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# Collaborative Prototyping and the Pricing of Custom-Designed Products

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A major challenge in the creation of custom-designed products lies in the elicitation of customer needs. As customers are frequently unable to accurately articulate their needs, designers typically create one or several prototypes, which they then present to the customer. This process, which we call *collaborative prototyping*, allows both parties to anticipate the outcome of the design process. Prototypes have two advantages: They help the customer to evaluate the unknown customized product, and they guide both parties in the search for the ideal product specification. Collaborative prototyping involves two economic agents, with different information structures and different—and potentially conflicting—objective functions. This raises several interesting questions: how many prototypes should be built, who should pay for them, and how should they and the customized product be priced. We show that, depending on the design problem and the market characteristics, the designer should offer prototypes at a profit, at cost, or even for free.

*Key words*: prototyping; collaboration; customization; search models; search contracts; design services
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## 1. Introduction

Many products are designed and built with the objective of fulfilling the unique needs of one individual customer. These customized products include capital goods, such as production equipment or defense systems acquired by institutional buyers, and consumer goods, such as architectural services or customized perfumes. A major challenge in the creation of customized products lies in the elicitation of customer needs, because customers are often unable to accurately articulate those needs (Zipkin 2001). Designers often create one or several prototypes to elicit customer needs, and present them to the customer for evaluation. This process, which we call *collaborative prototyping*, allows both parties to anticipate the outcome of the design process ("This kitchen design is worth an extra $1,000 to me") and to direct the search for potential design improvements ("I like this golf club, but could you make the shaft longer?").

Although there exists a rapidly growing stream of literature on prototyping and experimentation, previous work has assumed that prototyping occurs *within* the firm, i.e., that both costs and benefits are incurred within the same organizational entity. The objective of the present article is to examine a situation where prototyping involves two economic agents, with different information structures and different—and potentially conflicting—objective functions. This novel setup raises several interesting questions: how many prototypes should be built, who should pay for them, and how should the prototypes and the product itself be priced.

We formulate the collaborative prototyping process as a search model, in which the customizing producer sets prices and the buyer decides how long to continue the search for a better design (Theorem 1). Based on our search model, we present the following two results. First, we examine collaborative prototyping of a monopolist producer whose design capabilities are known. If the design problem is unstructured, which prevents learning between prototypes, it is optimal for the producer to offer a linear (in the number of prototypes) pricing scheme, and to sell prototypes at cost (Theorem 2). If the design problem is structured, successive prototypes create learning about the optimal design solution. The monopolist can not only anticipate (in expectation), but also precisely plan his profit, and freely allocate it between the prototypes and the final product (Theorem 4).

Second, we examine the case of customers who do not know the producer's design capabilities. Customized designs inherently pose an information asymmetry between the customer and the customizing producer. Given that the customer herself is not able to define the product's specification, she cannot use a single prototype to judge the competence of the customizing producer. An unsatisfactory prototype (e.g., a house design that the customer does not find appealing) could reflect a low-quality producer, or it could be a random outcome reflecting the uncertain nature of the design process. For the unstructured setting, Theorem 3 shows how the customizing producer will use the prototype prices as a signal of his capability. Theorem 5 provides the corresponding results for the structured case. We also extend our results to the case of customers who are heterogeneous in their valuation of design quality (Theorems 6 and 7).

## 2. Motivating Examples

Few consumers would feel comfortable with committing to a construction plan without having seen detailed drawings or models of the expected outcome. For this reason, the interaction between an architect and his client typically begins with an elicitation of user needs, consisting of questions about taste and style, and a discussion of existing house designs that appeal to the client. Over the course of this early stage of the collaboration (referred to as "initial design phase" in architecture), the architect creates two or three elaborate prototypes, requiring extensive drawing work and sometimes physical model building.

In the United States, the contractual basis for the initial design part of collaboration between client and architect typically takes the form of a "Letter of Agreement." While there exists a wide range of recommendations on how architects should charge for their design work, including lump-sum fees, cost-plus contracts, or a percentage of the construction costs (see guidelines from the American Institute of Architects (AIA)), architects for residential projects typically charge an hourly rate for initial design work. Only once the overall project is well defined will the parties sign a more detailed contract (most commonly AIA form B141).[1] For example, Franklin (2000, p. 219), author of a widely used professional guideline for architects, recommends: "In principle, the architect quotes a fixed fee on only those services for which the extent and duration can be reasonably anticipated. The rest—including initial design up to schematic design—are performed at hourly rates."

The architect collects revenues from two sources. First, he charges for the initial design work on an hourly basis, including the creation of prototypes. The hours spent on the project are driven primarily by the number of prototypes built. Second, the architect collects a fixed fee for the remaining part of the construction project, which includes the preparation of detailed construction drawings and overall project management. The 1998 Mean Square Footage Cost Data survey indicates that architectural fees for a custom house range from 5% to 15% of the total anticipated cost of construction (see www.aia.org). An estimated 15% to 20% of these fees are incurred during the initial design phase, which is the primary focus of this article.[2] We examine the questions of how many prototypes the architect should create for the client and how much he should charge for them.[3]

Another example of collaborative prototyping is provided by Thomke (2000), who describes a buyer-supplier collaboration in the development of new food flavors. Consider the development of a new snack—an energy bar, for example. The producer of energy bars requests the supplier to provide various flavors to fine-tune the taste of a new bar. Creating a new flavor is a complex process and is more art than science (there exist more than 1,000 variations of strawberry flavor alone!). Given this complexity, the buyer is not able to provide a specification for the flavor (e.g., in the form of a chemical recipe), but has to rely on collaborative prototyping with the supplier. In this process, the supplier commits R&D resources to creating customized flavors, which leads to a prototype energy bar. This prototype is then evaluated by the buyer, based on traditional market research. Similar to the case of the architect, the flavor supplier charges the buyer for both the collaborative prototyping and the procurement of the flavors once they have been developed. This example illustrates that collaborative prototyping is also costly for the buyer, who commits resources to evaluating the prototype.

Our economic analysis is motivated by the current importance of collaborative prototyping, as illustrated by the examples of architecture and flavorings, in combination with an emerging customization revolution in many other industries. Throughout this article, we refer to the supplier as the customizing producer and to the buyer as the customer. We assume that it is the producer who determines the contractual relationship. The customer only decides whether she wants to engage in a collaboration, and how many prototype iterations she is willing to participate in. This represents the situation in consumer markets and markets

[1] We thank architects Alan Chu and Jim Rowe for providing us with information about architectural pricing and contracting.

[2] If the architect's fee after the initial design is a percentage of construction cost, there exists a moral hazard of boosting the design complexity and cost. In such cases, the project management literature recommends the use of fixed-price contracts (see, e.g., Kerzner 1995).

[3] Note that our model represents only the early stages of the project (initial design up to schematic design). Another interesting contracting problem relates to the pricing of design changes *after* the construction documents are complete. The dynamics of this stage are very different, driven mainly by renegotiation (Bajari and Tadelis 2001). See also Plambeck and Taylor (2002) for a model of renegotiations in a supply chain setting.

of powerful producers. It does not represent cases in which the customer is sufficiently powerful to determine the contract, including screening mechanisms or the solicitation of competing proposals (e.g., Snir and Hitt 2003). While such mechanisms exist in the architectural profession, they only apply in the case of large institutional customers, and are rarely used for residential projects.

## 3. Literature Background

Our model builds on two existing literature streams: the theory of search and its application in new product development, and the pricing of *experience goods*. Economists define an experience good as a product whose quality cannot be fully determined before it is purchased (Nelson 1970). Experience goods include a dinner in a restaurant, and most professional services, such as those of a law firm. A common problem in markets for experience goods is potential opportunism on the part of the seller, who might claim a higher quality of the product or service ex ante than the customer experiences ex post. Reputation is a key factor in controlling the seller's opportunism (Liebeskind and Rumelt 1989). Over time, customers learn which sellers "shirk" and which sellers make a true attempt to keep their promises, and reward the "good" sellers with repeated business while penalizing the "bad" ones with boycotts.[4] Moreover, a good seller can attempt to provide an informative signal concerning his type by acting in a way which would be uneconomical to imitate for a bad seller (Spence 1975).

Although the situation we study also exhibits uncertainty about the customer's postpurchase utility, it differs from that of traditional experience goods along two dimensions. First, in our model, the source of the uncertainty lies not in opportunistic behavior on the part of the seller, but in the customer's inability to fully express her needs and preferences. Current customers interacting with past customers do not benefit from word-of-mouth communication, because the outcome of any custom design project is unique and jointly determined by designer and customer. Second, while one may learn about the quality of restaurants by trial and error, a repeated sampling strategy is unrealistic for a residential architecture project with a total cost of $20,000. When the product price is high and consumption frequency low, the customer will resort to learning mechanisms other than trial and error.

[4] Shapiro (1983) models a firm using low initial prices to have the consumer experience the product. Learning can occur at the individual level, which typically takes the form of repeated sampling (trial and error), or at the community level, reflecting information exchanged among customers (word of mouth).

The learning mechanism most commonly used in the case of customized design is prototyping. Prototypes, broadly defined, are approximations of the final product along one or several dimensions of interest (Ulrich and Eppinger 1994). They allow designers to anticipate how the product will be received by their customers, without incurring the cost of an actual launch. Recent work in new product development has addressed economic trade-offs in prototyping, including when to build prototypes (Thomke and Bell 2001), how many to build (Dahan and Mendelson 2001), how much development time to devote to prototyping (Terwiesch and Loch 1999), and what search strategies to pursue (Loch et al. 2001). These studies assume that the prototyping occurs within one firm that both incurs the costs and experiences the benefits of prototyping.

In contrast, in this article we consider a situation that involves two economic agents, with different information structures and different—and potentially conflicting—objective functions. Given her limited understanding of the design domain, the customer herself cannot codify her preferences. Codifiability in the manufacturing context captures the degree to which knowledge can be encoded, even if the individual operator does not have the facility to understand it (Zander and Kogut 1995). Levi et al. (2002) define codifiability in the context of an electronic marketplace as the ability of the trade partners to create a commonly understood document that lists all aspects of the transaction. In our architect example, such a document corresponds to the construction drawings that the architect develops and provides to the construction company. This involves noncodifiable knowledge—the customer cannot translate her needs and preferences into construction drawings.

## 4. A Model of Collaborative Prototyping

Consider a customer interested in purchasing a custom-designed product. The customer ("she") knows her reservation utility $u_0$, the expected utility of consuming a standard product that currently exists on the market. The producer ("he") possesses only a prior distribution $H(\cdot)$ about $u_0$. We normalize the price of the standard product to zero. The customer cannot foresee the utility associated with the customized product. Therefore, she requests the customizing producer to create prototypes. Prototypes offer two benefits. First, they help to overcome the design uncertainty of the customer and eliminate potential ex post regrets. We assume that a prototype allows the customer to perfectly anticipate the utility experienced after the purchase. Second, an increase in the number of prototypes provides the customer with more options to choose from, and thus with a higher expected design quality.

By testing or examining the prototype, the customer observes the utility she would realize from the final product if it were built to the corresponding specifications. Let $u_n$ denote the realized utility of the $n$th prototype. This utility is not observable to the customizing producer. We assume that $u_n$ is drawn from a distribution function $F_n(\cdot)$ with finite mean and variance. The fact that the utilities are drawn from a distribution function $F_n(\cdot)$ reflects that there exists uncertainty about the outcome of any given prototyping trial. This uncertainty includes the customer's uncertainty about her own preferences and uncertainty about the producer's ability to meet the specific needs of a given customer.

An important element in our model is the learning mechanism associated with the prototyping process. It determines how $F_n(\cdot)$ changes from one prototype to the next. We contrast two extreme cases, an unstructured design space and a structured one-dimensional design space. If the design space is unstructured and the solution landscape exhibits multiple local optima, prototyping is likely to follow a trial-and-error process (Simon 1969). The observation of the $n$th prototype does not provide any guidance as to how to choose the specifications for the $(n+1)$st prototype, thus $F_n(\cdot) = F_{n+1}(\cdot) = F(\cdot)$. We assume $F(\cdot)$ to be common knowledge. The design space of "all contemporary designed houses" represents an unstructured problem. In unstructured design spaces, even relatively minor modifications may make a significant aesthetic difference, as is typical for holistic designs (Ulrich and Ellison 1999). Other examples of unstructured solution spaces include interior design, portraits, and photography. We study the unstructured design space in §5.

In the other extreme case, the design space has a one-dimensional structure with a unique "best specification." Learning takes the form of a search for an unknown specification parameter $\xi$. For example, in designing the length of a customized golf club, the customer can, after trying out a prototype, clearly indicate the direction toward the true solution ("make it longer"). Thus, the expected utility of a prototype increases from iteration to iteration ($E[u_{n+1}] > E[u_n]$, hence $F_{n+1}(x) < F_n(x)$) as the prototypes approach the best specification. We study this case in §6. In addition to these two learning mechanisms, many other forms of learning exist, and many—if not most—design problems are somewhere between the two extreme cases we study.

Prototype costs are incurred by the customizing producer as well as by the customer. The customizing producer pays a cost $c_t$ per prototype for labor and material, which we assume to be constant over subsequent trials. We assume that investments in prototyping are idiosyncratic for the customer they are built for, i.e., a customizing producer cannot "reuse" a prototype he built for a previous customer. The customer considers two types of costs. First, she must invest time and effort in testing and waiting for the prototype, represented by a disutility $b$. Second, the producer may charge the customer a design fee per prototype built. In the most general form, the fee is some increasing function $T(N)$, where $N$ is the number of prototypes actually built. At the end of the collaborative prototyping process, the customer will compare the utility of the best prototype she has seen so far with the price of the final product. Let $p$ denote the price for this final product and assume that $p$ is independent of the design solution chosen. The customer will purchase the product from the customizing producer if the best prototype she has seen so far, net of the purchase price $p$, exceeds her reservation utility $u_0$.

**The Customer's Perspective**

It is an important feature of our model that the customer does not commit to the number of prototypes ex ante, but keeps the flexibility of making the stopping decision conditional on the prototypes realized so far. An ex ante commitment would eliminate the learning benefit from subsequent prototypes. The collaborative prototyping process would reduce to one single "wave" of prototypes built in parallel (Dahan and Mendelson 2001). A flexible stopping decision corresponds to a search model, similar to the model presented by Weitzman (1979). At the beginning of the prototyping process and on the completion of each prototype, the customer decides whether or not to request an additional trial. She compares the expected benefits of an additional prototype number $n$ with its associated costs $t_n = b + T(n) - T(n-1)$. If she stops, she can keep the utility of the best prototype she has seen so far, $z$. If she continues to test, she must pay the cost $t_n$, but she gets a potentially more valuable prototype, which has an expected utility as defined by the integral in Equation (1). Thus, using dynamic programming, we can write the customer's expected utility as a Bellmann equation with state space $(z, n)$:

$$\Psi(z, n) = \text{Max}\left\{z, -t_n + \Psi(z, n+1)F_n(z) + \int_z^\infty \Psi(\xi, n+1)\, dF_n(\xi)\right\}. \qquad (1)$$

Theorem 1. *There is a unique threshold $z_n^*$ such that it is optimal for the customer to stop the search if $x \geq z_n^*$, and to continue otherwise.*

Proof. First, we show that the value function $\Psi(z, n)$ is increasing in $z$. From (1), $\Psi'(z, n) = 1$ when stopping is chosen, and $\Psi'(z, n) = \Psi'(z, n+1) \cdot F_n(z)$ when continuation is chosen. Iterating backward establishes that $\Psi(z, n)$ is increasing in $z$.

A unique threshold is implied if $\Psi(z, n)$ grows more slowly in $z$ in the domain of continuation than in the stopping domain (in which the slope of $\Psi(z, n)$ is 1). In the continuation domain, $\Psi'(z, n) = \Psi'(z, n+1) \cdot F_n(z)$, which becomes $F_n(z)$ if the search stops after the next stage and $\Psi'(z, n+2) F_{n+1}(z) F_n(z)$ if it continues. Iterating this over a large number $M$ of stages yields $\Psi'(z, n) = \Psi'(z, n+M) \prod_{i=0}^{M-1} F_{n+i}(z)$ (if continuation is chosen over all $M$ stages), which converges to 0, or $\Psi'(z, n) \leq F_n(z)$ if the search is stopped anywhere. Thus, the slope is always larger in the stopping domain, which implies a unique threshold (which may be infinite). □

The existence of a threshold policy implies that Equation (1) characterizes a stopping problem that uniquely specifies the expected number of prototyping rounds, $N$. Let $z_N$ be the expected utility of the best prototype the customer has seen at the time she ends the prototyping process. Observe that $N$ depends on both the design space characterized by $F_n(\cdot)$, as well as on the prices of prototypes ($T_N$) and product ($p$).

The customer orders the first prototype only if her expected utility of the customized product, $\Psi(u_0, 1)$, exceeds her reservation utility $u_0$. When stopping, the customer faces two alternatives. First, she can choose the best prototype encountered so far, offering a utility of $u(N)$ exceeding the threshold $z_N$. This is compared to a price of $p$, since the investment $T(N) + Nb$ in prototypes is sunk at this point. Her total utility is $u(N) - p - T(N) - Nb$, assuming that the customer's utility function is additive in the utility associated with the product and its total price. Second, the customer can abandon the transaction (or if $N = 0$, never begin it) and consume the standard product with utility $u_0$. Under this option, she does not recoup any of the design fees or effort invested, resulting in a total utility of $u_0 - T(N) - Nb$. These two alternatives, together with the sequential prototyping process, are summarized in Figure 1.

**Customizing Producer's Perspective**

The customizing producer creates the design fee menu $T(\cdot)$ and the product price $p$. Let $c$, the cost of producing the customized product, be independent of the ultimately chosen specifications. This is often realistic because the specifications are a question not of "more or less" of something, but of the right configuration. The optimal prices are obtained from the producer's profit-maximization problem:

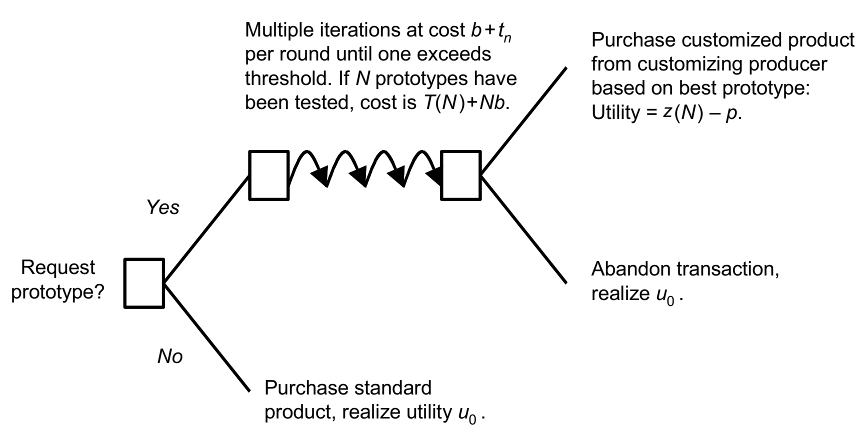
$$\underset{p,\,T(\cdot)}{\text{Maximize}}\; H(E[z_N - T(N) - Nb - p]) \cdot [p + E[T(N)] - E[N]c_t - c], \quad (2)$$

where $N$ is determined by (1). In (2), $H(E[z_N - T(N) - Nb - p])$ captures the probability that the customer is willing to enter prototyping in the first place because her reservation utility is below their ex ante expected utility. Recall that the expected number of prototypes requested by the customer, $E[N]$, is a function of the price menu $p$, $T(n)$. Thus, when solving (2), we first need to solve the customer problem (1) and then optimize over the producer's prices.

## 5. Unstructured Design Space

In an unstructured design space, the utility of subsequent trials is drawn from the same distribution function $F(\cdot)$. There is no learning from prototypes; their only benefit lies in the creation of a larger consideration set. In this setting, we will first analyze a situation where $F(\cdot)$ is known to both the customizing producer and the customer. We will then extend our analysis to a case of information asymmetry, where the customer has uncertainty about the capability of the customizing producer.

**Figure 1 Customer Decision Tree**



**Known Producer Capabilities**

Assume the customer has full information about $F(\cdot)$. However, full information does not mean that there is no uncertainty for the customer, since there still exists the "regular" uncertainty inherent in the collaborative prototyping process. Theorem 2 predicts that all prototypes cost the same; a linear pricing in the number of prototypes is thus optimal. This is comparable to an architect charging an hourly rate for a conceptual design. The intuition behind this result is that since the unstructured design space does not allow for learning between consecutive prototypes, each prototype has, conditional on the fact that it is built, the same expected utility.

Theorem 2. *Facing an unstructured search space, the customizing producer optimally sets a linear contract* $(t, p)$, *in which* $t$ *is the constant price per prototype, and* $p$ *the monopoly price of the product. The unique profit-maximizing prices are* $t = c_t$ *and* $p$ *solving*

$$H(z-p) = (p-c)h(z-p), \tag{3}$$

*where* $z$ *solves* $c_t + b = \int_z^\infty (\xi - z)\, dF(\xi)$, *provided that* $ph'(z-p) - 2h(z-p) < 0$.

Proof. First, we establish that the contract takes the form $p + Nt$. Because the prototypes' utility realizations have the same distribution $F(\cdot)$, Theorem 1 implies for any fixed product price $p$ that at trial $n$ the probability that the customer continues is $F(z_n)$. Thus, the supplier faces the following dynamic programming value function for the price of prototyping round $n$, given that the customer has not already stopped before:

$$V(t_n, n) = [1 - F(z_n)]p + F(z_n)[t_n - c_t + V(t_{n+1}, n+1)]. \tag{4}$$

This is independent of all previous prices $t_1, \dots, t_{n-1}$, and $V(n+1, t_{n+1})$ is independent of $t_n$. As the single period (direct) payoff and the transition depend only on the supplier's action $t_n$, the optimal solution is myopic (Heyman and Sobel 1984, p. 84). Moreover, setting $t_n = t$ for all $n$ fulfills the optimality equation and is, therefore, an optimal solution. Thus, the dynamic program is stationary, and the customer's value function (1) can be rewritten as a condition on the threshold $z$, which must solve

$$t + b = \int_z^\infty (\xi - z)\, dF(\xi). \tag{5}$$

In the customer's stationary problem, the expected number of prototypes becomes $E[N] = 1/(1 - F(z))$. The expected value of the final prototype (the one that the customer takes) is conditional on the fact that it must lie above $z$. Thus, the customer's expected utility, at the signing of the contract, becomes

$$\begin{aligned} E[\text{customer utility}] &= \frac{\int_z^\infty \xi\, dF(\xi) - b - t}{1 - F(z)} - p \\ &= z - p \quad \text{(from (5))}. \end{aligned} \tag{6}$$

Now, the producer's profit function simplifies to $E[\pi] = H(z-p)[p - c + (t - c_t)/(1 - F(z))]$. Take $z$ as a function of $t$, with $dz/dt = -1/(1 - F(z))$. Thus, the first derivatives of the profit function become

$$\begin{aligned} \frac{\partial E[\pi]}{\partial t} &= -\frac{h(z-p)}{1-F(z)}\left[\frac{t - c_t}{1 - F(z)} + p - c\right] \\ &\quad + \frac{H(z-p)}{1-F(z)}\left[1 - \frac{(t-c_t)f(z)}{[1-F(z)]^2}\right], \end{aligned} \tag{7}$$

$$\frac{\partial E[\pi]}{\partial p} = -\frac{h(z-p)}{1-F(z)}\left[\frac{t-c_t}{1-F(z)} + p - c\right] + H(z-p). \tag{8}$$

The two derivatives can only be equal (=0) if $t = c_t$. Then, the condition for $p$ becomes (8). The Hessian is negative definite if the solution to the first-order condition if $ph'(z-p) - 2h(z-p) < 0$ (this technical condition ensures uniqueness of $p$). □

Thus, the customizing producer sells prototypes at cost to maximize the probability that the customer signs the contract times the price extracted. Maximizing the surplus in the relationship is in the interest of the customizing producer since he can use his second decision variable, the product price $p$, to extract this surplus, except for an information rent.

The condition $ph'(z-p) - 2h(z-p) < 0$ is fulfilled for all distributions with a decreasing hazard rate (such as the exponential and the uniform). For more general distributions, we observe that this inequality if fulfilled as long as the customer's expected value from the custom-designed product, $(z - p)$, exceeds the mode of the no-purchase utility distribution, $H(\cdot)$. In other words, the customer's expected value has to be high enough to appeal to a sufficient number of customer types.

The result of Theorem 1 changes if the customizing producer cannot freely choose $p$, because of, for instance, regulation or competitive forces. If the product price is fixed exogeneously at $p = \bar{p}$, the role of prototyping changes. Specifically, if $\bar{p}$ is large, leaving the customizing producer with a significant profit margin, he is willing to subsidize his prototyping activity to increase customer utility and thus the probability of purchase. If, on the other hand, $\bar{p}$ is low, leaving the producer without an opportunity to obtain profits from the sales of the final product, he must sell the prototypes above cost.

Corollary. *If the product price is fixed at* $\bar{p}$, *prototypes may optimally be sold at a profit* (*if* $\bar{p}$ *is low, leaving little or no profit from the product*) *or at a loss* (*if* $\bar{p}$ *is high, thus selling the product is very profitable*).

**Unknown Producer Capabilities and Signaling**
Now, consider the case where the customizing producer's design capability is not observable to the customer ex ante. For simplicity, we consider only two producers: high capability (H) and low capability (L). The prototype outcome of producer H is stochastically higher than that of producer L, thus $F_H(\xi) < F_L(\xi)$. To focus on the producer's capability to create valuable designs, we assume that the cost structures are identical for both. Thus, the customer faces an adverse selection problem, and we investigate if producer H can credibly signal his higher quality. This can be modeled by a sequential game of incomplete information: The customizing producer moves first and announces the product and prototype prices. The customer moves second and decides whether or not to engage in the collaborative prototyping process. We are interested in an equilibrium in which producer H can signal his quality type, that is the two producer types employ different strategies. Consistent with research in economics (e.g., Gibbons 1992) and marketing (e.g., Moorthy and Srinivasan 1995), we call such an equilibrium a *separating equilibrium*.

In a separating equilibrium, producer L is identified as the low quality producer. Thus, based on Theorem 2, we know that he optimally sets $t_L = c_t$ and $p_L$ solving $H(z_L - p_L) = p_L h(z_L - p_L)$. Then, producer H solves the following problem in order to force a separating equilibrium.

$$\underset{t_H, p_H}{\text{Maximize}}\ E\pi_H = H(z_H - p_H)\left[\frac{t_H - c_t}{1 - F_H(z_H)} + p_H\right], \quad (9)$$

subject to the following four constraints:

$$t_H + b = \int_{z_H}^{\infty} (\xi - z_H)\, dF_H(\xi) \quad (10)$$

$$z_H - p_H \ge z_L - p_L \quad (11)$$

$$E\pi_H \ge H(z_L - p_L)p_L \quad (12)$$

$$H(z_L - p_L)p_L \ge H(z_H - p_H)\left[\frac{t_H - c_t}{1 - F_L(z_H)} + p_H\right]. \quad (13)$$

The first constraint (10) accounts for the customer's dynamic ordering choice. Constraint (11) ensures the customer's incentive compatibility in choosing H over to L. (12) discourages H from pretending to be L, and (13) discourages L from pretending to be H (the producers' incentive compatibility). Theorem 3 describes the separating equilibrium.

Theorem 3. *There exist two separating equilibria in which producer H differentiates himself by selling the prototypes below cost ($t_H < c_t$) and by charging a higher product price than producer L ($p_H > p_L$). In both, producer H's profit is producer L's monopoly profit.*

$$\textit{Equilibrium 1:}\quad p_H = p_L + z_H - z_L;\quad z_H + \frac{t_H - c_t}{1 - F_L(z_H)} = z_L, \quad (14)$$

$$\textit{Equilibrium 2:}\quad p_H = p_L + z_H - z_L;\quad z_H + \frac{t_H - c_t}{1 - F_H(z_H)} = z_L. \quad (15)$$

Proof. It is straightforward to show that $t_H = c_t$ is not an equilibrium, as (11) and (13) become incompatible: Either the customer wants to switch, or producer L wants to adopt H's price menu. Checking the constraints reveals that, in both equilibria, the second constraint is binding (the customer is indifferent about which producer to buy from). In addition, the last constraint is binding in the first equilibrium (producer L is indifferent about which price menu to adopt), and in equilibrium 2, the third constraint is binding (producer H is indifferent as to which menu to adopt). No other combination of binding constraints is possible without violating a constraint. □

Thus, the high-capability producer can signal his identity and win the business. He does this by subsidizing the prototypes (the exact level of subsidization differs somewhat between the two equilibria) and compensates the associated losses by charging a higher price for the end product. Since L's distribution of prototype outcomes is stochastically worse, he would need more prototypes to replicate the same product quality in the end. This makes it unprofitable for L to imitate H by subsidizing the prototypes.

Despite the ability of the high-quality producer to signal quality, he suffers from unknown capability and ends up with lower profits than in the case of known quality. Because customers differ only in their reservation utility, but not in their evaluation of the customized product itself, the high-capability producer has to pay a price for signaling his capability and thereby winning the business: His profit is competed down to the monopoly profit of the low-capability producer.

## 6. One-Dimensional Structured Design Space

Now, suppose the customized product can be described in a well-ordered specification space, with dimensions such as the size of a swimming pool or the shaft length of a golf club. For simplicity, we consider the specification space to be one dimensional. In contrast to the unstructured design space, there exists an "ideal point" that perfectly matches the customer's preferences. However, this point $\xi$ is unknown beforehand. It has a prior distribution function $F(\xi)$ with finite mean and variance, known to both parties. If the customized design hits this ideal point exactly, the customer experiences a known utility $U$. If the design specification of point $x$ deviates from the ideal point, the customer experiences a loss $L(\xi, x)$, which we assume to be quadratic.[5] Thus, the customer's realized utility from the $n$th prototype with design $x_n$ is $u_n = U - A(\xi - x_n)^2$.

**Known Capabilities**

Suppose the customer can, when trying out a prototype, make the judgment of "too small" or "too large," but not by how much. In other words, the customer cannot estimate the size of the design quality loss function—otherwise, the optimal specifications could be found in one step. Thus, prototypes serve to search an "ordered list" of design options, with subintervals of $[-W, W]$ serving as the items on the list. In this case, the binary search algorithm, cutting the interval in half at each step, is optimal (Baase 1988, pp. 38–42).

We assume that both parties have minimal information—that is, the customer's ideal point $F(\xi)$ is uniformly distributed over some interval $[-W, W]$. The assumption of a symmetric distribution is without loss of generality, since the space can always be calibrated to be symmetric around some anchor point.[6] As in the previous section, we assume that the customizing producer commits to a general nonlinear contract with a price of $T(N)$ for creating $N$ prototypes, and $p$ for the product.

Now, suppose testing has reduced the remaining interval to some $[x, y]$. This interval represents an expected design quality loss of $2A\int_x^{(y+x)/2}(\xi - x)^2\,d\xi = (A/12)(y-x)^2$. Thus, cutting the interval in half reduces the expected loss by a factor of four. Starting from the initial interval of width $2W$, the $n$th prototype reduces the design quality loss by

$$\Delta EL(n) = 4^{-n} W^2 A. \tag{16}$$

The residual design quality loss after $n$ prototypes is $EL(n) = 4^{-n}W^2A/3$. As before, define $t_n = T(n) - T(n-1)$ as the price for the $n$th prototype (net of the customer's search cost). The supplier must respect the customer's participation constraint. Her expected utility at the outset is obtained by subtracting the expected search cost and the residual quality loss from the ideal utility:

$$EU_{\text{cust.}} = U - p - Nb - \sum_{n=1}^{N} t_n - 4^{-N}\frac{W^2A}{3}. \tag{17}$$

The customer signs the initial contract only if $EU_{\text{cust.}} \geq u_0$. The producer has only a distribution $H(\cdot)$ about $u_0$, which we assume again to have a decreasing hazard rate $h(\cdot)$. This implies a probability of $H(EU_{\text{cust.}})$ that the customer signs, and thus the following optimization problem:

$$\underset{t_n\ \forall n,\, p,\, N}{\text{Maximize}}\ E[\pi_m] = H\left(U - p - Nb - \sum_{n=1}^{N} t_n - 4^{-N}\frac{W^2A}{3}\right) \cdot \left[p + \sum_{n=1}^{N} t_n - Nc_t\right],$$

subject to:

$$b + t_n \leq 4^{-n}W^2A \quad \forall n$$
$$\text{(customer's individual rationality);}$$
$$b + t_{N+1} > 4^{-(N+1)}W^2A$$
$$\text{(incentive for the customer to stop).}$$

The individual rationality constraint gives the customer the incentive to continue testing rather than buying the product with the current design quality, until the $(N+1)$st prototype which is priced so that the customer decides to stop.

Theorem 4. *The optimal number of prototypes is*

$$N^* = \frac{1}{2}\log_2\left[\frac{\ln 4}{3}\frac{W^2A}{c_t + b}\right].$$

*The total optimal price $P^* = p + \sum_{n=1}^{N} t_n$ is uniquely determined by*

$$H\left(U - P^* - N^*b - \frac{c_t + b}{\ln 4}\right) = h\left(U - P^* - N^*b - \frac{c_t + b}{\ln 4}\right)(P^* - N^*c_t). \tag{18}$$

*It makes no difference how $P^*$ is split among prototypes and the final product as long as $t_n$ fulfills the customer's individual rationality constraint, $b + t_n \leq 4^{-n}W^2A\ \forall n < N^*$.*

Proof. Observe that $p + \sum_{n=1}^{N} t_n$ appears in the objective function only as a sum. Thus, we have only the two decision variables, $P$ and $N$. The first derivatives become

$$\frac{\partial E[\pi_m]}{\partial P} = H(EU_{\text{cust.}}) - h(EU_{\text{cust.}})(P - Nc_t),$$
$$\frac{\partial E[\pi_m]}{\partial N} = -c_tH(EU_{\text{cust.}}) + h(EU_{\text{cust.}}) \cdot (P - Nc_t)\left(\frac{W^2A\ln 4}{3(4^N)} - b\right).$$

Both derivatives can only be zero if $N = N^*$. Solving the second first-order condition (FOC) and verifying

[5] The assumption of a quadratic loss function is common. It is also the local Taylor expansion of a general loss function. All our results remain valid for more general loss functions of the shape $L(\xi, x) = (\xi - x)^a$ for $a > 1$ (the factor 4 becomes $2^a$). The results also remain similar for multidimensional solution spaces as long as regular hill-climbing algorithms can identify the optimal solution (i.e., a search direction can be specified).

[6] Suppose the customer's ideal specification has a general prior distribution $F$. The binary search proceeds by setting a test at $x_1 = F^{-1}(0.5)$, updating the distribution to $2F(\cdot)$, setting a test again at the median $x_2 = F^{-1}(0.25)$ or 0.75, etc. When the resulting interval has become small, we can take $F$ as approximately linear, and prices are set as in Theorem 3.

that the Hessian is negative definite in the FOC (given that $h(\cdot) \leq 0$) yields (18). □

It is intuitive that the more expensive the production of a prototype $c_t$, and the higher the customer's impatience $b$, the fewer iterations, $N^*$, the supplier will allow. If $(c_t + b) \geq (\ln 4/12) W^2 A$, $N^*$ in Theorem 4 falls below 1, no testing can be economically offered. A higher design quality loss $W^2 A$ (a wider search interval or a higher customer sensitivity to deviations), on the other hand, increases the optimal number of prototypes.

What is fundamentally different from Theorem 2 is the fact that the total price $P$ can be arbitrarily split among prototypes and the final product (as long as the prototypes do not cost more, including the customer's delay, than their value $4^{-n} W^2 A$). It is irrelevant to even speak of the profitability of the prototypes versus the final product; only the total package matters. The reason for this is that once the customer has signed the contract, the product quality becomes predictable: Learning allows the producer not only to anticipate (in expectation), but to achieve exactly a desired design quality loss reduction (albeit with a stochastic number of trials).

**Unknown Producer Capabilities and Signaling**

Now, consider two producer types, H (high capability) and L (low capability).[7] The customer's utility from the perfect product is given by $U$; it is not influenced by the producer. What differentiates producer H from producer L is the speed with which he can find this optimal point through prototyping. Producer L requires more prototypes to please the customer, incurring additional costs for the producer and extra charges and effort for the customer. Based on experience or interviews, producer H is able to restrict prototyping to a smaller subinterval of the overall space, $W_H \subset W$, than producer L, who needs $W_L \supset W_H$. Thus, the ability to rule out suboptimal designs enables producer H to use fewer prototypes, in expectation, than producer L.

Again, the customer faces an adverse selection problem, which raises the question of whether producer H can credibly signal his higher quality in a separating equilibrium. In equilibrium, the low-quality supplier sets his optimal strategy by Theorem 4 to

$$N_L = \frac{1}{2} \log_2 \left( \frac{\ln 4}{3} \frac{A W_L^2}{c_t + b} \right).$$

[7] The H signifying the high-quality producer will appear in subscripts in the formulas and not be confused with the customer distribution H(·).

Thus, the customer's residual utility shortfall is $(c_t + b)/\ln 4$ and by (18), the prices $p_L$ and $t_{iL}$ are determined by

$$H\left(U - P_L - bN_L - \frac{c_t + b}{\ln 4}\right) = h\left(U - P_L - bN_L - \frac{c_t + b}{\ln 4}\right)(P_L - N_L c_t),$$

where again $P_L = p_L + \sum_{i=1}^{N_L} t_{iL}$, and $P_H$ is defined analogously. We call producer L's profit $\pi_L$. Similarly, we write producer H's expected profit as

$$\max_{P_H,\, N_H} H\left(U - P_H - bN_H - \frac{1}{3}\frac{W_H^2 A}{4^{N_H}}\right)[P_H - N_H c_t],$$

subject to the following constraints. First, producer H needs to induce the customer to choose the desired stopping point $N_H$:

$$b + t_{nH} \leq \frac{W_H^2 A}{4^{N_H}}; \quad n = 1, .., N_H \quad \text{and}$$
$$b + t_{N_H H} > \frac{W_H^2 A}{4^{N_H + 1}}. \tag{19}$$

Second, producer H's incentive compatibility requires that he does not want to imitate producer L. Let $EU_H = U - P_H - bN_H - \frac{1}{3}(W_H^2 A / 4^{N_H})$, and $EU_L = U - P_L - bN_L - (c_t + b)/\ln 4$.

$$H(EU_H)(P_H - N_H c_t) \geq H(EU_L)\left(p_L + \sum_{i=1}^{N_H} t_{iL} - N_H c_t\right). \tag{20}$$

Third, producer L's incentive compatibility requires:

$$H(EU_L)(P_L - N_L c_t) \geq H(EU_H)\left(p_H + \sum_{i=1}^{N_L} t_{iH} - N_L c_t\right). \tag{21}$$

Finally, the customer's incentive compatibility (she prefers to buy from producer H) has to be fulfilled independent of the location of her ideal design in the overall solution space:

$$EU_H \geq EU_L. \tag{22}$$

We now characterize the separating equilibrium. To keep the analysis tractable, we assume that both producers charge $t_n = 0$ for the first $N_L$ and $N_H$, respectively, prototypes, and that producer H cannot offer a product at the end that has a lower quality than the product offered by producer L (i.e., the residual design loss cannot exceed $(c_t + b)/\ln 4$).

Theorem 5. *The unique separating equilibrium is given by*

$$N_H = \frac{1}{2}\log_2\left(\frac{\ln 4}{3}\frac{AW_H^2}{c_t+b}\right) < N_L,$$

*and* $P_H = \pi_L + N_L c_t < P_L$. *Thus, producer H offers his optimal number of prototypes but charges less for the final product than producer L. Producer H obtains a higher profit than producer L only because of lower costs*: $\pi_H = \pi_L + (N_L - N_H)c_t$.

Proof. Suppose producer H chose $P_H$ and $N_H$ as if optimizing his profit in isolation. This would obey Constraints (20) and (22), but violate (21): Producer L would find it attractive to mimic producer H. Thus, (21) must be binding. Substituting it into the objective function gives $\pi_H = \pi_L(P_H - N_H c_t)/(P_H - N_L c_t)$. The first derivatives are $\partial\pi_H/\partial P_H = \pi_L c_t(N_H - N_L)/(P_H - N_L c_t)^2$ and $\partial\pi_H/\partial N_H = -\pi_L c_t/(P_H - N_L c_t)$. The latter is negative, and moreover, the Hessian is indefinite, implying that the solutions are extreme. Thus,

$$N_H = \frac{1}{2}\log_2\left(\frac{\ln 4}{3}\frac{AW_H^2}{c_t+b}\right)$$

in order to not exceed the design quality loss $(c_t + b)/\ln 4$. This implies that $\partial\pi_H/\partial P_H$ is also negative, and the minimum possible value of $P_H$ is determined by Constraint (21): $H(EU_H) = \pi_L/(P_H - N_L c_t)$, the left-hand side of which cannot exceed the value 1. This uniquely determines the equilibrium, and it can easily be checked that the other two constraints are fulfilled. □

Producer H must compromise compared to his optimal menu in isolation, but still retains a higher profit than producer L because he needs fewer trials to achieve the same design quality at the end. The lower product price makes it unprofitable for producer L to mimic producer H—because he incurs higher prototyping costs to achieve the same design quality, he cannot compromise on the product price.

## 7. Extension: Heterogeneous Quality Tastes

In Theorem 3, we saw a separating equilibrium, in which the high-quality producer's profit was competed down to that of the low-quality competitor. Customer homogeneity in evaluation of product quality prevented effective differentiation. We now extend our results to the case of an unstructured design space and a market in which customers are differentiated not only by their no-purchase utility, but also by their taste for quality.

### Known Producer Capabilities

Consider a population of customers differentiated by their respective *quality taste* parameter $\theta$. When customer $\theta$ obtains a product of quality $x$, she enjoys a utility of $\theta x$. In other words, the same product is worth more to the high-quality taste customer (see, e.g., Weber 2002). If the producer can identify customers (recognize their $\theta$) and set a price for each, both Theorem 1 and Theorem 2 still hold: The customer decides whether to continue testing with a threshold policy, and the producer sets a linear pricing scheme for the prototypes (the reader can easily check this by inserting $\theta$ into the proofs of the theorems). Now, customer $\theta$ compares the following when deciding about the next trial (the analog to (5)):

$$t + b = \int_z^\infty \theta(\xi - z)\,dF(\xi), \tag{23}$$

and the customer's expected utility becomes $\theta z(\theta, F, t) - p$ (the analog of (6)). The customer's threshold depends on three variables, and it can easily be verified that

$$\frac{\partial z}{\partial\theta} = \frac{\int_z^\infty(\xi - z)\,dF(\xi)}{1 - F(z(\theta, F, t))}; \qquad \frac{\partial z}{\partial t} = \frac{-1/\theta}{1 - F(z(\theta, F, t))}. \tag{24}$$

Now, suppose the producer cannot identify the type of the customer. For simplicity, consider the case of two customers—one who has a high-value taste, $\theta_H$, and one who has a lower taste, $\theta_L$. It is important for the producer to find a pricing scheme that allows him to separate the customers in order to be able to extract their surplus. Theorem 6 shows that this cannot be done with a simple two-part tariff (fixed price plus linear prototype price).

Theorem 6. *There is no linear two-part tariff pricing scheme* $(t_H, p_H)$, $(t_L, p_L)$, *with which the producer can separate the two customers.*

Proof. First, suppose the producer serves only one customer with quality taste $\theta$ and reservation utility 0. If he can identify this customer, the optimal prototype price is $t = c_t$, and the optimal product price is $p = \theta z(\theta, F, t)$. The higher the $\theta$, the higher the producer's optimal product price and total profit. To see this, consider the producer's objective function:

$$\underset{t,p}{\text{Maximize}}\ \ E\pi = \frac{t - c_t}{1 - F(z(\theta, F, t))} + p,$$
$$\text{subject to:}\ \ \theta z(\theta, F, t) \geq 0.$$

The constraint must be binding, and after substituting in, the first-order condition with respect to $t$ becomes $(t - c_t)dF(z(\theta, F, t))/[1 - F(z(\theta, F, t))]^3 = 0$. $t = c_t$ follows as in Theorem 2.

We now turn to the producer serving two different customers. Suppose the producer charges a linear two-part tariff. His objective function is

$$\text{Maximize } E\pi = \frac{t_H - c_t}{1 - F(z(\theta_H, F, t_H))} + \frac{t_L - c_t}{1 - F(z(\theta_L, F, t_L))} + p_H + p_L, \quad (25)$$

subject to:

$$\theta_H z(\theta_H, F, t_H) \geq p_H$$
(customer H's participation),

$$\theta_L z(\theta_L, F, t_L) \geq p_L,$$
(customer L's participation),

$$\theta_H z(\theta_H, F, t_H) - p_H \geq \theta_H z(\theta_H, F, t_L) - p_L$$
(customer H's incentive compatibility),

$$\theta_L z(\theta_L, F, t_L) - p_L \geq \theta_L z(\theta_L, F, t_H) - p_H,$$
(customer L's incentive compatibility). (26)

If the producer simply charges the optimal prices for each customer in isolation, the profit is optimal, but customer H's incentive compatibility is violated; she would prefer to present herself as a customer L. Therefore, the producer must lower either the product price $p_H$ or the prototype price $t_L$. Suppose, first, that the producer lowers $p_H$ until customer H's incentive compatibility becomes binding. But this implies $p_H = p_L$ (check the constraint), and thus the two-part tariff collapses.

Now, suppose the producer reduces the prototype price to set $t_H < c_t$. This still requires customer H's incentive compatibility to be binding, which determines $p_H$. Now, by how much should the prototype price be reduced? The one-dimensional objective function for $t_H$ becomes the same as if there were only one customer (see the start of the proof). Thus, the optimal solution is $t_H = c_t$, which makes both incentive compatibility constraints binding, and again collapses the two-part tariff to the price being the same for both customers. In summary, no two-part tariff can distinguish the customers. □

Although the customizing producer cannot execute vertical price differentiation with a linear two-part tariff, he may still be able to find a more complex scheme that accomplishes differentiation. It is intractable to evaluate more complex schemes analytically. The following numerical example illustrates the nature of such pricing schemes. Take a customizing producer whose prototypes have a value that is exponentially distributed with expectation 0.5 ($\lambda = 2$). From a prototype of value $\xi$, the customers experience a product utility $U(\xi) = \theta\xi$, and their quality taste parameters are $\theta_H = 5$ and $\theta_L = 2$. Prototype costs are $c_t = b = 0.2$ for the producer's and the customer's efforts.

The following pricing menu achieves differentiation: The customer can either pay a low product price of $p_L = 0.6$ and get one prototype at cost 0.2 (every additional prototype costs $M$, a high number), or she can pay a product price of $p_H = 3$ and get up to 20 trials at cost (and at $M$ thereafter). Customer L's reservation constraint and customer H's incentive compatibility constraints are binding, and the producer makes a profit of 3.6. Customer H tests, on average, 6.2 times with a stopping threshold of $z = 0.916$. The average utility of her last prototype is 7.1, and her net utility is 1.7.

This contract is optimal in the class of *stepwise linear prototype prices* (for the given parameters). For example, allowing customer L two prototypes at cost would make it impossible to maintain customer H's incentive compatibility. A general analytic characterization of this contract class is intractable, because the customers' trial thresholds $z$ change over the course of testing.

**Unknown Producer Capabilities and Signaling**

Now, we again consider two producers, L and H, who compete for the two customers, H and L. As in Theorem 3, the producers differ in their prototyping capabilities, expressed by $F_H(\xi) < F_L(\xi)$ for all $\xi$. The difference from Theorem 3 is that the customers are now heterogeneous in terms of their evaluation of the quality of the customized product. To simplify the algebra, we normalize the low-quality taste $\theta_L = 1$ (without loss of generality). Theorem 7 shows that there may exist a separating equilibrium in which producer H serves customer H and makes a higher profit, and producer L serves customer L. Producer L sets his prices optimally (given that he is identified anyway), thus $t_L = c_t$ and $p_L = \theta z(\theta_L, F_L, c_t)$, and customer L has expected utility 0 (i.e., her participation constraint is binding). Producer H's optimization problem is

$$\underset{t_H, p_H}{\text{Maximize}}\ E\pi_H = \frac{t_H - c_t}{1 - F_H(z(\theta_H, F_H, t_H))} + p_H \quad (27)$$

subject to:

$$\theta_H z(\theta_H, F_H, t_H) \geq p_H$$
(customer H's participation), (28)

$$\theta_H[z(\theta_H, F_H, t_H) - z(\theta_H, F_L, c_t)] \geq p_H - p_L$$
(customer H's incentive compatibility), (29)

$$0 \geq \theta_L z(\theta_L, F_H, t_H) - p_H$$
(customer L's incentive compatibility), (30)

$$\frac{t_H - c_t}{1 - F_H[z(\theta_H, F_H, t_H)]} + p_H \geq p_L$$
(producer H's incentive compatibility), (31)

$$p_L \geq \frac{t_H - c_t}{1 - F_L[z(\theta_H, F_H, t_H)]} + p_H$$
(producer L's incentive compatibility). (32)

Theorem 7. *Suppose a producer H with capability $F_H$ and a producer L with capability $F_L$ ($F_L(\xi) > F_H(\xi)$ for all $\xi$) serve two customers of quality tastes $\theta_H > \theta_L = 1$. There are parameter values for which there exists a separating equilibrium, in which Constraint* (29) *and either Constraint* (30) *or* (32) *are binding. Producer H makes a higher profit than producer L.*

Proof. Suppose again that producer H is able to serve customer H with his optimal profit (as in the proof of Theorem 6), as if he were alone. Checking the constraints, we find that they are all fulfilled except customer H's incentive Compatibility (29). Customer H wants to switch to producer L, because she is reduced to her reservation utility when served by producer H, while she gets additional value (above customer L) from producer L because she more highly values the quality. Thus, producer H has to give in a bit, in order to prevent the lucrative customer from switching. The minimal amount of giving in is to make customer H indifferent, by setting (29) binding. Checking the other constraints shows that (31) binding produces a contradiction to (32), but either (30) or (32) may be binding, depending on function values. In all cases, checking the objective function shows a higher profit for producer H. Numerical examples show that an equilibrium exists for some, but not all, parameter constellations. □

These results show that customer heterogeneity in the valuation of design (not only in their reservation utility) allows differentiation by producer H, along with a higher profit than producer L. This differentiation goes along with a vertical differentiation—producer H serves the quality-conscious end of the market, and producer L serves the low end of the market. Nothing can be said in general about the pricing of the prototypes—they may be priced above or at cost, depending on the functional parameters of the problem.

## 8. Conclusion

In this article, we have developed an economic intuition about how collaborative prototyping proceeds: how many prototypes should be built, who should pay for them, and how the prototypes should be priced relative to their costs. We have developed a model of a search in the design space using prototypes. Under quite general conditions, the customer chooses a design quality threshold as a stopping point (Theorem 1) and continues prototype trials until this threshold is reached. We have investigated two basic learning mechanisms. In an unstructured design space, the customer's utility is driven by the *n*th order statistic of the associated utility distribution. Since the conditional expectation of this distribution is constant across rounds, each additional prototype offers the same benefit and must have the same price (linear contract). The monopolist prices prototypes at cost and derives his profit from the product price (Theorem 2), which maximizes the total surplus as well as the producer's share. This contract reflects the practice of an architect charging customers on a cost-plus basis for the initial design part, the highest uncertainty phase of a project (Franklin 2000). If the design space is structured, the nature and value of the design end point are known (although there is stochastic variation in the number of trials it may take to find it). Both producer and customer care only about the price of the total package, which allows the producer to freely shift revenues between the prototypes and the final product (Theorem 4). This corresponds to a fixed-price contract. Using a fixed price for projects that are predictable in outcome is consistent with architectural practice (Franklin 2000).

We also investigate the effect of information structure, particularly adverse selection. If the customer is uncertain about the producer's ability to create appealing prototypes, a high-quality producer will use the prototype price to signal his type (Theorem 3). By providing prototypes below cost and charging a premium for the final product, he makes imitation unprofitable for a low-quality competitor, who would need more subsidized prototypes to achieve a comparable design outcome. Since the customer is free to decide whether or not to order the final product, choosing a high product price is only possible for a producer who is confident that he will be able to please the customer in the collaborative design process. This holds for both design space structures (Theorems 3 and 5).

Finally, we extend our results for the unstructured design space by considering customer heterogeneity in valuation of design. In this setting, the producer needs a nonlinear price menu to induce customers to reveal their quality preferences, and thus to vertically differentiate between them. In the optimal price menu, the low-quality customer chooses a menu in which she buys the first prototypes inexpensively, but is deterred from further trials by a steep premium for subsequent prototypes. The high-quality customer, in contrast, is allowed to perform many trials at cost. The additional trials create a substantial value for the high-value customer who is therefore willing to pay a much higher product price (Theorem 6). Table 1 summarizes our results.

**Table 1 Summary of Main Results**

| Design space | Information structure | Main result |
|---|---|---|
| Unstructured | Known producer capability | Linear contract; prototypes priced at cost. |
| Unstructured | Product price fixed by the market | If market price is low (high), prototypes are priced with a profit (loss). |
| Unstructured | Unknown producer capability | The high-capability designer sells prototypes below cost to signal capability. |
| Structured | Known producer capability | Prototypes and products are sold as one overall customization service. |
| Structured | Unknown producer capability | High-capability producer charges less for the final product. |
| Unstructured | Heterogeneous tastes | Nonlinear pricing required. |

Customer-need elicitation in product customization has been underresearched, although it is important in a number of industries. Our model takes an important first step into this new field. Additional research is needed to fully explore this area. First, we have focused on a customer-market setting, in which the producer determines the conditions of the contract. Of course, there exist numerous cases, especially in industrial-market settings, in which the customer has the power to determine the conditions of the contract. Our model takes a first step toward extending research in defense contracting, which has made empirical observations similar to our findings related to the usage of cost-plus and fixed-price contracts, yet has not considered the actual design process in detail (Anton and Yao 1990). Second, examining the effect of competition from another customizing producer promises to be another avenue for future research. This is interesting, both in the case of the customizing producer choosing prices (e.g., competing residential architects) and in the case of the customer choosing price and contract (e.g., a customer who invites several architects to submit prototypes in a procurement auction). Third, empirical and experimental research is needed to estimate the effectiveness of existing forms of prototyping. As discussed in Dahan and Hauser (2002), new low-fidelity prototype technologies, which allow customers to configure and create product specifications, are offered via the Internet. Little is known about the effectiveness of these processes in mimicking the collaborative process discussed in this article.

New-era product customization has been compared to the skills and flexibility of craftsmen creating products before the Industrial Revolution. However, while new technologies may now be able to replicate the process of turning a set of product specifications into a custom-built product, they still fail to match the extensive interaction a master craftsman had to elicit what his customers *really* wanted.

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