Transactional risk reduction in design outsourcing through multi-phase prototyping

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Abstract
Prototyping serves as a means of reducing transactional risk in design outsourcing; however, it is extremely expensive in capital intensive industry. In this paper, a Bayesian updating method and a modified real option method are introduced to quantify the risk reduction and value added, respectively, through prototyping.

Keywords: prototyping, real options, risk management

Introduction
In manufacturing industry, design outsourcing is becoming more and more popular, from cell phone (Engardio, B. Einhorn et al. 2005) to airplane (Economist 2006). Due to the innovative essence of the design service, the design buyer is uncertain of what the designer will provide; on the other hand, the designer is also uncertain of what the buyer truly wants. This uncertainty between the two parties is referred as transactional risk in this paper. Prototyping serves as a means of reducing transactional risk in design outsourcing process. The prototype signals the design value to the design buyer, and conveys the design cost to the designer. In multi-phase design development, after each prototyping phase, the designer has the option to continue or terminate the development process. However, prototyping is extremely expensive in capital intensive industry. For instance, the Airbus A380 costs billions of dollars and decades to develop (Thomas 2001). It is crucial to make the investment decision of whether to prototype.

In multiple-step prototype model, the design buyer is assumed to invest on a serial of prototypes during a long time horizon. Instead of making lump sum investment at the front end, the buyer can make a serial investment decisions (continue or cancel) along the development phase with more flexibility, as illustrated in Figure 1. This assumption implies that the buyer has the right to continue or cancel the deal after any prototyping phase. This feature coincides with the real option analysis, a multi-step valuation method.

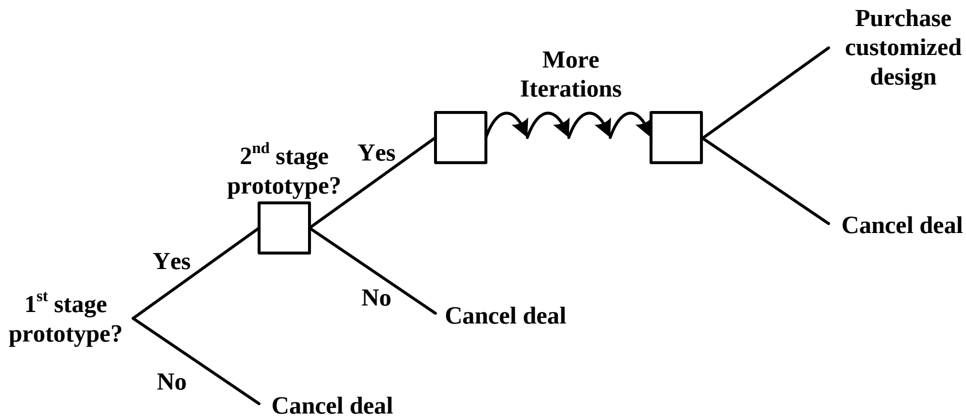

Figure 1 – Multiple-step prototype model (Terwiesch and Loch 2004)

In literature, researchers used and developed real option valuation models to deal with multiple-step investment problem (Trigeorgis 1996). Real option analysis origins from the financial options valuation method, which is a right but not obligation to purchase (call option) or sell (put option) the underlying asset. The underlying asset of real option is not stock or other financial instrument, but the real asset instead. Real option analysis is widely used in the decision-making in capital intensive industry, such as pharmaceutical R&D or real estate development. However, the traditional real options models assume that the underlying asset has a constant volatility level throughout the development process. In practice, the risk level will be gradually reduced as more information gained in the development process (Cassimon, Engelen et al. 2011). In this paper, a Bayesian updating method is introduced to quantify the transactional risk reduction through prototyping. The reducing risk is then incorporated into a modified real option model to quantify the tradeoff between the risk reduction and value added, respectively, through prototyping.

Reducing transactional risk via prototyping

In order to quantitatively value the risk reduction effect of prototyping, it is assumed that the buyer could estimate the final design value reflected from prototype, v_p , based on his past experience and expertise. For instance that, before launching the new designed car to the market, the automobile maker is not able to accurately evaluate how the market would react, which means that v remains unknown. However, after observing the prototype of a new design, he may have an expectation of the market response (v_p) based on the years of experience in automobile industry.

v_p can be taken as a sample of actual value v distorted by a noise factor ε , $v_p = v + \varepsilon$, where ε is assumed as a non-biased normal random variable with variance Σ , $\varepsilon \sim N(0, \Sigma)$. Σ indicates the level of fidelity of the prototype, with lower variance implying higher fidelity rate. The prototype that is closer to final design has higher fidelity rate than that closer to the early conceptual design stage. Without prototyping, the buyer's best estimate of the value of v is v_0, so v_p can be modeled as,

$$v_p = v_0 + \varepsilon, \tag{1}$$

$$v_p \sim N\left(\mu_0, Q_0 + \Sigma\right). \tag{2}$$

The design buyer is able to update his estimated value of the final design after observing the outcome of prototyping. Suppose that the updated design value after observing prototyping is v_1, the probability of which is mathematically represented as

$$p(v_1) = p(v_0 \vert v_{p1}) = \frac{p(v_{p1} \vert v_0) \cdot p(v_0)}{p(v_{p1})}, \tag{3}$$

where, v_{p1} is the observation from first phase of prototyping. Chen and Sun (2011) showed that the updated mean and variance of v_1 are in the format of prior estimation,

$$\mu_1 = \frac{Q_0 v_p + \mu_0 \Sigma_1}{Q_0 + \Sigma_1}, \tag{4}$$

$$Q_1 = \frac{Q_0 \Sigma_1}{Q_0 + \Sigma_1}, \tag{5}$$

where Σ_1 is the estimated fidelity of the first phase of prototype. It can be observed that the updated mean μ_1 will shift towards the observation v_p from the original mean μ_0. The variance of the new estimate, Q_1, contracts from the initial estimate, Q_0. The value of the second prototype, v_2, could be similarly shown with Bayesian updating from v_1,

$$p(v_2) = p(v_1 \vert v_{p2}) = \frac{p(v_{p2} \vert v_1) \cdot p(v_1)}{p(v_{p2})}, \tag{6}$$

and the mean and variance of v_2 are,

$$\mu_2 = \frac{Q_1 v_{p2} + \mu_1 \Sigma_2}{Q_1 + \Sigma_2}, \tag{7}$$

$$Q_2 = \frac{Q_1 \Sigma_2}{Q_1 + \Sigma_2}, \tag{8}$$

where $\mu_1 = (Q_0 v_{p1} + \mu_0 \Sigma_1) / (Q_0 + \Sigma_1)$, $Q_1 = Q_0 \Sigma_1 / (Q_0 + \Sigma_1)$ and Σ_2 is the estimated fidelity of the second prototype. A recursive relationship could be written as,

$$\mu_{n+1} = \frac{Q_n v_{p_{n+1}} + \mu_n \Sigma_{n+1}}{Q_n + \Sigma_{n+1}} , \tag{9}$$

$$Q_{n+1} = \frac{Q_n \Sigma_{n+1}}{Q_n + \Sigma_{n+1}} . \tag{10}$$

Equation (10) quantifies the transactional risk level at each prototyping phase, and implies that the risk level keeps reducing throughout the development process.

Bayesian-based option analysis

The traditional three ways to calculate option value are, Black-Scholes partial differential equation, binomial tree method, and Monte Carlo simulation; among which, the binomial tree method is the most flexible way to adapt to adjustments and modifications. In this paper, the Bayesian-based option analysis is modified based on the traditional binomial tree model. For the comparison purpose, both traditional and Bayesian-based models are illustrated in Figure 2 and Figure 3, respectively.

Figure 2 illustrates a simplified example of two-phase prototyping investment. The initial estimated design value is assumed to be 100, the transactional risk level is 100%, and the planned investments in two prototypes are 50 and 50. The time interval between successive steps is set to 0.5. Following the Cox-Ross-Rubinstein method (Cox, Ross et al. 1979), the upward and downward movements of the design value in each time interval, and the respective possibilities can be calculated. The values of the initial and derived variables are illustrated in Table 1. Figure 3 illustrates the Bayesian-based binomial tree. Different from the traditional recombinant tree, the Bayesian-based tree is non-recombinant after t_1, as the design value's probability of moving up is updated from 34.7% to 42.9%. The updated variables are also illustrated in Table 1.

Table 1 – The variables in the simplified two-phase prototyping model

Description of Variable	**Notation**	**Value**
Initial Inputs		
The estimated design value	S	100
Transactional risk	σ	100%
Time interval	Δt	0.5
Phase 1 investment	I_1	50
Phase 2 investment	I_2	50
Calculated from CRR Model		
Upward movement	$u = \exp(\sigma\sqrt{\Delta t})$	2.208
Downward movement	$d = 1/u$	0.493
Probability of moving up	$q = \left(\exp\left(r\Delta t\right) - d\right)/\left(u - d\right)$	34.7%
Updated variables through Bayesian		
Prototyping fidelity rate	Σ	50%
Updated transactional risk	σ_2	57.7%
Upward movement in phase 2	$u_2 = \exp(\sigma_2\sqrt{\Delta t})$	1.504
Downward movement in phase 2	$d_2 = 1/u_2$	0.665
Probability of moving up in phase 2	$q_2 = \left(\exp\left(r_2\Delta t\right) - d_2\right)/\left(u_2 - d_2\right)$	42.9%

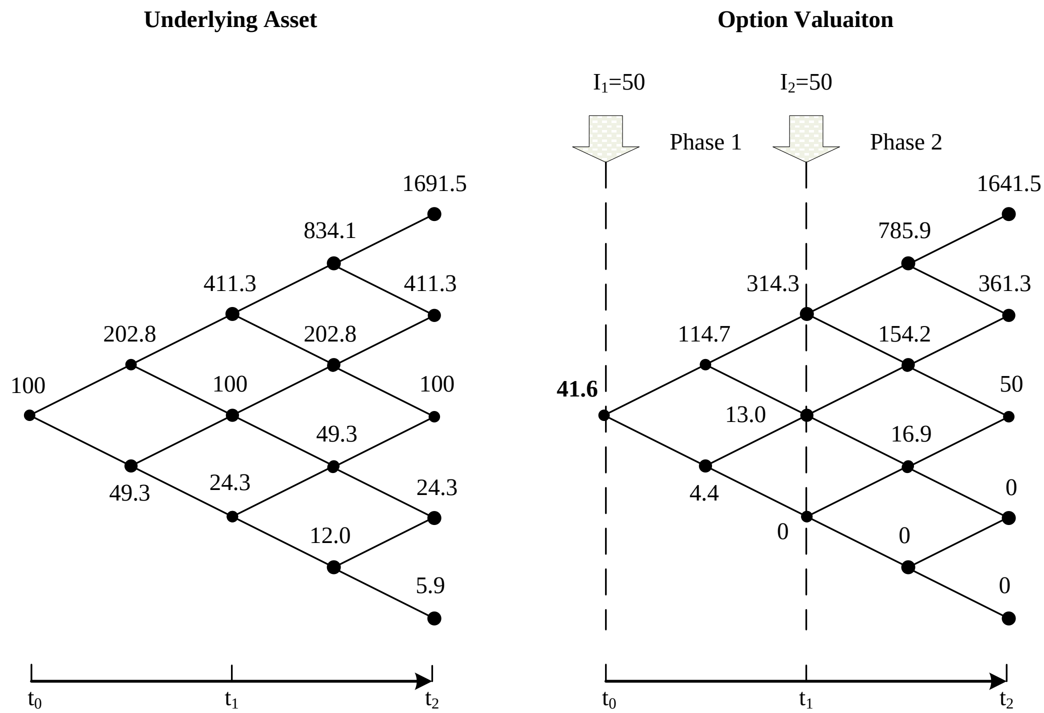

Figure 2 – Traditional binomial tree model

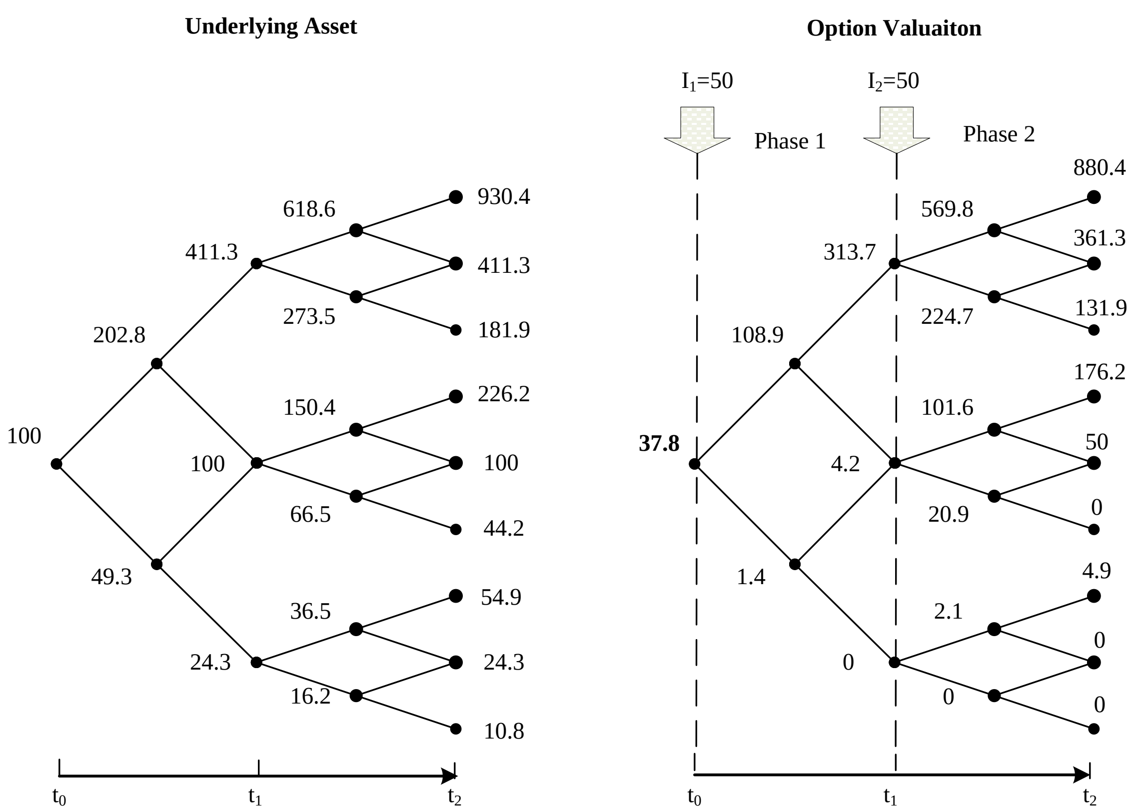

Figure 3 – Bayesian-based binomial tree

The option value is calculated backward in time from maturity. For instance, the top right node in traditional option valuation tree is calculated to be max(1691.5-50,0)=1641.5, where the 50 is the second prototype investment. The rest nodes at t_2 are then calculated in the similar fashion. Discounted back one time interval, 785.9 is calculated as the present value of the two forward values 1641.5 and 361.3.

$$785.9 = \frac{1641.5 \times 34.7\% + 361.3 \times 65.3\%}{e^{r\Delta t}} \tag{11}$$

Further discounting back one step, the payoff 314.3 is calculated as the present value with the consideration of Phase 1 investment.

$$314.3 = \max\left(\frac{785.9 \times 34.7\% + 154.2 \times 65.3\%}{e^{r\Delta t}} - 50, 0 \right) \tag{12}$$

Discounting the payoff in time to t_0, the option value is calculated to be *41.6*. With similar fashion, the Bayesian-based option value is calculated to be *37.8*, which is slightly lower than the traditional model result, which coincides with one of the properties of the option theory, that the lower the volatility, the lower the option value.

An Illustrative Case on Aircraft Design Process

To make the abstractive concept easy to understand, an illustrative case is presented in this section. Airline could not commit to buying new customized plane without a detailed understanding of payload capabilities, maximum range, operating costs per seat mile, and price per plane; and aircraft manufacturer could not provide these data to the airlines without a thorough conceptual or preliminary design.

After analyzing the requirements from airline (the buyer), the aircraft manufacturer (the designer) estimated that the total cost of design process is about $100 million, which can be disassembled into four phases:

- Phase 1: conceptual study, 1 year, 10 million,
- Phase 2: project definition, 1 year, 10 million,
- Phase 3, detailed design, 1 year, 70 million,
- Phase 4, certification, 1 year, 10 million.

The airline is concerning the uncertain value of the final design, so they decide to invest $10 million on phase 1 first, which can be regarded as creating an *option to expand*. The investment in the conceptual study gives the buyer an opportunity to learn the value of the eventual design before committing a large investment on the following detailed design and prototyping.

If the outcome is satisfactory after phase 1, the buyer will proceed to the detailed design and prototyping in the following phases. If the phase 1 result is not favorable, the buyer will cancel the deal before potentially losing the total $100 million investment. The $10 million preliminary design creates an option to reduce the buyer's risk exposure. The timeline of the design process is illustrated in Figure 4.

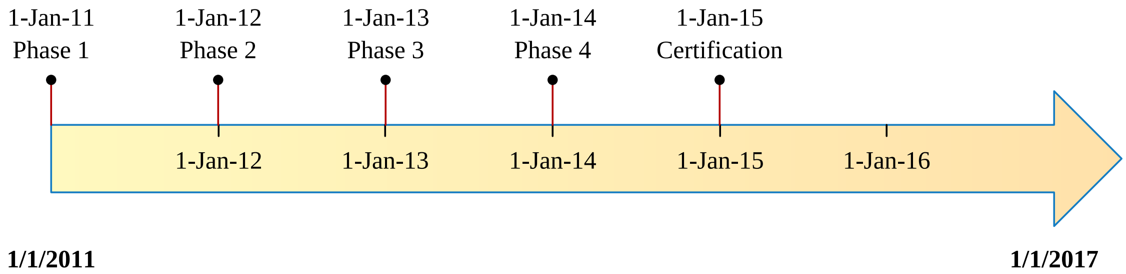

Figure 4 – Timeline of Aircraft Design Development

The decision-making process is shown in Figure 5.

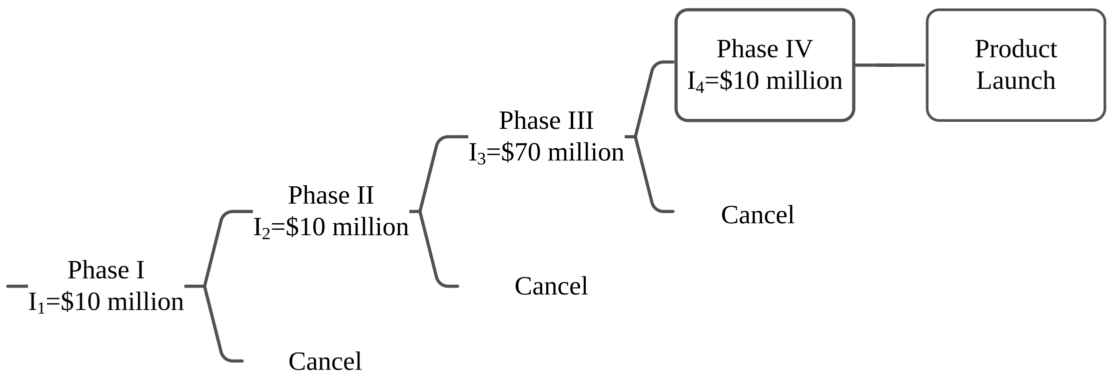

Figure 5 – Decision making of Aircraft Design Development

For the sake of illustration, the basic settings of this deal are given,

- The risk-free interest rate is assumed to be, $r = 5\%$.
- The initial estimated design value is $v_0 = \$90$ million.
- The volatility of return is estimated to be $\sigma_0 = 50\%$.

On top of the basic setting, we assume that the prototyping fidelity rate at four phases are $\Sigma_1 = 100\%$, $\Sigma_2 = 50\%$, $\Sigma_3 = 30\%$, and $\Sigma_4 = 10\%$, respectively. As Equation (10) indicates,

$$\sigma^2_{n+1} = \frac{\sigma^2_n \cdot \Sigma_{n+1}}{\sigma^2_n + \Sigma_{n+1}},$$

the updated volatilities at the following phases are calculated to be, $\sigma_1 = 44.72\%$, $\sigma_2 = 37.80\%$, $\sigma_3 = 31.11\%$ and $\sigma_4 = 22.18\%$.

Decision analysis
The analysis starts from the very last decision the buyer makes, either (1) spend $10 million to certify the design, and then launch the product, or (2) walk away. Moving backwards in time, the next-earlier decision to make is to either (1) spend $70 million on detailed design, or (2) walk away. The choice of making the detailed design creates an option in future. The time to maturity is 1 years. The strike price is $70 million. The underlying asset is what will be received in exchange for the strike price, which is the certificated aircraft. The volatility is the uncertainty in phase 3 estimate of the value of design in phase 4. The risk-free rate is 5%.

If go back one more step to the decision making in phase 2, the buyer would decide to either (1) spend $70 million and 1 year of time on detailed design, or (2) walk away from the project. The investment in phase 2 means that the management purchases an *option on option* on a certified design. Here, the time to duration is 1 year. The strike price is $10 million. The volatility is the buyer's uncertainty of the design value in phase 3. Similar analysis can be repeated until the phase 1 is reached.

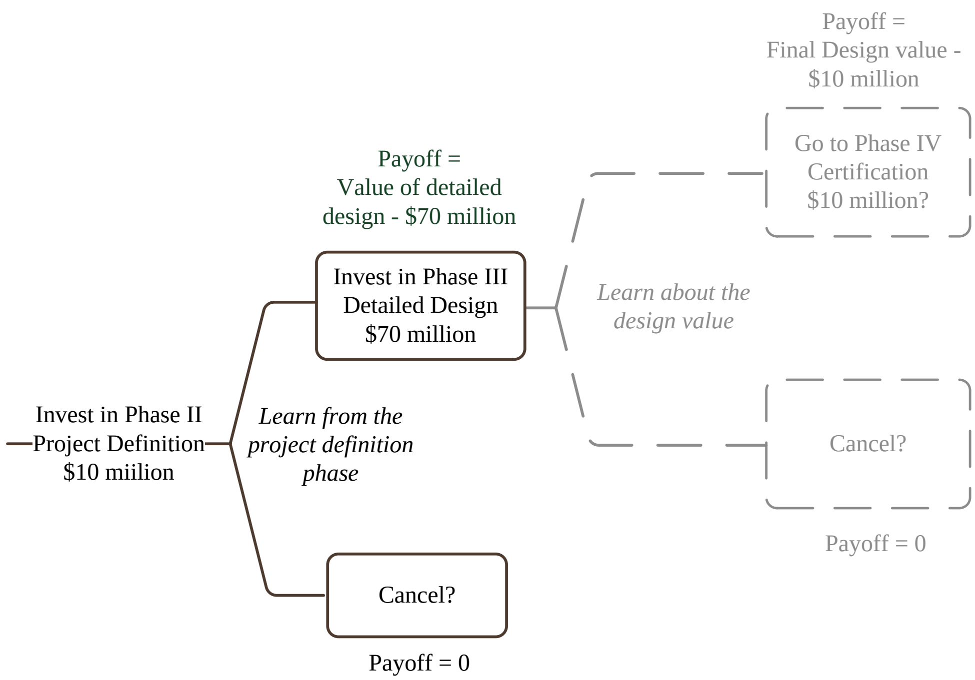

Figure 6 – Decision Making at Phase 2

Comparing traditional vs. Bayesian-based model
The settings of the traditional and Bayesian-based are separately illustrated in Table 2. The settings of both methods are almost identical, except that the Bayesian-based model takes the reducing volatilities into consideration. After inputting all the above settings into the both models, each of them will generate an option value, which is **24.91** for traditional model and **24.06** for the Bayesian-based one. The Bayesian-based model will give a slightly smaller value comparing to the traditional one in the *exact* settings. It's worth to consider series of values for comparison.

Table 2 – Traditional and Bayesian-based Model

Parameters	**Traditional Model**	**Bayesian-based Model**
Initial estimated value	$v_0 = 90$	$v_0 = 90$
Risk-free rate	$r = 5\%$	$r = 5\%$
Cost of phase 1	$I_1 = 10$	$I_1 = 10$
Cost of phase 2	$I_2 = 10$	$I_2 = 10$
Cost of phase 3	$I_3 = 70$	$I_3 = 70$
Cost of phase 4	$I_4 = 10$	$I_4 = 10$
Time of period of phase 1	$T_1 = 1$	$T_1 = 1$
Time of period of phase 2	$T_2 = 1$	$T_2 = 1$
Time of period of phase 3	$T_3 = 1$	$T_3 = 1$
Time of period of phase 4	$T_4 = 1$	$T_4 = 1$
Volatility in phase 1	$\sigma_0 = 50\%$	$\sigma_0 = 50\%$
Fidelity of phase 1	-	$\Sigma_1 =100\%$
Fidelity of phase 2	-	$\Sigma_2 =50\%$
Fidelity of phase 3	-	$\Sigma_3 =30\%$
Fidelity of phase 4	-	$\Sigma_4 =10\%$
Volatility in phase 2	-	$\sigma_1 = 44.72\%$
Volatility in phase 3	-	$\sigma_2 = 37.80\%$
Volatility in phase 4	-	$\sigma_0 = 31.11\%$
Time interval of each step	$\Delta t = 1/20$	$\Delta t = 1/20$

Figure 7 illustrates the comparisons between the two models when the initial estimated value is given in the range v_0 = [50, 90], within which the Bayesian model constantly gives a lower value than the traditional one. The dark color indicates an area of non-investable. As the cost of phase 1 development is 10, which means that only the option value larger than 10 is favorable. This chart gives a break-even point at v_0 = 67 for Bayesian model. In other words, given the above settings, only when the initial estimated value of proposed project is larger than 67, the management can potentially profit from investing in Phase 1.

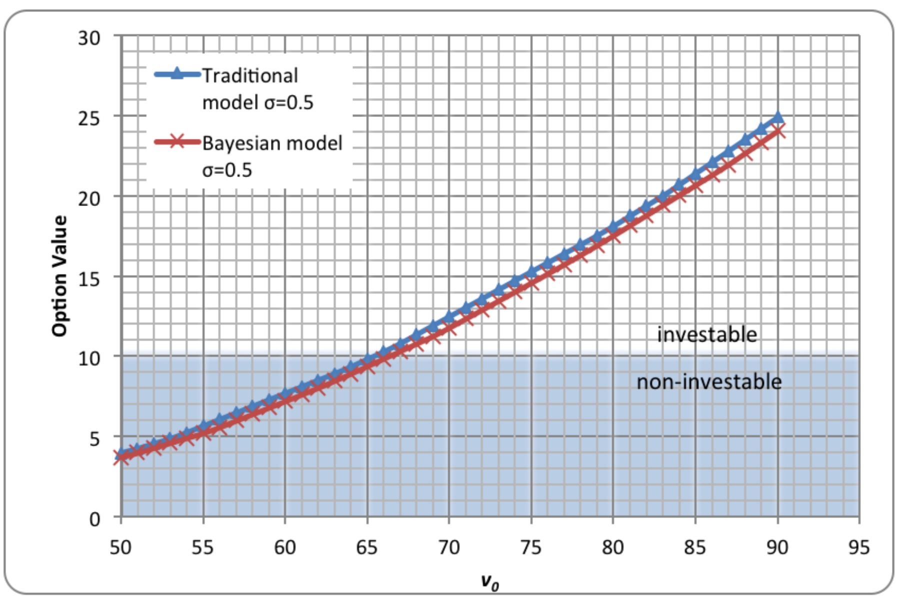

Figure 7 – Comparing traditional and Bayesian-based model

Conclusion

The analysis of the multiple-step prototyping model is developed based on real option analysis due to its popularity in valuing multi-stage projects in recent decades. In this model, investing on each prototyping stage is seen as purchasing an option for the future development. The traditional real option analysis assumes constant risk level throughout the product development; however it is not applicable in the real practical case with dynamic risk level. The Bayesian updating process is employed to measure the reduced risk level through prototyping. The Bayesian-based option valuation model takes the amount of investment and development duration at each development phase into consideration, and calculates an option value that assists the buyer's decision on whether to prototype and how to allocate the investment.

An illustrative case on aircraft development is subsequently created based on the multiple-step prototypes model. The results show that, the Bayesian-based method generates more conservative option values than the traditional one due to the reduced volatilities. This means that the traditional model will overestimate the option value in this research context and may jeopardize the management's profitability.

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