INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

REAL OPTIONS FOR PRODUCT FAMILY DESIGN

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ABSTRACT

This paper presents a real options approach to product family design by modelling product family design as an investment strategy being crafted by a series of real options that are continuously exercised to achieve expected returns on investment. A hybrid real options model is proposed to recognize the value of flexibility either inherent in a project or that can be built in product platforms. The real options approach surmounts traditional design evaluation methods in that it excels in integrating engineering analysis and financial analysis into a coherent framework.

Keywords: Product family, configuration design, flexibility, valuation, real option

1 INTRODUCTION

The fundamental concern underlying product family design manifests itself through the fact that the manufacturer must make tradeoffs between customer-perceived variety offered by the product families and complexity of product fulfillment resulting from product differentiation. It thus becomes imperative to assess the value and cost associated with the ability of configure-to-order through various options (referred to as management flexibility) inherent in product family design [1]. While substantial efforts have been devoted to optimal product design [2], the economic justification of product families has received only limited attention [3].

The general gist of most existing approaches coincides with the traditional principle of capital budgeting that is based on unit costs. As a result, opportunities for cost savings from management flexibility are always missed due to unit cost comparisons [4]. Moreover, typical approaches to estimate costs and values associated with a project are based on discounted cash flows (DCF) analysis. However, DCF analysis usually underestimates the upside value of investment [5]. In addition, the NPV approach treats projects as independent investment opportunities and considers only a positive value of the computed NPV as the criterion for accepting a project. This implies an inflexible management that makes at the outset an irrevocable commitment to a certain operating strategy, and abides by it, until the end of its prespecified project life [6]. Obviously, this assumption contradicts the practical case of product families, where flexibility to configure among different options is the key enabler for mass customization [7].

This paper applies the real options theory to the valuation of management flexibility associated with product family configuration design. The use of real options has proven to be an accessible approach for the valuation of certain types of flexibility. When using real options for capital budgeting purposes, it is possible to take flexibility options into account in the valuation process. This paper specifically deals with how to measure and evaluate flexibility associated with product family design in accordance with economic considerations.

2 REAL OPTIONS

Based on the real options theory, product family design can be treated as a design project under an investment. Table 1 draws the parallel between product family design and the options concept. To take into account the uncertainty involved in mass customization, product family design is modeled as a stochastic process. Variant derivation can be referred to as design project decisions regarding a portfolio of options (investment "installments") within the project life. For example, design flexibility of an earlier option execution represents the exercise value required to acquire a subsequent option to continue the operation of the project until the next installment of flexibility becomes due.

Table 1 Real options concept in PFCD

Stock Call Option	Real Option	Product Family Configuration Design
Current value of stock call option	(Gross) Present value of expected cash flow	Expected PFCD value
Exercise price	Investment cost	Information content & value-added cycle time
Expiration time	Time until opportunity disappears	Time to market
Expected rate of return on the asset	Risk-free interest rate	Design flexibility & Process flexibility
Volatility of asset (probability)	Project value uncertainty	Uncertainty of customer needs

3 A REAL OPTIONS APPROACH

Product family design involves two aspects: (1) product-related options, referred to as technical real options, and (2) project-related options, referred to as financial real options. Technical real options characterize the physical flexibility built in the product families that contributes to the technical performance of design. Financial real options, on the other hand, indicate the management flexibility staged along the project life, which constitutes the justification of profit performance of design. Therefore, the valuation of product family design calls for a hybrid approach combining engineering analysis with financial analysis.

3.1 Technical real options

Technical real options are directly related to the configuration process of product family design [8]. Product family design decision making starts with the selection of a product platform, and then generates product variants by configuring predefined modules within this particular platform. As such, a screening real option is introduced, denoted as $x^{SCRE}(\bullet)$. For instance, screen option $x^{SCRE}(PdP_1)$ represents the screening option with regard to product platform PdP$_1$.

Corresponding to the basic variety generation methods, four types of primitive real options are identified as attaching, removing, swapping, and scaling, denoted as $x^{ATTA}(\bullet)$, $x^{REMO}(\bullet)$, $x^{SWAP}(\bullet)$, and $x^{SCAL}(\bullet)$, respectively. Based on variety nesting operations, a nesting real option is constructed from a series of primitive real options, and thus is described as a compound real option, $x^{NEST}(\bullet)$. A nesting real option is only applicable to a subsystem that consists of multiple differentiation modules.

3.2 Financial real options

In the context of product family design, four types of financial real options are considered: launch, defer, abandon and switch options, denoted as $x^{Lau}(\bullet)$, $x^{Def}(\bullet)$, $x^{Aba}(\bullet)$ and $x^{Swi}(\bullet)$, respectively. A launch option indicates when a design is to be built along the project life, whereas a defer or abandon option suggests that a design project would be suspended and postponed to a later time or canceled to deal with market uncertainty. Switch options coincide with flexible changes among different configuration alternatives. Each financial option treats a technical option as a subproject of investment.

3.3 Valuation of technical real options

Let $\{F_{iq} \mid q = 1, \ldots, Q\}$ be a set of functional features to be fulfilled by a technical real option, $x_i^T \in X^T \equiv \{x_i^T \mid i = 1, \ldots, I\}$. From a customer's viewpoint, the expected performance of design with respect to a particular functional feature, F_{iq}, is described as a utility function, $u(F_{iq})$ – a function defining the relationship between the degree of customer preference in terms of utility, $u \in [0,1]$, and a specific level of the expected performance, $\forall F_{iq} \in [F_{iq}^L, F_{iq}^U]$, where F_{iq}^L and F_{iq}^U are the lower and upper bounds of functional feature values, respectively. Over this range, customers usually demonstrate different preferences for specific performance values.

From the technical viewpoint, the achieved performance, $\tilde{F}_{iq}$, of real option (a design) x_i^T with respect to F_{iq} is described as a probabilistic distribution, $p(\tilde{F}_{iq})$, over the range $[\tilde{F}_{iq}^L, \tilde{F}_{iq}^U]$, where $\tilde{F}_{iq}^L$ and $\tilde{F}_{iq}^U$ are the lower and upper bounds of the performance, respectively. Jiao and Tseng [1] propose to measure customer satisfaction according to the probability of design success – the overlap of $p(\tilde{F}_{iq})$ and $u(F_{iq})$. Therefore, the technical value of real option x_i^T with respect to functional feature F_{iq} is given as,

$$v_q^T\left(x_i^T\right) = \frac{1}{1 - \log_2 \int_{F_{iq}^L}^{F_{iq}^U} u(F_{iq}) p(\tilde{F}_{iq}) dF_{iq}}. \tag{1}$$

3.4 Valuation of financial real options

Let $x_j^F \in X^F \equiv \left\{x_j^F \mid j = 1, \ldots, J\right\}$ denote a financial real option associated with PFCD, may it be a launch, defer, abandon or switch option. Such options can be regarded as ordinary European call options, as the decision rule is that the revenue must exceed the product cost. The payoff from exercising option x_j^F on the expiration date, *T*, is defined as:

$$v^F(x_j^F, T) = \max\left[\frac{A_j^F}{C_j^F} D_k, 0\right], \tag{2}$$

where A_j^F is the price of option x_j^F, C_j^F is the cost incurred if enacting option x_j^F, and D_k is the demanded quantity of product y_k that requires option x_j^F. In the context of PFCD, the price of a financial real option x_j^F is defined as the total value of all technical real options, $\left\{x_i^T \mid i = 1, \ldots, I_j\right\}$, operated by x_j^F, that is, $A_j^F = \sum_{i=1}^{I_j} V^T\left(x_i^T\right)$. Likewise, the cost estimate of financial option x_j^F is defined as the total cost of all technical real options, $\left\{x_i^T\right\}_{I_j}$, operated by x_j^F, that is, $C_j^F = \sum_{i=1}^{I_j} C^T\left(x_i^T\right)$, where $C^T\left(x_i^T\right)$ is the specific cost measure of each individual technical option x_i^T [1].

4 PRODUCT FAMILY DESIGN OPTIMIZATION

Product family design essentially entails the selection of specific technical real options along with their relevant financial real options. Given a customer order expressed as a set of customer needs, $\left\{CN_m \mid m = 1, \ldots, M\right\}$, a few product variants, $\left\{y_k\right\}_K$, may be configured from existing product platforms. Each configured product, y_k, is achieved through a portfolio of call options, including a subset of existing technical real options, $X_{y_k}^T \equiv \left\{x_r^T \mid r = 1, \ldots, R_{y_k} < I\right\} \subset \left\{x_i^T\right\}_I$, and a subset of available financial real options, $X_{y_k}^F \equiv \left\{x_s^F \mid s = 1, \ldots, S_{y_k} < J\right\} \subset \left\{x_j^F\right\}_J$. The performance variables of each technical real option x_r^T originate from a subset of original customer needs, i.e.,

$\{\tilde{F}_{rq} \mid q = 1, \mathbf{L}, Q_r\} \subset \{CN_m\}_M$. The objective is to achieve the overall optimization of the selected portfolio of real options. Therefore, the expected payoff of product y_k is introduced as the objective function, which is defined as:

$$max \quad \mathrm{E}[V(y_k)] = V^T\left(X_{y_k}^T\right)V^F\left(X_{y_k}^F\right) = \sum_{r=1}^{R_{y_k}} V^T\left(x_r^T\right) \sum_{s=1}^{S_{y_k}} V^F\left(x_s^F\right), \tag{3}$$

where $V(y_k)$ is the payoff function defined for product y_k, $V^T\left(x_r^T\right)$ suggests the technical value of a technical real option involved in y_k according to Equation (3), and $V^F\left(x_s^F\right)$ indicates the financial value of a financial real option associated with y_k, which is calculated using the multivariate binomial lattice approach.

5 APPLICATION

The proposed framework has been tested in an electronics company producing mass customized vibration motors for mobile phones. Based on the analysis of historical data on the company's product fulfillment and existing manufacturing capabilities, the vibration motor product platform is constructed and accordingly the associated standard routings are identified. The functional features expressing customer needs and the specifications of vibration motor product platforms are summarized in Table 2. Targeting the low-, medium- and high-end market segments, three respective vibration motor product platforms are established: PdP$_1$, PdP$_2$ and PdP$_3$. Two customer orders are selected for testing purpose: CNA and CNB, representing low- and high-end customer needs, respectively. The specifications of individual customer needs and the product demand distributions in the respective markets are given in Table 2 as well.

Table 2 Specifications of customer needs and product platforms for market segments

Functional Feature $\{CN_m\}_M$		Individual Customer Needs $[CN_m^L, CN_m^U]$ & $u(CN_m)$		Product Platform (Customer Needs per Market Segment) $[F_{iq}^L, F_{iq}^U]$ & $u(F_{iq})$		
		Customer CNA	Customer CNB	PdP$_1$	PdP$_2$	PdP$_3$
Armature (A)	A1 (Current / mA)	60±15 / Triangular	80±20 / Triangular	[50, 70] / Triangular	[65, 80] / Triangular	[85, 110] / Triangular
	A2 (Pb free)	N / Uniform	Y / Uniform	[Y, N] / Uniform	[Y, N] / Uniform	[Y, N] / Uniform
Frame (F)	F1 (Length / mm)	9.5±3 / Triangular	13.5±4 / Triangular	[8.5, 12] / Triangular	[11, 15] / Triangular	[14, 17] / Triangular
	F2 (Diameter / mm)	10±4.5 / Triangular	19±8 / Triangular	[6.5, 15] / Triangular	[11, 19] / Triangular	[15, 27] / Triangular
Bracket (B)	B1 (Color)	R / Uniform	B / Uniform	[R, W, B] / Uniform	[R, Y, B] / Uniform	**[R, B, G] / Uniform**
	B2 (Connected Method)	U / Uniform	M / Uniform	[U, X, L] / Uniform	[U, F, D] / Uniform	[U, M, T] / Uniform
	B3 (Coating)	N / Uniform	Y / Uniform	[Y, N] / Uniform	[Y, N] / Uniform	[Y, N] / Uniform
Weight (W)	W1 (Shape)	P / Uniform	U / Uniform	[P, T] / Uniform	[P, T, U] / Uniform	[P, T, U] / Uniform
	W2 (Holding Strength / kg)	4±2.5 / Triangular	5±3 / Triangular	[2.5, 5] / Triangular	[3.5, 6.5] / Triangular	[5.5, 8.5] / Triangular
	W3 (Speed / rpm)	5500±200 / Triangular	10500±1500 / Triangular	[5000, 9200] / Triangular	[8000, 10000] / Triangular	[9500, 14000] / Triangular
Magnet (M)	M1 (Pb free)	N / Uniform	Y / Uniform	[Y, N] / Uniform	[Y, N] / Uniform	[Y, N] / Uniform
Rubber Holder (RH)	RH1 (Color)	R / Uniform	B / Uniform	[R, W, B] / Uniform	[R, Y, B] / Uniform	[R, B, G] / Uniform
	RH2 (Shape)	P / Uniform	T / Uniform	[P, T] / Uniform	[P, T, U] / Uniform	[P, T, U] / Uniform
Product Demand	Increase Rate m_{CN}	1%	5%			
	Volatility s_{CN}	0.1	0.45			
	Initial Demand $D_{CN}(0)$	15000	950			

Each product platform, for example PdP$_3$, supports a class of product family design. Figure 1 illustrates the established configuration mechanism within platform PdP$_3$, whereby product variants are generated by configuring options of variety generation on top of those common modules of the product architecture. In accordance with the identified variety generation methods, product family design real options are defined for PdP$_3$, as shown in Table 3. The specification of each technical real option of PdP$_3$ and the corresponding process data are shown in Table 4. As far as platform PdP$_3$ is concerned, 1 screening real option, 7 primitive technical real options and 4 nesting real options are identified. Considering four types of financial real options in relation to each technical real option, the total number of financial real options for platform PdP$_3$ is 48. Likewise, the total numbers of real options associated with PdP$_1$ and PdP$_2$ are identified as 5 and 9, respectively. This gives rise to 20 and 36 financial real options for PdP$_1$ and PdP$_2$, respectively.

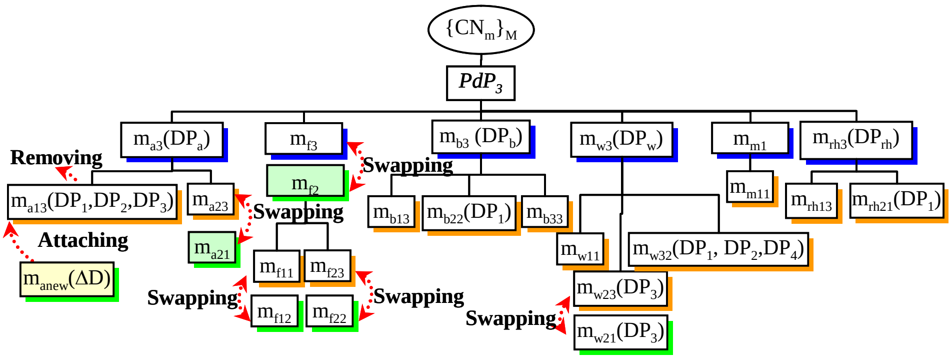

Figure 1 Variety generation within platform PdP_3

Figures 2 and 3 show the results of a GA solution for customer CNB. As shown in Figure 2, the moving average error keeps being reduced, indicating the improvement of fitness value (maximal expected payoff) as illustrated in Figure 3, along the reproduction process generation by generation. Certain local optima (e.g., around 75th generation) are successfully overcome. The saturation period (200-300 generations) is quite short, indicating the GA search is efficient. This proves that the moving average rule is a reasonable convergence measure. It helps avoid such a possible problem that the GA procedure may run unnecessarily up to 1000 generations. For customer CNB, the GA procedure terminates at the 299th generation and returns a near-optimal design that achieves an expected payoff of 711.63K. The details of this optimal design for customer CNB are shown in Table 5.

Table 3 Real options associated with the PdP_3 family

ID	Technical Real Option $\{x_i^T\}$	Financial Real Option $\{x_j^F\}$
A	$x^{ATTA}(M_{anew})$	$x^{Lau}(A)$, $x^{Def}(A)$, $x^{Aba}(A)$, $x^{Swi}(A)$.
B	$x^{REMO}(M_{a13})$	$x^{Lau}(B)$, $x^{Def}(B)$, $x^{Aba}(B)$, $x^{Swi}(B)$.
C	$x^{SWAP}(M_{a23}, M_{a21})$	$x^{Lau}(C)$, $x^{Def}(C)$, $x^{Aba}(C)$, $x^{Swi}(C)$.
D	$x^{SWAP}(M_{f11}, M_{f12})$	$x^{Lau}(D)$, $x^{Def}(D)$, $x^{Aba}(D)$, $x^{Swi}(D)$.
E	$x^{SWAP}(M_{f23}, M_{f22})$	$x^{Lau}(E)$, $x^{Def}(E)$, $x^{Aba}(E)$, $x^{Swi}(E)$.
F	$x^{SWAP}(M_{f3}, M_{f2})$	$x^{Lau}(F)$, $x^{Def}(F)$, $x^{Aba}(F)$, $x^{Swi}(F)$.
G	$x^{SWAP}(M_{w23}, M_{w21})$	$x^{Lau}(G)$, $x^{Def}(G)$, $x^{Aba}(G)$, $x^{Swi}(G)$.
H	$x^{SCRE}(PdP_3)$	$x^{Lau}(H)$, $x^{Def}(H)$, $x^{Aba}(H)$, $x^{Swi}(H)$.
DE	$x^{NEST}(x^{SWAP}(M_{f11}, M_{f12})x^{SWAP}(M_{f23}, M_{f22}))$	$x^{Lau}(DE)$, $x^{Def}(DE)$, $x^{Aba}(DE)$, $x^{Swi}(DE)$.
DF	$x^{NEST}(x^{SWAP}(M_{f11}, M_{f12})x^{SWAP}(M_{f3}, M_{f2}))$	$x^{Lau}(DF)$, $x^{Def}(DF)$, $x^{Aba}(DF)$, $x^{Swi}(DF)$.
EF	$x^{NEST}(x^{SWAP}(M_{f23}, M_{f22})x^{SWAP}(M_{f3}, M_{f2}))$	$x^{Lau}(EF)$, $x^{Def}(EF)$, $x^{Aba}(EF)$, $x^{Swi}(EF)$.
DEF	$x^{NEST}(x^{SWAP}(M_{f11}, M_{f12})x^{SWAP}(M_{f23}, M_{f22})x^{SWAP}(M_{f3}, M_{f2}))$	$x^{Lau}(DEF)$, $x^{Def}(DEF)$, $x^{Aba}(DEF)$, $x^{Swi}(DEF)$.

Figure 4 compares the results of the technical value achieved for customer CNB among generations. It is interesting to observe that the distribution of technical performance does not tally with that of the fitness shown in Figure 3. The optimal solution (i.e., the last generation) does not produce the maximal technical value. On the other hand, a number of high technical value achievements do not correspond to high fitness. Likewise, as shown in Figure 5, the distribution of cost performance among generations disorders the pattern of fitness distribution shown in Figure 3. This may illustrate the fact that a high technical achievement is usually accompanied with a high cost to incur. Therefore, the expected payoff is a more reasonable fitness measure, than the technical value, to model tradeoffs between design performance and the cost.

Table 4 Specifications of technical real options and their process performances

Technical Option $\{x_i^T\}_I$		Technical Performance		Process Performance		
		$\{\tilde{F}_{iq}\}_Q$	$[\tilde{F}_{iq}^L, \tilde{F}_{iq}^U] / p(\tilde{F}_{iq})$	u_i^T	s_i^T	USL_i^T
Primitive Options	A	A2	[Y, N] / Uniform	28.7	6.8	56.4
	B	A1	[45, 100] / Triangular	26.3	9.5	47.5
		A2	[Y, N] / Uniform			
	C	M1	[Y, N] / Uniform	11.6	8.4	32.1
	D	F1	[10, 17] / Triangular	15.5	6.3	22.3
	E	F2	[15, 24] / Triangular	14.6	7.8	21.2
	F	F1	[8, 18] / Triangular	78.6	18.1	114.5
		F2	[5.5, 28] / Triangular			
		B1	[R, W, Y, B, G] / Uniform			
		B2	[U, X, L, F, D, M, T] / Uniform			
		B3	[Y, N] / Uniform			
		RH1	[R, W, B, Y, G] / Uniform			
	G	W1	[P, T, U] / Uniform	35.5	5.2	65.0
		W2	[1.5, 10] / Triangular			
		W3	[5000, 15000] / Triangular			
		RH2	[P, T, U] / Uniform			
	H	Specifications of PdP_3 in Table 3		447.9	76.5	555.0
Compound Options	DE	F1	[13, 17.5] / Triangular	35.0	10.1	48.7
		F2	[10.5, 18.5] / Triangular			
	DF	...	...	...	...	...
	EF	...	...	...	...	...
	DEF	F1	[12, 16] / Triangular	67.4	19.8	105.0
		F2	[14, 18] / Triangular			
		B1	[R, Y, G] / Uniform			
		B2	[U, M, L, T] / Uniform			
		B3	[Y, Y] / Uniform			
		RH1	[R, G] / Uniform			

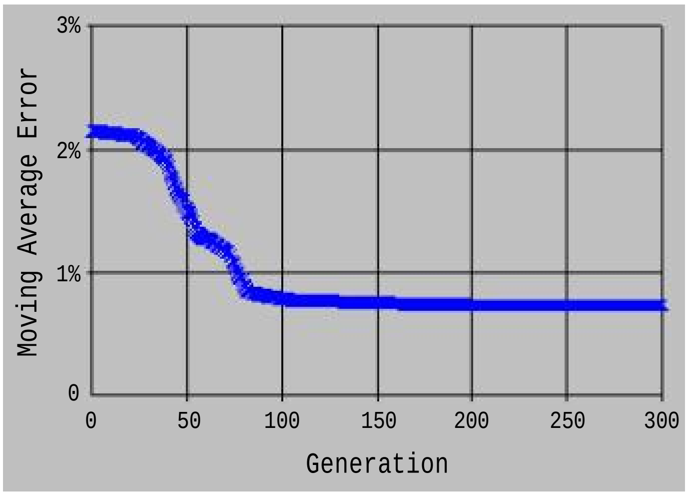

Figure 2 Convergence of GA solution for customer CNB

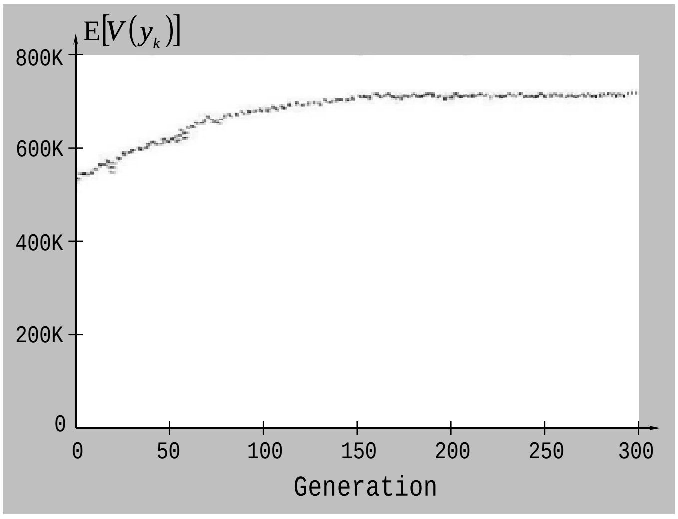

Figure 3 Maximal expected payoffs for customer CNB among generations

Table 5 PFCD solution for customer CNB at the 299th generation

Platform	PdP_3
Common Modules (CBs)	m_{a3}, m_{a2} , $_{b3}$, $_{b13}$, m_{b22}, m_{b33}, m_{w} , m_{w11}, m_{w32}, m_{m1}, m_{m11}, $_{rh3}$, m_{rh13}, m_{rh21}.
Differentiatio Module (DEs)	m_{a1} , m_{f2}, $_{f12}$, $_{f22}$, m_{w21}
Technical Option $\{\hat{x}_r^T\}_{R_{\hat{y}}}$	$x^{SCRE}(PdP_3)$, $x^{REMO}(M_{a13})$, $x^{SWAP}(M_{w23}, M_{w21})$, $x^{NEST}(x^{SWAP}(M_{f11}, M_{f12}), x^{SWAP}(M_{f23}, M_{f22}), x^{SWAP}(M_{f3}, M_{f2}))$.
Financial Option $\{\hat{x}_s^F\}_{S_{\hat{y}}}$	$x^{Lau}(H)$, $x^{Def}(H)$, $x^{Aba}(H)$, $x^{Swi}(H)$, $x^{Lau}(B)$, $x^{Def}(B)$, $x^{Aba}(B)$, $x^{Swi}(B)$, $x^{Lau}(G)$, $x^{Def}(G)$, $x^{Aba}(G)$, $x^{Swi}(G)$, $x^{Lau}(DEF)$, $x^{Def}(DEF)$, $x^{Aba}(DEF)$, $x^{Swi}(DEF)$.
Expected Payoff $E[V(\hat{y})]$	711.63K

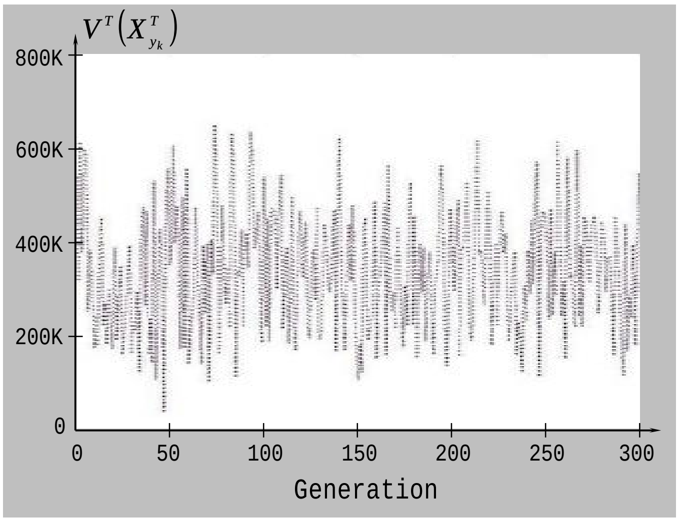

Figure 4 Achieved technical values for customer CNB among generations

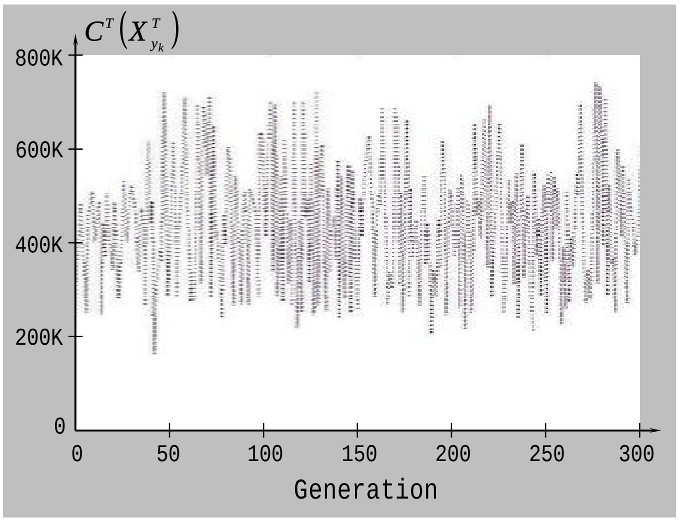

Figure 5 Cost performance of optimal designs for customer CNB among generations

Figure 6 compares the achievements, in terms of the normalized expected payoff, technical value and cost of top 5 product designs for customer CNB in the 299th generation that returns the optimal solution. Among these designs in the population, three ($\hat{y}_1^{CNB}, \hat{y}_2^{CNB}$ and $\hat{y}_3^{CNB}$) are derived from platform PdP_3, whereas $\hat{y}_4^{CNB}$ and $\hat{y}_5^{CNB}$ are based on platforms PdP_2 and PdP_1, respectively. Obviously, in terms of an overall satisfaction of CNB, those designs derived from a high-end product platform outperform those based on the low-end ones.

It is interesting to notice that the peak of technical achievement ($\hat{y}_2^{CNB}$) does not contribute to producing the best fitness as its cost is estimated to be high. On the other hand, the minimum cost measure ($\hat{y}_5^{CNB}$) does not mean the best achievement of overall performance measure as its technical performance is moderate. Also interesting to observe is that, within the same platform, the worst fitness ($\hat{y}_3^{CNB}$@PdP_3) may not perform with the highest cost figure (it is $\hat{y}_2^{CNB}$@PdP_3 instead). Likewise, the highest technical achievement ($\hat{y}_2^{CNB}$@PdP_3) may not correspond to the best fitness (it is $\hat{y}_1^{CNB}$@PdP_3 instead). The best design ($\hat{y}_1^{CNB}$@PdP_3) results from a leverage of both technical and cost performances.

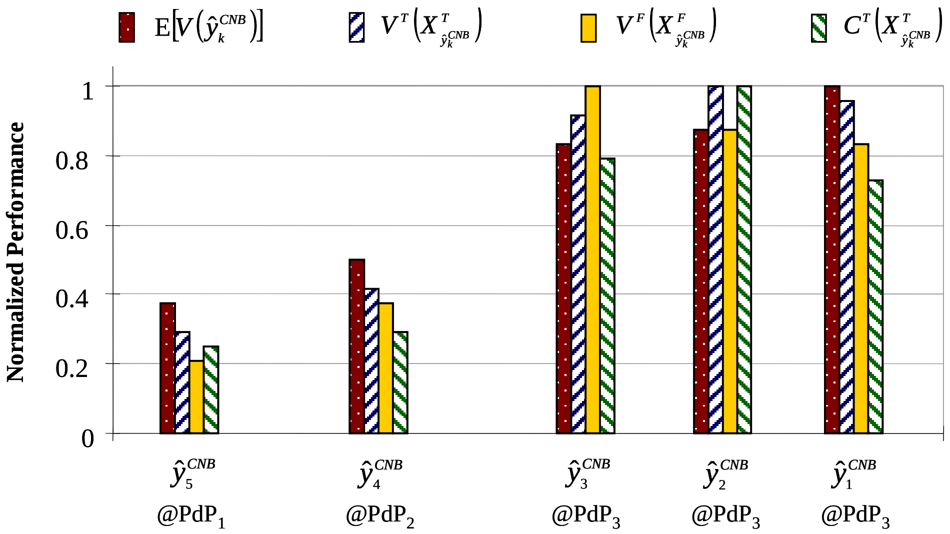

Figure 6 Performance comparison of optimal design population for customer CNB in the 299th generation

6 SUMMARY

This paper presents the application of real option valuation as a practical and effective framework to evaluate product family design. Through integration of engineering analysis and financial analysis, the procedure clearly recognizes the value of management control and the exercise of choices at key decision points along the product family design project life. It permits a consistent choice of the risk-free discount rate for the valuation, because the project risks can be diversified and the market risks are accounted for by the options analysis. It utilizes the knowledge of the technical and financial experts for the respective evaluation of product and project related flexibility.

An application of the real options framework to the vibration motor manufacturer illustrates the feasibility and potential of the proposed approach. As witnessed in the case study, the implementation of this method is straightforward. Most importantly, this approach leads to significant improvements in the value of product family design by recognizing the value of flexibility either inherent in a project or that can be built in product platforms. These improvements are more promising when uncertain demands are concerned, and when the downstream costs are relatively large.

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