Research Article

European Option Based R&D Investment Decision Making under Uncertainties

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Received 17 July 2015; Revised 19 October 2015; Accepted 21 October 2015

Academic Editor: Zoran Gajic

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This paper establishes the payoff models of the European option for research and development (R&D) projects with two enterprises in a research joint venture (RJV). The models are used to assess the timing and payoffs of the R&D project investment under quantified uncertainties. After the option game, the two enterprises can make optimal investment decision for the R&D project investment in the RJV.

1. Introduction

The success of a research and development (R&D) project will bring huge profits for the high technology enterprises. R&D project includes software project and hardware project. Both of them have some uncertainties that may come from the limitation of the R&D capabilities, external market volatility, or complexity of the project. Because of the existence of these uncertainties, it is not easy for an enterprise to seize the opportunities in R&D project investment.

To cope with the uncertainties and pressure of market competition in a R&D project, the enterprises will establish a research joint venture (RJV) for the alliance of financing and technology development before the commercialization of product. The competition among enterprises has been transformed from a zero-sum game to a non-zero-sum game. As discussed in Dong et al. [1], one of the best business partners usually is their largest competitors. However, due to self-interest, any alliance could collapse. If the only purpose of any enterprise is to take advantage of the technology from its partners without share, it will inevitably cause concealment of the achievement and the failure of the joint venture.

Kamien et al. [2] and Amir et al. [3] divide collaboration in R&D projects into three categories: R&D cartel, RJV, and cartelized RJV. The result of Liu and Zhang [4] shows that the RJV is more applicable in R&D projects. According to Sheng [5], the enterprises in a RJV fully share their R&D activities amongst the partners and seek to maximize their own business profits. This alliance is only for technology sharing but not for the strategic timing to invest. Therefore, in a RJV, the enterprises also compete with each other in investment decision making.

Due to the financial attributes of real option, therefore, in the transfer, investment, acquisition, and distribution of benefits, it is necessary to quantify the European option value for a R&D project. The real option method has already been used to quantify the option value. However, the calculations of the value and payoffs are not accurate when the uncertainties and other competitors’ strategies exist. Based on the above considerations, this paper from the perspective of enterprises investment in a R&D project firstly considers the impact of a R&V with other competitors, then quantifies and evaluates a variety of uncertainties in the R&D project, and finally builds the models of the investment decision payoffs. After the option game, the enterprises can obtain optimal R&D project investment decisions by Nash equilibrium point in the R&V.

2. European Option Model for R&D Project Investment under Market Uncertainty

According to the definition in Margrabe [12], European option holders may exchange asset I for asset V at time T. In the R&D project investment, it can be explained that the holder of the commercial investment I exchanges it for the market value V at time T. Increasing market demand will result in a scale expansion of production, which will decrease the production cost. Market uncertainty is the exogenous risks associated with acceptance by the market, which relates to the compatibility of a new technology with the preference of customers [13]. The main source of this uncertainty is from the market value V_T of R&D project at time T. Taking the learning effect into account, the cumulative experience will cause unit profit Q_T = e^bδ with the market penetration rate b (the learning speed) and unit cost reduction rate δ. Assuming that V_T follows the Brownian motion process, after the application of Ito lemma, we have

\[ dV_T = \left( \mu - \frac{1}{2}\sigma^2 \right) V_T dT + \sigma V_T dZ_T + dQ_T. \tag{1} \]

The stochastic variable dZ_T follows a standard Wiener process. The market growth rate can be measured by μ = r + εσ, where ε and σ represent market price of risk and market volatility and r is the risk-free interest rate. Then we have

\[ dV_T = \left( r - \frac{1}{2}\sigma^2 \right) V_T dT + \sigma V_T (edT + dZ_T) + dQ_T. \tag{2} \]

By the Girsanov theorem, the process dZ_T = edT + dZ_T is a new Brownian motion under risk-neutral measure, so (2) can be written as

\[ \frac{dV_T}{V_T} = \left( r - \frac{1}{2}\sigma^2 + b\delta \right) dT + \sigma dZ_T^*. \tag{3} \]

A stochastic process is a sequence of probability distributions that provides the transition likelihood of future values. It adjusts the probabilities of future outcomes, which can be incorporated in the effects of risk [14]. Hence, dV_T shows that the value of R&D project is also a stochastic process with drift r + bδ. Taking the market uncertainty into account, the project value will become

\[ V_T = V e^{(r - \frac{1}{2}\sigma^2 + b\delta)T + \sigma Z_T^*}. \tag{4} \]

The stochastic variable Z_T^* in (4) follows a standard Wiener process in which Z_T^* \sim N(0, \sqrt{T}), so that \( \varphi \equiv (-1/2)\sigma^2T + \sigma Z_T^* \sim N((-1/2)\sigma^2T, \sigma \sqrt{T}) \). Therefore, \( e^\varphi \) is lognormally distributed with \( E(e^\varphi) = e^{-\frac{1}{2}\sigma^2T} e^\mu \), so \( E[v_T] = V e^{b\delta T} \) which is the unconditional expected value of \( V_T \).

The payoff of the R&D project at time T is \( \max[V_T - I, 0] \) and the European option \( s(V, I, T) \) can be denoted as the value of investment opportunity. In this paper, we show that market uncertainty in a R&D project can be simplified to the European option model introduced by Geske [15] with increased discount rate:

\[ s(V, I, T) = E \left[ \max \left\{ V e^{-(r/2)\sigma^2T + b\delta T} - I, 0 \right\} \right]. \tag{5} \]

Thus, we can obtain the European option model of a R&D project under market uncertainty:

\[ s(V, I, T) = V e^{b\delta T} N_1 \left( d_1 \left( \frac{K}{V}, T \right) \right) - I e^{-rT} N_2 \left( d_2 \left( \frac{K}{V}, T \right) \right), \tag{6} \]

where \( d_1 = \left( \log K + \left( r + \frac{1}{2}\sigma^2 \right) T \right) \sigma \sqrt{T} / \sigma \sqrt{T} ; d_2 = d_1 - \sigma \sqrt{T} ; K = V / I ; \sigma_I \) and \( \sigma_V \) are the volatility of \( V \) and \( I \); \( \sigma = \sqrt{\sigma^2 - 2\rho_{VI} \sigma_I \sigma_V + \sigma_V^2} \); \( \rho_{VI} \) is the correlation between V and I; and \( N_1 \) is a normal distribution.

Because the investment decisions in a R&D project can be made in stages, and the stages are nested to each other [16], the R&D project evaluation can be made in a two-phase compound option model. As above, the market uncertainty with the market factors outside the enterprises may cause marginal changes in the asset value of compound option. The terminal market value of the R&D project at time \( T_1 \)

\[ V_{T_1} = V e^{(r - \frac{1}{2}\sigma^2 + b\delta)T_1 + \sigma \sqrt{T_1}}, \tag{7} \]

The compound option valuation can be boiled down to the following:

\[ c(s, I_1, T_1) = E \left[ \max \left\{ s(V, I, T) - I, 0 \right\} \right]. \tag{8} \]

From the derivation in Carr [17] and Paxson [18], we can obtain the compound option model under market uncertainty, given by

\[ c(s, I_1, T_1) = V e^{b\delta T} N_2 \left( d_1 \left( \frac{K}{K^*}, T_1 \right), d_1 \left( K, T_1 \right) \right), \]

\[ - I e^{-rT_1} N_2 \left( d_2 \left( K, T_1 \right), d_2 \left( K, T_1 \right) \right), \]

\[ - I e^{-rT_1} N_2 \left( d_2 \left( K, T_1 \right), d_2 \left( K, T_1 \right) \right), \]

\[ \text{where } d_1(K/K^*, T_1) = (\log(K/K^*) + \left( r + \frac{1}{2}\sigma^2 \right) T_1 \sigma \sqrt{T_1} ; d_2(K, T_1) = d_1(K/K^*, T_1) - \sigma \sqrt{T_1} ; \text{ and } N_2 \text{ is a normal distribution.} \]
3. The Payoffs of the R&D Project Investment Decisions

Under dynamic competition, the enterprises can generally be divided into leader, follower, or competitors who make the investment decisions at the same time. Although the follower often follows the leader to make decisions, it does not mean that the leader is always the winner. Having more time to observe the market and make decisions, the follower can also occupy favorable position in the market. Due to the constraints of the market size, the follower, when entering the market, will influence the benefits of the leader. Therefore, when making investment decisions, the leader should take the decisions of the follower into full account. Hence, it is necessary for the enterprises to assess all possible decisions of the competitors in the R&D project investment.

In the process of a R&D project investment, except market uncertainty, the technology uncertainty could exist [19]. It refers to the chance to successfully impel the transition at each R&D stage from technological concerns. Assume that there are two enterprises: A and B. In the RJV, they have the same success rate $p$ [19]. To obtain the same payoffs in the R&D project, the competitor with stronger R&D capabilities needs relatively less investment. Assume that the R&D project investment amount of the two enterprises is $I_A$ and $I_B$, and enterprise A is more competitive in the R&D project than enterprise B; that is, $I_A < I_B$.

In this paper, we assume the R&D project investment of the leader is made at time $T_0$ earlier than that of the follower. The market shares of the two enterprises are different: the share of leader is $\alpha$ ($\alpha > 0.5$) and that of the follower is $1 - \alpha$. The implicit condition is that the two enterprises occupy the entire market and become duopoly. In reality, there may be more than two competitors, where we can still apply this model by treating the homogeneous pioneers as one leader and all the rest as one follower.

According to the definition of the European option, all the decision points must be fixed, and all the investment has to be made at time $T_0$. The two enterprises have to face the situation that invest in R&D projects at time $T_0$ or delay investment until time $T_1$, which requires the payoffs of all possible investment decisions to be calculated and analyzed accurately. In the RJV, there could be four investment decisions for an enterprise: being the leader at time $T_0$; being the follower at time $T_1$; investing together with the other at time $T_0$; or waiting until time $T_1$ to invest together with the other.

3.1. The Leader’s Payoff in the RJV. In the RJV of the R&D project investment, it can be assumed that enterprise A as the leader enters the market first at time $T_0$ and enterprise B as the follower decides to postpone investment. In this situation, the leader claims the market share $\alpha$ and takes the option $s(\alpha V, I, T)$. For the payoffs in making the commercialization investment $I$, Pennings and Sereno [20] state that $s(\alpha V, I, T)$ must be larger than $I_A$ for the R&D project to succeed. According to (6), combining with the probability of success $p$, the payoff of the leader $A$ at time $T_0$ is the following:

$$L_A = ps(\alpha V, I, T) - I_A$$
$$= p\left[\alpha Ve^{\delta T}N_1\left(d_1\left(K/K^*_B, T_1\right)\right) - Ie^{-rT}N_1\left(d_2\left(K/K^*_B, T_1\right)\right)\right] - I_A. \quad (10)$$

Symmetrically, if we assume that enterprise $B$ is the leader in the R&D project making an investment, at time $T_0$, the payoff of the leader $B$ is the following:

$$L_B = ps(\alpha V, I, T) - I_B$$
$$= p\left[\alpha Ve^{\delta T}N_1\left(d_1\left(K/K^*_B, T_1\right)\right) - Ie^{-rT}N_1\left(d_2\left(K/K^*_B, T_1\right)\right)\right] - I_B. \quad (11)$$

3.2. The Follower’s Payoff in the RJV. It can be assumed that the follower has to invest at time $T_1$, so it takes R&D time $T+T_1$ in the R&D project. In the RJV, the two enterprises fully carry out technology share, and the follower can obtain the technology from the leader, which can reduce the amount of investment at time $T_1$. Assuming that the investment is used at constant rate over time, the amount of investment of the follower $B$ reduces to $I_B = ((T - T_1)/T)I_B$. The follower takes the market share $1 - \alpha$. Because the first stage is waiting from time $T_0$, and the second stage is investing at time $T_1$, the strike price of the option is $s((1 - \alpha)V, I, (T + T_1))$ [16], the mature time is $T + T_1$, and the payoff of the follower enterprise $B$ is $G_B = c(ps((1 - \alpha)V, I, (T + T_1)), I_B, T_1)$. According to (9), the follower’s payoff at time $T_0$ is

$$G_B = p\left[(1 - \alpha)Ve^{\delta T}N_2\left(d_1\left(K/K^*_B, T_1\right)\right), d_1\left(K, (T + T_1)\right); \tau \right) - Ie^{-r(T+T_1)}N_2\left(d_2\left(K/K^*_B, T_1\right)\right),$$
$$d_2\left(K, (T + T_1)\right); \tau \right) - Ie^{-rT}N_1\left(d_2\left(K/K^*_B, T_1\right)\right), \quad (12)$$

where $K^*_B$ is the critical value of the solution from $ps((1 - \alpha)V, I, T) = I_B$; we can rewrite it as

$$\frac{I_B}{T} = p\left((1 - \alpha)K^*_B Ve^{\delta T}N_1\left(d_1\left(K^*_B, T\right)\right),$$
$$-e^{-rT}N_1\left(d_2\left(K^*_B, T\right)\right)\right). \quad (13)$$

Similarly, in the RJV, the payoff of follower $A$ at time $T_0$ is the following:

$$G_A = p\left((1 - \alpha)Ve^{\delta T}N_2\left(d_1\left(K/K_A, T_1\right)\right),$$
$$d_1\left(K, (T + T_1)\right); \tau \right) - Ie^{-r(T+T_1)}N_2\left(d_2\left(K/K_A, T_1\right)\right),$$
\[ d_2 (K, (T + T_1)); \tau) - I_A e^{-rT_1} N_1 \left( d_2 \left( \frac{K}{K_A^*} \right), T_1 \right), \]

where \( K_A^* \) is the critical value of the solution from

\[ I_A^* = p \left((1 - \alpha) K_A^* e^{\delta T} N_1 \left(d_1 (K_A^*, T)\right) - e^{-rT} N_1 (d_2 (K_A^*, T)) \right). \]

3.3. The Payoffs When Both Enterprises Invest Simultaneously in the RJV. If the two enterprises A and B decide to invest in the R&D project at the same time \( T_0 \), it can be assumed that the two enterprises can capture the same market share \( \alpha = 0.5 \). Because they have the same amount of commercialization investment in the R&D project, the enterprises hold the same option \( s(0.5V, I, T) \). According to (6), the payoff of \( A \) in the RJV is the following:

\[ T_A = ps (0.5V, I, T) - I_A \]

\[ = p \left( \frac{1}{2} V e^{\delta T} N_1 \left(d_1 (K, T)\right) - e^{-rT} N_1 (d_2 (K, T)) \right) \]

\[ - I_A^*. \]

Similarly, the payoff of \( B \) is the following:

\[ T_B = ps (0.5V, I, T) - I_B \]

\[ = p \left( \frac{1}{2} V e^{\delta T} N_1 \left(d_1 (K, T)\right) - e^{-rT} N_1 (d_2 (K, T)) \right) \]

\[ - I_B. \]

3.4. The Payoffs When Both Enterprises Wait to Invest Simultaneously in the RJV. In the RJV, when both enterprises simultaneously postpone their investments to time \( T_1 \) at time \( T_0 \), the maturity time will be postponed to \( T + T_1 \). The two enterprises have the same market share \( \alpha = 0.5 \). Both enterprises hold the same option \( s(0.5V, I, (T + T_1)) \) as strike price of two-stage compound option [16]. After investments \( I_A \) and \( I_B \) in the second stage at time \( T_1 \), according to (9), the payoff of enterprise \( A \) at time \( T_0 \) is given by

\[ D_A = c (ps (0.5V, I, (T + T_1)), I_A, T_1) \]

\[ = p \left( 0.5V e^{\delta T} N_2 \left(d_1 \left( \frac{K}{K_A^{**}} \right), T_1 \right), \right) \]

\[ d_1 (K, (T + T_1)); \tau \]

\[ - I_A e^{-r(T+T_1)} N_2 \left(d_2 \left( \frac{K}{K_A^{**}} \right), T_1 \right), d_2 (K, (T + T_1)); \tau \)

\[ - I_A e^{-rT_1} N_1 \left(d_2 \left( \frac{K}{K_A^{**}} \right), T_1 \right), \]

where \( K_A^{**} \) is the critical value of the solution from the following:

\[ \frac{I_A}{I} = p \left( 0.5K_A^{**} e^{\delta T} N_1 \left(d_1 (K_A^{**}, T)\right) - e^{-rT} N_1 (d_2 (K_A^{**}, T)) \right). \]

Similarly, the payoff of enterprise \( B \) at time \( T_0 \) is given by

\[ D_B = c \left( ps (0.5V, I, (T + T_1)), I_B, T_1 \right) \]

\[ = p \left( 0.5V e^{\delta T} N_2 \left(d_1 \left( \frac{K}{K_B^{**}} \right), T_1 \right), \right) \]

\[ d_1 (K, (T + T_1)); \tau \]

\[ - I_B e^{-r(T+T_1)} N_2 \left(d_2 \left( \frac{K}{K_B^{**}} \right), T_1 \right), d_2 (K, (T + T_1)); \tau \)

\[ - I_B e^{-rT_1} N_1 \left(d_2 \left( \frac{K}{K_B^{**}} \right), T_1 \right), \]

where \( K_B^{**} \) is the critical value of the solution from the following:

\[ \frac{I_B}{I} = p \left( 0.5K_B^{**} e^{\delta T} N_1 \left(d_1 (K_B^{**}, T)\right) - e^{-rT} N_1 (d_2 (K_B^{**}, T)) \right). \]

4. Numerical Example

In this example, we use the following parameter values to conduct the numerical study: the investment of enterprise \( A \) with stronger R&D capabilities is \( I_A = 8000 \) in the R&D project, and the other enterprise \( B \) is \( I_B = 10000 \). The success rate of the R&D project is \( p = 0.7 \). The market value and commercialization investment volatilities are \( \sigma_V = 0.70 \) and \( \sigma_I = 0.33 \), respectively, and the correlation between \( V \) and \( I \) is \( \rho_{VI} = 0.15 \). The expiration time of the R&D project is \( T = 3 \) years, and the investment of the follower is at time \( T_1 = 0.5 \) years. The market share of the leader is \( \alpha = 0.60 \). The risk-free interest rate is \( r = 0.05 \). The market value is \( V = 30000 \). The market penetration rate is \( b = 1.02 \) and the unit cost reduction rate is \( \delta = 0.2 \).

Table 1 shows the payoffs of the two enterprises for different commercialization investment in the RJV and the Nash equilibrium for the optimal investment decision after the option game. For the enterprises in the RJV, if less commercialization investment of the R&D project is required, such as \( I = 5000 \), the two enterprises will anticipate investment at time \( T_0 \). If the amount of commercialization investment increases, such as in the range \( 10000 \leq I \leq 25000 \), all kinds of payoffs will reduce, and the optimal investment decisions will change, and enterprise \( A \) with stronger R&D capabilities will try to invest in the R&D project at first. When the value becomes larger, such as \( I = 30000 \), the optimal decisions for the two enterprises are
Table 1: The payoffs of different commercialization investment for enterprises $A$ and $B$.

<table>
<thead>
<tr>
<th>$T$</th>
<th>$L_A$</th>
<th>$D_A$</th>
<th>$T_A$</th>
<th>$G_A$</th>
<th>$L_B$</th>
<th>$D_B$</th>
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<th>$G_B$</th>
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<td>4167</td>
<td>3709</td>
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<td>2558</td>
<td>2780</td>
<td>3754</td>
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<td>2124</td>
<td>$(L_A, G_B), (L_B, G_A)$</td>
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Table 2: The payoffs of different $T_1$ for enterprises $A$ and $B$.

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<th>$G_A$</th>
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</tbody>
</table>

the postponement for the investment at time $T_0$ and then simultaneous investment at time $T_1$, resulting in $(D_A, D_B)$. As the optimal investment decisions for the R&D project, the results are consistent with practices. When the amount of commercialization investment of the R&D project is large, for the decrease of the sunk costs, the two enterprises will observe the investment behavior from other competitors and market dynamics for more market information. If the amount of commercialization investment is reduced, the enterprises with weaker R&D capabilities will wait for a better investment opportunity. If the amount of commercialization investment is further reduced, all enterprises in the RJV will invest immediately to compete and obtain more profits in the R&D projects. With the commercialization investment $I = 20000$, Table 2 shows the payoffs of the investment decisions under different investment timing in the RJV and the optimal investment decisions after the option game. Because the two enterprises in the RJV fully share technology with each other, the success rate of the two enterprises is always the same. A shorter $T_1$ means the follower enterprises have to make investment decision more quickly. Table 2 illustrates that the payoffs of $D_A$, $D_B$, $G_A$, and $G_B$ could increase with the increase in $T_1$. This is the reason that waiting can increase the option value and the enterprises will incline to collect more information before investment. However, the R&D project investment cannot be delayed for too long, because delays will result in reduced future market shares and future payoffs. Hence, the enterprises can select the most acceptable investment decision as the optimal decision and determine the optimal investment timing.

5. Conclusions

In this paper, we apply the real option theory in R&D project investment decision making by considering various uncertainties. By using our model, combined with the competitive actions in the RJV, the payoffs of the enterprises can be computed accurately. After quantifying the market uncertainty and technology uncertainty of the R&D project investment, the two enterprises can make optimal investment decisions through option game from the payoffs of four kinds of investment decisions: as the leader, as the follower, investing at the same time, or deferring investment at the same time. If the expiration time of the compound option increases, the payoffs of follower and delayed investment will increase. The enterprises can make the optimal investment decision of R&D project and find the optimal investment timing. With the decrease in the commercialization investment in the R&D project, all the payoffs of the investment decisions will increase and the optimal decisions will be changed. Our theoretical and numerical results are consistent with what have been observed in practice in R&D project investment.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (70871030), Yanshan University Science Foundation for Youths (13SKB013), the Science and Technology Bureau Foundation of Qinhuangdao (201402B041), the Development of Social Science Research Foundation of Hebei Province (2014031332), and the National Defense Science and Industry Bureau Technology Foundation Research Project of China (JZ20150006).
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