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Research Article

European Option Based R&D Investment Decision Making under Uncertainties

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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.

The various uncertainties in a R&D project are considered by real option theory, which can be used as a kind of business analysis and management tool in a R&D project investment decision making. The enterprises can have the right to invest or abandon the R&D project. When the internal or external conditions change and become not conducive to invest, the enterprises may give up the investment opportunities, and their losses are only the irreversible investment.

Azevedo and Paxson [6] review the real option game models for the last two decades. McDonald and Siegel [7] assess European option with dividends in their model. Cassimon et al. [8] extend compound option model to allow for phase-specific volatility estimates, but it does not discuss uncertainties for this model. Ghosh and Troutt [9] develop a more sophisticated multistage compound option model, but the model is hard to apply. Angelou and Economides [10] integrate compound real option and game theory and adopt price competition analysis for the optimal business strategy. Lukas and Welling [11] illustrate the influence of uncertainty on the associated first-mover advantage in a U-shaped pattern.

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 RJV 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 RJV.

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 $Q_T = e^{b\delta}$ with the market penetration rate b (the learning speed) and unit cost reduction rate δ. The trend of V_T should include the part of the increased profit $(dQ_T/dT)(1/\Delta Q_T) = b\delta$. 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 $\mu = r+\varepsilon\sigma$, where ε and σ represent market price of risk and market volatility and r is the risk-free interest rate. Then we have

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

By the Girsanov theorem, the process $dZ_T^* = \varepsilon dT + dZ_T$ 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 $r+b\delta$. Taking the market uncertainty into account, the project value will become

$$V_T = Ve^{(r-(1/2)\sigma^2+b\delta)T+\sigma Z_T^*}. \tag{4}$$

The stochastic variable Z_T^* in (4) follows a standard Wiener process in which $Z_T^* \sim N(0, \sqrt{T})$, so that $\varphi \equiv (-(1/2)\sigma^2 T + \sigma Z_T^*) \sim N(-(1/2)\sigma^2 T, \sigma\sqrt{T})$. Therefore, e^{φ} is lognormally distributed with $E[e^{\varphi}] = e^{(-(1/2)\sigma^2 T+(1/2)\sigma^2 T)} = 1$ and $E[V_T] = Ve^{(r+b\delta)T}$, 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:

$$s(V, I, T) = E\left[\max\left\{Ve^{(r-(1/2)\sigma^2+b\delta)T+\sigma u\sqrt{T}} - I, 0\right\}\right]. \tag{5}$$

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

$$s(V, I, T) = Ve^{b\delta T} N_1(d_1) - Ie^{-rT} N_1(d_2), \tag{6}$$

where $d_1 = (\log K + (r + \sigma^2/2 + b\delta)T)/\sigma\sqrt{T}$; $d_2 = d_1 - \sigma\sqrt{T}$; $K = V/I$; σ_V and σ_I are the volatility of V and I; $\sigma = \sqrt{\sigma_V^2 - 2\rho_{VI}\sigma_V\sigma_I + \sigma_I^2}$; ρ_{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 is

$$V_{T_1} = Ve^{(r-(1/2)\sigma^2+b\delta)T_1+\sigma Z_{T_1}^*}. \tag{7}$$

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

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

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

$$\begin{aligned} c(s, I_1, T_1) = {} & Ve^{b\delta T} N_2\left(d_1\left(\frac{K}{K^*}, T_1\right), d_1(K, T); \tau\right) \\ & - Ie^{-rT} N_2\left(d_2\left(\frac{K}{K^*}, T_1\right), d_2(K, T); \tau\right) \\ & - I_1 e^{-rT_1} N_1\left(d_2\left(\frac{K}{K^*}, T_1\right)\right), \end{aligned} \tag{9}$$

where $d_1(K/K^*, T_1) = (\log(K/K^*) + (r + (\sigma^2/2) + b\delta)T_1)/\sigma\sqrt{T_1}$; $d_2(K/K^*, T_1) = d_1(K/K^*, T_1) - \sigma\sqrt{T_1}$; T_1 is the expiration date of the compound option; $T_2 = T - T_1$, $\tau = \sqrt{T_1/T}$, $T > T_1$; I_1 is the investment at time T_1; K^* is the critical price ratio that solves the equation $I_1/I = K^* e^{b\delta T} N_1(d_1(K^*, T_2)) - e^{-rT_2} N_1(d_2(K^*, T_2))$; and N_2 is a bivariate 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 α ($\alpha > 0.5$) 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 α 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:

$$\begin{aligned} L_A &= ps(\alpha V, I, T) - I_A \\ &= p\left(\alpha V e^{b\delta T} N_1\left(d_1(K,T)\right) - I e^{-rT} N_1\left(d_2(K,T)\right)\right) \\ &\quad - I_A. \end{aligned} \tag{10}$$

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:

$$\begin{aligned} L_B &= ps(\alpha V, I, T) - I_B \\ &= p\left(\alpha V e^{b\delta T} N_1\left(d_1(K,T)\right) - I e^{-rT} N_1\left(d_2(K,T)\right)\right) \\ &\quad - I_B. \end{aligned} \tag{11}$$

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

$$\begin{aligned} G_B = p\Bigg(& (1-\alpha) V e^{b\delta T} N_2\left(d_1\left(\frac{K}{K_B^*}, T_1\right),\right. \\ & \left. d_1\left(K, (T+T_1)\right); \tau\right) - I e^{-r(T+T_1)} N_2\left(d_2\left(\frac{K}{K_B^*}, T_1\right),\right. \\ & \left.\left. d_2\left(K,(T+T_1)\right); \tau\right)\right) - I_B^* e^{-rT_1} N_1\left(d_2\left(\frac{K}{K_B^*},\right.\right. \\ & \left.\left. T_1\right)\right), \end{aligned} \tag{12}$$

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

$$\begin{aligned} \frac{I_B^*}{I} &= p\left((1-\alpha) K_B^* e^{b\delta T} N_1\left(d_1\left(K_B^*, T\right)\right)\right. \\ &\quad \left. - e^{-rT} N_1\left(d_2\left(K_B^*, T\right)\right)\right). \end{aligned} \tag{13}$$

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

$$\begin{aligned} G_A = p\Bigg(& (1-\alpha) V e^{b\delta T} N_2\left(d_1\left(\frac{K}{K_A^*}, T_1\right),\right. \\ & \left. d_1\left(K, (T+T_1)\right); \tau\right) - I e^{-r(T+T_1)} N_2\left(d_2\left(\frac{K}{K_A^*}, T_1\right),\right. \end{aligned}$$

$$d_2\left(K,\left(T+T_1\right);\tau\right)\Big)\Big)-I_A^*e^{-rT_1}N_1\left(d_2\left(\frac{K}{K_A^*},T_1\right)\right), \tag{14}$$

where K_A^* is the critical value of the solution from

$$I_A^* = pI\left(\left(1-\alpha\right)K_A^*e^{b\delta T}N_1\left(d_1\left(K_A^*,T\right)\right) - e^{-rT}N_1\left(d_2\left(K_A^*,T\right)\right)\right). \tag{15}$$

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:

$$\begin{aligned} T_A &= ps\left(0.5V, I, T\right) - I_A \\ &= p\left(\frac{1}{2}Ve^{b\delta T}N_1\left(d_1\left(K,T\right)\right) - Ie^{-rT}N_1\left(d_2\left(K,T\right)\right)\right) \\ &\quad - I_A. \end{aligned} \tag{16}$$

Similarly, the payoff of B is the following:

$$\begin{aligned} T_B &= ps\left(0.5V, I, T\right) - I_B \\ &= p\left(\frac{1}{2}Ve^{b\delta T}N_1\left(d_1\left(K,T\right)\right) - Ie^{-rT}N_1\left(d_2\left(K,T\right)\right)\right) \\ &\quad - I_B. \end{aligned} \tag{17}$$

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 of $\alpha = 0.5$. 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

$$\begin{aligned} D_A &= c\left(ps\left(0.5V, I, \left(T+T_1\right)\right), I_A, T_1\right) \\ &= p\Bigg(0.5Ve^{b\delta T}N_2\left(d_1\left(\frac{K}{K_A^{**}},T_1\right),\right. \\ &\quad \left. d_1\left(K,\left(T+T_1\right)\right);\tau\right) \\ &\quad - Ie^{-r(T+T_1)}N_2\left(d_2\left(\frac{K}{K_A^{**}},T_1\right), d_2\left(K,\left(T+T_1\right)\right);\right. \\ &\quad \left.\tau\right)\Bigg) - I_Ae^{-rT_1}N_1\left(d_2\left(\frac{K}{K_A^{**}},T_1\right)\right), \end{aligned} \tag{18}$$

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

$$\begin{aligned} \frac{I_A}{I} &= p\left(0.5K_A^{**}e^{b\delta T}N_1\left(d_1\left(K_A^{**},T\right)\right)\right. \\ &\quad \left. - e^{-rT}N_1\left(d_2\left(K_A^{**},T\right)\right)\right). \end{aligned} \tag{19}$$

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

$$\begin{aligned} D_B &= c\left(ps\left(0.5V, I, \left(T+T_1\right)\right), I_B, T_1\right) \\ &= p\Bigg(0.5Ve^{b\delta T}N_2\left(d_1\left(\frac{K}{K_B^{**}},T_1\right),\right. \\ &\quad \left. d_1\left(K,\left(T+T_1\right)\right);\tau\right) \\ &\quad - Ie^{-r(T+T_1)}N_2\left(d_2\left(\frac{K}{K_B^{**}},T_1\right), d_2\left(K,\left(T+T_1\right)\right);\right. \\ &\quad \left.\tau\right)\Bigg) - I_Be^{-rT_1}N_1\left(d_2\left(\frac{K}{K_B^{**}},T_1\right)\right), \end{aligned} \tag{20}$$

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

$$\begin{aligned} I_B &= pI\left(0.5K_A^{**}e^{b\delta T}N_1\left(d_1\left(K_A^{**},T\right)\right)\right. \\ &\quad \left. - e^{-rT}N_1\left(d_2\left(K_A^{**},T\right)\right)\right). \end{aligned} \tag{21}$$

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 $10000 \le I \le 25000$, 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.

I	L_A	D_A	T_A	G_A	L_B	D_B	T_B	G_B	Optimum
5000	9465	6971	6159	5033	7465	5588	4159	3975	(T_A, T_B)
10000	7428	5507	4167	3709	5428	4344	2167	2877	(L_A, G_B)
15000	5754	4418	2558	2780	3754	3437	558	2124	(L_A, G_B), (L_B, G_A)
20000	4359	3589	1238	2111	2359	2758	−761	1593	(L_A, G_B)
25000	3179	2945	138	1621	1179	2237	−1861	1209	(L_A, G_B)
30000	2168	2436	−790	1254	168	1832	−2790	926	(D_A, D_B)

TABLE 2: The payoffs of different T_1 for enterprises A and B.

T_1	L_A	D_A	T_A	G_A	L_B	D_B	T_B	G_B	Optimum
0.1	6419	3259	2778	939	4419	1951	778	414	(T_A, T_B)
0.3	6419	4177	2778	2062	4419	3095	778	1430	(L_A, G_B)
0.5	6419	4866	2778	2899	4419	3883	778	2272	(L_A, G_B), (L_B, G_A)
0.7	6419	5430	2778	3602	4419	4512	778	3003	(L_A, G_B)
0.9	6419	5909	2778	4221	4419	5040	778	3658	(L_A, G_B)
1.1	6419	6327	2778	4778	4419	5497	778	4256	(L_A, G_B)
1.3	6419	6695	2778	5288	4419	5899	778	4809	(D_A, D_B)
1.5	6419	7022	2778	5762	4419	6255	778	5327	(D_A, D_B)

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.

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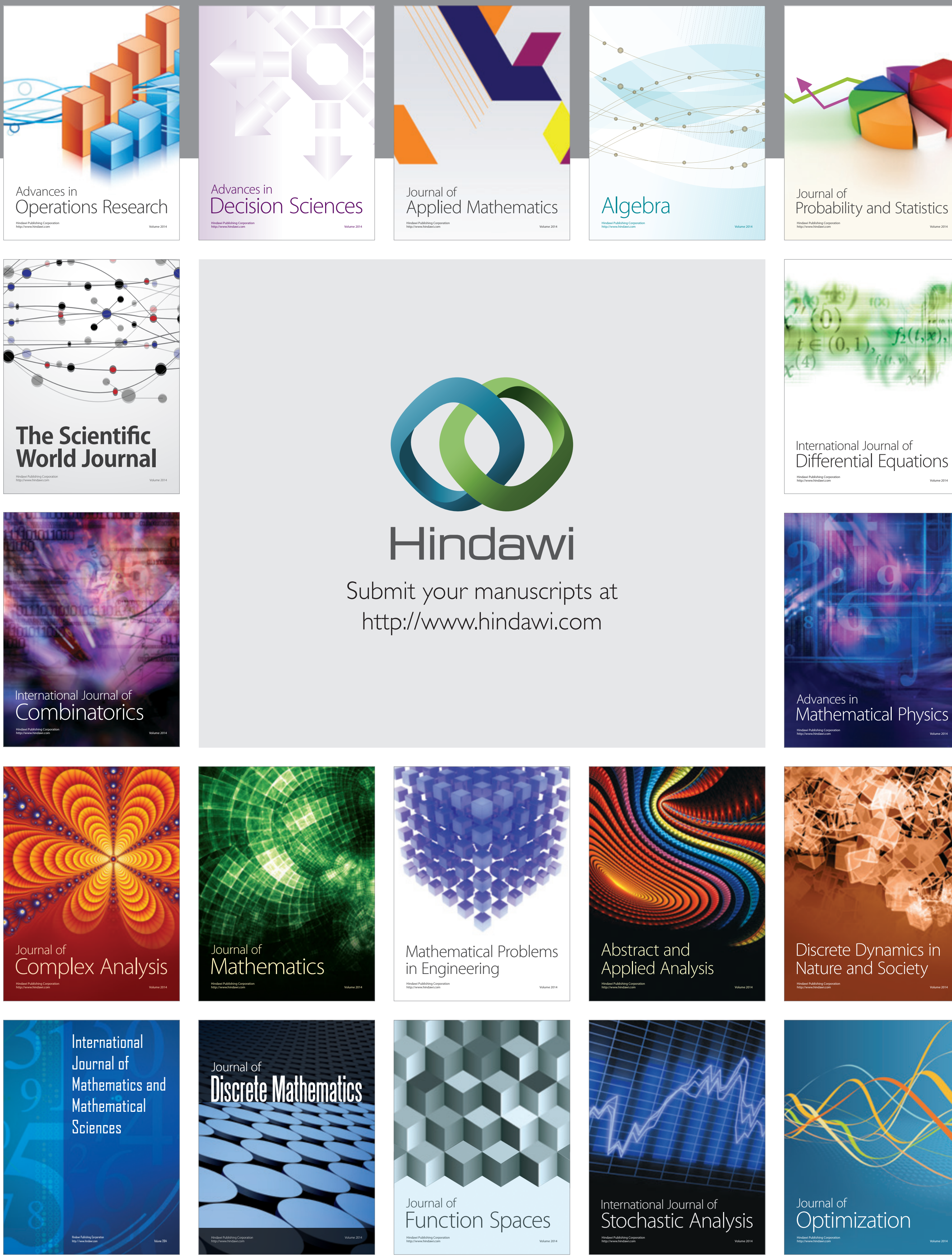
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