Risk Reduction via Prototyping in Customized Product Development

K. Sun, S. L. Chen
Division of Systems and Engineering Management, School of Mechanical & Aerospace Engineering,
Nanyang Technological University, Singapore 639798, Singapore
su0001ke@e.ntu.edu.sg, songlin@ntu.edu.sg

Abstract
Risks are inherent in customized product development for both customers and manufacturers due to their inability to accurately articulate requirements and estimate costs, respectively. The presence of risks creates transactional barriers when decision makers are risk averse. Prototyping, commonly used for customer requirements elicitation and manufacturing cost estimation, is interpreted in this paper as a means of risk reduction and modelled via a Bayesian estimation process. A quantitative risk model is subsequently developed to investigate the investment decision upon prototyping, taking into consideration the fidelity and cost of the prototype. This paper provides a decision framework for practitioners to understand and manage transaction risks in customized product development.

Keywords:
Risk reduction, customization, prototype, product development

1 INTRODUCTION

Customized products are designed and manufactured to fulfill the particular needs of individual customers [1]. There is an increasing output of customized products, spanning from capital goods like machinery, network servers, and information systems to consumer goods like personal computers, cars, golf clubs, and sneakers among many others [2]. Product customization has been recognized as a frontier for manufacturers in many different industries to gain a competitive edge in an increasingly diversified and dynamic marketplace [3]. However, in customized product development, both customers and manufacturers are faced with risks. Given the large solution space implied in customization, it is often difficult for customers to clearly articulate their requirements; and it is also difficult for manufacturers to clearly communicate their capabilities in sufficient details without confusing customers.

Prototypes are commonly used for risk reduction in product development [4]. For instance, in concept development, experimental prototypes can be built and tested to elicit customer needs; in detail design, prototypes are often created for customers' reviews and comments; in testing and refinement, prototypes are tested to determine whether the product works as designed and whether the product meets customer needs [5]. Prototypes can be categorized into two types. The first type can be seen as a part of a manufacturer's internal performance testing, assessing functionality or verifying fitness. The second type of prototype is primarily used for enriching communication between manufacturers and customers. For instance, architects often construct models of buildings to get design feedback. Through such prototypes, customers can convey their reviews back to manufacturers as well as to refine their requirements and update their estimated value of the final product. In this sense, prototypes can be taken as a tool for information collection and communication, which reduce uncertainties and risk exposure for both customers and manufacturers.

Despite the fact that prototypes are quite useful in risk reduction, they are not free and can be very costly. For instance, the prototype of an aircraft could cost up to hundreds of millions of dollars. There are a number of significant but difficult questions regarding the investment decision upon prototyping, especially in capital intensive industries where there is normally a high degree of customization. Typical questions include: is it cost-effective to build a prototype? Who should pay for it? And, how much should the final product be priced?

To answer these questions, this paper develops a quantitative risk model from a manufacturer's perspective. The prototyping process is interpreted as a sampling of the final product with different degrees of fidelity. A prototype with a higher fidelity rate means that it can better represent the final product. The potential of risk reduction through prototyping is then modelled via a Bayesian estimation process. Decision models are subsequently developed to analyze the manufacturer's decision in product customization, with or without prototyping. The decision models take into consideration both the fidelity and cost of the prototype. Numerical analysis-based simulation is conducted to investigate the prototyping decision with respect to a number of factors, including the manufacturer's risk attitude, estimated cost and uncertainties of the final product, price quoted by manufacturer, the fidelity and cost of prototype, and the proportion of prototyping cost to be shared by manufacturer. This model thus provides a framework for investment decisions about prototyping in customized product development.

2 RELEVANT LITERATURE

This research relates to prototyping decision-making in product development. The past relevant literature can be generally categorized into two streams, which models prototyping either as a “trial and error” process or as a “learning process” to examine the utilities of a series of prototypes.

2.1 Trial and Error

Trial and error is a general method of problem solving. It is a process of reaching the final solution by experimenting with various methods until the error is sufficiently reduced. Prototypes can be seen as experience goods, which are defined as products or services whose quality is difficult to observe before consumption, where quality refers to any valued attribute such as taste, efficiency, or durability [6]. The fidelity of the prototype, i.e. how well the prototype resembles the final product, serves as an indicator of the quality of the prototype. By observing the outcome of the prototyping, designers can update their estimate of the final product. In this sense, prototypes are a means of trial and error to search for a good design solution.

A main drawback of random “trial and error” in prototyping is that it is usually cost and time consuming. The cost and time to build a test prototype depends highly on the available technology and the required degree of fidelity [7-8]. Prototyping costs vary from a few dollars to hundreds of thousands of dollars. For example, manufacturing a physical prototype used in automobile crash tests can cost hundreds of thousands of dollars and may take months to build. In such cases, it is not cost-effective to use a trial and error mechanism.

2.2 Learning Mechanism

Terwiesch and Loch has proposed a learning mechanism to search for product design in a series of prototypes [1]. In general, the customer chooses a design quality threshold as a stopping point and continues prototyping until this threshold is reached. This mechanism is investigated in both unstructured and structured design space. Unstructured design space prevents learning between prototypes. In this case, it is optimal for the manufacturer to offer a linear pricing scheme, and sell prototypes at cost. In structured design space, successive prototypes create learning about the optimal design solution. This method provides a model for the manufacturer to offer prototypes at a profit, at cost, or even for free based on the design problem and market characteristics. This learning mechanism assumes that prototyping is required in the development of custom-design products without regard to the costs and uncertainty outcomes of prototypes.

Although both the “trial and error” and the “learning mechanism” provide a framework to model prototyping decisions in product development, they tend to focus on the engineering aspects. This paper studies prototyping decision, especially its effect on risk reduction, in the context of customized product development. This paper also introduces Bayesian estimation as a novel new method to model prototyping decisions in the product development process.

3 RISK MODELING IN CUSTOMIZED PRODUCT DEVELOPMENT

3.1 Risk sources

In customized product development, both customers and manufacturers are faced with certain level of risk. For customers, a major source of risk stems from their inability to accurately articulate needs in terms of concrete and clear requirements, particularly when the product is complex and customers do not have sufficient technical knowledge [9]. Distorted need information will mislead manufacturers in design problem solving and result in solutions that are not what customers have expected. Costly design changes or disputes may ensue. Another source of risk for customers is their inability to accurately evaluate a customized solution. Customers are often not technically savvy and could get ‘confused’ by the large variety of solutions that are embedded in customization [10].

For manufacturers, a major source of risk stems from uncertainty concerning resources that may be required in product customization. Coinciding with customers’ inability to accurately articulate needs, manufacturers are often unable to accurately communicate their capabilities. It is often hard, if not impossible, to represent or describe a customized solution in sufficient details without confusing customers. Furthermore, manufacturers are often exposed to the risks of requirement changes from customers. Even though customers are contractually responsible for customer-initiated design changes, it is often the case in practice that manufacturers need to modify their solutions to cope with customers’ updated requirements. Such design changes are often costly, especially in the later stage of product design and development.

3.2 Risk attitude

In general, decision makers can be categorized into three kinds, risk averse, risk neutral and risk seeking, depending on their risk attitudes. In this paper, both customers and manufacturers are assumed to be risk averse, and an exponential utility function is assumed without loss of generality.

$$u\left(x\right)=1-e^{-\frac{x}{R}}, \qquad (1)$$

where $u(x)$ represents the utility function, x is the evaluation measure, and R indicates the degrees of risk aversion. R is a positive real number and higher value implies less risk aversion.

As the decision faced with the customer and a manufacturer in the contracting stage can be taken as symmetric, this paper focuses on the manufacturer’s decision without loss of generality. The true cost of the final product (c) remains unknown until observing it after manufacturing. We assume that c_0 is the prior estimation of the product cost before prototyping, which is a random number that is assumed to follow a normal distribution:

$$c_0 \sim N\left(\mu_0^c, Q_0^c\right). \qquad (2)$$

As Figure 1 shows, the manufacturer can weigh his decision based on his estimation of the product cost, c_0.

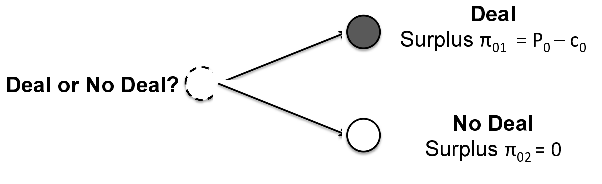

Figure 1: Manufacturer's initial decision making

The manufacturer quotes price P_0 after analyzing his costs, risks and profits. When the manufacturer’s estimated cost is lower than the selling price P_0, making the deal would generate the buyer a surplus of π_{01}. If c_0 is larger than P_0, the manufacturer is unwilling to make the deal, which generating 0 surplus.

3.3 Certainty equivalent

π_{01} is a random number depending on c_0. To help the manufacturer make the decision in the face of uncertainty, this paper introduces the concept of "certainty equivalent", which transforms a set of random outputs into a certain value taking into account the decision maker's risk attitude. For instance, if $\hat{x}$ is the certainty equivalent of a lottery *L*, a decision maker would be indifferent between lottery *L* and $\hat{x}$. The mathematical relationship between lottery *L* and $\hat{x}$ is given as [12]:

$$u(\hat{x}) = E\left[u(x)\right], \tag{3}$$

where x indicates the uncertain outcome of lottery *L*.

Given that the probability density function of x is $f(x)$, the certainty equivalent can be solved based on the following relationship:

$$u(\hat{x}) = E\left[u(x)\right] = \int u(x) f(x) dx . \tag{4}$$

As *f(c₀)* is the probability density function of the estimated cost c_0, the certainty equivalent of π_{01} is calculated as,

$$\begin{aligned} u(\hat{\pi}_{01}) &= \int_{-\infty}^{\infty} u(\pi_{01}) f(c_0) dc_0 \\ &= \int_{-\infty}^{\infty} \left(1 - e^{-\frac{P_0 - c_0}{R}}\right)\left(\frac{1}{\sqrt{2\pi Q_0^c}} e^{-\frac{(c_0-\mu_0^c)^2}{2Q_0^c}}\right) dc_0 \end{aligned} . \tag{5}$$

$u\left(\hat{\pi}_{01}\right)$ can be represented in a form of $g\left(P_0, R, \mu_0^c, Q_0^c\right)$, such that the inverse function for $u\left(\hat{\pi}_{01}\right)$ is $\hat{\pi}_{01} = u^{-1}\left[g\left(P_0, R, \mu_0^c, Q_0^c\right)\right]$. By calculations, $\hat{\pi}_{01}$ can be mathematically expressed as

$$\hat{\pi}_{01} = P_0 - \mu_0^c - \frac{Q_0^c}{2R} . \tag{6}$$

Given that $\pi_{02} = 0$, the certainty equivalent of which is fixed at 0 as well, $\hat{\pi}_{02} = 0$. The manufacturer can thus weigh the decision between Deal and No Deal by comparing $\hat{\pi}_{01}$ with $\hat{\pi}_{02}$.

Equation (6) indicates that the manufacturer's economic surplus decreases as *R* increases, which implies that the value of customization would be less if the manufacturer is more risk averse. Similar conclusions can be drawn for the customer. Thus, the presence of risk creates a barrier in customized product development, as it reduces the perceived value of customization.

4 RISK REDUCTION THROUGH PROTOTYPING

4.1 Prototyping as sampling

Figure 2 shows the manufacturer's decision-making process when he is given a third option of prototyping other than deal or no deal. $\hat{\pi}_{01} \geq 0$ means that without prototyping, making deal is expected to be profitable.

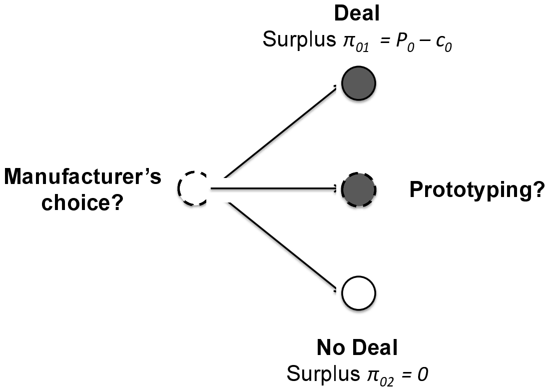

Figure 2: Manufacturer's third option of prototyping

In product development, the cost of the final product could be reflected from its prototypes in certain degrees of fidelity. A prototype with a higher fidelity rate can be used to better estimate the cost of the final product for the manufacturer. The product cost reflected from prototyping (c_p) can be taken as a sample of actual cost (*c*) distorted by a noise factor ε, which is assumed to be a non-biased normal random variables with variance Σ, $\varepsilon \sim N(0, \Sigma)$.

$$c_p = c + \varepsilon . \tag{7}$$

Σ indicates the fidelity of the prototype, with lower variance implying higher fidelity. Prototypes that are closer to the final production of the product generally have higher fidelity than those closer to the early conceptual design stage. Before prototyping, the manufacturer's best estimate of the value of c is c_0:

$$c_p = c_0 + \varepsilon , \tag{8}$$

$$c_p \sim N\left(\mu_0^c, Q_0^c + \Sigma\right) . \tag{9}$$

4.2 Bayesian updating

Conditional on the outcome of prototyping, the manufacturer can update his estimated cost of the final product. The updating process can be generally modelled via Bayesian estimation. The posterior estimated cost after prototyping is represented by c_1, which is assumed to follow normal distribution with mean μ_1^c and variance Q_1^c,

$$c_1 \sim N\left(\mu_1^c, Q_1^c\right) . \tag{10}$$

The mean (μ_1^c) and variance (Q_1^c) can be calculated via Bayesian updating as:

$$\mu_1^c = \mu_0^c + \frac{\left(c_p - \mu_0^c\right) Q_0^c}{Q_0^c + \Sigma} , \tag{11}$$

$$Q_1^c = \frac{Q_0^c \Sigma}{Q_0^c + \Sigma} . \tag{12}$$

From equation (11) and (12), it can be observed that the mean value of the new estimates will shift from its initial value μ_0^c towards μ_1^c after prototyping. The variance of the new estimates, Q_1^c, is smaller than that of initial estimates, Q_0^c, which indicates risk reduction. Thus, if the mean cost does not increase dramatically while risk reduction is significant, the transaction could become possible.

4.3 Prototyping decisions

The Bayesian estimation process described above provides a qualitative interpretation of the use of prototypes for risk reduction. However, prototypes can be very expensive in some cases. This section develops a quantitative model to assist decision-making, regarding whether a prototype is justified under different situations. The decision-making procedures are summarized in Figure 3.

The manufacturer could decide to have a deal or no deal after prototyping. However, the question remains in terms of favouring prototyping or not. The manufacturer may only want to build a prototype when his expected surplus after prototyping, $\hat{\pi}_1$, is higher than the expected surplus without a prototype, which can be represented as $\max\left(\hat{\pi}_{01}, \hat{\pi}_{02}\right)$.

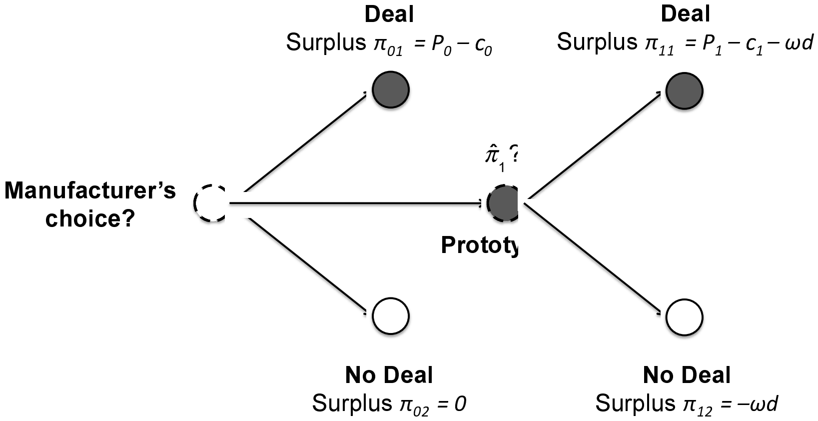

Figure 3: Decision making process

Suppose the cost of prototyping is *d*, and manufacturer shares *ω* ($0 \le \omega \le 100\%$) proportion of the cost, which is *ωd*. The manufacturer asks for a new price, *P₁*, which is adjusted after observing the prototype. π_{11} and π_{12} are the surpluses of deal and no deal after prototyping, respectively, with certainty equivalents $\hat{\pi}_{11}$ and $\hat{\pi}_{12}$.

By adopting the same method of calculating $u\left(\hat{\pi}_{01}\right)$ and $\hat{\pi}_{01}$, $u\left(\hat{\pi}_{11}\right)$ and $\hat{\pi}_{11}$ are represented as below:

$$u\left(\hat{\pi}_{11}\right) = \int_{-\infty}^{\infty} u\left(\pi_{11}\right) f\left(c_1\right) dc_1 = \int_{-\infty}^{\infty} \left(1 - e^{-\frac{P_1 - c_1 - \omega d}{R}}\right) \left(\frac{1}{\sqrt{2\pi Q_1^c}} e^{-\frac{\left(c_1 - \mu_1^c\right)^2}{2 Q_1^c}}\right) dc_1, \qquad (13)$$

$$\hat{\pi}_{11} = P_1 - \mu_1^c - \omega d - \frac{Q_1^c}{2R}, \qquad (14)$$

where $\mu_1^c = \mu_0^c + \frac{\left(c_p - \mu_0^c\right) Q_0^c}{Q_0^c + \Sigma}$ and $Q_1^c = \frac{Q_0^c \Sigma}{Q_0^c + \Sigma}$.

Given that $\pi_{12} = -\omega d$, the certainty equivalent of which is $\hat{\pi}_{12} = -\omega d$ as well. The choice between $\hat{\pi}_{11}$ and $\hat{\pi}_{12}$ depends on several parameters, that include ω, d, P_1, R, μ_0^c, Q_0^c, Σ, and c_p. All other variables could be assumed as given, except c_p, which is a random number with mean μ_0^c and variance $\left(Q_0^c + \Sigma\right)$. This decision-making process could be seen as a lottery with possible outputs $\hat{\pi}_{11}$ or $\hat{\pi}_{12}$ depending on the outcome of prototype, c_p. c_p^* is defined as a threshold of c_p, where the manufacturer will choose to make a deal if $c_p{}^* < c_p$, otherwise no deal. $c_p{}^*$ if the value that satisfies the condition: $\hat{\pi}_{11} = \hat{\pi}_{12}$.

$\hat{\pi}_1$ is the certainty equivalent of the uncertain outcome between $\hat{\pi}_{11}$ and $\hat{\pi}_{12}$, which can be mathematically expressed as:

$$u\left(\hat{\pi}_1\right) = \int_{-\infty}^{c_p{}^*} u\left(\hat{\pi}_{11}\right) f\left(c_p\right) dc_p + \int_{c_p{}^*}^{\infty} u\left(\hat{\pi}_{12}\right) f\left(c_p\right) dc_p. \qquad (15)$$

$\hat{\pi}_1$ can be calculated from the inverse function of equation (15). Thus, the manufacturer could make the prototyping decision based on the comparisons between $\hat{\pi}_{01}$ and $\hat{\pi}_1$. In the case of no deal, where $\hat{\pi}_{01} < 0$ and $\hat{\pi}_1 < 0$, the decision maker could make the deal possible through adjusting some parameters, such as d or ω. Four simulated studies are investigated with different settings in Section 5 to provide a quantitative guide in applying the model.

5 SIMULATIONS

The risk model is implemented in Mathematica® with parameter settings as in Table 1. The input parameters include the manufacturer's initial estimates of the product cost, $c_0 \sim N(\mu_0^c, Q_0^c)$, risk attitudes, and the fidelity and cost of the prototypes. Four scenarios are investigated in the simulation study. In setting 1, the relationship between μ_0^c and expected surpluses ($\hat{\pi}_{01}$ and $\hat{\pi}_1$) is studied. Setting 2 studies the effects of cost variance Q_0^c, which represents the risk level in product cost estimation. Setting 3 focuses on the changes of $\hat{\pi}_{01}$ and $\hat{\pi}_1$ with respect to the increase of *d*. The output is concerned with choices among expected economic surpluses at different conditions. Last but not least, setting 4 investigates the prototype cost sharing *ω*, which is an important factor in contracting between customer and manufacturer.

Setting	μ_0^c	Q_0^c	R	P_0	P_1	Σ	d	ω
1	0~10	5	1	10	9.75	1	0.5	0.5
2	7	0.1~10	1	10	9.75	1	0.5	0.5
3	7	5	1	10	10	1	0~10	0.5
4	7	5	1	10	10	1	5	0~1

Table 1: Variables and descriptions

5.1 The effect of mean product cost, μ_0

The manufacturer's risk attitude can be measured in a quantitative way. In this scenario, *R* is assumed to be 1, which indicates that the manufacturer is risk averse. Given Q_0^c = 5, the manufacturer is uncertain about cost. The variance of fidelity is given as Σ = 1, which indicates a fairly good fidelity rate. The prototype costs *d* = 0.5, which is 5% of the initial price, P_0 = 10. The manufacturer shares 50% of prototype cost, ω = 0.5. P_1 decreases to 9.75 in order to make up for customer's prototype cost. The decision outcome is illustrated in Figure 4, which is plotted with the horizontal axis representing estimated mean value of product cost, μ_0, and the vertical axis representing $\hat{\pi}_{01}$ and $\hat{\pi}_1$.

The results show that expected economic surpluses ($\hat{\pi}_{01}$ and $\hat{\pi}_1$) are decreasing with respect to the increase of μ_0. $\hat{\pi}_{01}$ and $\hat{\pi}_1$ cross at (5.8, 1.9). This indicates that beyond this threshold point, prototyping is expected to generate more surpluses for the manufacturer. If the expected cost is not significant, say μ_0 = 4, there's no need to prototype in this situation.

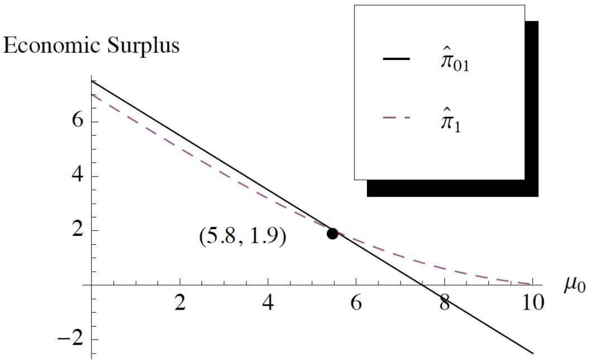

Figure 4: Setting 1

5.2 The effect of product cost variance, Q_0

For the sake of comparison, setting 2 is similar to setting 1, except μ_0 is fixed to 7 and Q_0 spans from 0.1 to 10.

$\hat{\pi}_{01}$ and $\hat{\pi}_1$ decrease as Q_0 increases from 0.1 to 10. This is reasonable as Q_0 represents risks in product cost estimation. For a risk adverse decision maker, *R*=1, he prefers lower risk. $\hat{\pi}_{01}$ and $\hat{\pi}_1$ cross at the point of (3.5, 1.2). When Q_0 is larger than 3.5, $\hat{\pi}_1$ is higher than $\hat{\pi}_{01}$ as risk is significantly reduced through prototyping.

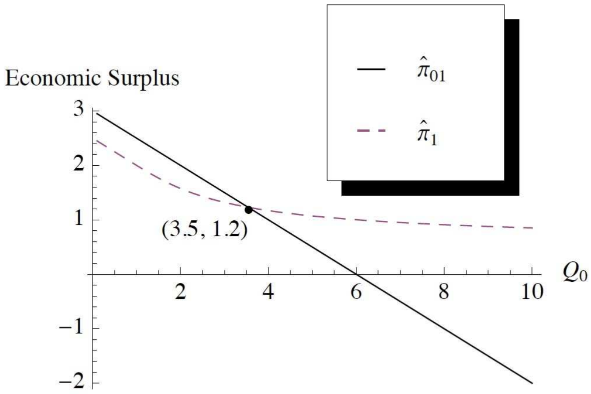

Figure 5: Setting 2

5.3 The effect of prototype cost, *d*

It is assumed that $c_0 \sim N(7,5)$. The manufacturer has the same risk attitude as the previous cases, *R = 1*. In this scenario, It is given that *P₁ = P₂ = 10*, which means that the manufacturer doesn't compensate the customer for prototyping cost, 50% of which is borne by manufacturer. The results are shown in Figure 6.

$\hat{\pi}_{01}$ is a horizontal line, as it is the certainty equivalent before prototyping, not a function of d. $\hat{\pi}_1$ decreases with the increase of *d*. The two lines cross at (2.1, 0.5), which means that it is worth to prototype when d < 2.1 with the given parameter settings.

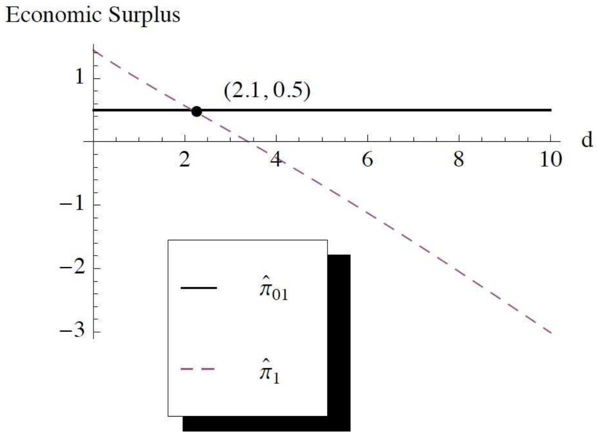

Figure 6: Setting 3

5.4 The effect of prototyping cost sharing, *ω*

In setting 4 the prototyping cost is fixed to 5. $\hat{\pi}_{01}$ and $\hat{\pi}_1$ cross at (0.2, 0.5), which means that in this given situation, the manufacturer can only bear less than 20% of the prototyping cost in order to profit from this deal.

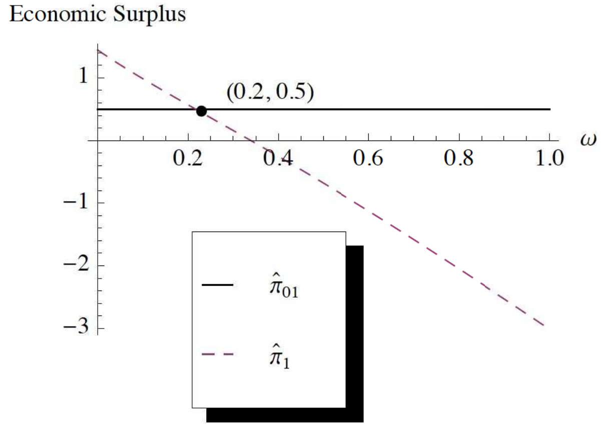

Figure 7: Setting 4

6 AN ILLUSTRATIVE CASE

This section provides the simulation of an illustrative case which helps to explain how this risk model can be applied to a practical design scenario.

In the case of house construction, an architect (manufacturer) cannot identify what the customer wants. As a result he is uncertain of his estimated cost due to the information barrier. Through the initial brief discussion with the customer, the architect may roughly estimate the cost c_0 based on the house size, style, material, decoration, etc. Here, two cases are designed to illustrate the effects of prototyping in risk reduction.

In case 1, c_0 is assumed to follow a normal distribution with mean $\mu_0^c = 7$ (\$ million) and variance $Q_0^c = 5$ (\$ million); and in case 2, c_0 follows a normal distribution with mean $\mu_0^c = 7$ and variance $Q_0^c = 10$. Assume that through a specifically designed survey, the customer's risk tolerance, *R*, is measured to be 1 (\$ million). The price that architect asks for is $P_0 = 10$ (\$ million). The settings of the scenario are summarized in Table 2.

Table 2: Architect's initial setting

Case	μ_0^c	Q_0^c	R	P_0	$\hat{\pi}_{01}$
1	7	5	1	10	0.5
2	7	10	1	10	-2

The certainty equivalent of the architect's surplus without prototyping, $\hat{\pi}_{01}$, is calculated to be *0.5* in case 1 and *-2* in case 2. This means that in case 1, the architect is willing to make the deal; however, he declines the deal in case 2 because of the high risk.

These two cases are illustrated in Figure 8, which is presented in 3-dimensiond figure with horizontal axes representing *R* and Q_0, vertical axis representing $\hat{\pi}_{01}$, and the horizontal surface indicating the frontier of $\hat{\pi}_{01} = 0$.

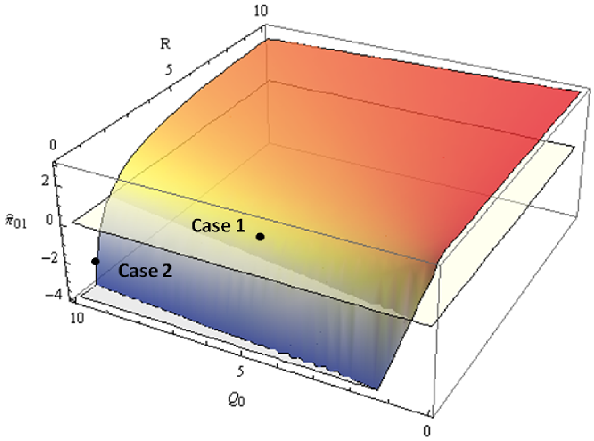

Figure 8: Architect's surplus without prototyping

The prototype of a construction project could be in different forms, such as detailed drawings, 3D rendered graphs, or small scale physical model. Such prototypes help the architect collect more information which results in a more accurate estimation of the final product cost.

In addition to the initial settings without prototyping (Table 2), the prototyping cost is assumed to be, $d = 1$ (\$ million). This cost consists of consulting fees, model construction fees, etc. The architect and the customer share half of the prototyping cost each, $\omega = 0.5$. The prototype is assumed to well represent the final product, $\Sigma = 3$. The architect charges the same amount even after prototyping, *P₁ = 10.*

The same prototype settings (Table 3) are applied to both cases. Then, the certainty equivalents of the architect's surplus after prototyping, $\hat{\pi}_1$, could be found for each case.

Case	μ_0^c	Q_0^c	R	P_1	d	Σ	ω	$\hat{\pi}_{01}$	$\hat{\pi}_1$
1	7	*5*	1	10	1	3	0.5	*0.5*	*0.78*
2	7	*10*	1	10	1	3	0.5	***-2***	***0.52***

Table 3: Prototype setting

In case 1, $\hat{\pi}_1 = 0.78$ which is higher than $\hat{\pi}_{01} = 0.5$. This means that the architect is willing to prototype even though he could make the deal without prototyping. This is because of the risk reduction and relative low prototyping cost. For case 2, $\hat{\pi}_1 = 0.52$ which is significantly higher than $\hat{\pi}_{01} = -2$, this positive result shows that the architect is willing to return to deal although he refused it before prototyping. This change from no deal to deal explains the risk reduction effect of prototyping. The results are shown in Figure 9.

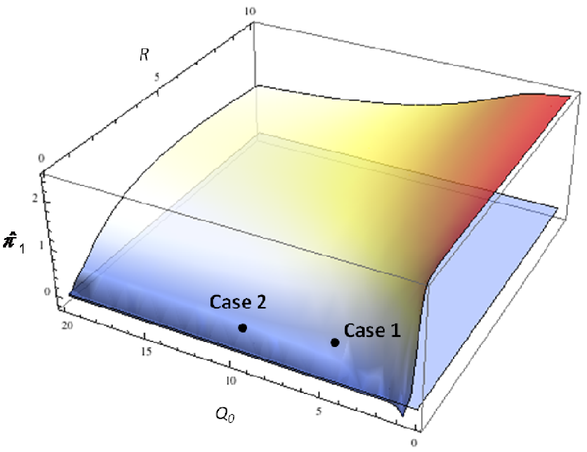

Figure 9: Architect's surplus with prototyping

7 CONCLUSION

The risk model developed in this study shows that the inherent uncertainties and the consequent risks concerning the value and cost of product create barriers for customers and manufacturers to engage in making deals in product customization. Unlike the prevailing research considering series of prototypes in product development, this study provides a quantitative guide for manufacturers in making the prototype-initiating decision.

The use of prototypes in product development is interpreted as a means for risk reduction. Information updating via prototyping is modeled as a Bayesian estimation process, which succinctly captures the dynamics of risk evolvement. This paper also develops a prototyping decision model based on risk analysis, taking into consideration a number of factors including manufacturers' risk attitudes, their initial estimation accuracies, and the fidelity and cost of the prototype, as well as the proportion of prototype cost shared by the manufacturer. A numerical study based on simulation reveals that an informed decision upon prototyping requires an intricate balance among the fidelity and cost of the prototype, sharing cost and price of the final product.

To fully understand the risks associated with customized product development, this study can be extended and enriched in a number of directions. First, this model can be developed to investigate multiple prototypes in product development. A second direction to extend this research is to consider multiple customers and manufactures in a more general sales or procurement scenario concerning product development. Although the competition among multiple parties makes decisions more complex, it provides incentives for truthful information sharing as well as a pricing mechanism. This paper makes a contribution towards this end by providing a general risk model.

8 ACKNOWLEDGMENTS

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