systems

MDPI

Article

Reducing Risks in Design Outsourcing of Complex Systems via Prototyping

Jiayi Zu *, Ke Sun and Songlin Chen

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore; sunke.mark@gmail.com (K.S.); songlin@ntu.edu.sg (S.C.)
* Correspondence: jiaiy020@e.ntu.edu.sg

Abstract

For the design and production of complex systems, manufacturers are increasingly favoring design outsourcing to obtain external expertise and innovation. The inherent risk in design outsourcing, unlike traditional production outsourcing that caters to detailed specifications, stems from its incomplete contracting nature. This paper focuses on the transaction risk between customers and design contractors, which hampers both parties from benefitting from the contract and obtaining mutual benefits. Prototyping, commonly used for eliciting customer requirements and estimating manufacturing costs, is interpreted in this paper as a means of risk reduction and modeled 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 the design outsourcing of complex systems.

Keywords: risk reduction; design outsourcing; prototyping; transaction risk; Bayesian estimation

1. Introduction

The source of innovation is increasingly coming from outside instead of from within as systems become increasingly complex. According to a study on BusinessWeek [1], 20% of the designs for mobile phones, 30% for digital cameras, 65% for notebook PCs, and 70% for personal digital assistants (PDAs) are outsourced by original equipment manufacturers (OEMs) to suppliers or specialized design firms. Design outsourcing is not constrained to the electronics industry but is spreading to other industries like commercial airplanes, as showcased by Boeing's revolutionary development of the Boeing 787 Dreamliner [2]. In the automobile industry, manufacturers outsource the design of complete systems, such as dashboards, seats, and safety systems, to suppliers that have the ability to provide entire systems [3].

However, a significant problem in design outsourcing is the transaction risk in the contracting stage, which stems from the information asymmetry between customers and design contractors. From a system perspective, such transaction risks are not isolated issues but emerge from complex interdependencies and feedback effects across organizational boundaries [4]. Unlike production or manufacturing, design is essentially a type of service with high density of knowledge content. Because of the incomplete contracting nature of design outsourcing, the outcome of design may not be accurately predetermined. As design is about creating something new, it is nearly impossible for a customer to precisely

Check for updates

Received: 2 February 2026
Revised: 19 March 2026
Accepted: 12 April 2026
Published: 8 June 2026

specify design requirements, for a contractor to accurately articulate design capabilities, or for a third party (e.g., a court) to unambiguously verify design quality [5]. As summarized by von Hippel, design is about innovative problem solving that requires the integration of need information and solution information, which, however, are usually distributed asymmetrically with customers and design contractors, respectively, and both of which are 'sticky' in the sense that they are difficult to extract, transfer, or use in a different location [6].

Furthermore, as in any transaction, customers and contractors are not fully aligned in their interests. Consequently, design outsourcing is a both technically and contractually challenging task. Reaching an agreement over design outsourcing is often an iterative and lengthy process with laborious back-and-forth negotiations. General systems theory suggests that such iterative coordination processes reflect adaptive behavior in response to feedback and evolving system states rather than inefficient contracting alone [4]. Unplanned design iteration is therefore considered a class of uncertain events that negatively impact project schedules [7]. From a system dynamics perspective, such iterations can be interpreted as feedback-driven learning cycles that influence how risk accumulates and propagates over time within a design outsourcing system [8].

Transaction risk limits the scope of design outsourcing and prevents companies from tapping into external sources of innovation. Prototypes are commonly used in practice to reduce both technical and transaction risks. Prototyping is essentially a means of eliciting customer needs and reducing the costly iterations of design development. In many situations, the outcome of a test based on a prototype may dictate whether a development task will have to be repeated [9]. Although prototypes are useful in risk reduction, high prototyping costs may pose serious challenges. For instance, a prototype for a new commercial aircraft could easily cost up to hundreds of millions of dollars. Regarding the investment decision upon prototyping, especially in capital-intensive industries, several significant but intricate questions are raised, including *whether it is cost-effective to build a prototype, who should pay for the prototype*, and *how should the final system be priced*?

Quantitative analyses of the effects of prototyping in transaction risk reduction are rare in the existing literature. This paper develops a quantitative risk model to answer the above questions. The potential for risk reduction through prototyping is modeled via a Bayesian estimation process. Decision models are subsequently developed to analyze customer decision making in a supply chain context, with or without prototyping. The decision models take both the fidelity and cost of a prototype into consideration. Simulation based numerical analysis is conducted to investigate the prototyping decision with respect to several key factors, such as decision-makers' risk attitude, design fees quoted by contractors, and sharing of prototyping costs. This model thus provides a framework to assist with informed investment decision-making upon prototyping in design outsourcing.

2. Related Literature

Outsourcing allows managers to leverage their companies' skills and resources for increased competitiveness [10]. The reasons for outsourcing activities mainly fall into five categories: the desire to save costs, the need to focus on core competencies, the need for better quality, the pressure to increase responsiveness, and the lack of enough in-house innovation capability [11]. It has become a common strategical approach in manufacturing and service industry to seek benefits from external expertise, cost savings, quality improvement, and focus on core business. Nike Inc. outsources its entire shoe production and manufactures only the key technical components of its "Nike Air" product line [10]. Procter Gamble has outsourced everything from IT infrastructure and human resources to the management of its offices [12]. In the electronic industry, original equipment manufacturers (OEMs) began to outsource product design to specialized original design

https://doi.org/10.3390/systems14060660

manufacturers (ODMs) [13]. PalmOne Inc. is a smartphone manufacturer headquartered in Sunnyvale, California, that completely outsources its hardware design and production to Taiwanese ODMs. The result is that PalmOne cut months off development times, reduced defects by 50%, and boosted gross margins by around 20% [1].

In contrast, most of the production in the fashion industry is outsourced, which explains the limited academic attention in this area [14]. Unlike conventional manufacturing and service outsourcing, there are no standard specifications in design contracting due to the innovation essence that underlies more uncertainties in transactions. Indeed, design outsourcing is an incomplete contracting process, which assumes that the exact nature of the service is uncertain and customers and contractors need to renegotiate the contract according to the shifting state of this nature. However, due to the limited protection of the abovementioned innovation in the OEM outsourcing process, technology spillover may happen, and manufacturers may be able to manufacture their own-branded products with the same consumer preference as the ODM's [15].

Academic research on design outsourcing and the role of prototyping has been scattered across multiple disciplines, including engineering design, operations research, and risk modeling and management, especially within a supply chain context. This research is interdisciplinary in nature in the sense that it is positioned between engineering decisions (prototyping) and business decisions (contract negotiation). Our review of the literature is thus focused on the problem of *how to reach a final design solution and a contract agreement between customers and contractors in an incomplete contracting scenario*.

The existing literature on this topic can be generally categorized into two streams. One stream of the literature models prototyping as a "trial-and-error" process, and the other takes it as a "learning process" to examine the utilities of prototypes. Trial and error is a process of reaching a final solution by experimenting with various methods until error is sufficiently reduced. For instance, when a consumer decides to purchase an automobile from the market, they are willing to try out several types of vehicles before payment. The main drawback of this method is that the cost of each trial must be small, as a repeated sampling strategy is often applied. The tryouts before car purchase are normally bearable due to the low cost of each trial. However, the trial-and-error method would be unrealistic for an automobile development project with the total cost up to millions of dollars. When the product price is high and consumption frequency is low, the customer will prefer learning mechanisms rather than trial and error.

In design outsourcing, learning mechanisms are often represented via prototyping. Designers often create one or several prototypes to elicit customer needs, obtain evaluations, and collect feedback before committing significant investment to the eventual production. Terwiesch and Loch proposed a learning mechanism, also called collaborative prototyping, for searching for product design with a string of prototypes in a situation that involves two economic agents [16]. In general, the customer chooses a design quality threshold as a stopping criterion and continues prototyping until this threshold is reached. This method provides a model for the contractor to offer prototypes at a profit, at cost, or even for free based on the design problem and market characteristics.

However, the collaborative design process does not consider the economic incentive conflicts between customers and contractors in a supply chain context. Takele et al. discussed the issue of capability misalignment between buyers and suppliers in product con-development from an information processing theory perspective [17]. Collaborative design process focuses on technical problem solving and assumes complete information sharing. Instead, design outsourcing approaches the problem in the transaction level and assumes both parties are reluctant to unveil all their private information, such as the customer's baseline for budget. Outsourcing design is not risk-free. The uncertainty in the design outcome amplifies the variance in customers' estimated value and contractors' estimated cost. This transaction risk thus discourages customers and contractors from engaging in a contract due to risk aversion.

In this research, prototypes are employed as a means for risk reduction in design outsourcing. Whereas business model innovation has become recognized as a source of sustainable competitive advantage, the means of driving these business model innovations, such as prototyping, experimentation, and piloting, have not been mapped or documented in a systematic way [18]. Viewing design outsourcing as a complex adaptive system, this paper models prototyping as a coordination mechanism that enables agents to respond to emergent behaviors and system-level uncertainties [19]. The customer advises design service providers of the basic requirements of the design, and the design service provider creates one or a series of prototypes for the customer to review. The prototypes can be either tangible or intangible; for instance, house interior design is commonly presented in 3D rendered drawings, and electronic device prototypes are usually built in physical form. As prototypes progress along with the design process and become more detailed, the associated risks to both customers and contractors reduce following a Bayesian process [20].

3. Transaction Risk in Design Outsourcing

The transaction risk in design outsourcing for customers involves uncertainties in potential value and for design contractors the uncertainties in potential cost. For customers, the major source of risk stems from the inability to accurately articulate needs in terms of concrete and clear requirements, particularly when the system is complex and the customer is not technically savvy [6]. For instance, when a house owner hires a designer to do interior design, they may have difficulties in articulating what they exactly want. The ambiguity in requirements leads to variations in final design value and cost. Customers' distorted need information will mislead contractors in design problem-solving and result in costly design changes or disputes. Another source of risk for customers is their inability to accurately evaluate a design solution. Because of the lack of technical understanding, customers could be 'confused' by the large variety of solutions that are embedded in customized design [21].

For design contractors, the main source of risk comes from uncertainty concerning resources that may be required. Coinciding with customers' inability to accurately articulate needs, designers are often unable to accurately explain their capabilities. It is often hard, if not impossible, to represent or describe a design or innovative solution in sufficient detail without confusing customers. Furthermore, designers are often exposed to the risk of requirement changes by customers. Even though customers could be contractually responsible for customer-initiated design changes, it is often the case in practice that designers need to modify the solutions to handle with customer's modified requirements. Such design changes late in the process are not only complicated but also expensive and may lead to delays [3].

Altogether, both customers and contractors are exposed to certain degrees of transaction risk in design outsourcing due to information and communication barriers. From a systems perspective, such risks emerge at the system level through interactions among multiple decision layers, nonlinear responses, and delayed communication across organizational hierarchies internally and across corporate boundaries externally [22]. The resolution to differences and the realization of design contracts between both parties depend on the level of risks and the participating parties' attitudes toward risks [23]. In this customer–contractor relationship, although the specific parameters differ as customers focus more on design performance and value, while contracts are generally more concerned about technical feasibility and costs, it can be generally modeled as a buyer–seller relationship from a business contract perspective. Thus, for simplicity of analysis without loss of generality, this paper focuses on decisions from the customer's perspective. Furthermore, this research adopts a partisan perspective, i.e., providing decision support for one party instead of finding equilibrium solutions for both parties, as most of the literature on incomplete contract theories has implicitly assumed.

3.1. Risk Attitude and Utility Function

In general, decision-makers can be categorized into three kinds, risk-averse, risk-neutral and risk-seeking, depending on their attitudes towards risk. In this paper, both customers and contractors are assumed to be risk averse without loss of generality. The different degrees of risk aversion can be reflected in the changes in the decision-maker's utilities to a certain evaluation measure. Utility is a measure of relative satisfaction and preference. In this model, customer and contractor utilities gauge their satisfaction with the design outcome in terms of economic benefits. Decision-maker's risk attitude is modeled via an exponential utility function [24], with a mathematical representation of:

$$u(x) = 1 - e^{-\frac{x}{R}} \tag{1}$$

where $u(x)$ represents the utility function, x is the evaluation measure, and R is a positive real value indicating risk tolerance, with higher R implying less risk aversion. In the context of design outsourcing, this study focuses on the value for customers. Therefore, the evaluation measure x in the exponential utility function indicates a customer's economic surplus $\pi = v - p$, where v is the value of final design for customers, and p is the price that the design contractor quotes. The true value of v remains unknown until the final design is observed. Before that, customers may have prior knowledge or experience of the expected design according to the degree of complexity of the designed system and the expertise of the designer. It is assumed that the customer has an estimation of the final design value without observing any prototype, which follows a normal distribution.

$$v_0 \sim N(\mu_0, Q_0) \tag{2}$$

The initial price quoted by contractors without prototyping is assumed to be p_0. For a customer, the goal is to maximize the economic surplus, and they will only consent to a transaction when $\pi_0 \geq 0$. At the initial stage, the customer faces a decision between an uncertain economic surplus if they choose to make the deal and an economic surplus of 0 if they decline the deal.

3.2. Certainty Equivalent

Certainty equivalent is a mathematical concept that transforms a set of random outputs into a certain value considering the decision-maker's risk attitude. For instance, the decision-maker is indifferent between π_0 and $\hat{\pi}_0$ when the following relationship is fulfilled:

$$u(\hat{\pi}_0) = E[u(\pi_0)]. \tag{3}$$

For a normal distribution, the certainty equivalent of the uncertain economic surplus can be derived as:

$$\hat{\pi}_0 = u^{-1}(E[u(\pi_0)]) = \mu_0 - p_0 - \frac{Q_0}{2R} \tag{4}$$

This equation indicates that $\hat{\pi}_0$ decreases as R decreases, which implies that the customer will obtain less value from the outsourced design if they are more risk-averse; and higher uncertainty represented by variance Q_0 will result in lower $\hat{\pi}_0$, which denotes the negative effect of risk. A customer will choose to make the deal with the contractor only when $\hat{\pi}_0 \geq 0$; otherwise, they will decline the deal. However, even the in case of

$\hat{\pi}_0 < 0$, it' is possible to increase $\hat{\pi}_0$ to positive value through risk reduction measures like prototyping.

4. Risk Reduction via Prototyping

4.1. Prototyping as Sampling

To quantitatively value the risk reduction effect of prototyping, it is assumed that the customer can estimate the final design value reflected from prototype v_p based on their experience and expertise. For instance, before launching a new car model, a manufacturer cannot accurately evaluate how the market will react, which means that the value of the car model v remains unknown. However, after observing the prototype of a new design, they may have an expectation of the market response (v_p) based on previous experience in the automobile industry. In other words, v_p can be taken as a sample of actual value v distorted by noise factor ε, i.e.,

$$v_p = v + \varepsilon \tag{5}$$

where ε is assumed to be a non-biased random variable that follows a normal distribution, $\varepsilon \sim N(0, \Sigma)$. The variance in the noise factor indicates the level of fidelity of the prototype, with lower variance implying higher fidelity. In a practical context, fidelity can be measured or assessed based on the level of detail in the prototype in terms of achieving design specifications. Generally, prototypes that are closer to design concepts have lower fidelity while prototypes that are closer to the final design or production model have higher fidelity. Without prototyping, the customer's best estimate of the final value is v_0. v_0 can be seen as the prior knowledge of the final design value, and v_p as the new observation. Assuming the noise factor is independent from the prior value estimate, the value estimate based on the prototype also follows a normal distribution:

$$v_p \sim N(\mu_0, Q_0 + \Sigma) \tag{6}$$

4.2. Bayesian Updating

Conditional on the outcome of prototyping, the customer can update their estimated value of the final design. The updated design value, v_1, can be derived through Bayesian theorem:

$$P(v_1) = p(v_0|v_p) = \frac{P(v_p|v_0) \cdot P(v_0)}{\int P(v_p|v_0) \cdot P(v_0) dv_0} = \frac{P(v_p|v_0) \cdot P(v_0)}{P(v_p)} \tag{7}$$

The updated value of design v_1 also follows a normal distribution, $v_1 \sim N(\mu_1, Q_1)$, with mean and variance as follows:

$$\mu_1 = \mu_0 + \frac{(v_p - \mu_0) Q_0}{Q_0 + \Sigma} \tag{8}$$

$$Q_1 = \frac{Q_0 \Sigma}{Q_0 + \Sigma} \tag{9}$$

From the above two equations, it can be observed that the updated mean value μ_1 will shift toward the observation v_p from the original mean value of μ_0. The variance in the new estimate Q_1 is lower than the initial estimate Q_0, which indicates that risks are reduced through prototyping. Thus, a no-deal scenario based on initial estimates of value and cost could be transformed into a scenario where a deal is possible if risks can be reduced significantly.

https://doi.org/10.3390/systems14060660

5. Optimal Prototyping Decision

The Bayesian estimation process described above provides a qualitative interpretation of the use of prototypes for risk reduction. However, it is important to quantitatively analyze the tradeoff between the risk reduction effects and the additional cost of prototype d, which in general is borne by design contractors. However, if the cost of prototyping exceeds the contractor's upper cost limit, the contractor will not participate in the deal. In such cases, if the customer is willing to share a proportion of the prototyping cost, it would help the contractor return to a deal that may benefit both parties.

In this paper, we assume that the customer shares as ω proportion of the prototyping cost. After prototyping, it is assumed that the contractor could ask for a new price quote P_1, which is adjusted from P_0 with consideration of prototyping cost and the design outcome. The customer decides whether to choose a deal or not after observing the prototype. The customer may only want to build a prototype when their expected surplus with prototyping $\hat{\pi}_1$ is higher than the expected surplus without a prototype. $\hat{\pi}_1$ is calculated from $\hat{\pi}_{11}$ and $\hat{\pi}_{12}$, which represent the customer's expected economic surpluses of a deal and no deal with prototyping, respectively. Figure 1 summarizes the customer's decision process.

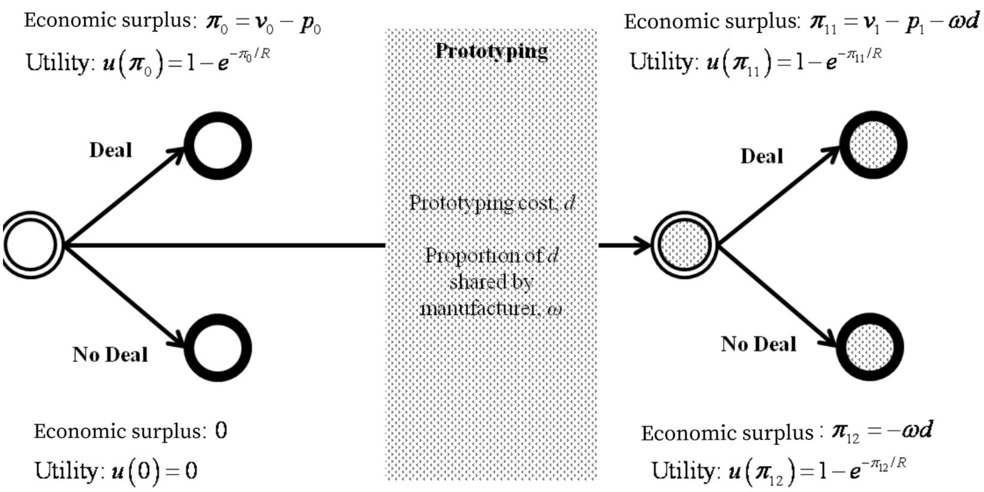

Figure 1. Decision process regarding prototyping.

The economic surpluses of different scenarios can be calculated as follows:

$$u(\hat{\pi}_{11}) = \int_{-\infty}^{\infty} u(\pi_{11}) f(v_1) dv_1 = \int_{-\infty}^{\infty} \left(1 - e^{-\frac{v_1 - P_1 - \omega d}{R}}\right)\left(\frac{1}{\sqrt{2\pi Q_1}} e^{-\frac{(v_1 - \mu_1)^2}{2Q_1}}\right) dv_1 \tag{10}$$

$$\hat{\pi}_{11} = \mu_1 - P_1 - \omega d - \frac{Q_1}{2R} \tag{11}$$

$$\hat{\pi}_{12} = \pi_{12} = -\omega \cdot d \tag{12}$$

The relationship between $\hat{\pi}_{11}$ and $\hat{\pi}_{12}$ hinges on the value of v_p, i.e., the value estimate based on the prototype, as other variables are assumed as fixed within a given supply chain context. In this paper, a prototype is modeled as a sampling of the final system, thus following the same normal distribution, i.e., $v_p \sim N(\mu_0, Q_0 + \Sigma)$. v_p^* denotes the threshold value that satisfies the condition $\hat{\pi}_{11} = \hat{\pi}_{12}$.

$$v_p* = P_1 + \frac{\Sigma}{2R} + \frac{\Sigma}{Q_0}(P_1 - \mu_0) \tag{13}$$

$\hat{\pi}_1$ is the certainty equivalent of the uncertain outcomes of $\hat{\pi}_{11}$ and $\hat{\pi}_{12}$:

$$u(\hat{\pi}_1) = \int_{-\infty}^{v_p^*} u(\hat{\pi}_{12}) f(v_p) dv_p + \int_{v_p^*}^{\infty} u(\hat{\pi}_{11}) f(v_p) dv_p \tag{14}$$

$\hat{\pi}_1$ can be calculated from the inverse function of $u(\hat{\pi}_1)$, as illustrated in the following:

$$\hat{\pi}_1 = -R \log \left[\begin{array}{l} 1 - \frac{1}{2}\left(e^{\frac{\omega d}{R}} - 1\right)\left(-1 - \mathrm{erf}\left(\frac{v_p * - \mu_0}{\sqrt{2(Q_0+\Sigma)}}\right)\right) + \frac{1}{2}\left(1 - \mathrm{erf}\left(\frac{v_p * - \mu_0}{\sqrt{2(Q_0+\Sigma)}}\right)\right) \\ + \frac{1}{2} e^{\frac{Q_0 + 2R(P_1 - \mu_0 + \omega d)}{2R^2}} \left(-1 + \mathrm{erf}\left(\frac{Q_0}{R\sqrt{2(Q_0+\Sigma)}} + \frac{(v_p * - \mu_0)}{\sqrt{2(Q_0+\Sigma)}}\right)\right) \end{array} \right] \tag{15}$$

With the mathematical models developed above, a customer can make a prototyping decision based on the values of $\hat{\pi}_0$ and $\hat{\pi}_1$. When $\hat{\pi}_0 > 0$, the parties should have a deal without resorting to prototyping, meaning that the perceived value significantly exceeds the risks. When $\hat{\pi}_0 < 0$ but $\hat{\pi}_1 > 0$, the parties should engage in prototyping, meaning that the risk reduction with prototyping exceeds the cost of the prototype. When both $\hat{\pi}_0 < 0$ and $\hat{\pi}_1 < 0$, there is no deal with or without prototyping, but both parties could still explore opportunities for a deal through negotiation of some parameters, such as prototyping cost d and the share of prototyping cost ω, which is essentially risk sharing.

6. A Simulation Study

Negotiations in the actual design outsourcing of complex systems are often complicated with legal considerations besides commercial incentives. To illustrate the application of the risk models developed in this study, a case study in the context of a housing project using simulation is outlined. It is assumed that a customer is interested in hiring an architect to build a custom-designed house. After a brief consultation with the architect, the customer has a rough estimate of the value of the final design based on factors like the size, style, material, decoration of the desired house. However, the true value of the final design remains unknown due to information barriers; in other words, the transaction risk between the customer and the architect is rather high.

In practice, design outsourcing entails a plethora of factors that are not amenable to precise and accurate descriptions. The purpose of this simulation was to illustrate, instead of enumerating, the possible applications of the developed model and its implications in actual decision-making. Thus, typical decision scenarios were selected to represent a more general design outsourcing context, with the assumed input values of each parameter listed in Table 1, where Case 1 is the base scenario with parameters set without prototyping, and Cases 2 to 5 outline four different settings with prototyping.

Table 1. Decision scenarios with and without prototyping.

Case	Without Prototyping					With Prototyping				
	μ_0	Q_0	R	P_0	$\hat{\pi}_0$	P_1	d	Σ	ω	$\hat{\pi}_1$
1	9	5	2	8	−0.5	-	-	-	-	-
2	9	5	2	-	-	8	1.2	2	0.5	0.183
3	9	5	2	-	-	8	4	2	0.1	0.384
4	9	5	2	-	-	9	1.2	2	0.5	−0.191
5	9	5	2	-	-	7	1.2	2	0.5	0.726

https://doi.org/10.3390/systems14060660

6.1. Case 1: Basic Settings Without Prototyping

Case 1 illustrates a situation where the customer possesses limited information and knowledge of the designer's capabilities without prototyping. v_0 is assumed to follow a normal distribution $N(9,5)$, the customer's risk tolerance is R = 2, and the price that designer asks for is 8. In a perfect world with no risks or the customer is risk-neutral, the customer would be willing to accept the deal as the expected value of the design exceeds the price, i.e., $\mu_0 > P_0$. However, in the given scenario, the customer's expected surplus is calculated as $\hat{\pi}_0 = -0.5$, which indicates that the customer is reluctant to engage in a deal due to the present amount of risk.

Case 1 is illustrated in Figure 2, presented in a 3-dimensional graph with horizontal axes representing the expected value and variance of the design, and the vertical axis representing the expected economic surplus $\hat{\pi}_0$. The blue horizontal surface indicates the frontier of $\hat{\pi}_0 = 0$, and the green surface shows $\hat{\pi}_0$ in Case 1. It can be observed that the value of $\hat{\pi}_0$ increases with the increase in μ_0 and decrease in Q_0. This makes sense as the higher the customer's initial estimate of the design value, the higher the expected economic surplus. When the uncertainty of the initial estimation is high, the customer's willingness to participate in the contract is reduced due to risk aversion.

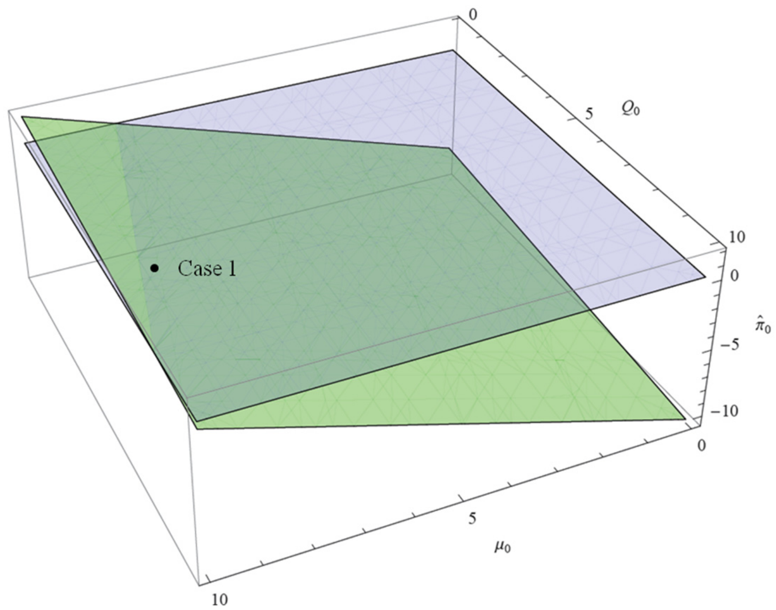

Figure 2. Decision scenario without prototyping.

6.2. Case 2 Prototyping as Sampling

Case 2 builds on Case 1 with additional prototyping settings. P_1 is assumed to be 8, which is the same as P_0. The cost of prototype is assumed to be d = 1.2 with a variance of $\Sigma = 2$, and the customer is assumed to share half of the cost. The customer's expected economic surplus after prototyping is calculated to be $\hat{\pi}_1 = 0.184$, which is positive. This case shows that a deal becomes feasible when transaction risk is significantly reduced with prototyping, even when the price quote remains the same.

Figure 3 illustrates the change in $\hat{\pi}_1$ with respect to the expected value and variance of the design. The positive $\hat{\pi}_1$ in Case 2 indicates that the customer is willing to make the deal even though they bear some portion of the prototyping cost. It demonstrates the value of prototyping at the system level, as risks are reduced through coordination between the customer and the contractor.

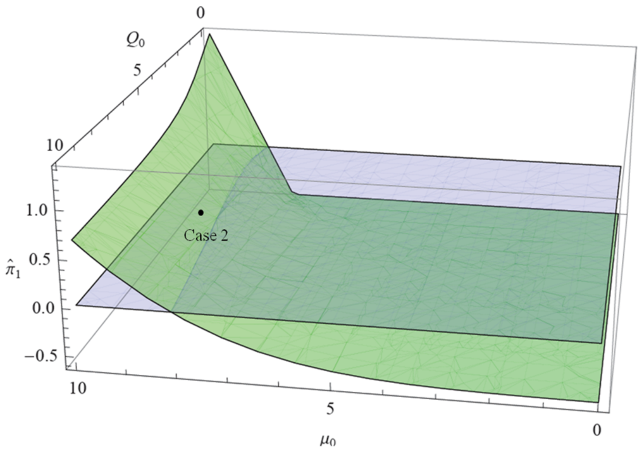

Figure 3. Decision scenario with prototyping.

6.3. Case 3 Budget for Prototyping

The risk model developed in this study can be applied to compute the customer's budget for prototyping as well. By varying the values of d and w, we can observe how the prototyping cost and the share of this cost affect the customer's economic surplus.

In Figure 4, the horizontal axes represent different values of d and w, and the vertical axis represents the expected economic surplus $\hat{\pi}_1$, which increases with decreases in d and w. This observation is reasonable because increasing the prototyping cost reduces the customer's willingness to accept the deal. Thus, the model can be used by the customer to determine budget allocation for prototyping.

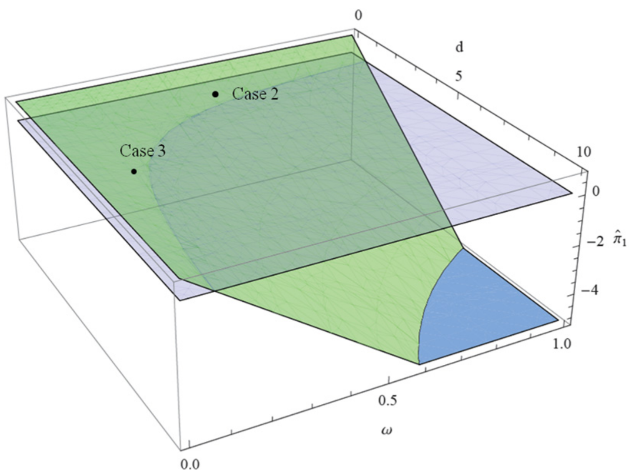

Figure 4. Shared cost of prototyping.

6.4. Cases 4–5 Price Negotiation with Prototyping

The price quote from the contractor plays a critical role in the customer's decision-making during the transaction stage. This model helps the customer to gauge their own acceptable price limit with and without prototyping.

Figure 5 illustrates the effects of changes in P_1 and R on the expected economic surplus $\hat{\pi}_1$. As the price quotes go higher, the customer is more reluctant to strike a deal. A customer with higher risk tolerance is more willing to bear higher risk and accept a deal at higher prices. Thus, the risk model developed in this study could be employed as a decision support tool to assist with price negotiation during design outsourcing.

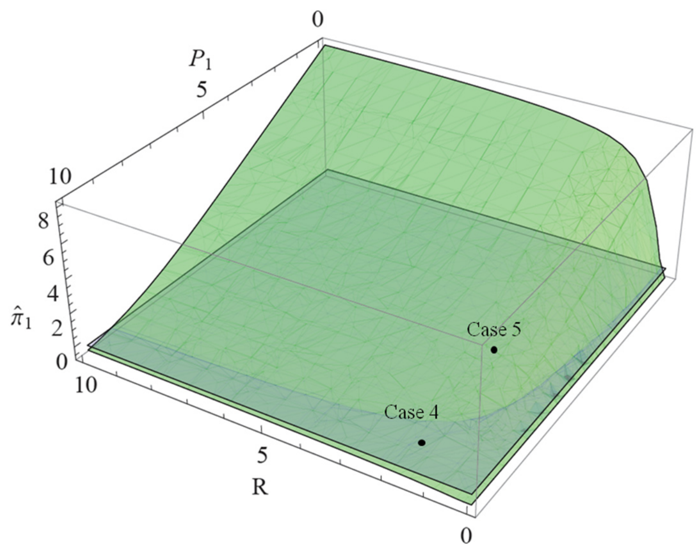

Figure 5. Risk attitude and price negotiation.

7. Conclusions

As systems become more complex, more supply chain partners have engaged in design outsourcing to tap into each other's expertise and capabilities to collectively design, manufacture, and deliver such systems. However, design outsourcing is significantly more challenging than production outsourcing due to the inherent uncertainty and risks involved, which manifest in terms of customers' incapability to articulate requirements and assess values as well as contractors' inability to accurately quote solutions and estimate costs. These risks may hamper deal-making, even when mutually beneficial agreements are possible.

The risk model developed in this study shows that the inherent risks in the value and cost of complex systems create barriers for customers and contractors to make deals in design outsourcing. This study provides a quantitative model to assist decision-making concerning prototyping. The use of prototypes in design outsourcing was interpreted as a method of risk reduction. Information updating via prototyping was modeled as a Bayesian estimation process, which succinctly captures the dynamics of risk evolution. We also developed a prototyping decision model based on risk analysis, taking into consideration multiple factors including risk attitude, initial estimate variance, the fidelity and cost of a prototype, and the proportion of prototype cost shared between customers and contractors. A numerical study based on simulation revealed that an informed prototyping decision requires intricate trade-offs among these factors, and mutually beneficial agreements could be reached with the right prototyping strategies.

The key novelty of the current paper in addition to that of our previous preliminary research [25] is the development of a comprehensive analytical framework focusing on the transactional risks in the design outsourcing of complex systems instead of product development. The main theoretical contribution of this paper is the modeling of prototypes as a random sampling of the final design outcome with increasing levels of fidelity, based on which a mathematical model based on Bayesian estimation was developed to quantify risks. The practical implications of this research include the development of a computational model that can systematically guide companies in managing the risks associated with the design outsourcing of complex systems, instead of relying on manager experience. As demonstrated with the simulations, the model could assist companies in finding mutually beneficial agreements and capturing better value through risk reduction.

https://doi.org/10.3390/systems14060660

The focus of the current research was laying a theoretical foundation for modeling prototypes as a means for reducing risk and developing a working model for risk quantification. It can be extended and enriched in several directions. First, the model developed in this paper can be enhanced to investigate multiple sequential prototypes in design outsourcing. A second direction is simultaneously modeling both customers' and contractors' decisions in an integrated model. Given the coexistence of incentives to collaborate (in design) and compete (in contract negotiation), a game-theoretical model would provide more practical decision support on both sides. A third direction for future research is to consider multiple customers and designers in a more general sales or procurement scenario. Although competition among multiple parties makes decisions more complex, it provides incentives for truthful information sharing as well as a price discovery mechanism. The increasingly complex supply chain structures call for further research to develop quantitative models and find empirical support for effective decision-making in the design outsourcing of increasingly complex systems.

Author Contributions: Conceptualization, J.Z., K.S. and S.C.; methodology, J.Z. and K.S.; formal analysis, J.Z. and K.S.; investigation, J.Z.; data curation, J.Z.; visualization, J.Z.; writing—original draft preparation, J.Z.; writing—review and editing, J.Z., K.S. and S.C.; supervision, S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Engardio, P.; Einhorn, B.; Kripalani, M.; Reinhardt, A.; Burrows, P. Outsourcing innovation. *BusinessWeek*, 21 March 2005.
2. Manufacturing complexity. *The Economist*, 17 June 2006. Available online: https://www.economist.com/special-report/2006/06/17/manufacturing-complexity (accessed on 11 April 2026).
3. Zirpoli, F.; Becker, M.C. What happens when you outsource too much? *Sloan Manag. Rev.* **2011**, *52*, 59–65.
4. Turner, J.R.; Baker, R.M. Complexity theory: An overview with potential applications for the social sciences. *Systems* **2019**, *7*, 4. [CrossRef]
5. Anton, J.J.; Yao, D.A. The sale of ideas: Strategic disclosure, property rights, and contracting. *Rev. Econ. Stud.* **2002**, *69*, 513–531. [CrossRef]
6. von Hippel, E. *Democratizing Innovation*; MIT Press: Cambridge, MA, USA, 2005.
7. Shafqat, A.; Oehmen, J.; Welo, T. Planning unplanned design iterations using risk management and learning strategies. *J. Eng. Des.* **2022**, *33*, 120–143. [CrossRef]
8. Zanker, M.; Bureš, V.; Tučník, P. Environment, business, and health care prevail: A comprehensive, systematic review of system dynamics application domains. *Systems* **2021**, *9*, 28. [CrossRef]
9. Ulrich, K.T.; Eppinger, S.D. *Product Design and Development*; McGraw-Hill: New York, NY, USA, 2000.
10. Quinn, J.B.; Hillmer, F.G. Strategic outsourcing. *McKinsey Q.* **1995**, *1*, 48–70.
11. Uygun, Y.; Gotsadze, N.; Schupp, F.; Gzirishvili, L.; Nana, B.S.T. A holistic model for understanding the dynamics of outsourcing. *Int. J. Prod. Res.* **2023**, *61*, 1202–1232. [CrossRef]
12. Engardio, P.; Arndt, M.; Foust, D. The future of outsourcing. *BusinessWeek*, 29 January 2006.
13. Vakil, B. Design Outsourcing in the High-Tech Industry and Its Impact on Supply Chain Strategies. Master's Thesis, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, USA, 2005.
14. Stahl, C.; Stein, N.; Flath, C.M. Analytics applications in fashion supply chain management—A review of literature and practice. *IEEE Trans. Eng. Manag.* **2023**, *70*, 1258–1282. [CrossRef]
15. Li, G.; Wu, H.; Dai, J. Production sourcing strategy for an apparel original brand manufacturer in the presence of technology spillover. *IEEE Trans. Eng. Manag.* **2023**, *70*, 1283–1294. [CrossRef]

16. Terwiesch, C.; Loch, C.H. Collaborative prototyping and the pricing of custom-designed products. *Manag. Sci.* **2004**, *50*, 145–158. [CrossRef]
17. Takele Koyra, K.; Wang, M.; Zhang, C. How IT capability misalignment between buyers and suppliers affects product co-development: An information processing theory perspective. *Int. J. Oper. Prod. Manag.* 2026, *ahead-of-print*. [CrossRef]
18. Geissdoerfer, M.; Savaget, P.; Bocken, N.; Hultink, E.J. Prototyping, experimentation, and piloting in the business model context. *Ind. Mark. Manag.* **2022**, *102*, 564–575. [CrossRef]
19. Ahmad, M.A.; Baryannis, G.; Hill, R. Defining complex adaptive systems: An algorithmic approach. *Systems* **2024**, *12*, 45. [CrossRef]
20. Asru, A.S.; Khosravi, H.; Ahmed, I.; Azeem, A. From automation to autonomy in smart manufacturing: A Bayesian optimization framework for modeling multi-objective experimentation and sequential decision making. *Int. J. Adv. Manuf. Technol.* **2025**, *137*, 5027–5057. [CrossRef]
21. Huffman, C.; Kahn, B.E. Variety for sale: Mass customization or mass confusion? *J. Retail.* **1998**, *74*, 491–513. [CrossRef]
22. Ottaviani, F.M.; De Marco, A.; Rafele, C.; Castelblanco, G. Risk perception-based project contingency management framework. *Systems* **2024**, *12*, 93. [CrossRef]
23. Jia, J.; Dyer, J.S. A standard measure of risk and risk-value models. *Manag. Sci.* **1996**, *42*, 1691–1705. [CrossRef]
24. Kirkwood, C.W. *Notes on Attitude Toward Risk Taking and the Exponential Utility Function*; Technical Report; Arizona State University: Tempe, AZ, USA, 1997.
25. Sun, L.; Chen, W. Risk Reduction via Prototyping in Customized Product Development. In *Proceedings of the 21st CIRP Design Conference*; KAIST: Daejeon, Republic of Korea, 2011.

https://doi.org/10.3390/systems14060660