Int J Adv Manuf Technol (2006) 30: 1–9
DOI 10.1007/s00170-005-0020-2

ORIGINAL ARTICLE

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Flexibility valuation of product family architecture: a real-option approach

Received: 3 September 2004 / Accepted: 28 February 2005 / Published online: 29 October 2005

Abstract The rationale of a product family architecture (PFA) has been well recognized as an effective means to achieve mass customization. Investing into a PFA creates flexibility for the company to accommodate future customization requirements while taking a risk by increasing complexity in design and production. Thus an important issue of PFA is the economic justification of flexibility. This paper applies the real option theory to the valuation of PFA flexibility. A real option model is proposed, in which product family design within a PFA is referred to as an investment strategy being crafted by a series of options that are continuously exercised to achieve expected returns on investment. The real option approach surmounts traditional discounted cash flow analysis based valuation methods that tend to ignore the upside potentials to an investment from management flexibility.

Keywords Design · Flexibility · Product family · Real option

1 Introduction

There are increasing evidences in many industries that developing product families based upon one common product platform can contribute to the satisfaction of individual customer needs while leveraging investments in design and production through economy of scale [1]. The fundamental concern underlying a product family architecture (PFA) 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 [2]. It thus becomes imperative to assess the value and cost of flexibility inherent in the PFA [3]. This paper focuses on such a flexibility valuation issue. Specifically dealt with is how to define, measure, and evaluate flexibility associated with product families in accordance with economic considerations. The goal is to present design and process engineers with insights into product customization and its impact on the economy of scale in design and production.

While substantial efforts have been devoted to the study of manufacturing flexibility [4–6], flexibility issues related to design have received only limited attention [3, 7]. Some methods have been introduced in an effort to manage the tradeoffs between complexity and variety related to product families [8]. Gonzalez-Zugasti et al. propose a quantitative measure of the value of product families to the company and apply it to select the best design from a set of possible alternatives [9]. Simpson et al. employ a market segmentation grid to identify suitable scaling factors based on which a common product platform can be customized to satisfy a range of performance requirements [10]. Collier establishes the basis of commonality indices for measuring the degree of commonality underlying a product structure [11]. Kota et al. introduce a product line commonality index to assist in product family design [12]. McAdams and Wood study the issue of similarity measure from a functional design perspective [13]. Ho and Tang discuss the modeling and analysis of value and cost tradeoffs from marketing and economics perspectives [14]. Kusiak and He suggest design-for-agility rules to make product designs robust against the changes in production schedules [15]. MacDuffy et al. suggest that the impact of product variety on performance varies, and is generally much less than the conventional manufacturing wisdom predicts [16].

Nonetheless, 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 [6]. Moreover, typical approaches to estimate costs and values associated with a project are based on Discounted Cash Flows (DCF) analysis, e.g., measuring Net Present Value

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(NPV). The DCF-based methods assume a priori to embed a single operation, which implies management's passive commitment to a certain operating strategy. Therefore, DCF analysis usually underestimates the upside value of investment [17]. 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 pre-specified project life [18]. Obviously, this assumption contradicts the practical case of PFA, where flexibility to configure among different options is the key enabler for mass customization [2].

Towards this end, this paper applies the real option theory to the valuation of flexibility associated with product families. The use of real options has proven to be an accessible approach for the valuation of certain types of flexibility [6][18]. When using real options for capital budgeting purposes, it is possible to take flexibility options into account in the valuation process [17].

2 Real options for flexibility valuation

The real option theory applies the principles and valuation techniques of financial options to real assets [18]. In general, two basic types of options can be distinguished, namely calls and puts. A call/put labels the option holder's right to buy/sell an underlying asset for a fixed exercise price. There are three characteristics associated with options: flexibility, uncertainty and irreversibility. Flexibility refers to the very important incident that the option holder has the right, but not the obligation, to exercise the option. Options also contain an element of uncertainty because the economic attractiveness of the option primarily depends on the development of the underlying asset. An option holder will use his right to exercise the call/put only if the price of the underlying asset increases/decreases so that it is higher/lower than the exercise price. The irreversibility is related to the fact that the option holder's right ceases to exist once the option is exercised. In essence, options limit the downside potential of the underlying asset while at the same time offering an upside potential. As a result, options have an inherent value and investors accept to pay a price for that—option premium.

The option's value and hence its premium is assessed by option pricing models. Two fundamental methods for pricing options are the binomial model and the Black-Scholes model [18]. An option value is generally influenced by six factors: time period until investment opportunity disappears, uncertainty of expected cash flows, present value of expected cash flows, value lost over duration of option, risk-free interest rate, and present value of fixed costs [19].

As a benefit, real assets with a high option value possess asymmetric payoff structures because the downside potential is limited while the upside potential still exists. Real option evaluation thus accounts for the value of flexibility embedded within projects. Real option thinking furnishes managers to go beyond a single point estimate of the likely future but to recognize a broader domain of possible opportunities [17]. Traditional valuation models exclude the consideration of any opportunity for changing investment decisions, whereas real options provide powerful mechanisms for funding the pursuit of a broader bandwidth of opportunities. Most cost-effectiveness scenarios can be considered as sets of options.

3 Product family architecture

A PFA involves three aspects: common bases (CBs), differentiation enablers (DEs), and configuration mechanisms (CMs) [20]. Customers' needs are characterized by combinations of functional features (Fs), each of which possesses a few values (F*s). A product family is designed to address the requirements of a group of customers in a market segment, in which customers share some common F*s along with certain distinct F*s.

From the design perspective, the product variants of the family are derived by configuring some CBs and certain DEs in terms of design parameters (Ds), which are pre-identified for the product family. The CMs guarantee that only technologically-feasible and market-wanted product variants can be derived.

While the CBs exhibit the elements of a common product platform (PdP), DEs and CMs constitute the variety generation power of PFA. Correspondingly in the process domain, CBs comprise the process platform (PcP) and DEs are characterized as process variables (Ps). Within a PFA, four variety generation methods are identified: attaching (ATTA), removing (REMO), swapping (SWAP), and scaling (SCAL), as illustrated in Fig. 1. More complicated product differentiation can be achieved through recursive application of these basic methods, called variety nesting.

4 PFA flexibility valuation

Based on the real option theory, product family design within a PFA can be treated as a project under an investment, respectively. Table 1 draws the parallel between product family design and the option concept. To take into account the uncertainty involved in mass customization, product family design is modeled as a stochastic process. Variant derivation within a PFA can be referred to as intra-project interactions with a sequence of options (investment "installments") within the same project. 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 process flexibility becomes due.

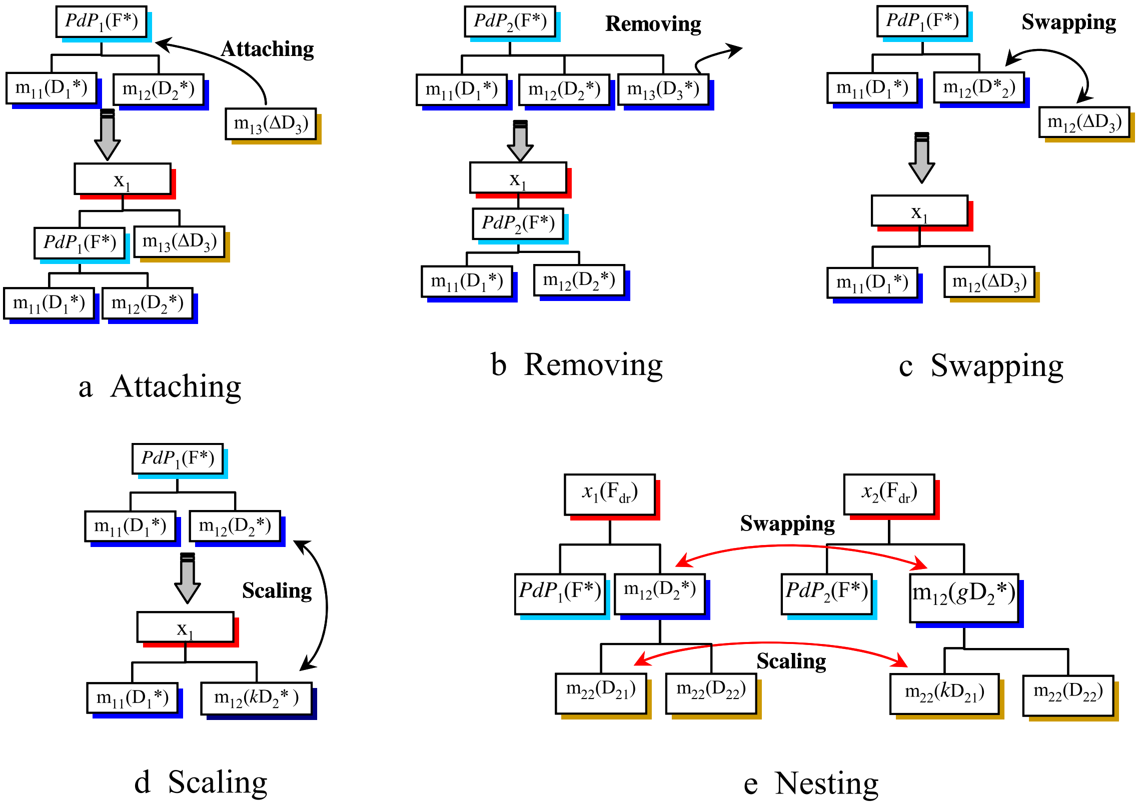


Fig. 1 Variety generation methods

To solve such an intra-project valuation problem, the log-transformed binomial method (LTBM) has been well-recognized for valuing multiple embedded real options [19]. With the LTBM, the interactions of various options are manipulated by using the conditional probability of their joint exercise according to the Bayes' Decision Rule.

4.1 Multiple real options

Two types of real options are introduced to model a PFA investment: strategic operating options and variety generation options. Strategic options related to manufacturing flexibility are generally categorized into the defer, time-to-build, alter, abandon, switch, growth and multi-interacting options [6]. In the context of PFA, three common real options are considered: the produce, defer and abandon options. Variety generation options represent all related manipulations of DEs at the module level. Four real options are thus proposed: the attaching (Δ(ATTA)), removing (Δ(REMO)), swapping (Δ(SWAP)) and scaling (Δ(SCAL)) options. A nesting option can further be composed, for example, Δ(SWAP(REMO)).

4.2 Flexibility measure

Jiao and Tseng [3] define the flexibility of PFA as the cost-effectiveness of a design and the associated production processes to be modified to accommodate certain expected variations in performance requirements. Based on customizability indices [3], two types of flexibility measures

Table 1 Analogy between options and product families

Stock call option	Real option	Product family design
Current value	(Gross) present value of expected cash flow	Expected profit
Exercise price	Investment cost	Design flexibility index Process flexibility index
Expiration time	Time until opportunity disappears	Time to market
Expected rate of return on the asset	Risk-free interest rate	Customer unsatisfactory risk Process deficiency risk
Volatility of asset (Probability)	Project value uncertainty	Uncertainty of customer needs

can be established: design flexibility index (FI^D) and process flexibility index (FI^P), that is,

$$FI_i^D = \frac{1}{1 - \log_2 \int_{F_i^L}^{F_i^U} u(F_i)p(F_i)dF_i}, \ \ 0 \le FI_i^D \le 1\,;$$

where $0 \le u(F_i) \le 1$ represents a customer preference function defined in terms of utility measure, $p(F_i)$ denotes the probability distribution of the achieved performance of a design with respect to functional feature $F_i^L \le F_i \le F_i^U \le$, $\exists F_i \in \{F_i\}_N$; and

$$FI^P = \frac{USL_T - \mu_T}{3\sigma_T}, \quad 0 \le FI^P \le 1\,;$$

where USL_T, μ_T, and σ_T are the upper specification limit, the average, and the standard deviation of the cycle time, respectively. Variations in the cycle time are characterized by μ_T, and σ_T, reflecting the compound consequence of customization in production in terms of process variations. Based on pre-determined time standards, the cycle time can perform as an indirect measure of the costs related to process variations. While FI^D characterizes the technical feasibility of fulfilling a customization requirement in design, FI^P indicates the costs of fulfilling this customization in production [3].

4.3 Valuation framework

The process of PFA flexibility valuation is modeled in a decision tree (called a binomial tree in the LTBM), as shown in Fig. 2. It consists of four stages: the testing profile, design, production and evaluation stages.

(1) Testing profile stage: Let $\tau_r = \{t | 0, \ldots, T\}, \forall r = 1$ be the time point when decision is made and let $\Delta(\bullet)$ describe a decision of option(s) as a real-valued function. Customer needs are screened according to their matching with pre-identified Fs and F*s of the PFA. This constitutes a defer option $\Delta(Defer)$, indicating if this customer can be met by the offerings of a given PFA. Customer needs are further characterized by their preference functions over individual Fs, $\{\mu(F_i)\}_N$. The corresponding utility functions $\{U(F_i)\}_N$ are obtained using conjoint analysis [3]. In addition, relative importance of Fs $\{w_i | \Sigma w_i = 1\}_N$ can be determined based on the analytic hierarchy process (AHP) [3].

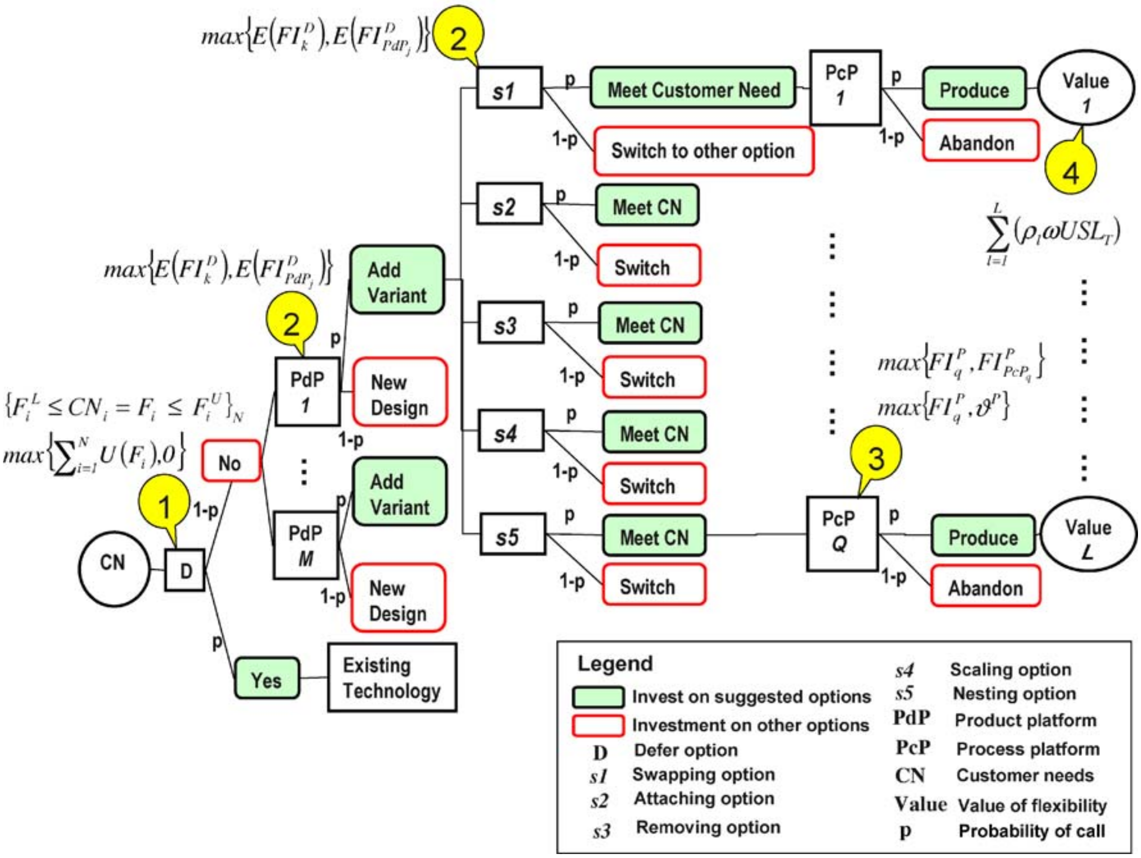


Fig. 2 Framework of PFA flexibility valuation

The LTBM always assumes that the expected payoff in a "monetary term" is the appropriate measure of consequences of taking action. In product family design, the decisions are made based on the expected customer perceived value, which is in a non-monetary term. For this, the utility theory is incorporated into LTBM in order to tackle subjective probability. Therefore, the value of a defer option at this stage is determined as:

$$V(\Delta(Defer)) = \max\left\{\sum_{i=1}^{N} U(F_i), 0\right\}.$$

(2) Design stage: A PFA consists of a set of common product platforms $\{PdP_j\}_M$ and a set of differentiation modules $\{D_k\}_K$. Design flexibility is achieved through configuring different PdP_j and D_k. This can be modeled by exercising various variety generation options $\Delta(\bullet)_k^D$, for example, $\Delta(SWAP(D_x, D_y))_k^D$ or $\Delta(SWAP(D_x, ATTA(D_y)))_k^D$. The value of each option is determined according to the expected design flexibility achieved by exercising this option, i.e.,

$$V\left(\Delta(\bullet)_k^D\right) = \max\left\{E\left(FI_k^D\right), E\left(FI_{PdP_j}^D\right)\right\},$$

where $E\left(FI_k^D\right) = \sum_{i=1}^{N}\left(w_i FI_{k,i}^D\right)$ is the expected design flexibility index for option $\Delta(\bullet)_k^D$, and denotes the ex-

Table 2 Specifications of vibration motor product platforms and their target market segments

PdPn Module (m)	Specification	*PdP₁*	*PdP₂*	*PdP₃*	*Customer 001*	*Customer 002*
Armature (A)	F_{a1n}(mA)/ $U(F_{a1n})$	[90~100]/Normal	[60~70]/Normal	[80~90]/Normal	90±2/Triangular	88±2/Triangular
	$F_{a2n}/U(F_{a2n})$	Yes	Yes	No	Yes	Yes
	DP_1(mm)/ $P(DP_1)$	[45~50]	[25~30]	[35~40]		
	DP_2(mm)/ $P(DP_2)$	[3.7~3.8]	[3~3.3]	[3.4~3.6]		
	DP_3(mm)/ $P(DP_3)$	[13~14.5]	[11~12]	[12.5~13]		
Frame (F)	F_{f1n}(mm)/ $U(F_{f1n})$	[13~16]/Normal	[10.5~13]/Normal	[13~16]/Normal	10.5±0.5/ Triangular	13±1.5/Triangular
	F_{f2n}(mm)/ $U(F_{f2n})$	[4~5]/Normal	[3~4]/Normal	[5.5~6]/Normal	3±1Triangular	4.5±1Triangular
Bracket (B)	$F_{b1n}/U(F_{b1n})$	Blue	Blue	Black	Black	Black
	$F_{b2n}/U(F_{b2n})$	Y	X	X	X	X
	$F_{b3n}/U(F_{b3n})$	Au	Au	Ni-CU Alloy	Ni-Cu Alloy	Ni-Cu Alloy
	DP_1(°)/$P(DP_1)$	[60°±0.2]	[30°±0.2]	[30°±0.5]		
Weight (W)	$F_{w1n}/U(F_{w1n})$	B	A	B	B	B
	F_{w2n}(kg)/ $U(F_{w2n})$	Min.4/Normal	Min.3.5/Normal	Min.3/Normal	Min.4/ Triangular	Min.3/Triangular
	F_{w3n}(rpm)/ $U(F_{w3n})$	[10,000~12,000]/ Normal	[9,000~12,000]/ Normal	[9,000~12,000]/ Normal	[9,500~11,000]/ Triangular	[9,000~12,000]/ Triangular
	DP_1(mm)/ $P(DP_1)$	[3.5±0.025]	[3.5±0.02]	[2±0.01]		
	DP_2(mm)/ $P(DP_2)$	[4.5±0.02]	[3.5±0.015]	[2.5±0.005]		
	DP_3(g)/$P(DP_3)$	[7~10]	[5.5~6.5]	[3~4.5]		
	DP_4(μm)/ $P(DP_4)$	[25±0.05]	[35±0.05]	[50±0.05]		
Magnet (M)	$F_{m1n}/U(F_{m1n})$	No	Yes	No	No	No
Rubber Holder (RH)	$F_{rh1n}/U(F_{rh1n})$	White	White	Red	Red	Red
	$F_{rh2n}/U(F_{rh2n})$	P	P	P	P	P
	DP_1(HB)/ $P(DP_1)$	[65~70]	[65~70]	[60~70]		

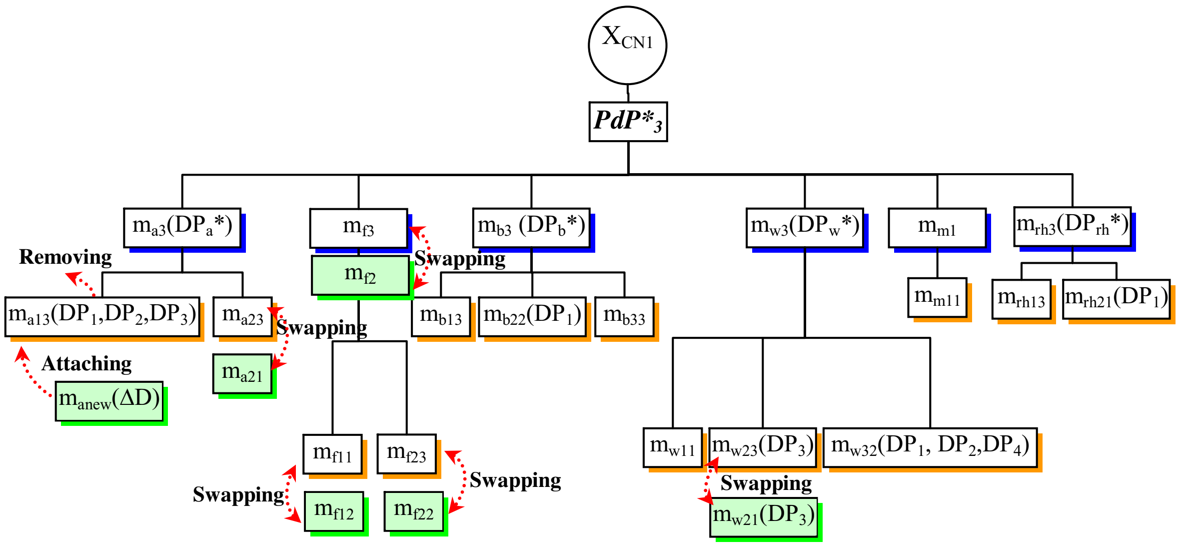


Fig. 3 An illustration of variety generation options

pected design flexibility for the platform PdP_j, to which $\Delta(\bullet)_k^D$ is applied.

(3) Production stage: Corresponding to each product variant derived at the design stage, a process variant can be determined by configuring existing common process platforms $\{PcP_g\}_G$ and differentiation processes $\{P_s\}_S$. Each process variant entails either a produce option $\Delta(Produce)_q^p$ or an abandon option $\Delta(Abandon)_q^p$. The value of a pro-

Table 3 Specification of a vibration motor process platform

Job No.	Sequence No.	Final Part	Operation	Work Centre (WC)	Machine (Mc)	Tooling	Fixture	Labor	Runtime Sec/item	Sub-part	Qty (Item)
20	50	Finished Product (EM)	Assy (a)	EMa	Wcaulking	–	Wsitting jig, Wcaulking head	1	15	{W,RH,MB Assy}	{1,1,1}
19	40	Mainbody (MB)	Assy (a)	MBa	Fcaulking and Ainserting	–	Caulking blade, Bracket holder	1	10	{A Assy, F Assy, B Assy}	{1,1,1}
18	30	Armature (A)	Assy (a)	Aa	Sinserting and Soldering	–	Supporting holder, Pallet	1	8	{Coil Assy, Shaft}	{1,1}
17	20	Coil (C)	Assy (a)	Ca	–	–	Guiding jig	1	7	{Coil, Tape, Commuter}	{1,1,1}
16	30		Fabrc (f)	Cf	Cwinding	–	Tray	1	6	{Raw Material }	N/A
15	20	Frame (F)	Assy (a)	Fa	FMPressing	–	Fholder, Mholder	1	5.1	{Magnet, Frame}	{1,1}
14	10		Fabrc (f)	Ff	Fstamping	Die	Holder	1	4.7	{Raw Material }	N/A
13	20	Bracket (B)	Assy (a)	Ba	Bfusing	Binserter	Bpressing jig	1	4	{Bracket A, Bracket B, Terminal}	{1,1,1}
12	10		Bracket A Fabrc (f)	BAf	Binjection	Badjuster	Blocator	1	5.25	{Raw material}	N/A
	10		Bracket B Fabrc (f)	BBf	Binjection	Badjuster	Bprealignment	1	5.25		
	10		Terminal Fabrc (f)	BTf	Tcutting	Die	Tholder	1	5		

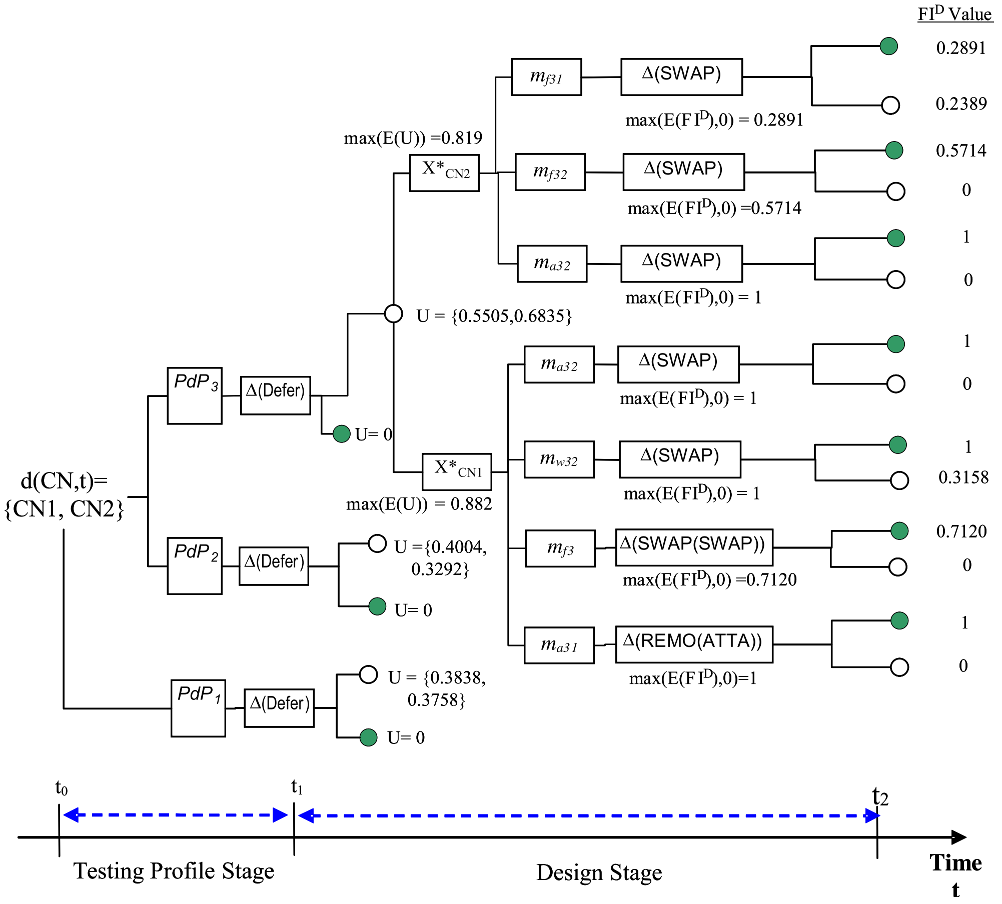


Fig. 4 Flexibility valuation at the design stage

duce option is calculated according to flexibility measure of the process variant:

$$V\left(\Delta(Produce)_q^P\right) = \max\left\{FI_q^P, FI_{PcP_q}^P\right\},$$

where FI_q^p is the process flexibility index for option $\Delta(Produce)_q^p$, and denotes the process flexibility for the PcP_q, which serves as the base line model of the process variant. The value of an abandon option is calculated in the similar way, except that the base line mode becomes a pre-specified threshold $0<\vartheta^P\le 1$, i.e.,

(4) Evaluation stage: The binominal tree in Fig. 2 models the probability distribution of the asset (PFA) value and the value of the asset for each option. The LTBM suggests the maturity price of a European call option contained in the PFA:

$$\rho_l = V_l N(d_1) - I_l e^{-\omega(T-t)} N(d_2)$$

$$d_1 = \frac{\ln(V_l/I_l)+\left(\omega+\sigma^2/2\right)(T-t)}{\sigma\sqrt{T-t}};\quad d_2 = d_1 - \sigma\sqrt{T-t},$$

where ρ_l denotes the price of the lth option with value V_l, I_l is the exercise price of the lth option, $N(\bullet)$ is the cumulative

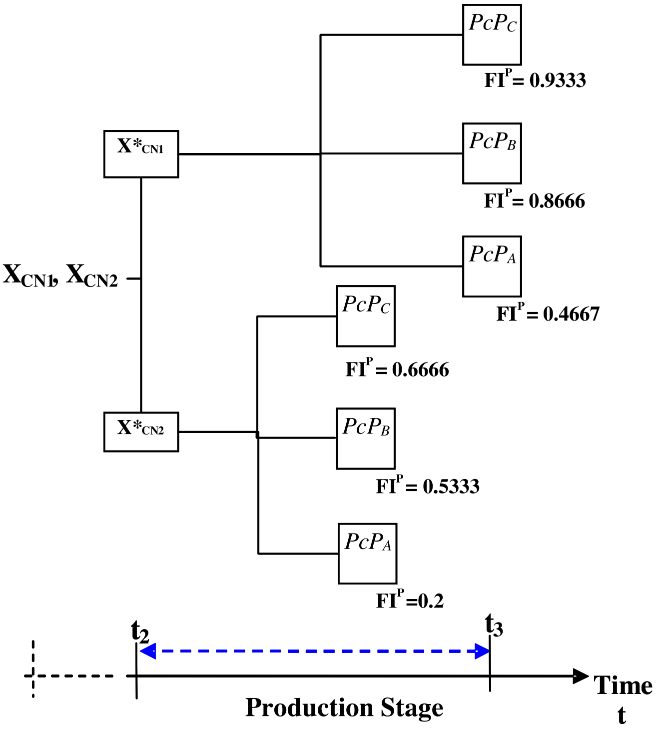


Fig. 5 Flexibility valuation at the production stage

Table 4 Spreadsheet for the valuation of BCD option

PdP_3	Product Platform (BCD Options)					Process Platform c	
	Platform Cost ($)	Variant Module Cost ($)	Variant Cost ($)	Time of Design Modification (secs)	Cost Deviation ($)	Operations	Throughput Time (secs)
Module	ξ_0^3	ξ_r^k	$\xi_r^k(M(\cdot))$	$t^k_{r\,M(\cdot)}$	$(\xi_r^k-\xi_0^3)$		
Armature (A)	5	6.5	3	6	1.5	Assy A	5
	5	0	0	0	0		
Frame (F)	5	5	3.75	7.5	0	Assy F	4.5
						Fabrc F	5
Bracket (B)	16					Assy B	4
						Fabrc Ba	5.25
						Fabrc Bb	5.25
						Fabrc T	5
Weight (W)	5.5	5.5	0.5	1	0	Assy C	5
Magnet (M)	10					Fabrc C	4.5
Rubber Holder (RH)	2					Assy MB	9.25
						Assy EM	9.5
Total	48.5		7.25	14.5	1.5	**Throughput Time (secs)**	62.25
V(*PdP_3*)*@ 0.5% discount rate for sharing*				48.7425		cycle time (hr)	0.0026
V(*PdP_3*) after adding variant				57.4925		V(*PcP_3*) @ 500 $/hr	1.3194
$E(V_{PdP})$				68.1516		$E(V_{PdP})$	1.7593
Price, ρ				90			
Profit, Ω				9%	6.05		

normal distribution, and σ is the variability (volatility) of the expected rate of return ω in regard to V_l.

Since the process performance is modeled as the cycle time measure that is scaled according to the standard time calculation, the expected rate of return is interpreted as the unit price of standard times. Therefore, the expected profit of the PFA, Ω, can be derived based on all terminal values in the binominal tree, accounted by established standard times:

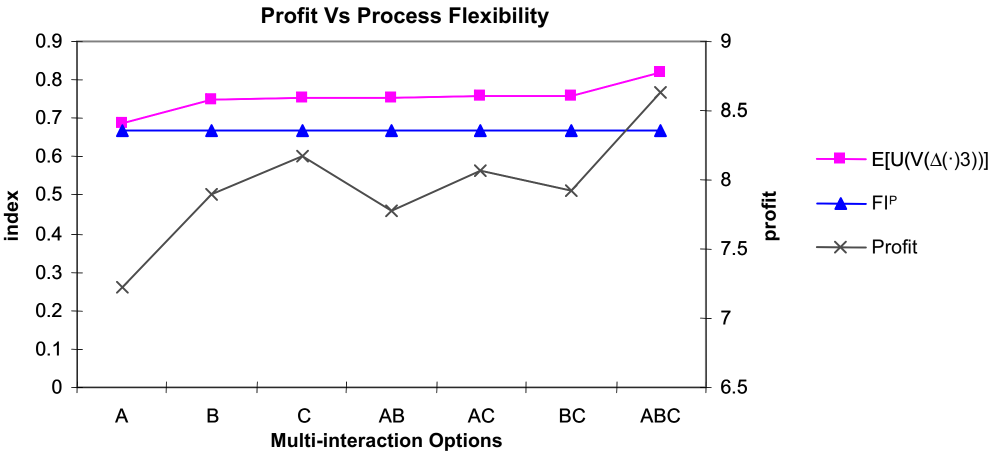
$$\Omega = \sum_{l=1}^{L} (\rho_l \omega USL_T),$$

where $L=N\times M\times Q$ is the total number of terminal values in the tree.

5 Case study

A case study is conducted in a consumer electronics company producing mass customized vibration motors for mobile phones. As shown in Table 2, three product platforms (PdP_1, PdP_2, and PdP_3) and two market segments (Customer001 and Customer002) are identified for vibration motors. Fig. 3 illustrates the variety generation options associated with platform PdP_3. Table 3 shows the process

Fig. 6 Comparison of expected profit with multiple options



platform for vibration motor assembly operations corresponding to PdP_3.

Following the valuation framework, the flexibility inherent in the vibration motor PFA is evaluated, as shown in Figs. 4 and 5. Table 4 presents an example of the spreadsheet used for the calculation of option values. The results of PFA flexibility valuation are summarized in plots (e.g., Fig. 6), in which many value-cost tradeoffs can be justified against various interactions among multiple options as well as their individual contributions to PFA flexibility. Based on these results, sensitivity analysis and factorial analysis can further be developed to gain insights into the PFA.

6 Conclusions

Investing into a product family architecture creates options for the company to accommodate future mass customization requirements. The company possesses the flexibility to choose, over the course of developing product families, whether to develop variants based on existing platforms or develop the desired products individually, or to configure the desired products based on many options of PFA elements. Flexibility of these real options bestows extra values to the company by hedging against volatility and turbulence in the market, design and production. The valuation of real options thus sheds light on the analysis of value-cost tradeoffs underlying a PFA. Real option models deserve a place in toolkits of decision making due to high uncertainty and costs of irreversible investment in PFA.

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