A Strategic R&D Investment with Flexible Development Time in Real Option Game Analysis

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Abstract

The real option theory provides a useful tool to evaluate an R&D investment under uncertainty because, unlike the NPV (Net Present Value), it considers the managerial flexibility that may be expand the investment opportunity value. However, most R&D investment projects are open to competing firms in the same industry or line of business, and so the strategic considerations become extremely important. In this paper we analyze a real option game between two firms that invest in R&D. The firm that invests first, defined as the Leader, acquires a first mover advantage that we assume as a higher market share than other one, namely the Follower, that postpones its R&D investment decision. But, several R&D investments present positive externalities and so, the option exercise by the Leader generates an "Information Revelation" that benefits the Follower. Moreover, to value the flexibility time to realize the development phase, we consider the American-Exchange type options.

JEL Code: G13, C72, C15, O32, D80.

Keywords: American Exchange options, game theory, Montecarlo simulation, R&D, information revelation.

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1 Introduction

The innovation is one of the important key strategies for firms to survive. Therefore, Research and Development (R&D) investment plays an important role in the successful performance for a firm. During the last two decades, the application of option pricing formula to R&D has become of interest and numerous studies have attempted to address how the real options analysis can help draw the proper line between knowledge building and strategic positioning. In fact it is widely recognised that the conventional NPV rule could in principle underestimate the value of an R&D project because this method fails to take the managerial flexibility into account. From a modelling perspective, real R&D options valuation methods have tended to follow financial option pricing techniques. Analogous to financial options on stocks, real options are options on real or physical assets such as technologies, production facilities and so on. When a firm "invests" means that it exercises its option by involving an initial cost to exchange for a real asset. According to Copeland & Antikarov (2003), a real option is "the right, but not the obligation, to take an action (e.g. deferring, expanding, contracting, or abandoning) at a predetermined cost called the exercise price, for a predetermined period of time - the life of option".

Several models, such as is assumed to be in Majd & Pindyck (1987), Trigeorgis (1991), Lee (1997), are based on this definition, in which the exercise price is fixed. But, for the evaluation of real R&D investment opportunity, it is appropriate to consider that also the investment cost is uncertain since the manager cannot make an accurate estimate of the future costs. So the R&D investment opportunity corresponds to an exchange option: it's the exchange of an uncertain investment cost for an uncertain gross project value. The most relevant models that value investment opportunities with two stochastic variables are given in Margrabe (1978), McDonald & Siegel (1985), Carr (1988), Carr (1995), Armada et al. (2007).

Margrabe (1978) developed a model to price the simple European exchange option (SEEO) to exchange one risky asset for another one at maturity date T and McDonald & Siegel (1985) considered that the assets distribute dividends. In a real options context, "dividends" are the opportunity costs inherent in the decision to defer an investment project. Furthermore, in a real options context, deferment implies the loss of the project's cash flows. Carr (1988) model, building on Margrabe (1978) and Geske (1979), provided the valuation of compound European exchange options (CEEO). This model may be interpreted as a combination of a time-to-build option (growth option) and an option to exchange (operating option). In addition, Carr (1988), Carr (1995) Armada et al. (2007) provided an approximation to value a simple American exchange option (SAEO). When the asset to be received in the exchange pays large dividend yields, there is always a probability that the American exchange option will be exercised prior to expiration. This means that managers have the timing choice for the development phase realization that gives the opportunity to capture the project's cash flows.

Moreover, competitive interaction becomes fundamentally important in the valuation and exercise of real options, while it may not be such a significant concern for financial options. Such competitive interactions may have profound effects on option exercise decisions and the resulting equilibrium. Real options and game-theory thinking have been embraced by strategic decision-makers who recognise the importance of making an early investment commitment (game theory) while maintaining managerial flexibility (real options) to adapt their choices to a changing market environment.

The aim of this paper is to analyse a real option game model between two firms that

invest in R&D. The first firm that invests, defined as the Leader, acquires a first mover advantage that we assume as a highest market share. But, several R&D investments, present positive externalities and so, the option exercise by the Leader, generates an "Information Revelation" that benefits the Follower. Moreover, to consider the managerial flexibility to realize the development investment D, we assume that the opportunity to entry in the market is like an American exchange option.
This paper follows the Dias & Teixeira (2004), Villani (2008) and Cortelezzi & Villani (2008) models that analyze the equilibrium strategies of two firms that invest in R&D assuming the uncertainty about the R&D implementation and also considering the information revelation process. We differentiate from them because we use American exchange options to value the stochastic processes for R&D costs (D and R) and for overall market value V deriving by R&D innovations and also to consider the managerial flexibility to realize the development investment D.
The paper is organized as follows. Section 2 reviews some of the relevant American option pricing literature while Section 3 derives the final payoffs of two firms. In Section 4, we present a real model implementation with computation of critical market values that delimit the several Nash equilibriums and, in Section 5, we analyze the effects that the most important parameters have on the game ranges. Finally, Section 6 concludes.

2 Exchange Options Methodology

In this section we present the final results to value American exchange options.

2.1 Simple American exchange option (SAEO)

Carr (1988) and Carr (1995) models give us the value of a Pseudo American exchange option (PSAEO). In particular way, let $t_0 = 0$ the evaluation date and T the maturity date of the exchange option, we assume that V and D follow a geometric Brownian motion process given by:

$$\frac{dV}{V} = (\mu_v - \delta_v)dt + \sigma_v dZ_v \tag{1}$$

$$\frac{dD}{D} = (\mu_d - \delta_d)dt + \sigma_d dZ_d \tag{2}$$

$$cov\left(\frac{dV}{V}, \frac{dD}{D}\right) = \rho_{vd}\sigma_v\sigma_d \, dt \tag{3}$$

where V and D are the Gross Project Value and the Investment Cost, respectively, μ_v and μ_d are the equilibrium expected rate of return on asset V, and the expected growth rate of the investment cost, δ_v and δ_d are the "dividend-yields" of V and D, Z_v and Z_d are the Brownian standard motions of asset V and D, σ_v and σ_d are the volatility of V and D respectively, ρ_{vd} is the correlation between changes in V and D.
Carr (1988) shows that the value of a PSAEO (S_2) exercisable at time $\frac{T}{2}$ or T is:

$$\begin{aligned} S_2(V,D,T) &= Ve^{-\delta_v T} N_2\left(-d_1^*, d_1; -\rho_1\right) - De^{-\delta_d T} N_2\left(-d_2^*, d_2; -\rho_1\right) \\ &\quad + Ve^{-\delta_v \frac{T}{2}} N(d_1^*) - De^{-\delta_d \frac{T}{2}} N(d_2^*) \end{aligned} \tag{4}$$

where:

- $P = \dfrac{V}{D}$; $\quad \sigma = \sqrt{\sigma_v^2 - 2\rho_{v,d}\sigma_v\sigma_d + \sigma_d^2}$; $\quad \delta = \delta_v - \delta_d$;

- $d_1 \equiv d_1(P,T) = \dfrac{\log P + \left(\frac{\sigma^2}{2} - \delta\right) T}{\sigma\sqrt{T}}$; $d_2(P,T) = d_1(P,T) - \sigma\sqrt{T}$;
- $d_1^* \equiv d_1\left(\dfrac{P}{P^*}, \dfrac{T}{2}\right) = \dfrac{\log(\frac{P}{P^*}) + \left(\frac{\sigma^2}{2} - \delta\right)\frac{T}{2}}{\sigma\sqrt{\frac{T}{2}}}$;
- $d_2^* \equiv d_2\left(\dfrac{P}{P^*}, \dfrac{T}{2}\right) = d_1^* - \sigma\sqrt{\dfrac{T}{2}}$; $\rho_1 = \sqrt{\dfrac{T}{2 \cdot T}} = \sqrt{0.5}$;
- $N(d)$ is the cumulative standard normal distribution;
- $N_2(x_1, x_2; \rho)$ is the standard bivariate normal distribution function evaluated at x_1 and x_2 with correlation ρ;
- P^* is the unique value which makes indifferent the option exercise or not at time $\frac{T}{2}$ and it solves the following equation:

$$P^* e^{-\delta_v \frac{T}{2}} N\left(d_1\left(P^*, \frac{T}{2}\right)\right) - e^{-\delta_d \frac{T}{2}} N\left(d_2\left(P^*, \frac{T}{2}\right)\right) = P^* - 1 \tag{5}$$

Moreover, Armada et al. (2007) correct the two-moments extrapolation given in Carr (1988) and Carr (1995) to approximate the value of a simple American exchange option $S(V,D,T)$. So, using the Armada et al. (2007) formula, we have that:

$$S(V,D,T) \simeq S_2(V,D,T) + \frac{S_2(V,D,T) - s(V,D,T)}{3} \tag{6}$$

where $s(V,D,T)$ is the value of a simple European exchange option (SEEO) given by McDonald & Siegel (1985):

$$s(V,D,T) = Ve^{-\delta_v T} N(d_1(P,T)) - De^{-\delta_d T} N(d_2(P,T)) \tag{7}$$

2.2 Compound American exchange option (CAEO)

Exchange option are simple or compound. If the underlying asset is another option, then the option is called compound. The underlying asset of a CAEO is the SAEO $S(V,D,\tau)$, the expiration date is t_1 and, following Carr (1988), the exercise price of a CAEO is a proportion φ of asset D. Using Armada et al. (2007) extrapolation, we can approximate the value of a CAEO as:

$$C(S(V,D,\tau), \varphi D, t_1) \simeq \frac{4c_2(S_2(V,D,\tau), \varphi D, t_1) - c(s(V,D,\tau), \varphi D, t_1)}{3} \tag{8}$$

where:

- $\tau = T - t_1$ is the time to maturity of the SAEO with $t_1 < T$;
- $c_2(S_2(V,D,\tau), \varphi D, t_1)$ is the Pseudo compound American exchange option (PCAEO) whose underlying asset is the PAEO $S_2(V,D,\tau)$ that can be exercised at middle $\frac{\tau}{2}$ and final time T, the maturity date is time t_1 and the exercise price is a proportion φ of asset D;
- $c(s(V,D,\tau), \varphi D, t_1)$ is the value of a compound European exchange option (CEEO) whose underlying asset is the simple European exchange option (SEEO) $s(V,D,\tau)$.

The value of PCAEO can be determined using Montecarlo simulation as illustrated in Cortelezzi & Villani (2009).

3 The Basic Model Game

In our model we consider a competitive interaction between two firms (A and B) face an R&D investment opportunity. Both firms can decide to invest at time t_0 or to wait to invest and so to postpone their decision at time t_1. As it is know, the R&D investments are uncertain and so, assuming by q and p the R&D success probability of firms A and B respectively, we can represent this situation by two Bernoulli distributions Y and X:

$$Y : \begin{cases} 1 & q \\ 0 & 1-q \end{cases} \qquad X : \begin{cases} 1 & p \\ 0 & 1-p \end{cases}$$

The value of q and p depend by the Know-How that each player holds on. Moreover, as it shown in Dias (2004), the R&D success or failure of one firm generates an information revelation that influences the investment decision of the other firm. So, if firm A's R&D is successful, the firm B's probability p changes in positive information revelation p^+, while p changes in negative information revelation p^- in case of A's failure. Symmetrically, the firm A's R&D success changes in q^+ or in q^- in case of firm B success or failure at time t_0. Using Dias (2004) model, it results that:

$$\begin{aligned}
p^+ &= Prob[X = 1/Y = 1] = p + \sqrt{\frac{1-q}{q}} \cdot \sqrt{p(1-p)} \cdot \rho(X,Y) \\
p^- &= Prob[X = 1/Y = 0] = p - \sqrt{\frac{q}{1-q}} \cdot \sqrt{p(1-p)} \cdot \rho(X,Y) \\
q^+ &= Prob[Y = 1/X = 1] = q + \sqrt{\frac{1-p}{p}} \cdot \sqrt{q(1-q)} \cdot \rho(Y,X) \\
q^- &= Prob[Y = 1/X = 0] = q - \sqrt{\frac{p}{1-p}} \cdot \sqrt{q(1-q)} \cdot \rho(Y,X)
\end{aligned}$$

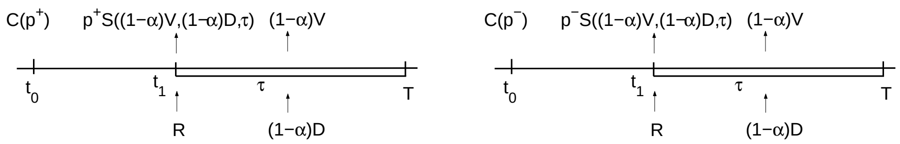
where the correlations $\rho(X,Y)$ and $\rho(Y,X)$ are a measure of information revelation from Y to X and from X to Y, respectively. Obviously, the information revelation is considerable when the investment is not realized in the same time. So, if both players invest simultaneously in R&D or they wait to invest, there is not information revelation and consequently it results that $p = p^+ = p^-$ and $q = q^+ = q^-$.

Under the threat of competition, the exercise of options strategically depends on the trade-off between the benefits and costs of going ahead with an investment against waiting for more information. So we state that the Leader is the pioneer firm (A or B) that invests in R&D at time t_0 earlier than other one, namely the Follower, that defers exercising its option at time t_1 to receive better information. Leader can take an advantage of being first in the market and, in particular way, we suppose that it achieves the market share opportunity $\alpha \in (\frac{1}{2}, 1]$ of V higher than Follower's one, that is $1-\alpha$. But, if the investment is realized in the same time, both players share the market equally and so $\alpha = \frac{1}{2}$.

We denote by R the R&D investment for the development of a new product, V the overall market value deriving by R&D innovations and D is the total investment cost to realize new goods. We consider that the production investment of each firm is proportional to its market share and it can be realized at anytime before T so we consider the managerial flexibility to realize the investment D. Therefore, the option to enter in the market is like an American exchange option. In particular, we assume that V and D follow the geometric Brownian motion defined in the Eqs.(1) and (2) respectively, and $R = \varphi D$ is a proportion φ of asset D, so R assumes the identical stochastic process of D except that it can be spent only at initial time t_0 or at time t_1.

3.1 The Follower's payoff.

First of all, we analyze the game in which the firm A (Leader) invests in R&D at time t_0 and the firm B (Follower) decides to delay its R&D investment decision at time t_1. So, assuming the Leader's R&D success, the Follower's R&D success probability changes in p^+ and, after the investment R, the Follower holds the development option $S((1-\alpha)V, (1-\alpha)D, \tau)$ to invest $(1-\alpha)D$ at anytime from t_1 and T and claims a share $1-\alpha$ of the overall market V. Of course, the investment R will be realized at time t_1 if the development option $p^+S((1-\alpha)V, (1-\alpha)D, \tau)$ is bigger than R. So, the Follower's payoff at time t_0 is a CAEO with maturity t_1, exercise price equal to R and the underlying asset is the development option $S((1-\alpha)V, (1-\alpha)D, \tau)$, as shown in Fig.1(a).



(a) Follower's Payoff in case of Leader's success

(b) Follower's Payoff in case of Leader's failure

Figure 1: Follower's payoffs

The CAEO payoff at expiration date t_1 with positive information revelation is:

$$C(p^+S((1-\alpha)V, (1-\alpha)D, \tau), R, 0) = \max[p^+S((1-\alpha)V, (1-\alpha)D, \tau) - R, 0]$$

Considering that $R = \varphi D$ is a proportion φ of asset D and denoting with $C(p^+)$ the CAEO at time t_0, i.e.:

$$C(p^+) \equiv C(p^+s((1-\alpha)V, (1-\alpha)D, \tau), \varphi D, t_1)$$

we can write, using the Eq.(8), the value of CAEO with positive information:

$$C(p^+) \simeq \frac{4c_2(p^+S_2((1-\alpha)V, (1-\alpha)D, \tau), \varphi D, t_1) - c(p^+s((1-\alpha)V, (1-\alpha)D, \tau), \varphi D, t_1)}{3} \quad (9)$$

Alternatively, in case of Leader's R&D failure, the Follower success probability changes in p^- and the Follower holds, after the investment R at time t_1, the development option $S((1-\alpha)V, (1-\alpha)D, \tau)$ to invest $(1-\alpha)D$ at anytime between t_1 and T and claims the market value $(1-\alpha)V$. So the Follower's payoff at time t_0 is a CAEO with maturity t_1, exercise price equal to R and the underlying asset is the development option $S((1-\alpha)V, (1-\alpha)D, \tau)$ as shown in Fig. 1(b). Hence, the CAEO payoff with negative information revelation at expiration date t_1 is:

$$C(p^-S((1-\alpha)V, (1-\alpha)D, \tau), R, 0) = \max[p^-S((1-\alpha)V, (1-\alpha)D, \tau) - R, 0]$$

So, denoting with $C(p^-)$ the CAEO at time t_0, i.e.:

$$C(p^-) \equiv C(p^-S((1-\alpha)V, (1-\alpha)D, \tau), \varphi D, t_1)$$

we can write, using the Eq.(8), the value of CAEO with negative information:

$$C(p^-) \simeq \frac{4c_2(p^- S_2((1-\alpha)V,(1-\alpha)D,\tau),\varphi D,t_1) - c(p^- s((1-\alpha)V,(1-\alpha)D,\tau),\varphi D,t_1)}{3} \tag{10}$$

The Follower obtains the CAEO $C(p^+)$ in case of Leader's success with a probability q or the CAEO $C(p^-)$ in case of Leader's failure with a probability $(1-q)$. Hence, the Follower's payoff at time t_0 is the expectation value:

$$F_B(V,D) = q\,C(p^+) + (1-q)\,C(p^-) \tag{11}$$

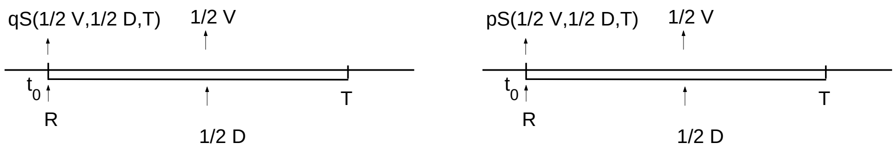
Similarly, if we consider that firm B (Leader) invests in R&D at time t_0 and firm A (Follower) decides to wait to invest it results:

$$F_A(V,D) = p\,C(q^+) + (1-p)\,C(q^-) \tag{12}$$

Using Cortelezzi & Villani (2009) model, we are able to determine the Follower's payoff through Montecarlo simulation. In particular way, the appendix (A) shows the Matlab algorithm to obtain the values given by Eqs. (11) and (12).

3.2 The A and B payoffs when both firms invest simultaneously in R&D.

In this situation, both players decide to realize the R&D investment simultaneously at time t_0. Hence, we can setting that there is not information revelation and consequently it results that $\rho(Y,X) = \rho(X,Y) = 0$. Since the investment R is equal for both firms, we assume that A and B can capture the same fraction $\alpha = \frac{1}{2}$ of the overall market value. So, after the investment R in t_0, A and B hold with a probability q and p respectively, the development option $S\left(\frac{1}{2}V, \frac{1}{2}D, T\right)$ to invest $\frac{1}{2}D$ at anytime before T, as illustrated in the Figs. 2(a) and 2(b).



(a) Firm A's payoff (b) Firm B's payoff

Figure 2: A and B payoffs in case of simultaneous investment

According to Eq.(6), we can write the A and B payoffs in case of simultaneous R&D investment at time t_0 as:

$$\begin{aligned} S_A(V,D) &= -R + q \cdot S\left(\frac{1}{2}V, \frac{1}{2}D, T\right) \\ &\simeq -R + q\left(\frac{4S_2(\frac{1}{2}V, \frac{1}{2}D, T) - s(\frac{1}{2}V, \frac{1}{2}D, T)}{3}\right) \end{aligned} \tag{13}$$

$$\begin{aligned} S_B(V,D) &= -R + p \cdot S\left(\frac{1}{2}V, \frac{1}{2}D, T\right) \\ &\simeq -R + p\left(\frac{4S_2(\frac{1}{2}V, \frac{1}{2}D, T) - s(\frac{1}{2}V, \frac{1}{2}D, T)}{3}\right) \end{aligned} \tag{14}$$

3.3 The Leader's payoff

Now we analyse the game in which firm A (Leader) invests in R&D at time t_0, assuming that firm B (Follower) decides to postpones its decision waiting better information. In this case, the Leader spends the investment R at time t_0 and obtains, in case of success with a probability q, the development option $S(\alpha V, \alpha D, T)$ that gives the opportunity to invest αD at anytime before T and to claim a market share $\alpha > \frac{1}{2}$, as illustrated in the Fig. 3. Thus the Leader's payoff (firm A) will be:

$$\begin{aligned} L_A(V,D) &= -R + q \cdot S\left(\alpha\, V, \alpha D, T\right) \\ &\simeq -R + q\left(\frac{4S_2(\alpha V, \alpha D, T) - s(\alpha V, \alpha D, T)}{3}\right) \end{aligned} \tag{15}$$

Symmetrically, if we consider that firm B (Leader) realizes the R&D investment at time t_0 and player A postpones its decision, the firm B payoff will be:

$$\begin{aligned} L_A(V,D) &= -R + p \cdot S\left(\alpha\, V, \alpha D, T\right) \\ &\simeq -R + p\left(\frac{4S_2(\alpha V, \alpha D, T) - s(\alpha V, \alpha D, T)}{3}\right) \end{aligned} \tag{16}$$

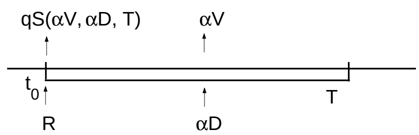


Figure 3: Leader's payoff

3.4 The A and B payoffs when both firms wait to invest.

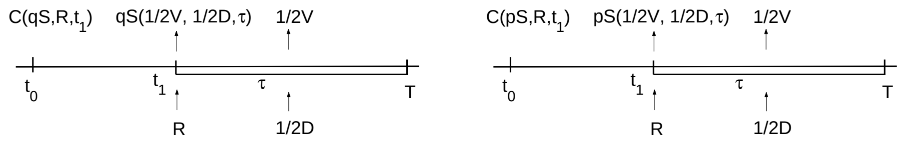
Finally, we suppose that both players decide to delay their R&D investment decision at time t_1 and, specifically, we can assume that there is not information revelation and consequently $\rho(Y, X) = \rho(X, Y) = 0$. As we have seen in simultaneous case, we can setting that A and B share the market equally and so $\alpha = \frac{1}{2}$. Then, after the investment R in t_1, each player holds in case of R&D success the development option $S\left(\frac{1}{2}\, V, \frac{1}{2} D, \tau\right)$ to invest $\frac{1}{2}D$ at anytime before T and claims a market share $\frac{1}{2}V$. So, at time t_0, the A and B payoffs are CAEO with maturity t_1, exercise price equal to $R = \varphi D$ and the underlying asset is the development option $S(\frac{1}{2}V, \frac{1}{2}D, T)$ with probability q and p respectively, as illustrated in the Figs 4(a) and 4(b).
Thus, A and B payoffs at time t_0 are given by:

$$W_A(V,D) = C\left(q \cdot S\left(\frac{1}{2}V, \frac{1}{2}D, \tau\right), \varphi D, t_1\right) \tag{17}$$

$$W_B(V,D) = C\left(p \cdot S\left(\frac{1}{2}V, \frac{1}{2}D, \tau\right), \varphi D, t_1\right) \tag{18}$$

Using the Eq.(8) we can determine the firms A and B waiting payoffs as:

$$W_A(V,D) \simeq \frac{4c_2(qS_2(\frac{1}{2}V, \frac{1}{2}D, \tau), \varphi D, t_1) - c(qS(\frac{1}{2}V, \frac{1}{2}D, \tau), \varphi D, t_1)}{3} \tag{19}$$



(a) Firm A's payoff (b) Firm B's payoff

Figure 4: A and B payoffs in case waiting to invest

$$W_B(V,D) \simeq \frac{4c_2(pS_2(\frac{1}{2}V, \frac{1}{2}D, \tau), \varphi D, t_1) - c(pS(\frac{1}{2}V, \frac{1}{2}D, \tau), \varphi D, t_1)}{3} \tag{20}$$

So, the appendix (A) shows the Matlab algorithm to determine the firms A and B waiting payoffs through Montecarlo simulation. It's sufficient to consider that information revelation $\rho(X, Y) = 0$ and $\alpha = \frac{1}{2}$.

3.5 Final payoffs at time t_0

The two-by-two matrix represented in the Fig.5 summarizes the final payoffs. The first value in each cell indicates the strategic investment opportunity for A at time t_0, while the second represents the firm B's value. We can distinguish four basic cases: (i) when both firms decide to postpone the R&D investment at time t_1; (ii) and (iii) when one firm invests first (as a Leader) and the other decides to invest later (as a Follower); (iv) when both firms decide to invest simultaneously in R&D at time t_0.

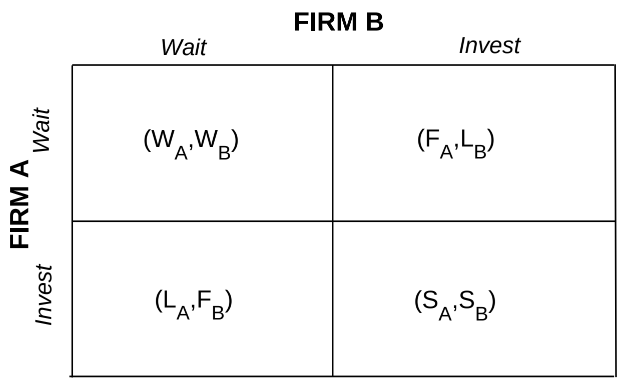


Figure 5: Final payoffs at time t_0

4 Real Applications

4.1 Assumptions and Inputs

This model can be applied to analyse industries such as high-tech, pharmaceutical, telecommunication, oil, in which competitors can substantially influence a firms investment opportunity. In fact, a firm may pre-empt competition and capture a significant share of the market $\alpha > \frac{1}{2}$ by setting the R&D investment early on. This is

an important source of advantage that may establish a sustainable strategic position. But, the firm that delays investment, can derive information about its R&D success from observing the R&D performance of the other player.
So, to illustrate the concepts and equations presented, we develop a numerical example for the competitive R&D game between firms A and B with the following parameters:

- R&D Investment: R= 150 000 \$;
- Development Investment: D= 400 000 \$;
- Market and Costs Volatility: $\sigma_v = 0.90$; $\sigma_d = 0.23$;
- Proportion of D required for R: $\varphi = \frac{R}{D} = 0.375$
- Correlation between V and D: $\rho_{vd} = 0.15$;
- Dividend-Yields of V and D: $\delta_v = 0.15$; $\delta_d = 0$;
- Expiration Time of Compound Option: $t_1 = 0.5$ years;
- Expiration Time of Simple Option: $T = 3$ years;
- A and B success probability: $q = 0.60$; $p = 0.55$;
- Information Revelation: $\rho(X, Y) = \rho(Y, X) = 0.70$;
- Leader's Market Share: $\alpha = 0.60$;
- Critical Price $K = 1.6722$:

We consider five expected total market values V : 800 000 \$ (low expected return), 1 000 000 \$, 1 200 000 \$ (medium expected return) and 1 400 000 \$ and 1 600 000 \$ (high expected return). V corresponds to present value of the expected cash flows deriving by R&D innovations . We assume that V follows the Brownian motion presented in Eq.(1).
The total investment cost D is the exercise price for the development option. We consider that the investment cost is proportional to market share, namely if the firm's market share is α then its investment cost will be αD. We assume that D follows the Brownian motion process defined in Eq.(2). The total current value of D is 400 000 \$ and it can be spent at anytime before T.
The R&D investment R can be realized at time t_0 or t_1. If it is made in t_0, then $R = 150\,000$ \$ otherwise the investment R assumes the identical stochastic process of D, except that it occurs at time t_1 and it is proportional to $\varphi = 0.375$ of D.
Appropriately, we assume that the volatility of quoted shares and traded options is an adequate proxy for the volatility of asset V and investment cost D. As the R&D investments present a high uncertainty about their results, we assume that $\sigma_v = 0.90$ and the cost volatility is $\sigma_d = 0.23$.
According to financial options, δ denotes the opportunity cost in holding the option instead of the stock. So, in real option world, δ_v is the opportunity cost of deferring the project and δ_d is the "dividend yield" on asset D. As at the beginning the cash flows are very low, so we assume that $\delta_v = 0.15$ and $\delta_d = 0$.
The time to maturity T denotes project's deferment option after that each opportunity disappears and we adopt $T = 3$ years. Moreover, we state that Follower needs about six months to know the Leader's outcome and consequently to receive the information revelation. So we assume that $t_1 = 0.5$ years.
K denotes the critical price value that makes indifferent the exercise or not at middle time $\frac{\tau}{2}$ of a PSAEO $S_2(V, D, \frac{\tau}{2})$. So to determine K it is sufficient to use Eq. (5) with $T = \tau$. For our adapted numbers it results $K = 1.6722$.
Finally, we consider that firm A has an higher and more efficient Know-How than firm B and so, the firm A's success probability is $q = 0.60$ while the firm B's one is $p = 0.55$.

4.2 Empirical Results

The Table 1 shows the Montecarlo simulation assuming the several overall market values. In particular way we compute, for each player, four Montecarlo simulations and, to determine the final Follower and the Waiting strategic payoffs, we compute the average value. We assume that the number of simulations n is equal to 100 000. As it is shown in Cortelezzi & Villani (2009), this simulations number allows us to obtain a very low variance and to improve the efficiency of computations.

Strategy	1^{st} MC	2^{nd} MC	3^{rd} MC	4^{th} MC	Average Value
$F_A(800\,000)$	26 620	26 525	26 573	26 663	**26 595**
$F_B(800\,000)$	23 936	23 862	23 916	23 999	**23 928**
$W_A(800\,000)$	30 760	30 675	30 777	30 875	**30 772**
$W_B(800\,000)$	25 191	25 133	25 227	25 323	**25 219**
$F_A(1\,000\,000)$	47 146	47 147	47 103	47 087	**47 120**
$F_B(1\,000\,000)$	43 232	43 060	43 024	42 988	**43 076**
$W_A(1\,000\,000)$	56 355	56 123	56 089	56 004	**56 143**
$W_B(1\,000\,000)$	47 146	46 925	46 900	46 780	**46 938**
$F_A(1\,200\,000)$	72 288	72 286	71 908	72 176	**72 164**
$F_B(1\,200\,000)$	66 707	66 711	66 359	66 608	**66 596**
$W_A(1\,200\,000)$	87 566	87 618	87 150	87 484	**87 455**
$W_B(1\,200\,000)$	74 349	74 369	73 977	74 261	**74 239**
$F_A(1\,400\,000)$	100 510	100 750	100 510	100 420	**100 548**
$F_B(1\,400\,000)$	93 460	93 687	93 460	93 356	**93 491**
$W_A(1\,400\,000)$	123 240	123 530	123 240	123 030	**123 260**
$W_B(1\,400\,000)$	105 810	106 060	105 810	105 650	**105 833**
$F_A(1\,600\,000)$	130 940	131 290	131 430	131 440	**131 275**
$F_B(1\,600\,000)$	122 380	122 720	122 830	122 870	**122 700**
$W_A(1\,600\,000)$	161 490	162 000	162 020	162 130	**161 910**
$W_B(1\,600\,000)$	139 850	140 290	140 330	140 460	**140 233**

Table 1: Simulated Values of Follower and Waiting Strategies

The Tables 2 and 3 summarize the strategic A and B payoffs considering the several expected total market values. The Figs. 6 and 7 show the A and B strategic values. We can observe that, when the expected market value $V = 0$, the simple and the compound American exchange option values are zero and so it results that $L_i(0) = S_i(0) = -R$ and $F_i(0) = W_i(0) = 0$, for $i = A, B$. Now, to determine the several Nash equilibriums, we introduce the critical market values that realize the equality among the four strategic values. We define by V^*_{WA} and V^*_{WB} the critical market values that make $L_i(V^*_{Wi}) = W_i(V^*_{Wi})$, for $i = A, B$ and by V^*_{SA} and V^*_{SB} the critical market values such that $F_i(V^*_{Si}) = F_i(V^*_{Si})$, for $i = A, B$. Through Figs. 6 and

Market Value V	Leader's Value L_A	Follower's Value F_A	Simultaneous Value S_A	Waiting Value W_A
800 000	-4 474	26 595	-28 728	30 772
1 000 000	48 152	47 120	15 126	56 143
1 200 000	102 894	72 164	60 745	87 455
1 400 000	159 113	100 548	107 594	123 260
1 600 000	216 402	131 275	155 335	161 910

Table 2: Firm A's final payoffs assuming $\alpha = 0.60$ and $\rho(X, Y) = 0.70$

Market Value V	Leader's Value L_B	Follower's Value F_B	Simultaneous Value S_B	Waiting Value W_B
800 000	-16 601	23 928	-38 834	25 219
1 000 000	31 639	43 076	1 366	46 938
1 200 000	81 819	66 596	43 183	74 239
1 400 000	133 354	93 491	86 128	105 833
1 600 000	185 869	122 700	129 891	140 233

Table 3: Firm B's final payoffs assuming $\alpha = 0.60$ and $\rho(X, Y) = 0.70$

7, we obtain:

$$V^*_{WA} \simeq 1\,070\,000; \quad V^*_{WB} \simeq 1\,130\,000; \quad V^*_{SA} \simeq 1\,320\,000; \quad V^*_{SB} \simeq 1\,490\,000.$$

When the expected market value $V < V^*_{WA}$, we have the following inequality among the strategic values:

$$L_A(V) < W_A(V); \quad L_B(V) < W_B(V); \quad F_A(V) > S_A(V); \quad F_B(V) > S_B(V);$$

So, using this inequality, we have one Nash equilibrium (W_A, W_B). For instance, assuming that the expected market value is equal to $V = 800\,000$ (low return), the two by two matrix represented in Fig. 8(a) shows the (W_A, W_B) Nash equilibrium in which firms A and B prefer to wait for best market evolutions and so they decide to delay their R&D investment decision at time t_1.
Instead, if the expected market value $V > V^*_{SB}$, it results the following inequality among the stratigic values:

$$L_A(V) > W_A(V); \quad L_B(V) > W_B(V); \quad F_A(V) < S_A(V); \quad F_B(V) < S_B(V);$$

So, assuming that the expected market value $V = 1\,600\,000$ (high return), there is one Nash equilibrium (S_A, S_B) as shown in the Fig. 8(d). Both firms decide to invest simultaneously in R&D at time t_0 to take advantage of high market value.
If we consider that the overall expected market value $V \in]V^*_{WA}, V^*_{WB}[$, the relation among the strategic payoffs is:

$$L_A(V) > W_A(V); \quad L_B(V) < W_B(V); \quad F_A(V) > S_A(V); \quad F_B(V) > S_B(V);$$

In this case we have one Nash equilibriums (L_A, F_B). Specifically, the firm with the highest success probability (firm A) realizes the R&D investment at time t_0 earlier

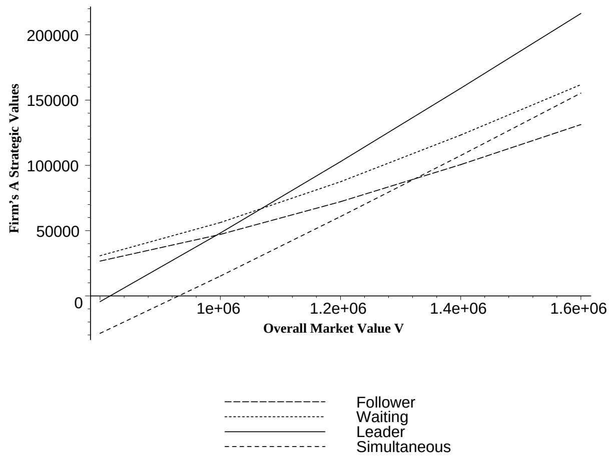


Figure 6: Firm's A Strategic Values

that other one (firm B) that postpones its R&D investment decision at time t_1 waiting better information. Moreover, if we assume that $V \in]V^*_{SA}, V^*_{SB}[$, we have the following relation among the strategic payoffs:

$$L_A(V) > W_A(V); \quad L_B(V) > W_B(V); \quad F_A(V) < S_A(V); \quad F_B(V) > S_B(V);$$

Also in this case, using the above relations, we have one Nash equilibrium (L_A, F_B). For instance, if $V = 1\,400\,000$, the Fig. 8(c) shows that there exists one Nash equilibrium (L_A, F_B).
Finally, if we assume that $V \in]V^*_{WB}, V^*_{SA}[$, we have the following inequality among the strategic values:

$$L_A(V) > W_A(V); \quad L_B(V) > W_B(V); \quad F_A(V) > S_A(V); \quad F_B(V) > S_B(V);$$

In this case we have two Nash equilibriums: (L_A, F_B) and (F_A, L_B). In the first equilibrium firm A invests immediately at time t_0 while B postpones its R&D decision at time t_1 waiting better information, vice versa in the second equilibrium. If we consider that $V = 1\,200\,000$, we have two Nash equilibriums as it is represented in the Fig. 8(b).

5 The effects of $\rho(X, Y)$, α and δ_v on the equilibriums

As we have seen above, in the range game $[V^*_{WA}, V^*_{SB}]$ we have one Nash equilibrium (L_A, F_B) or two Nash equilibriums $(L_A, F_B); (F_A, L_B)$ that we can solve by mixed strategies. Now we are interested to analyse the effects that the information revelation $\rho(X, Y)$, the first mover's advantage α and the dividend yield δ_v have on Nash equilibriums of both players.
First of all, it is obvious that the strategic payoffs using American exchange options are bigger then European one since American options give the managerial flexibility value to realize the investment D prior to maturity T. In particular way, comparing the results given in Villani (2008), we can remark that the critical market values using

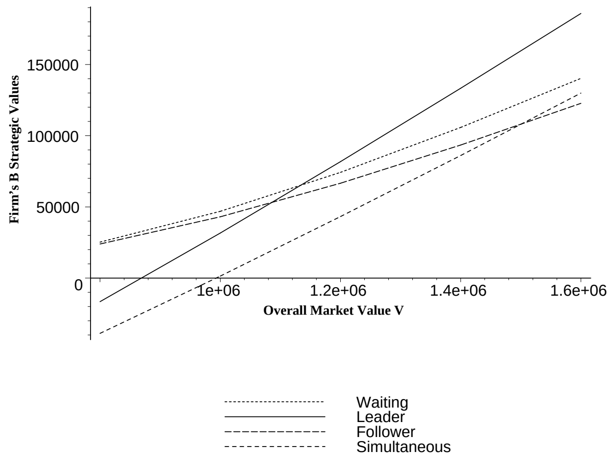
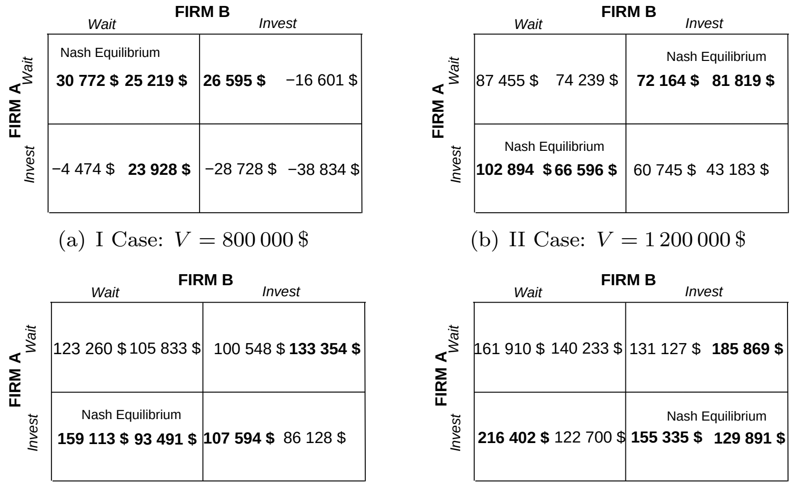


Figure 7: Firm's B Strategic Values

American exchange options V^*_{WA} and V^*_{SB} go down with respect to European options and the length of range game $[V^*_{WA}, V^*_{SB}] \simeq [1\,070\,000, 1\,490\,000] = 420\,000$ is smaller then $[1\,349\,400, 1\,898\,700] = 549\,300$ using European options. So we can state that, using the managerial flexibility, both firms reduce the critical market values that bound both the opportunity to delay the R&D investment decision (wait and see policy) and the simultaneous investment implementation. So, with American options, the R&D investment can be realized at time t_0 when $V = 1\,070\,000\,\$$ instead of $V = 1\,349\,400\,\$$. Moreover, when the dividend yields δ_d and δ_v go to zero, then the CAEO and SAEO prices are equal to CEEO (see Carr (1988)) and SEEO (see McDonald & Siegel (1985)) respectively, since there is not the incentive to exercise the American option prior to maturity date T. So for our adapted number, assuming that $\delta_v = 0$, we have that $V^*_{WA} \simeq 860\,000$ and $V^*_{SB} \simeq 1\,305\,000$.
The Table 4 shows the effects that the information revelation has got on the game ranges. To simplify, we assume that $\rho(X, Y) = \rho(Y, X)$. The conditions to respect to have $0 \leq p^+ \leq 1$ and $0 \leq p^- \leq 1$ is that:

$$0 \leq \rho(X, Y) \leq \min\left\{\sqrt{\frac{p(1-q)}{q(1-p)}}, \sqrt{\frac{q(1-p)}{p(1-q)}}\right\} \tag{21}$$

In our applications it results that $0 \leq \rho(X, Y) \leq 0.9026$. We can observe that the Leader and Waiting payoffs are independent by $\rho(X, Y)$ and so the critical market values V^*_{WA} and V^*_{WB} do not change and therefore the length of range $[V^*_{WA}, V^*_{WB}]$ is always about 60 000\$. But, if the information revelation increases, then the game ranges $]V^*_{WB}, V^*_{SA}[$ (in which we have two Nash equilibriums) and $]V^*_{SA}, V^*_{SB}[$ (in which we have one Nash equilibrium) enlarge.
The Table 5 shows the effects that the first mover's advantage has on the critical market values and in particular way we can note that, if the Leader's market share α increases, then all the critical market values go down. When $\alpha = 1$ then the Follower's strategy values zero since its market share is $1 - \alpha = 0$.



(a) I Case: $V = 800\,000\,\$$

(b) II Case: $V = 1\,200\,000\,\$$

(c) III Case: $V = 1\,400\,000\,\$$

(d) IV Case: $V = 1\,600\,000\,\$$

Figure 8: Final payoffs

$\rho(X,Y)$	V^*_{SA}	V^*_{SB}	$V^*_{WB} - V^*_{WA}$	$V^*_{SA} - V^*_{WB}$	$V^*_{SB} - V^*_{SA}$
0	1 155 000	1 228 000	60 000	25 000	73 000
0.10	1 165 000	1 262 000	60 000	35 000	97 000
0.30	1 203 000	1 307 000	60 000	73 000	104 000
0.50	1 235 000	1 380 000	60 000	105 000	145 000
0.70	1 320 000	1 490 000	60 000	190 000	170 000
0.90	1 439 000	1 690 000	60 000	309 000	251 000

Table 4: Variation of Information Revelation with $\alpha = 0,60$ and $\delta_v = 0.15$

α	V^*_{WA}	V^*_{WB}	V^*_{SA}	V^*_{SB}
0.60	1 070 000	1 130 000	1 320 000	1 490 000
0.70	858 000	906 000	1 070 000	1 161 000
0.80	742 000	791 000	975 000	1 042 000
0.90	662 000	703 000	935 000	998 000
1	609 000	645 000	932 000	993 000

Table 5: Variation of Leader's Market Share with $\rho(X,Y) = 0.70$ and $\delta_v = 0.15$

6 Concluding Remarks.

The R&D investment is an important successful key for the firm performance. An R&D investment opportunity is not held by one firm in isolation and so the competitive considerations become extremely important. The theory of option games combines two successful theories, namely real options and game theory. By real options we value an R&D investment opportunity using financial techniques and, in particular way, we use Montecarlo simulations to value an American exchange options that take into account the managerial flexibility to realize the investment D at anytime before the maturity T. By the game theory, we consider strategic interactions between two firms. The first firm that invests, defined as the Leader, acquires a first mover advantage that we assume as a higher market share then Follower's one, that postpones the R&D investment. But, in our model, we assume that Follower receives an information revelation from Leader's R&D investment. Through the critical market values V^*_{WA}, V^*_{WB}, V^*_{SA} and V^*_{SB}, we are able to determine the range game in which is optimal each strategy policy in Nash meaning and we have showed the effects that most important parameters have on the game. So, when $V < V^*_{WA}$ we have one Nash equilibrium (W_A, W_B) and if $V > V^*_{SB}$ the optimal Nash policy is the simultaneous investment (S_A, S_B) at time t_0. Moreover, if V is in the ranges $]V^*_{WA}, V^*_{WB}[$ and $]V^*_{SA}, V^*_{SB}[$ we have one Nash equilibrium (L_A, F_B) in which the firm with the highest success probability realizes the R&D investment earlier then other one, while in the interval $]V^*_{WB}, V^*_{SA}[$ we have two Nash equilibriums: (L_A, F_B) and (F_A, L_B). In this case we need to use the mixed strategies to solve the game.

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A Montecarlo Simulation to determine Follower's payoff

In this algorithm, we denote by 'f' the proportion φ of asset D to determine the research investment R, by 'pL' and 'pF' the R&D success probability of Leader and Follower respectively, and by 'rev' the information revelation. Moreover, 'n' is the number of simulations and 'K' denotes the critical market value that makes indifferent the exercise or not at middle time $\frac{\tau}{2}$ a PSAEO $S_2(V, D, \tau)$.

```
function FOLLOWER=MCAmerComp(V0,D0,f,dV,dD,T1,T2,K,sigV,sigD,rhoVD,...
pL,pF,rev,alpha,n);
% R&D success probability with positive and negative information revelation
pp=pF+sqrt((1-pL)/(pL))*sqrt(pF*(1-pF))*rev;
pm=pF-sqrt((1-pL)/(pL))*sqrt(pF*(1-pF))*rev;
sig=sqrt(sigV.^2+sigD.^2-2*rhoVD.*sigV.*sigD); %Variance of asset P;
u=rand(1,n); %Random uniform values between 0 and 1;
P0=V0/D0;
d=(dV-dD);
rho=sqrt(T1/T2);
%Value of asset P at time t1 to compute the PAEO
PT1=P0*exp(norminv(u,-d*T1-sig^2*T1*0.5,sig*sqrt(T1)));
ds1=((log((PT1*exp(-d*(0.5*(T2-T1))))/(K))+0.5*(sig.^2)*0.5*(T2-T1))/...
(sig*sqrt(0.5*(T2-T1))));
```

```
d1=(log(PT1*exp(-d*(T2-T1)))+0.5*(sig^2)*(T2-T1))/(sig*sqrt(T2-T1));
ds2=((log((PT1*exp(-d*(0.5*(T2-T1))))/(K))-0.5*(sig.^2)*0.5*(T2-T1))/...
(sig*sqrt(0.5*(T2-T1))));
d2=(log(PT1*exp(-d*(T2-T1)))-0.5*(sig^2)*(T2-T1))/(sig*sqrt(T2-T1));
%Computation of simulations;
for i=1:n
R1(i)=bivnormcdf(-ds1(i),d1(i),-rho);
R2(i)=bivnormcdf(-ds2(i),d2(i),-rho);
end
%Payoff of PCAEO with positive and negative information revelation;
vpp=max(pp*(1-alpha)*(PT1*exp(-dV*(T2-T1)).*R1+PT1*...
exp(-dV*0.5*(T2-T1)).*normcdf(ds1)-exp(-dD*(T2-T1)).*R2...
-exp(-dD*0.5*(T2-T1)).*normcdf(ds2))-f,0);
vpm=max(pm*(1-alpha)*(PT1*exp(-dV*(T2-T1)).*R1+PT1*...
exp(-dV*0.5*(T2-T1)).*normcdf(ds1)-exp(-dD*(T2-T1)).*R2...
-exp(-dD*0.5*(T2-T1)).*normcdf(ds2))-f,0);
PCAEOpp=D0*exp(-dD*T1)*mean(vpp)
PCAEOpm=D0*exp(-dD*T1)*mean(vpm)
%Payoff of CEEO with positive and negative information revelation;
zpp=max(pp*(1-alpha)*(PT1*exp(-dV*(T2-T1)).*normcdf(d1)...
-exp(-dD*(T2-T1)).*normcdf(d2))-f,0);
zpm=max(pm*(1-alpha)*(PT1*exp(-dV*(T2-T1)).*normcdf(d1)...
-exp(-dD*(T2-T1)).*normcdf(d2))-f,0);
CEEOpp=D0*exp(-dD*T1)*mean(zpp)
CEEOpm=D0*exp(-dD*T1)*mean(zpm)
%Follower's payoff
FOLLpp=PCAEOpp+(PCAEOpp-CEEOpp)/3
FOLLpm=PCAEOpm+(PCAEOpm-CEEOpm)/3
FOLLOWER=pL*FOLLpp+(1-pL)*FOLLpm
```

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