A Generalized Fuzzy Optimization Framework for R&D Project Selection Using Real Options Valuation*

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Abstract. Global marketplace and intense competition in the business environment lead organizations to focus on selecting the best R&D project portfolio among available projects using their scarce resources in the most effective manner. This happens to be a *sine qua non* for high technology firms to sharpen their competitive advantage and realize long-term survival with sustainable growth. To accomplish that, firms should take into account both the uncertainty inherent in R&D using appropriate valuation techniques accounting for flexibility in making investment decisions and all possible interactions between the candidate projects within an optimization framework. This paper provides a fuzzy optimization model for dealing with the complexities and uncertainties regarding the construction of an R&D project portfolio. Real options analysis, which accounts for managerial flexibility, is employed to correct the deficiency of traditional discounted cash flow valuation that excludes any form of flexibility. An example is provided to illustrate the proposed decision approach.

1 Introduction

In this paper, the research and development (R&D) project selection problem is addressed. R&D project selection examines the allocation of company's scarce resources such as budget, manpower, etc. to a set of proposals to enhance its strategic performance on a scientific and technological basis. R&D is crucial for a company's competitive advantage, survival and sustainable growth. R&D enables the company to develop new products or services, enhance existing ones, and increase efficiency while lowering cost of the production processes. This paper focuses on the problem of selecting a portfolio of R&D projects when both vagueness and uncertainty in data and interactions between candidate projects exist.

For the case of crisp data, early work dates back to Weingartner [16], and since then R&D project selection has been an active area of research for academics and practitioners. Liberatore [10] proposed a decision framework based on the analytic hierarchy process (AHP) and integer programming for R&D project selection. Inadequate representation of project interdependencies, and the inability to incorporate the uncertainty inherent in projects and interactions between projects are the major

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shortcomings of the previously proposed analytical models for R&D project selection. Within the last decade, researchers, in particular, addressed the proper treatment of project interdependencies. Schmidt [13] presented a model that considered benefit, outcome and resource interactions and proposed a branch and bound algorithm to obtain a solution for the nonlinear integer programming problem with quadratic constraints. Meade and Presley [12] proposed the utilization of the analytic network process (ANP) that enables the decision-maker to take into consideration interdependencies among criteria and candidate projects. One should note the resource feasibility problem that may be encountered while using the ANP by itself. Lee and Kim [8] presented an integrated application of the ANP and zero-one goal programming for information system project selection to consider resource feasibility as well as project interdependence.

Although the aforementioned valuable contributions considered interactions between projects, they all relied on crisp data. R&D projects comprise a high degree of uncertainty, which generally precludes the availability of obtaining exact data regarding benefit, resource usage, and interactions between projects. Fuzzy set theory appears as a useful tool to account for vagueness and uncertainty inherent in the R&D project selection process. Recently, a model that handles fuzzy benefit and resource usage assuming that a project can influence at most one other was developed; however, an optimization procedure was not presented to solve the proposed model [7].

Furthermore, the research studies cited above use the traditional discounted cash flow (DCF) techniques such as net present value (NPV) in its static form for calculating the benefits from R&D investments. Lately, options valuation approach has been proposed as a more suitable alternative for determining the benefits from R&D projects [9]. Options approach deviates from the conventional DCF approach in that it views future investment opportunities as rights without obligations to take some action in the future [3]. The asymmetry in the options expands the NPV to include a premium beyond the static NPV calculation, and thus presumably increase the total value of the project and the probability of justification. Carlsson and Fullér [1] further extended the use of options approach in R&D project valuation by considering the possibilistic mean and variance of fuzzy cash flow estimates.

This paper presents a novel fuzzy formulation for R&D project selection accounting for project interactions with the objective of maximizing the net benefit based on expanded net present value which incorporates the real options inherent in R&D projects in a fuzzy setting. Although a fuzzy optimization model is provided for R&D portfolio selection in [14], the project interactions are completely ignored. Compared with the real options valuation procedures delineated in [1, 14], the valuation approach utilized in this paper models exercise price as a stochastic variable enabling to deal with technological uncertainties in real options analysis, and considers both the benefits of keeping the development option alive and the opportunity cost of delaying development. Moreover, this paper's focus is not limited to valuation of R&D projects using fuzzy cash flow estimates since the proposed optimization framework enables constructing an optimal portfolio of R&D projects considering the commonly encountered project interdependencies regarding resource usage. The proposed model will lead to a binary integer program with nonlinear constraints. In this paper, a solution procedure based on linearization of the nonlinear constraints is provided and thus the resulting linear problem can be solved with widely available solvers. The proposed optimization approach is also advantageous compared with heuristics in that the obtained solution is the global optimum of the problem.

The rest of the paper is organized as follows. Section 2 reviews the sequential exchange options for valuing R&D projects. Section 3 outlines the approach to incorporate fuzzy cash flows into the valuation methodology. A fuzzy optimization model with nonlinear constraints which is later converted into a crisp linear binary integer program is introduced in Section 4. A comprehensive example is presented in the subsequent section to illustrate the application of the proposed framework. Finally, conclusions and directions for future research are provided in Section 6.

2 Real Options Approach to Valuation of R&D Projects

An option is the right, but not the obligation, to buy (if a call) or sell (if a put) a particular asset at a specified price on or before a certain expiration date. The buyer of an option may choose to exercise his right and take a position in the underlying asset while the option seller, also known as the option writer, is contractually obligated to take the opposite position in the underlying asset if the buyer exercises his right. The price at which the buyer of an option may buy or sell the underlying asset is the exercise price. An American option can be exercised at any time prior to expiration, while a European option allows exercise only on its expiration date. An American exchange option, which can be cited among options with more complicated payoffs than the standard European or American calls and puts, gives its owner the right to exchange one asset for another at any time up to and including expiration.

While financial options are options on financial assets, real options are opportunities on real assets that can provide management with valuable operating flexibility and strategic adaptability. Akin to financial options, real options enable their owners to revise future investment and operating decisions according to the market conditions. A substantial part of the market value of companies operating in volatile and unpredictable industries such as electronics, telecommunications, and biotechnology can be attributed to the real options that they possess [3]. Real options preclude the traditional passive analysis of investments, and imply active management approach with an ability to respond to changing conditions. Real options approach enables the firm to evaluate the project in a multi-stage context, providing the means to revise the decisions based on new information.

It is reported that American sequential exchange options provide a more realistic valuation of R&D projects compared with other option models when R&D projects incorporate stages of research and/or sequential investment opportunities [9]. In this paper, an efficient method for valuing American sequential exchange options when both underlying assets pay dividends continuously and there exists a possibility of early exercise is employed. The earlier work on exchange options dates back to Margrabe [11], who derived a pricing equation for the exchange options on non-dividend-paying assets. Although elegant by its ability to model exercise price as a stochastic variable enabling to deal with technological uncertainties in real options analysis, easy to use formula developed by Margrabe [11] falls short of incorporating dividends into the analysis, which may especially be crucial in valuation of real options due to the fact that the underlying assets are generally not traded.

Here, an option to exchange asset *D* for asset *V* at time *T* is considered. Asset *D* is referred as the delivery asset, and asset *V* as the optioned asset. The payoff to this European option at time *T* is given as $max(0, V_T - D_T)$, where V_T and D_T are the underlying assets' terminal prices. The asset prices prior to expiration, i.e. V and D, are assumed to follow geometric Brownian motion as

$$\frac{dV}{V} = (\alpha_v - \delta_v)dt + \sigma_v dZ_v ,$$
$$\frac{dD}{D} = (\alpha_d - \delta_d)dt + \sigma_d dZ_d , \tag{1}$$
$$\operatorname{cov}\left(\frac{dV}{V}, \frac{dD}{D}\right) = \rho_{vd}\sigma_v\sigma_d dt .$$

where α_v and α_d are the expected rates of return on the two assets, δ_v and δ_d are the corresponding dividend yields, σ_v^2 and σ_d^2 are the respective variance rates, and dZ_v and dZ_d are increments of the Wiener processes at time t $(t \in [0, T])$. The rates of price change, i.e. $\left(\frac{dV}{V}\right)$ and $\left(\frac{dD}{D}\right)$, can be correlated with the correlation coefficient denoted by ρ_{vd}. The parameters δ_v, δ_d, σ_v, σ_d, and ρ_{vd} are non-negative constants. δ, which denotes the difference in dividend yields, can be defined as $\delta_v - \delta_d$.

In this paper, the model proposed by Carr [2] for valuing American exchange options on dividend-paying assets is used. Carr [2] generalized the solution of Geske and Johnson [4], which was initially developed for valuing an American put option, to American exchange options on assets with continuous dividends. Geske and Johnson [4] viewed an American put option as the limit to a sequence of pseudo-American puts. A pseudo-American option can only be exercised at a finite number of discrete exercise points. In the limiting case, the value of a pseudo-American option approaches the exact value of a true American put option. Geske and Johnson [4] achieved accuracy by considering put options which can be exercised at a small number of discrete time points, and then employed the values obtained at these exercise dates to extrapolate to the value of a put option that can be exercised at any date. The details of the valuation formula for the general pseudo-American exchange option are not provided here due to limited space. The reader may refer to Karsak and Özogul [6] for a detailed presentation.

3 Using Fuzzy Sets for Modeling Uncertainty in Project Selection

The fuzzy set theory deals with problems in which a source of imprecision and vagueness is involved. A fuzzy set can be defined mathematically by assigning to each possible individual in the universe of discourse a value representing its grade of membership in the fuzzy set. This grade corresponds to the degree to which individual is compatible with the concept represented by the fuzzy set. A convex and normalized fuzzy set defined on $\Re$ with a piecewise continuous membership function is called a fuzzy number. Uncertainty and imprecision in parameters such as cash flow estimates can be incorporated into the R&D project selection framework using fuzzy numbers. $\tilde{A} = (c_L, c_R, s_L, s_R)$ is a trapezoidal fuzzy number with the membership function defined as

$$f_{\tilde{A}}(x) = \begin{cases} (x-(c_L - s_L))/s_L, & c_L - s_L \le x \le c_L \\ 1, & c_L \le x \le c_R \\ ((c_R + s_R)-x)/s_R, & c_R \le x \le c_R + s_R \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where c_L and c_R are the left and right core values, and s_L and s_R are the left and right spreads, respectively. The support of $\tilde{A}$ is (c_L - s_L, c_R + s_R). If $c_L = c_R = c$, the resulting fuzzy number is a triangular fuzzy number denoted as $\tilde{A} = (c, s_L, s_R)$. Further, when $s_L = s_R = s$, a symmetric triangular fuzzy number $\tilde{A} = (c, s)$ is obtained.

The possibilistic mean and variance of a trapezoidal fuzzy number $\tilde{A}$ are defined as [1]

$$E(\tilde{A}) = \frac{c_L + c_R}{2} + \frac{s_R - s_L}{6}, \tag{3}$$

$$Var(\tilde{A}) = \frac{(c_R - c_L)^2}{4} + \frac{(c_R - c_L)(s_L + s_R)}{6} + \frac{(s_L + s_R)^2}{24}. \tag{4}$$

4 Fuzzy Optimization Framework for R&D Project Selection

This paper considers constructing an R&D project portfolio, where there are m candidate R&D projects. The binary decision variable x_i (i = 1, …, m) corresponds to the ith R&D project, where $x_i = 1$ if R&D project i is selected and $x_i = 0$ otherwise. The objective is to maximize the total net benefit obtained from the R&D project portfolio. Resource constraints related to the initial expenditures for the R&D projects and the skilled workforce (in man-hours) are considered as well as the interdependencies among the R&D projects regarding the use of these resources. There is an estimate for budget limit for initial expenditures ($\tilde{T}_B$) and an estimate for skilled workforce limit required for the development phase of R&D projects ($\tilde{T}_W$). Both of these estimates as well as the estimates for resource usages and shared resources for the R&D projects are represented as fuzzy numbers due to the imprecise nature of the problem. The proposed model also enables to account for project contingencies, which indicate a project cannot be implemented unless a related project is also selected. Other restrictions regarding the construction of the R&D project portfolio such as mutually exclusive projects or mandated projects can be readily appended to the proposed model.

$$\max Z^* = \sum_{i=1}^{m} V_i^e x_i \ , \tag{5}$$

subject to

$$\sum_{i=1}^{m} \tilde{C}_i x_i - \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} \tilde{C}_{ij} x_i x_j + \sum_{i=1}^{m-2} \sum_{j=i+1}^{m-1} \sum_{k=j+1}^{m} \tilde{C}_{ijk} x_i x_j x_k \le \tilde{T}_B \, , \tag{6}$$

$$\sum_{i=1}^{m} \tilde{W}_i x_i - \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} \tilde{W}_{ij} x_i x_j + \sum_{i=1}^{m-2} \sum_{j=i+1}^{m-1} \sum_{k=j+1}^{m} \tilde{W}_{ijk} x_i x_j x_k \le \tilde{T}_W \, , \tag{7}$$

$$\sum_{i \in Y_j} x_i \ge \left| Y_j \right| x_j , \quad j \in \Theta_Y \, , \tag{8}$$

$$x_i \in \{0,1\}, \quad i = 1, \ldots, m \, . \tag{9}$$

Formula (5) represents the objective of maximizing the total net benefit of the R&D project portfolio, where V_i^e denotes the net benefit obtained from project i using the expanded net present value (ENPV). Both formulae (6) and (7) represent resource constraints, which enable project interactions to be taken into account. Uncertain initial expenditure and shared initial expenditure parameters are denoted respectively as $\tilde{C}_i$ and $\tilde{C}_{ij}, \tilde{C}_{ijk}$, while $\tilde{W}_i$ and $\tilde{W}_{ij}, \tilde{W}_{ijk}$ represent fuzzy workforce and fuzzy shared workforce parameters, respectively, for the R&D projects. Although the current formulation assumes that interactions exist among at most three R&D projects, it can be easily extended to include higher number of interdependent projects. In addition to the resource constraints, the formulation includes contingency constraints given by formula (8) indicating that the implementation of the project j is contingent upon the implementation of all the projects in $Y_j \subset \{1, \cdots, m\}$, where $\left| Y_j \right|$ indicates the cardinal of Y_j and $\Theta_Y \subset \{1, \cdots, m\}$.

The formulation given above is a fuzzy nonlinear integer programming model and can be linearized using the approach delineated in [15]. For instance, the nonlinear term $x_i x_j$ can be linearized by introducing a new variable $x_{ij} := x_i x_j$, where $x_{ij} \in \{0,1\}$, and appending the following linear constraints to the model:

$$x_i + x_j - x_{ij} \le 1 \, , \tag{10}$$

$$-x_i - x_j + 2x_{ij} \le 0 \, . \tag{11}$$

After performing the linearization, the fuzzy linear integer programming formulation can be converted to a crisp mathematical programming model using the possibility theory. Formulae (6) and (7) that incorporate fuzzy parameters can be rewritten as crisp constraints employing the possibilistic approach [5]. For example, an inequality constraint given as

$$\tilde{a}_{1j}x_1 + \tilde{a}_{2j}x_2 + \ldots + \tilde{a}_{mj}x_m \le \tilde{b}_j \tag{12}$$

can be rewritten as

$$\sum_{i=1}^{m} a_{ij}^{cR}x_i + \lambda_j \sum_{i=1}^{m} a_{ij}^{sR}x_i \le b_j^{cR} + (1-\lambda_j)b_j^{sR}\,, \tag{13}$$

where λ_j is the satisfaction degree of the constraint, a_{ij}^{cR}, b_j^{cR} denote the right core values of $\tilde{a}_{ij}, \tilde{b}_j$, and a_{ij}^{sR}, b_j^{sR} denote their right spreads, respectively.

5 Illustrative Example

In this section, we consider a technology firm analyzing six R&D project alternatives, where each R&D project consists of a two-stage investment, namely the initial stage and the development stage. The company acquires the right to make a development investment by making the initial investment for each R&D project. Due to imprecise and uncertain nature of R&D investments, project cash flow estimates regarding the development stage are given as fuzzy numbers in Table 1. Although the methodology delineated in the previous section enables to use trapezoidal fuzzy numbers, in order to save space, fuzzy cash flow estimates are provided as symmetric triangular fuzzy numbers $\tilde{A}_j = (c, s)$ where c is the most likely (core) value and s is the spread, respectively. Resource data for the R&D project alternatives and data related to the project interactions are provided in Table 2 and Table 3, respectively. Project 2 is assumed to be contingent upon the implementation of project 5.

Table 1. Fuzzy cash flow estimates (in thousands of dollars) regarding the development stage of the R&D project alternatives

	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
A_0	(-27000,6000)	(-30000,6500)	(-35000,7500)	(-40000,8500)	(-25000,5500)	(-41000,9000)
A_1	(7000,1500)	(8000, 1800)	(11500,2700)	(7500,1800)	(4000,900)	(11000,2500)
A_2	(8000,1800)	(9000, 2100)	(14000,3200)	(9300,2400)	(5400,1300)	(13000,3100)
A_3	(8500,2200)	(9500, 2300)	(12000,2900)	(10500,2500)	(6500,1600)	(13500,3400)
A_4	(8000,2100)	(10500,2400)	(10600,2800)	(11500,3000)	(7000,1700)	(16500,4000)
A_5	(6700,1700)	(8800, 2500)	(9500,2500)	(14000,3200)	(7500,1900)	(17500,4300)
A_6	(6000,1600)	(8000, 2200)	(8500, 2200)	(12500,3000)	(9000,2200)	(15000,3800)

Equation (3) is employed to compute the expected value of the development stage investment and the expected value of returns from the development stage investment for each R&D project alternative. The standard deviation of the rate of change of the returns from the development stage investment and the standard deviation of the rate of change of the development stage investment are taken to be 0.1 and 0.3, respectively. It is assumed that the correlation between development investment and expected value of returns from development investment is 0.5 for each R&D project. The time interval in which the development investment can be realized is taken to be two years. The opportunity cost of delaying development investment (δ_v) is set as a constant proportional to expected value of returns from the development investment as 0.04 while the depreciation of development investment is determined as a constant proportional to value of development investment as $\delta_d = 0.02$. In practice, δ_v depends on competitive intensity and market structure characteristics in addition to the anticipated increase in demand and can be measured from market information using econometric methods, whereas δ_d can be estimated based on expert opinion [6].

Table 2. Resource data for the R&D project alternatives

Projects	Initial expenditures ($)	Workforce (in man-hours)
1	6,000,000	(200,000, 20,000)
2	9,500,000	(240,000, 20,000)
3	13,500,000	(300,000, 30,000)
4	7,000,000	(320,000, 30,000)
5	3,000,000	(160,000, 20,000)
6	20,000,000	(360,000, 40,000)

Table 3. Data regarding the R&D project interdependencies

Interdependent projects	Shared initial expenditures (in thousands of dollars)	Shared workforce (in man-hours)
1, 3	(2,000, 400)	(30,000, 6,000)
1, 6	(1,500, 200)	(40,000, 8,000)
2, 4	(2,500, 400)	(50,000, 10,000)
2, 5	(2,000, 200)	(24,000, 4,000)
3, 6	(3,000, 500)	(40,000, 10,000)
2, 4, 5	(2,000, 300)	(30,000, 8,000)

NPV for the development stage of each R&D project is calculated using an interest rate of 10%. ENPV for the development stage of each R&D project is obtained employing the real options valuation approach delineated in Section 2. The difference between ENPV and NPV gives the option value for each R&D project. The net benefit obtained from each R&D project using ENPV is computed using equation (14).

$$\text{Net Benefit (R\&D project)} = \text{Initial Expenditure} + \text{ENPV (development stage)} \qquad (14)$$

The results of these valuations are reported in Table 4. In Table 4, C denotes the initial expenditure, V represents the net benefit calculation based on NPV, and V^e

denotes the net benefit using ENPV for the respective R&D project. As shown in Table 4, the net benefit calculation based on NPV results in negative figures for projects 1, 2, 4 and 5, whereas the net benefit using ENPV yields positive results for every R&D project alternative. In other words, an optimization model that maximizes the total net benefit based on NPV would eliminate projects 1, 2, 4 and 5 as a result of an erroneous valuation procedure ignoring any form of flexibility.

Table 4. Valuation results (in dollars) for the R&D project alternatives

	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
NPV	5,372,507	8,999,775	13,977,295	5,996,415	2,500,989	20,489,506
ENPV	6,821,550	9,900,180	14,527,765	8,695,080	4,614,975	20,748,132
Option Value	1,449,043	900,405	550,470	2,698,665	2,113,986	258,626
V = NPV – C	-627,493	-500,225	477,295	-1,003,585	-499,011	489,506
V^e = ENPV - C	821,550	400,180	1,027,765	1,695,080	1,614,975	748,132

Considering $\tilde{T}_B =$ (30,000,000, 4,000,000) dollars, $\tilde{T}_W =$ (1,000,000, 100,000) hours and a satisfaction degree of 0.8 for the resource constraints ($\lambda_j = 0.8$), the optimal solution of the crisp mathematical programming model, which is obtained by applying the linearization scheme delineated in Section 4 and the possibility theory to the fuzzy nonlinear integer programming formulation represented by formulae (5)-(9), is determined as projects 1, 2, 4 and 5. The optimal R&D project portfolios for varying satisfaction degrees of resource constraints are presented in Table 5. As can be seen in Table 5, the portfolio including projects "1, 3, 4, 5", which yields a higher net benefit figure compared with the portfolio consisting of projects "1, 2, 4, 5", becomes infeasible as the satisfaction degree for resource constraints increases to 0.8. It is also worth noting that both the real options valuation approach and the optimization framework used in this paper enable further sensitivity analyses regarding parameter flexibilities.

Table 5. Optimal solutions for varying λ_j values

λ_j	z^*	Selected projects
0.6	5,159,370	1, 3, 4, 5
0.7	5,159,370	1, 3, 4, 5
0.8	4,531,785	1, 2, 4, 5
0.9	4,531,785	1, 2, 4, 5

6 Conclusions

This paper aims to develop a fuzzy optimization approach to select an R&D project portfolio while accounting for project interactions and determining the benefits resulting from the R&D investments using real options valuation in a fuzzy setting. Although a fuzzy approach to R&D project selection enables to hedge against the R&D

uncertainty, another important issue that needs to be considered is that traditional DCF valuation methods oftentimes undervalue the risky project. In this paper, American sequential exchange options are employed to address this problem. Since R&D projects generally involve phased research and sequential investment opportunities with uncertain expenditures as well as returns, the sequential exchange option model appears to be more suitable than other option pricing techniques. Sensitivity analysis with respect to parameters of the model, which is confined to a minimum here due to limited space, can be easily extended. A more efficient linearization scheme may also be applicable for the cases which include higher number of interdependent projects. The implementation of the proposed approach using real data remains as a future research objective.

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