end{cases}$$

Solving the replicator dynamics equation, we can obtain five equilibrium points of the evolutionary game, namely, (0, 0), (0, 1), (1, 0), (1, 1), and (x_0, y_0) in the plane $M=\{(x,y)|0\le x, y\le 1\}$, where

$$x_0=\frac{-(1-r)nR\frac{\beta}{\alpha+\beta}+(C_0+rp)\frac{\beta}{\alpha+\beta}+C_r+C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta}+kC_r+R_0+\frac{\alpha}{\alpha+\beta}C_m} \tag{A1}$$

$$y_0=\frac{-(1-r)mR\frac{\alpha}{\alpha+\beta}+(C_0+rp)\frac{\alpha}{\alpha+\beta}+C_r+C_m}{b(1-r)mR\frac{\alpha}{\alpha+\beta}+(1-k)C_r+\frac{\beta}{\alpha+\beta}C_m}. \tag{A2}$$

According to the equations above, we can obtain

$$\begin{aligned} x_0&=\frac{-(1-r)nR\frac{\beta}{\alpha+\beta}+(C_0+rp)\frac{\beta}{\alpha+\beta}+C_r+C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta}+kC_r+R_0+\frac{\alpha}{\alpha+\beta}C_m}\\ &=\frac{-(1-r)nR\frac{\beta}{\alpha+\beta}-\frac{1}{a}kC_r-\frac{1}{a}R_0-\frac{\alpha}{a(\alpha+\beta)}C_m+\frac{1}{a}kC_r+\frac{1}{a}R_0+\frac{\alpha}{a(\alpha+\beta)}C_m+(C_0+rp)\frac{\beta}{\alpha+\beta}+C_r+C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta}+kC_r+R_0+\frac{\alpha}{\alpha+\beta}C_m}\\ &=-\frac{1}{a}+\frac{(C_0+rp)\frac{\beta}{\alpha+\beta}+C_m\frac{\alpha}{a(\alpha+\beta)}+\frac{1}{a}R_0+\frac{1}{a}kC_r+C_r+C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta}+kC_r+R_0+C_m\frac{\alpha}{\alpha+\beta}} \end{aligned} \tag{A3}$$

and

$$\begin{aligned} y_0&=\frac{-(1-r)mR\frac{\alpha}{\alpha+\beta}+(C_0+rp)\frac{\alpha}{\alpha+\beta}+C_r+C_m}{b(1-r)mR\frac{\alpha}{\alpha+\beta}+(1-k)C_r+\frac{\beta}{\alpha+\beta}C_m}.\\ &=\frac{-(1-r)mR\frac{\alpha}{\alpha+\beta}-\frac{1}{b}(1-k)C_r-\frac{\beta}{b(\alpha+\beta)}C_m+\frac{1}{b}(1-k)C_r+\frac{\beta}{b(\alpha+\beta)}C_m+(C_0+rp)\frac{\alpha}{\alpha+\beta}+C_r+C_m}{b(1-r)mR\frac{\alpha}{\alpha+\beta}+(1-k)C_r+\frac{\beta}{\alpha+\beta}C_m}\\ &=-\frac{1}{b}+\frac{(C_0+rp)\frac{\alpha}{\alpha+\beta}+\frac{1}{b}(1-k)C_r+\frac{\beta}{b(\alpha+\beta)}C_m+C_r+C_m}{b(1-r)mR\frac{\alpha}{\alpha+\beta}+(1-k)C_r+C_m\frac{\beta}{\alpha+\beta}} \end{aligned} \tag{A4}$$

Additionally, by multiplying k and $1-k$, we can obtain

$$
\begin{aligned}
kx_0 &= \frac{-(1-r)nkR\frac{\beta}{\alpha+\beta} + (C_0+rp)k\frac{\beta}{\alpha+\beta} + kC_r + kC_m}{a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + R_0 + \frac{\alpha}{\alpha+\beta}C_m} \\
&= \frac{a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + R_0 + \frac{\alpha}{\alpha+\beta}C_m - (a+k)(1-r)nR\frac{\beta}{\alpha+\beta} + k(C_0+rp)\frac{\beta}{\alpha+\beta} - R_0 + (k-\frac{\alpha}{\alpha+\beta})C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + R_0 + \frac{\alpha}{\alpha+\beta}C_m} \\
&= 1 - \frac{(a+k)(1-r)nR\frac{\beta}{\alpha+\beta} - k(C_0+rp)\frac{\beta}{\alpha+\beta} + R_0 - (k-\frac{\alpha}{\alpha+\beta})C_m}{a(1-r)nR\frac{\beta}{\alpha+\beta} + kC_r + R_0 + \frac{\alpha}{\alpha+\beta}C_m} \\
(1-k)y_0 &= \frac{-(1-r)(1-k)mR\frac{\alpha}{\alpha+\beta} + (1-k)(C_0+rp)\frac{\alpha}{\alpha+\beta} + (1-k)C_r + (1-k)C_m}{b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m} \\
&= \frac{b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m - (1+b-k)(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k-\frac{\alpha}{\alpha+\beta})C_m + (1-k)(C_0+rp)\frac{\alpha}{\alpha+\beta}}{b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m} \\
&= 1 - \frac{(1+b-k)(1-r)mR\frac{\alpha}{\alpha+\beta} - (1-\frac{\alpha}{\alpha+\beta}-k)C_m - (1-k)(C_0+rp)\frac{\alpha}{\alpha+\beta}}{b(1-r)mR\frac{\alpha}{\alpha+\beta} + (1-k)C_r + \frac{\beta}{\alpha+\beta}C_m}.
\end{aligned}
$$

Then, we can obtain Equations (18) and (19) in the main text.