

***Spackling: Smoothing Make-to-Order Production of Custom Products with  
Make-to-Stock Production of Standard Items***

Kyle Cattani  
The Kenan-Flagler Business School  
UNC Chapel Hill  
Chapel Hill, NC 27599-3490  
(919) 962-3273 kyle\_cattani@unc.edu

Ely Dahan  
Anderson School at UCLA  
110 Westwood Plaza, B-514  
Los Angeles, CA 90095-1481  
(310) 206-4170 edahan@ucla.edu

Glen Schmidt  
The McDonough School of Business  
Georgetown University  
Washington, DC 20057  
(202) 687-4486 schmidtg@msb.edu

July, 2003

## Abstract

Consider a firm that makes custom products requiring flexible production resources and also produces standard items that are manufacturable in either an efficient or a flexible facility. We evaluate two options: produce the standard items in an efficient plant and make the custom variants in a flexible plant, or make everything in one flexible facility using a strategy we call *spackling*. With *spackling*, the firm first manufactures custom products as demanded each period, and then fills in, or *spackles*, the production schedule with make-to-stock output of standard products to restock inventory. Management can readily see the unit cost savings offered by the focus strategy, but may less readily note the lower amortized fixed cost that *spackling* yields by making better use of capacity. We evaluate this trade-off from a joint marketing / operations perspective. Near-optimality is achieved when operations sets capacity and marketing independently but cooperatively sets prices. In this case, under our logit-based assumptions, all products get the same absolute dollar markup. We illustrate our framework with data from a messenger bag manufacturer.

# ***Spackling: Smoothing Make-to-Order Production of Custom Products with Make-to-Stock Output of Standard Items***

## **1. Introduction**

Timbuk2, a San Francisco manufacturer of messenger bags, recently introduced an Internet site where customers configure and order a customized laptop bag direct from the manufacturer. This direct channel takes advantage of Timbuk2's flexible manufacturing capabilities and complements the firm's traditional retail channel where pre-configured (standard) bags are sold. In particular, Timbuk2's flexible San Francisco factory can produce rapidly a bag of any configuration and deliver it within days.

Timbuk2 considered producing the standard make-to-stock (MTS) bags offshore, in order to reduce production costs. While the off-shore capacity is less expensive, it is unable to fill demand for the customized make-to-order (MTO) bags in a timely manner. (We use the term MTS to refer to production in anticipation of demand, with output being added to inventory, and MTO to indicate that production fills specific end-customer orders after they are received.) Senior management wondered what overall effect a shift to off-shore production of standard bags would have on manufacturing cost and demand for both the standard bags and the custom units produced domestically. Ultimately, of course, Timbuk2 was concerned with profitability.

This paper developed as we sought to analyze Timbuk2's situation. Should it utilize efficient (off-shore) capacity? Or, should it continue to produce standard off-the-shelf MTS bags using the flexible San Francisco plant, thereby establishing a mix of MTO and MTS in the same factory<sup>1</sup>? Under the latter option it could implement a strategy we call *spackling*<sup>2</sup>, where it first makes custom MTO bags as demanded each period, and then fills in, or spackles, the production schedule with standard MTS products, to restock inventory. What are the optimal prices in the two channels? How many customers are expected to buy standard products through the traditional retail channel, and how many are expected to buy customized bags via the Internet?

---

<sup>1</sup> At Timbuk2, standard and custom products are associated with retail stores and internet sales, respectively. In reality, the distribution channel and product type need not be linked – it could also sell standard bags directly to customers and customized bags through retailers. The analysis would be similar.

<sup>2</sup> The American Heritage<sup>®</sup> Dictionary of the English Language: Fourth Edition 2000 defines spackle as “A trademark used for a ... paste designed to fill cracks and holes in plaster before painting or papering. This trademark often occurs in lowercase and as a verb...”

These questions are not unique to Timbuk2 and are strategic in nature. For example, senior managers at automobile manufacturers have been talking for a decade or more about the *five-day car*, where a large portion of cars would be produced only after orders are received, shipping within five days of the order. How might automobile manufacturers deal with day-to-day demand uncertainty if they implemented the five-day concept? Would they continue to produce cars for stocking at dealers in the same plant where they make the five-day cars? Or would they use separate facilities dedicated to the different production types? How much capacity would they need? How would they price the five-day car versus cars to be sold off-the-lot?

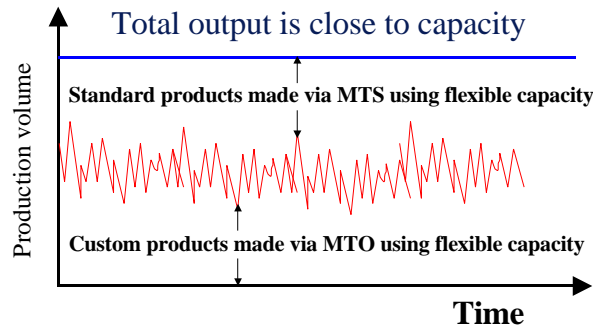
As another example, consider questions of keen interest to senior management at Dell Computer. Dell focuses on a single direct channel and must determine the optimal pricing and production strategies for segments such as mass customized desktop personal computers. Should Dell use off-shore production for long-lead time customers along with local capacity for short lead-time customers, or should it use local capacity for both? How should Dell price in the different segments, how much demand should it expect, and how variable will demand be?

To address these questions, we consider an operations decision that involves two types of resources: efficient capacity and flexible capacity. We define a *focused strategy* as one that uses both types of capacity: in the efficient plant it focuses on making standard items via MTS, while in the flexible facility it focuses on producing custom items as MTO. In contrast, a *spackling* strategy involves only flexible capacity (efficient capacity is set at zero). With spackling, the firm's first priority in any given period is to produce custom products via MTO. However, order patterns for custom products are bumpy (uncertain), yielding an undesirable production profile compared to smooth schedules that would allow for higher capacity utilization. Thus the firm uses the same (flexible) production capacity to produce standard products in MTS fashion, to "fill in the holes" in the production schedule, as shown in Figure 1. The result is that MTO production closely tracks demand for customized products, while MTS output tracks demand for standard products, not over the short-run but rather over the longer-run, with some inventory temporarily built-up. In the spackling case, total production output is relatively smooth, or spackled, allowing for higher utilization of the flexible capacity and improved efficiency.

Which strategy should the firm adopt? Management can readily calculate the direct unit cost savings the focus strategy offers via efficient production (reduced cost times units

produced). But the counter-benefits that spackling yields by making better use of capacity, resulting in lower amortized fixed cost per unit, are much less easily determined. Effectively, better capacity utilization arises as the fixed costs of flexible capacity are amortized over greater average volume produced under spackling.

**Figure 1 Spackling Yields Steady Total Output Stream From One Production Facility**



We model these important management decisions from a joint marketing / operations perspective. Prices set by marketing impact product demand expectations and variances, which in turn affect the capacities set by operations. On the demand (i.e., marketing) side, we assume the firm sells two main types of products, standard MTS and custom MTO. Customer choice follows the logit representative customer framework as described in Ben-Akiva and Lerman (1985). On the supply (i.e., the operations) side, we allow the efficient and flexible capacities to have different fixed and variable per-unit costs, and incorporate underage and overage costs into the model. We run numerical experiments over a wide range of conditions to examine how seven different parameters affect the decision of whether to choose a strategy of focus or spackling.

To gain further managerial insights, we derive analytical solutions using a near-optimal approach in which marketing separately optimizes prices, and operations separately optimizes capacities. In setting prices, marketing uses as inputs the costs implied by the capacities set by operations, and in setting capacities, operations uses as inputs the demand distributions implied by the prices set by marketing. Marketing and operations iteratively make decisions until the groups converge on a solution. We call this a cooperative tatonnement (CT) process. In our experiments, the solutions found for spackling via the CT process are virtually identical to results under the joint solution, while under the focus strategy, the CT process sacrifices only 0.09% profit on average – thus we call CT a near-optimal approach. This leads to a key managerial

insight. Marketing and operations may not necessarily need to be fully integrated within the firm for this set of decisions; they may be able to reach a near-optimal outcome by acting independently, but cooperatively.

The analytical solutions for prices and capacities that stem from the near-optimal CT process yield further managerial insights. For example, similar to Anderson, et al. (1992), we find the pricing policy (given that marketing makes its decision separate from operations) is one of constant markup. That is, the firm adds the same dollar markup to the costs of standard and custom products (see §4.1 and Theorem 1), with the markup level effectively set by the product(s) most highly valued by the customer. With regard to the (separate) capacity decision, we are able to explicitly define the point at which the firm changes from acquiring both efficient and flexible capacity to acquiring only flexible capacity. This boundary between focus and spackling is expressed in terms of a cost premium for flexible capacity, denoted by  $V$  and illustrated in Figure 2 (see §4.2 and Theorem 2).

**Figure 2 Optimal Strategy is Determined by the Cost Premium for Flexible Production**

<b>High cost premium</b>	<i>Cost Boundary, <math>V</math></i>	<b>Low cost premium</b>
<b>Focused Strategy:</b>		<b>Spackling Strategy:</b>
Use efficient capacity to make standard products via MTS. Use flexible capacity to make custom products via MTO.		Use one flexible capacity resource to make both standard products via MTS and custom products via MTO.

Finally, we apply the model to Timbuk2’s situation using data attained in a three-stage study regarding customer preferences. In the first stage, 297 MBA students at MIT completed a conjoint survey, in stage two they configured and “purchased”<sup>3</sup> a customized Timbuk2 bag, and in stage three they completed a follow-up questionnaire. On the operations side, we use cost information provided by Timbuk2. In essence, we determine for Timbuk2 the boundary between “focus” and “spackling” as illustrated in Figure 2. In doing so, we also inherently address their questions regarding pricing, relative volumes for custom and standard products, and profitability.

---

<sup>3</sup> Students were given money a \$100 allowance to buy a bag, and received a refund if their selection was priced at less than \$100.

## 2. Literature Review

Determining how best to supply a wider variety of products at low cost in the face of uncertain demand has been a topic of much recent attention. Some of the research deals with the *supply* side of the equation, e.g., the design, manufacture, and distribution of the product. Other work addresses the *demand* side, e.g., determining how demand reacts to broader product offerings or to shorter lead times. Our work incorporates both supply and demand issues.

On the supply side, we introduce the notion of spackling, which contributes to the body of research that demonstrates the benefit of flexible resources. Our research question relates to that of finding the optimal mix of less costly, dedicated capacity and more expensive, flexible capacity, as modeled by Van Mieghem (1998). In his model the firm decides between production using only dedicated capacity, only flexible capacity, or a mix of both, as determined by the marginal cost of flexible capacity. All production is MTO, in that capacities are allocated to products after demand is observed. Van Mieghem finds that it may be advantageous to invest in more expensive flexible resources even with perfectly positively correlated product demands. We also find support for expensive flexible resources but in a different framework: we assume that production can be MTO or MTS and that both fixed and variable costs are a function of the type of production. In our setup, flexible resources can improve capacity utilization through production smoothing.

Postponing product differentiation is another form of production flexibility that can reduce the risk of under-producing or over-producing varied product configurations. Graman and Magazine (2000) show that if postponement involves even only a relatively small fraction of production, the benefits are nearly as great as if the firm could delay differentiation for all units. Gupta and Benjaafar (2001) show that postponement helps reconcile the needs of high variety and quick response time. In our setting, risks of under or over-producing are partly eliminated by the firm's offering of custom products, but custom products require more expensive capacity and there is a risk of acquiring too much or too little capacity; our proposed spackling strategy mitigates this risk.

Eynan and Rosenblatt (1995) study the trade off between lower-cost MTS production and higher-cost MTO (or assemble-to-order, ATO) production to produce a single product. In our model, the customer chooses either a standard product that can be MTS or a custom MTO product, and we determine the appropriate production strategy. Rudi (2000) also assumes a

single product and considers the trade-off between low-cost, long-lead time MTS production in the Far East and higher-cost local production with short lead times and pre-positioning of components (ATO). In our model, which considers more than one product, only the standard products might benefit from lower-cost off-shore production, but by producing locally the firm is able to better utilize local capacity that is needed anyway, to produce custom products.

Muckstadt, et al. (2001) investigate the use of MTO production for items (called B/C-type) with highly erratic demand while using MTS production for more predictable A-type items. They develop a computationally efficient solution approach for setting inventory base-stock levels and for allocating capacity, comparing performance to an alternative where inventory and capacity decisions are made prior to observing demand (MTS). In contrast, in our setting MTS production of standard products can be achieved using lower cost efficient capacity, such that the capacity decision involves setting two capacity levels; for efficient and flexible resources. Our model considers high-level interactions between marketing and operations, while their model considers detailed operations considerations, such as target inventory levels.

Arreola-Risa and DeCroix (1998) study the optimality of a strict MTO policy versus a strict MTS policy for a company producing multiple heterogeneous products at a shared manufacturing facility. They model demands as independent Poisson processes with different arrival rates and derive optimality conditions for MTO versus MTS policies considering trade offs in inventory holding and backordering costs. They consider whether a specific product should be built MTO or MTS. Rajagopalan (2002) also considers the firm's portfolio of products using a model to determine which products should be made to order and which should be made to stock. We focus on a different problem: determining whether efficient capacity should be employed to produce MTS items. In our setting, standard products are always produced as MTS and custom products as MTO.

The idea of dedicated capacity and reactive capacity, as put forth by Fisher and Raman (1996), is also related to our approach. Early in the production season, capacity is dedicated to products having low demand variability (effectively production is MTS). Capacity used late in the season can react to closer-to-actual demand (effectively production is MTO). In Fisher and Raman, the focus is on the production sequence given the capacity (i.e., which products should be produced at each stage of the season) while we focus on the optimal structure of the capacity.

The demand side of the issue involves at least two key issues: variety and lead time.

Variety is an issue because as it increases, pooling benefits are lost and demand uncertainty generally increases. (Uncertainty creates an incentive for MTO: if we knew exactly how much product would be ordered, we could simply produce it as MTS without any risk.) Also, an increase in variety reduces the volume for any given product, such that the variable cost of MTS goes up if there are economies of scale. Lancaster (1990) offers a survey of papers addressing the variety issue. The second issue is lead time, as examined by Li (1992), for example. If customers were always willing to wait, all items would be produced as MTO without any risk. He finds a boundary between MTS and MTO as reflected by newsvendor-type results. We similarly find a boundary between spackling and focus reflected by newsvendor-type results. In our model, we address the variety issue by giving the customer a choice between standard and custom products, using the logit framework; and the issue of customer willingness-to-wait is not modeled explicitly but is folded into a product's reservation price.

Our research contributes to a growing literature that touches on the integration of marketing and operations management decisions, cf., Chase (1996), Eliashberg and Steinberg (1993), Karmarkar (1996), Lovejoy (1998), van Ryzin and Mahajan (1999), and Verma, et al. (2001). Our focus solution is similar to van Ryzin and Mahajan (1999) who use the multinomial logit model in a newsvendor setting and show that the optimal set of stocking levels has a simple structure.

### **3. Joint Marketing/Operations Model**

In our model, the firm first simultaneously makes a choice between focus and spackling, determines levels of flexible capacity and efficient capacity (the latter being zero if the firm spackles), and sets prices for its standard and custom products. The firm then realizes the demands for standard and custom products. We consider demands realized over a single period, divided into  $T$  subperiods (e.g., days). At the beginning of the period, the firm receives the total order for standard products (i.e., across all  $T$  subperiods), due at the end of the period. Thus  $T$  effectively represents the lead time offered to retailers for delivery of standard products. At the beginning of each subperiod (e.g., each day), the firm receives its order for customized products and must ship by the end of that subperiod. In making its capacity and pricing decisions (prior to any demand realization), the firm maximizes expected total profit, given a set of customer preferences and costs as outlined below.

We take as a given the feature levels the firm incorporates into its standard product(s), and the menu of customizable features (i.e., options) it offers on a custom item<sup>4</sup>. We assume the firm has measured each customer's willingness-to-pay for each product attribute, scaled into dollars. This might be done, for example, through conjoint analysis and user design, as described by Dahan and Hauser (2002). We further assume that this assessment also measures the perceived benefit the customer realizes by taking delivery immediately (as with standard products already in inventory) as opposed to having to wait for delivery of custom goods. Thus we can find each customer's dollar-scaled utility for any given product, be it a standard product, or any of the customized versions available.

Let product  $j$  denote any standard product (if there are multiple standard offerings) or any one of the custom products, with  $p_j$  denoting its price. Let  $r_j^i$  denote customer  $i$ 's expected dollar-equivalent utility for product  $j$ , excluding price: We refer to  $r_j^i$  as customer  $i$ 's reservation price for product  $j$ . If viewed deterministically, then given the choice of buying product  $j$  or buying nothing, customer  $i$  buys at a price below  $r_j^i$ . See Schmidt and Porteus (2000) for a similar approach.

Each customer's net utility is scaled by a price-sensitivity parameter  $\mathbf{b}^i$ , such that the net dollar value customer  $i$  attaches to product  $j$  is  $\mathbf{b}^i (r_j^i - p_j) + \mathbf{x}_j^i$  where  $\mathbf{x}_j^i$  is a random error term assumed to be distributed Gumbel, i.e. double exponential, such that  $\mathbf{x}_j^i - \mathbf{x}_k^i$  is distributed logistically; hence the standard logit formulation applies. Let  $q_j^i$  denote customer  $i$ 's probability of purchase for product  $j$ ;  $q_j^i$  is a function of prices. If the customer has the choice of buying one of  $w$  products, along with the option to buy nothing from the firm (for this choice we assume  $r_j^i - p_j = 0$ ), then customer  $i$ 's probability of purchase of product  $j$  is given by the logit formulation as:

$$q_j^i = \left[ \frac{\exp(\mathbf{b}^i (r_j^i - p_j))}{1 + \sum_{k=1}^w \exp(\mathbf{b}^i (r_k^i - p_k))} \right] \quad (1)$$

We adopt the *representative customer* approach, whereby the parameters for a single

---

<sup>4</sup> We assume a product is configured by adding or subtracting options from a base unit. The design of the base unit and the set of custom options, along with the design of the standard product(s) also impact profitability, but analyses of those effects are outside the scope of this article.

customer are used to approximate the aggregate characteristics of the population. Ben-Akiva and Lerman (1985) describe this approach in their discussion of aggregate forecasting techniques, and Anderson, et al. (1992) further discuss its validity. One interpretation is that  $\mathbf{x}_j^i$  is not a random error term, but rather accounts for customer preference heterogeneity. That is, the representative customer approach is valid if each customer's choice is deterministic and the variations in customer evaluations of a given product are distributed Gumbel. From here on, we simply use  $\mathbf{b}$  and  $r_j$  (without superscripts) to denote the characteristics of the representative customer, and use  $q_j$  to denote the representative customer's purchase probability for product  $j$ .

In our situation, the customer must, at one level, choose between buying a standard product off-the-shelf or ordering a custom product, and must, at another level, make a choice regarding which custom product to buy (or which standard one to buy). Since logit requires that the various alternatives be "equally dissimilar" (to avoid the "red bus/blue bus" paradox associated with the independence from irrelevant alternatives (IIA) property), we assume the customer has already selected her most-preferred custom product, and likewise has pre-selected her most-preferred standard product, and we focus on the customer's choice between her most-preferred standard product, her most-preferred custom product, and buying nothing. Accordingly, we now restrict our consideration of  $j$  to  $j \in \{c, s\}$ , where  $c$  denotes the customer's most-preferred custom product and  $s$  denotes her most-preferred standard product.<sup>5</sup> We make the following pricing assumption and offer some justification later in §4.1. Namely, we assume the firm prices the base custom product to achieve markup  $m_C^*$ , and then prices all options at cost. Similarly, the markup for a standard product (or products) is denoted by  $m_S^*$ .

We base our model on a normal approximation to Poisson arrivals of representative customers at rate  $\mathbf{m}$  per subperiod with each (representative) customer making a logit-based purchase decision between standard, custom, or no product. Under this formulation, demands are multiplicative, such that subperiod demand for product  $j$  is  $X_j = \mathbf{m}q_j \mathbf{e}_j$  where  $\mathbf{e}_j$  is distributed normally with mean 1 and variance  $1/\mathbf{m}q_j$ , representing the multiplicative random perturbation of that potential market, and  $q_j$  is from the logit model of equation (1). Subperiod demands for a given type of product are independently and identically distributed across

---

<sup>5</sup> A more detailed analysis, beyond the scope of this paper, might use nested logit (Guadagni and Little (1998)) to model the choice sequence, and simultaneously (or iteratively) find the firm's markup and the customer's representative custom product.

subperiods. The resulting demands for custom and standard products are denoted by  $X_C$  and  $X_S$ , respectively, where  $X_C \sim N(\mathbf{m}_C, \mathbf{s}_C^2)$  and  $X_S \sim N(\mathbf{m}_S, \mathbf{s}_S^2)$  and:

$$\mathbf{m}_C = \mathbf{s}_C^2 = \left[ \frac{\mathbf{m}e^{b(r_C - p_C)}}{1 + e^{b(r_S - p_S)} + e^{b(r_C - p_C)}} \right] \text{ and } \mathbf{m}_S = \mathbf{s}_S^2 = \left[ \frac{\mathbf{m}e^{b(r_S - p_S)}}{1 + e^{b(r_S - p_S)} + e^{b(r_C - p_C)}} \right] \quad (2)$$

As stated earlier, we assume the total period demand for standard products, denoted by  $X_P$ , is realized at the beginning of the period. This period demand is the sum of  $T$  subperiod demands for standard products. Thus,  $X_P \sim N(T\mathbf{m}_S, T\mathbf{s}_S^2)$ . Demands for custom products are realized at the beginning of each subperiod such that by the end of the period, total demand (the sum of custom and standard items), denoted by  $X_T$ , is  $X_T \sim N(\mathbf{m}_T, \mathbf{s}_T^2)$ , where  $\mathbf{m}_T = T(\mathbf{m}_C + \mathbf{m}_S)$  and  $\mathbf{s}_T^2 = T(\mathbf{s}_C^2 + \mathbf{s}_S^2)$ .

We denote  $F_C(x)$ ,  $F_S(x)$ ,  $F_P(x)$ , and  $F_T(x)$  as the distribution functions for subperiod custom demand, subperiod standard demand, period standard demand, and total period demand, respectively, with densities  $f_C(x)$ ,  $f_S(x)$ ,  $f_P(x)$ , and  $f_T(x)$ .

Prior to realizing any demands, the firm sets production capacities for efficient and flexible resources denoted by  $K_E$  and  $K_F$ , respectively, where one unit of capacity can make exactly one unit of product per sub-period (if the firm chooses  $K_E = 0$ , i.e., to spackle, then we simply denote flexible capacity by  $K$ ). If the firm acquires strictly positive amounts of both capacity types, it has effectively chosen the focus strategy, while the use of only flexible capacity corresponds to a spackle strategy. Let  $\mathbf{q}_E$  denote the fixed cost per subperiod for a unit of efficient capacity (used only with focus to make standard units) and let  $\mathbf{q}_F$  denote the fixed cost of flexible capacity (used to make custom units under the focus strategy, and to make both standard and custom units under the spackling strategy), and let  $c_E$  and  $c_F$  denote the variable production costs per unit for efficient and flexible capacities, respectively. If capacity is insufficient to meet demand, the firm experiences a penalty cost of  $c_P$  per unit. We do not account for intra-period holding costs.

Interpretations of  $\mathbf{q}_F$  and  $c_F$  merit some clarification. Recall that we can view a custom product to be some base product plus or minus a set of options. Without loss of generality, define such base product to be some given standard product. Since we assume the same markup on all custom products, we effectively sell all options at cost and simply set the markup on the base

product. Consistent with this marketing approach, here we assume  $\mathbf{q}_F$  and  $c_F$  apply to the base (standard) product. We assume that each unit built consumes the same amount of capacity, regardless of the unit's configuration.

We make the following assumptions:

- (A 1)  $c_p, c_F, c_E, \mathbf{q}_F, \mathbf{q}_E > 0$ : All production costs are greater than zero.
- (A 2)  $c_F + \mathbf{q}_F < c_p$ : We avoid the uninteresting case where flexible capacity is zero.
- (A 3) For spackling we assume  $\mathbf{m}_c \ll K$ : The firm has sufficient capacity each subperiod to meet customized orders, i.e.,  $x_C^d < K$  in every subperiod where  $x_C^d$  is the realization of demand for custom units in subperiod  $\mathbf{d}$ . (See Figure 1.) Significant demand for standard units will justify this assumption.

We provide below the firm's optimization problems first given that it chooses the spackle strategy, and then given that it chooses the focus strategy. To find the jointly optimal solution the firm chooses between spackling and focus on the basis of which strategy offers the higher profit.

In the case of spackling,  $K$  units are produced in total in each of the initial subperiods:  $x_C^d$  units of customized products and  $K - x_C^d$  units of standard products. Let  $x_p$  be the realization of demand for standard units for the full period (known at the beginning of the first subperiod). If demand over the  $T$  subperiods for customized products is less than  $TK - x_p$ , the firm makes  $x_p$  standard units and then stops producing standard products for the remaining subperiods. If period demand for customized products is greater than  $TK - x_p$ , there is a shortfall of standard units and a penalty cost of  $c_p$  is incurred per unit.

Given that it spackles, the firm maximizes its expected profit per subperiod, equal to the expected margin minus the cost of capacity minus the penalty for missed sales:

$$\max_{p_s, p_c, K} \Pi(p_s, p_c, K) = (p_s - c_F) \mathbf{m}_s + (p_c - c_F) \mathbf{m}_c - K \mathbf{q}_F - (c_p - c_F) \frac{n_T(K)}{T} \quad (3)$$

where  $n_T(K) = \int_K^\infty (x - K) f_T(x) dx$  is the loss function representing the expected number of missed sales given capacity  $K$ , and demand density  $f_T(x)$ .

In the case of focus, production of custom products in each subperiod is the minimum of demand and capacity, while production of standard products is  $K_E$  each subperiod until  $x_p$  are produced. If the firm chooses the focus strategy, it maximizes expected profit:

$$\begin{aligned} \max_{p_S, p_C, K_E, K_F} \Pi(p_S, p_C, K_E, K_F) = & (p_S - c_E) \mathbf{m}_S - K_E \mathbf{q}_E - (c_P - c_E) \frac{n_P(K_E)}{T} \\ & + (p_C - c_F) \mathbf{m}_C - K_F \mathbf{q}_F - (c_P - c_F) T n_C(K_F) \end{aligned} \quad (4)$$

where  $n_P(K_E) = \int_{K_E}^{\infty} (x - K_E) f_P(x) dx$  and  $n_C(K_F) = \int_{K_F}^{\infty} (x - K_F) f_C(x) dx$  are the relevant loss functions.

Aydin and Porteus (2003) demonstrate that the multi-product newsvendor problem under logit demand is well behaved: there is no known closed form solution but there exists a unique price vector that optimizes profit. If there is only one subperiod per period, i.e., if  $T=1$ , then our problem for the case of focus is very similar to their formulation, except that in our model the variance of demand (determined from the Poisson process) is a function of the prices while in their model it is independent. For focus with  $T > 1$  and for spackling, our setup differs further in that we pool some of the demand. Our numerical experiments, discussed in §5.1, suggest the profit function (4) for focus and the profit function (3) for spackling are also well-behaved, but as in Aydin and Porteus (2003), we do not find closed-form solutions for the joint problem. Thus we employ numerical analysis over a wide range of conditions, as described in §5.1. But before describing these numerical results, we present in §4 an approach that yields analytical solutions to marketing's pricing problem given the capacity decision by operations, and to operation's capacity problem given marketing's pricing decision. These closed-form solutions to the separate problems offer further managerial insights into marketing and operations decision making, and in our experiments of §5.1 yield near-optimal results.

## 4. Separate Marketing and Operations Optimizations

Continuing with the previous problem formulation and setup, we describe in this section an approach in which the marketing and operations aspects of the problem are modeled and optimized separately. That is, we solve marketing's pricing problem given that marketing considers costs (i.e., capacities) as exogenous, and we solve operation's capacity problem given that operations considers demands (i.e., prices) as exogenous.

### 4.1. Marketing Model

We start with a general setting where the firm markets  $w$  products. In the marketing model we take costs as given (these costs will be derived in §4.2 in the operations model): Let  $c_j$

denote product  $j$ 's per-unit cost, assumed to be constant over volume, such that  $m_j \equiv p_j - c_j$  denotes the firm's dollar markup on product  $j$ , where  $j \in \{1, 2, \dots, w\}$ . Define  $d_j \equiv r_j - c_j$  as the representative customer's discriminating markup for product  $j$ ; it is the markup the firm could achieve in selling product  $j$  if it could perfectly price discriminate at the individual customer level (to the first degree), under deterministic customer choice. The customer's net utility from buying product  $j$  at price  $p_j$  is  $(r_j - p_j) = (d_j - m_j)$ , since  $d_j \equiv r_j - c_j$  and  $m_j \equiv p_j - c_j$ . The expression  $(d_j - m_j)$  replaces the expression  $(r_j - p_j)$  in (1), and allows us to highlight the role of markup  $m$ , leading to a powerful result.

Given costs for each product, marketing's optimization problem is to set prices (and therefore markups) to maximize expected profit, denoted by  $P_M(p_1, p_2, \dots, p_w)$ . Here we ignore demand uncertainty and thus assume all demand is met. Overage and underage costs are addressed separately by the operations model. Given the logit representative customer approach described earlier, and recalling that  $q_j$  is the representative customer's probability of purchase of product  $j$ :

$$P_M(p_1, p_2, \dots, p_w) = \mathbf{m} \sum_{j=1}^w (p_j - c_j) q_j = \mathbf{m} \sum_{j=1}^w m_j q_j \quad (5)$$

Marketing's optimal pricing strategy is stated in Theorem 1, representing a version of the *constant absolute markup* property that follows from this formulation. This property is noted in Anderson, et al. (1992), p. 251, in a different context. We include in Appendix I a proof in the setting of our model.

**THEOREM 1.** *If the representative customer is choosing between buying any one of  $w$  products offered by a single firm or buying nothing from the firm, the firm should price all  $w$  products at the same absolute dollar markup, denoted by  $m^*$ . The implicit solution for  $m^*$ , which exists and is unique, is given by:*

$$m^* = \frac{1}{\mathbf{b} \left[ 1 - \sum_{j=1}^w q_j \right]}, \text{ where:} \quad (6)$$

$$q_j = \frac{\exp(\mathbf{b}(d_j - m^*))}{1 + \sum_{k=1}^w \exp(\mathbf{b}(d_k - m^*))} = \frac{\exp(\mathbf{b}d_j)}{\mathbf{b}m^* \exp(\mathbf{b}m^*)}. \quad (7)$$

Theorem 1 suggests that when applying the representative customer approach, the firm finds it optimal to price all products at a constant absolute dollar markup (but not at the same percent margin). If it deviates from  $m^*$  by, say, increasing the markup of product  $j$ , there are

several competing consequences. It gets higher margin on product  $j$ , but reduces  $j$ 's expected unit sales (i.e., its probability of purchase). In turn it increases the expected unit sales (and profit) derived from each of the other products, but it diminishes total expected unit sales. Thus it is not clear which effect will dominate: Theorem 1 suggests there is always a profit loss by deviating from  $m^*$  for any product.

Next, consider the firm's pricing strategy when it creates its product assortment by adding or deleting individual features (i.e., options) from a "base unit." For example, automobile manufacturers might typically suggest a retail price for a base configuration, along with prices for individual options (the firm may also quote deductions from the base price if certain features are deleted). We assume additive costs: the cost of any finished unit is equal to the cost of the base unit plus the cost of the supplemental features.

*COROLLARY 1. Applying Theorem 1 to a strategy for pricing options, it is optimal for the firm to price the base unit at cost plus  $m^*$ , and price each option to be added or deleted at cost.*

Corollary 1 suggests that the firm need not optimize the price of each individual option, but only the price of the base unit. Thus the constant markup result provides some justification for the assumption in §3 that all custom products are priced to achieve the same markup, and all standard products get the same markup. Of course, the base-unit price accounts for the desirability of the product, which depends to some extent on the menu of upgrade options that accompanies it. While the notion of pricing all options at cost seems counterintuitive, some examples of this type of pricing might be an auto dealer that advertises "any car on the lot for \$99 over invoice," or a fast-food restaurant that will super-size your meal for \$0.39. While outside the scope of this paper, further investigation of constant-markup pricing is merited.

In summary, given product costs, the logit-based marketing model yields the profit-maximizing prices for standard and custom products (equal to costs plus markup  $m^*$  as given by (6)). In turn, these prices determine the corresponding parameters of the demand distributions for standard and custom products as given by (2).

## **4.2. Operations Model**

Taking prices and the resulting stochastic demands for standard and custom products derived in §4.1 as exogenous to the operations model, the operations model determines optimal capacities for standard and custom products by minimizing the sum of underage and overage

costs, denoted by  $C(K_E, K_F)$  in the case of focus and  $C(K)$  in the case of spackling. Using notation previously defined, these costs are given by:

$$C(K_E, K_F) = T[\mathbf{q}_E K_E] + (c_P - c_E)n_P(K_E) + T[\mathbf{q}_F K_F + (c_P - c_F)n_C(K_F)] \text{ and}$$

$$C(K) = T\mathbf{q}_F K + (c_P - c_F)n_T(K).$$

Theorem 2 below indicates that the firm's decision to spackle or focus depends on the premium for flexible production,  $(c_F + \mathbf{q}_F) - (c_E + \mathbf{q}_E)$ . In preparation for Theorem 2, define  $V$  as follows (interpretation follows the theorem):

$$V = \frac{1}{T\mathbf{m}_s} \left[ (c_P - c_E)\sqrt{T}\mathbf{s}_s L(z_E^*) + (c_P - c_F)T\mathbf{s}_c L(z_F^*) - (c_P - c_F)\mathbf{s}_T L(z_F^*) + \mathbf{q}_E\sqrt{T}z_E^*\mathbf{s}_s + \mathbf{q}_F T z_F^*\mathbf{s}_c - \mathbf{q}_F z_F^*\mathbf{s}_T \right] \quad (8)$$

where  $z_i^* = \mathbf{F}^{-1}((c_P - c_i - \mathbf{q}_i)/(c_P - c_i))$ , the standardized variate for the given fractile  $i \in \{E, F\}$ ,

$$\text{and the standard normal loss function } L(z_E) = \frac{n_P(K_E)}{\mathbf{s}_P} \text{ and } L(z_F) = \frac{n_C(K_F)}{\mathbf{s}_C} = \frac{n_T(K)}{\mathbf{s}_T}.$$

**THEOREM 2.** *The optimal operating strategies and capacities  $K_E^*$  and  $K_F^*$  are:*

*Case A: If  $(c_F + \mathbf{q}_F) - (c_E + \mathbf{q}_E) \geq V$ , then the firm adopts the focus strategy, with*

$$K_E^* = \mathbf{m}_s + \frac{1}{\sqrt{T}} z_E^* \mathbf{s}_s \text{ and} \quad (9)$$

$$K_F^* = \mathbf{m}_c + z_F^* \mathbf{s}_c. \quad (10)$$

*Case B: If  $(c_F + \mathbf{q}_F) - (c_E + \mathbf{q}_E) < V$ , then the firm spackles, with  $K_E^* = 0$  and*

$$K^* = K_F^* = \mathbf{m}_c + \mathbf{m}_s + \frac{1}{T} z_F^* \mathbf{s}_T. \quad (11)$$

Case A corresponds to focus (efficient capacity for standard products and flexible for custom) while Case B corresponds to spackling (only flexible capacity with a dual role: part of it responds to custom orders while the remainder is used to produce standard items to inventory).

In the case of focus, optimal capacities are determined through traditional newsvendor formulations with net unit underage costs of  $c_P - c_F - \mathbf{q}_F$  and  $c_P - c_E - \mathbf{q}_E$  for flexible and efficient capacities, respectively, and overage costs of  $\mathbf{q}_F$  and  $\mathbf{q}_E$ , respectively, yielding

$$K_E^* = \frac{1}{T} F_P^{-1} \left[ (c_P - c_E - \mathbf{q}_E) / (c_P - c_E) \right] \text{ and } K_F^* = F_C^{-1} \left[ (c_P - c_F - \mathbf{q}_F) / (c_P - c_F) \right], \text{ equivalent to}$$

(9) and (10), respectively. In the case of spackling, the optimal capacity is

$K^* = \frac{1}{T} F_T^{-1} [(c_P - c_F - \mathbf{q}_F)/(c_P - c_F)]$ , equivalent to (11). Safety capacities for the two cases are  $(1/\sqrt{T})\mathbf{s}_S z_E^* + \mathbf{s}_C z_F^*$  and  $(1/T)\mathbf{s}_T z_F^*$ , respectively.

In Theorem 2,  $V$  determines the boundary between Case A and Case B (i.e., between the columns in Figure 2). That is, Figure 2 suggests spackling is preferred if the cost premium for flexible production is “low,” and Theorem 2 defines “low” to be anything below  $V$ .

To more clearly see what drives the magnitude of  $V$ , consider the special case where demand for standard units is deterministic, i.e.,  $\mathbf{s}_S = 0$  (retail orders for standard products total exactly  $T\mathbf{m}_S$  units, due at the end of the period). This modeling simplification might be reasonable if retail orders for restocking inventories have lead times of  $T$  subperiods and once an order is accepted, it can not be altered. It might also be viewed as the limit to the original problem as  $T$  becomes large, since demand for standard products is pooled across the  $T$  subperiods and thus the resulting safety stocks as well as expected losses are multiplied by  $1/\sqrt{T}$ . In this special case, equation (8) simplifies to

$$V \equiv \frac{\mathbf{s}_C}{\mathbf{m}_S} \left(1 - \frac{1}{\sqrt{T}}\right) \left(z^* \mathbf{q}_F + (c_P - c_F) L(z_F^*)\right). \quad (12)$$

From (12) we gain the following insights: spackling is most compelling when demand for custom products is more variable ( $\mathbf{s}_C$  is large), the lead-time for production of standard units is long ( $T$  is large), demand for standard products is low ( $\mathbf{m}_S$  is small), the penalty for lost sales is high ( $c_P$  is large) and, of course, the premium for flexible production is small (when  $(c_F + \mathbf{q}_F) - (c_E + \mathbf{q}_E)$  is small).

Summarizing, given prices as set by marketing, the operations model gives the firm a way to determine optimal capacities for efficient and flexible resources, thereby implicitly establishing overage and underage costs. These costs affect prices as they are fed back to the marketing model in an iterative process, as described in §4.3.

### 4.3. Cooperative Tattonement Solution

Separately, the marketing and operations models each find optimal outputs given their inputs, but the two solutions may not coincide. The marketing model takes an average cost as given and determines prices and demands. If these demands subsequently are fed into the

operations model the average cost resulting from the capacity decision will most likely differ from that used in the marketing model.

To find a consistent solution we iterate between the marketing and operations models. More formally, we use a cooperative tatonnement (CT) process in which each party acts in response to what the other party does until an equilibrium (i.e., a convergent solution) is reached. The mechanics are similar to those of a competitive tatonnement process described in a game theoretic setting (see Fudenberg and Tirole (1991)), but in our case both parties are seeking profit maximization for the same firm rather than for competing firms. The resulting solution is an approximation to the optimal solution of the joint model, since even at the coincident point each party is maximizing only its individual problem rather than the joint problem. We show the effectiveness of this heuristic in §5.1.

We describe here the CT process under a spackling strategy. The case of focus would follow similarly, and the spackling and focus solutions would be compared to find the preferred strategy.

To formulate the CT process for spackling, rewrite the overall profit function (3) using (14) as the formulation for  $c$ :

$$\Pi(p_S, p_C, K) = \mathbf{m}_S (p_S - c) + \mathbf{m}_C (p_C - c), \text{ where} \quad (13)$$

$$c = c_S = c_C = c_F + \frac{Kq_F + (c_P - c_F) \frac{n_T(K)}{T}}{(\mathbf{m}_C + \mathbf{m}_S)}. \quad (14)$$

Equation (13) now reflects the firm's profit maximization problem for the marketing model as given by (5), when using cost  $c$ . Of course, cost  $c$  depends on  $K$  and  $\mathbf{m}_C$  and  $\mathbf{m}_S$ . These are unknown at the outset but assume for the moment that for the first iteration we pick some starting value for the cost, denoted by  $c^0$ . Given cost  $c^0$ , we determine discriminating markups  $d_C^1$  and  $d_S^1$  (the superscript denotes the iteration) and marketing finds an optimal markup  $m^{*1}$  from (6), which suggests demand parameters  $\mathbf{m}_C^1$ ,  $\mathbf{m}_S^1$ ,  $\mathbf{s}_C^1$ , and  $\mathbf{s}_S^1$  per (2), and from which  $\mathbf{s}_T^1$  is calculated. These demand parameters are fed into the operations model to find  $K^{*1}$  using (11).

Now consider the product costs that result from operations' choice of capacity  $K$ . The total cost in a period under spackling is the variable plus fixed costs plus the expected overage and underage costs:  $T c_F (\mathbf{m}_C + \mathbf{m}_S) + T q_F K + (c_P - c_F) n_T(K)$ . Both standard and custom units are built in the same facility so we calculate an average unit cost, denoted by  $c$ , by dividing total

expected period cost by total mean demand,  $T(\mathbf{m}_c + \mathbf{m}_s)$ . This resulting average cost can be verified as equivalent to (14).

Substituting the expression for capacity  $K^*$  from (11) for  $K$  in (14), we rewrite (14) as:

$$c = c_F + \mathbf{q}_F + \left(\frac{v}{T}\right) \left[ z_F^* \mathbf{q}_F + (c_p - c_F) L(z_F^*) \right] \quad (15)$$

where  $v \equiv \mathbf{s}_T / (\mathbf{m}_c + \mathbf{m}_s)$  denotes the coefficient of variation in total demand given spackling. The third (right-hand) term in (15) indicates that underage and overage costs vary with marketing input only through the coefficient of variation, and in a linear manner.

This leads to an important insight. While others have highlighted the need to consider the effect of demand variability on operational decisions such as capacity, they generally take demand variability as given. Our work shows that demand variability itself is a function of the firm's marketing and operations decisions. That is, cost affects price, which determines not only the expected demand but also the demand variability, which in turn affect the capacity decisions and thereby costs.

The cost derived at the end of the first iteration,  $c^1$ , is fed back to marketing for use in the second iteration to derive new demand parameters, which are then fed into the operations model to derive an updated cost. This continues until convergence is achieved, that is, until the cost derived by the last iteration is less than some arbitrarily small value  $\epsilon$  from the previous cost, at which point the marketing and operations models are effectively consistent. In all of the experiments described in §5.1 for which our framework is appropriate, the CT process converged quickly when starting at an initial cost that ignores underage and overage costs:  $c^0 = c_F + \mathbf{q}_F$ .

## 5. Empirical Analysis and Examples

While the joint optimization problem does not yield an analytic solution, it can be solved numerically. We describe in §5.1 a set of numerical experiments covering a broad set of conditions, to determine how various operating parameters affect the choice of spackling versus focus. We also use these experiments to test the validity of the constant markup result and the cooperative tatonnement (CT) process. In §5.2 we provide the numerical Timbuk2 solution.

### 5.1. Numerical Study

We examine how the following parameters impact the choice of spackling versus focus

(see Table 1): the reservation prices of the representative customer  $r_S$  and  $r_C$ , the total unit cost of efficient capacity  $c_E + \mathbf{q}_E$ , the percentage of efficient capacity cost that is variable  $c_E / (c_E + \mathbf{q}_E)$ , the cost premium for flexible capacity  $(c_F + \mathbf{q}_F) / (c_E + \mathbf{q}_E)$ , the percentage of flexible capacity cost that is variable  $c_F / (c_F + \mathbf{q}_F)$ , and the shortage cost premium  $c_P - (c_F + \mathbf{q}_F)$ . High, medium, and low levels were chosen for each parameter. All experiments were run with  $T = 30$  sub-periods (a one month lead-time),  $m = 1,000$  customers per subperiod, and  $\mathbf{b} = 1$ .

**Table 1. Parameter Levels for the  $3^7 = 2,187$  Experiments**

	$r_S$	$r_C$	$c_E + \mathbf{q}_E$	$c_E / (c_E + \mathbf{q}_E)$	$(c_F + \mathbf{q}_F) / (c_E + \mathbf{q}_E)$	$c_F / (c_F + \mathbf{q}_F)$	$c_P - (c_F + \mathbf{q}_F)$
Low	-1	-1	0.1	10 %	101 %	10 %	0.1
Medium	0	0	1	50 %	105 %	50 %	2
High	1	1	2	90 %	110 %	90 %	5

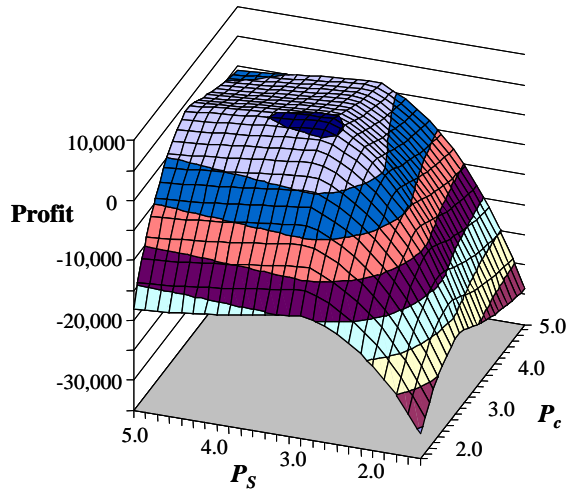
Setting  $\mathbf{b} = 1$  normalizes or scales the reservation price and cost parameters. For example, with  $\mathbf{b} = 1$ , if  $r_S$  is small, then the discriminating markup  $d_S = r_S - c_S$  is also small and by (1) the purchase probability goes to zero. A similar effect is observed if the cost  $c_S$  is large. That is, due to the dependencies, a purchase probability goes to zero if a cost  $c_P$ ,  $c_E$ ,  $\mathbf{q}_E$ ,  $c_F$ , or  $\mathbf{q}_F$  is large. For each parameter, we chose values to avoid a dramatic imbalance in demand (our model is inappropriate when demand for one product overshadows that of the other). Of the  $3^7 = 2,187$  experiments, we eliminated 52 that failed to meet three criteria: (1) average demand for standard products was greater than one standard deviation of the demand for custom products, (2) demand for custom products was at least 5% of the demand for standard products, and (3) the discriminating markup for a product type was greater than  $-10$  (in other words, the probability that a customer will buy something exceeded roughly 0.001%).

Note that this range of parameter values accounts for situations where manufacturing cost well exceeds what a customer is expected to be willing to pay (e.g., consider the experiment where  $c_E + \mathbf{q}_E = 2$  is matched with  $r_S = -1$ ), to the reverse (e.g., when  $c_E + \mathbf{q}_E = 0.1$  is matched with  $r_S = 1$ ). Further, we cover the case where most of the capacity cost is fixed, to the case where most of it is variable, and cover a wide range of shortage costs. This range of parameter values covers a wide range of possible firms that might be confronted with the questions we pose in our research.

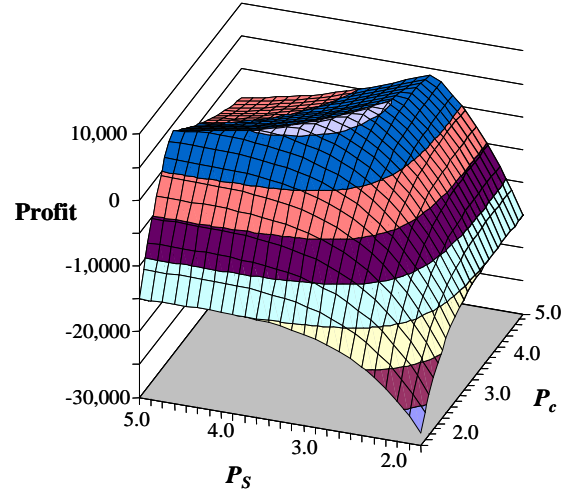
We show in Figure 3 the profits for spackle and focus as functions of  $p_c$  and  $p_s$  holding

capacity fixed at the optimal level, for a sample experiment where the two products have equal reservation prices. As in Aydin and Porteus (2003), the profit functions appear to be well behaved with, in this case, mild ridges at nearly a right angle. The ridges in Figure 3a and Figure 3b are approximately at or just below the optimal markups of each individual product: If one product is priced correctly and the other product sufficiently high, profit will be near optimal. In this experiment we used parameter values  $\mathbf{b} = \$1$ ,  $r_S = r_C = \$1$ ,  $\mathbf{q}_E = \$0.2$ ,  $c_E = \$1.8$ ,  $\mathbf{q}_F = \$1.89$ ,  $c_F = \$0.21$ ,  $c_P = \$4.1$ ,  $T=30$ , and  $n=1,000$ . In the focus case, optimal expected profit = \$5,841 with  $p_S^* = \$3.21$  and  $p_C^* = \$3.39$  ( $m_S^* = \$1.198$  and  $m_C^* = \$1.113$ ) while in the spackle case, optimal expected profit = \$5,887 with  $p_S^* = p_C^* = \$3.31$  ( $m_S^* = m_C^* = \$1.188$ ). Experiments with non-equal reservation prices also show ridges but suggest that, more specifically, it is more important to correctly price the highly valued product (the one with the higher reservation price), and then as long as the other product is priced high enough the firm will achieve near-optimal profit.

**Figure 3a: Sample Profit Function for Focus**



**Figure 3b: Sample Profit Function for Spackle**



In Table 2 we compare three sets of results. We used Solver to find numerically the profit maximizing solutions to (3) and (4); given that the profit functions appear well-behaved, we subsequently will refer to Solver's results as optimal (O). The constant markup optimal (CM Optimal or CMO) results were again found using Solver to optimize (3) and (4) but the results were constrained to be of constant markup. The cooperative tatonnement (CT) results (also of constant markup) were found using the process described in §4.3, applying five iterations.

The optimal markups for custom and standard products are effectively equal under spackling (in our 2,135 experiments the maximum difference in markup was 0.0003%), and are on average only 3.26% different under focus. Enforcing a constant markup result has no discernable effect on spackling profit and diminishes average focus profit by only 0.04%. The CT process under spackling yields profits in our experiments that are virtually identical to the optimal profits (the maximum drop in profit was 0.08%), while under focus the CT process reduces profit by 0.09% on average compared to the optimal.

Under a spackling strategy, the custom and standard products share capacity. The underage and overage costs affect both products simultaneously. Thus the discriminating markups for custom and standard products as calculated in the CT process both rise or both fall with the capacity decision. Theorem 1 demonstrates that constant markup is optimal given an exogenous operations cost, and in our experiments under spackling, the constant markups remain effectively optimal even in the presence of the interaction between costs and prices.

**Table 2. Comparison of Optimal, CM Optimal, and CT Results**

	Optimal (O)		CM Optimal (CMO)		CT	
	Focus	Spackle	Focus	Spackle	Focus	Spackle
# of cases preferring this strategy	963	1172	963*	1172*	982*	1153*
Avg. profit compared to O	–	–	99.96%	100.00%	99.91%	100.00%
Avg. difference in markups	3.26%	0.00%	–	–	–	–

\* In all cases, CMO agreed with O. In 19 cases, CT indicated focus was preferred whereas O indicated spackling, but in these cases spackling and focus profits differed by only 0.01% on average.

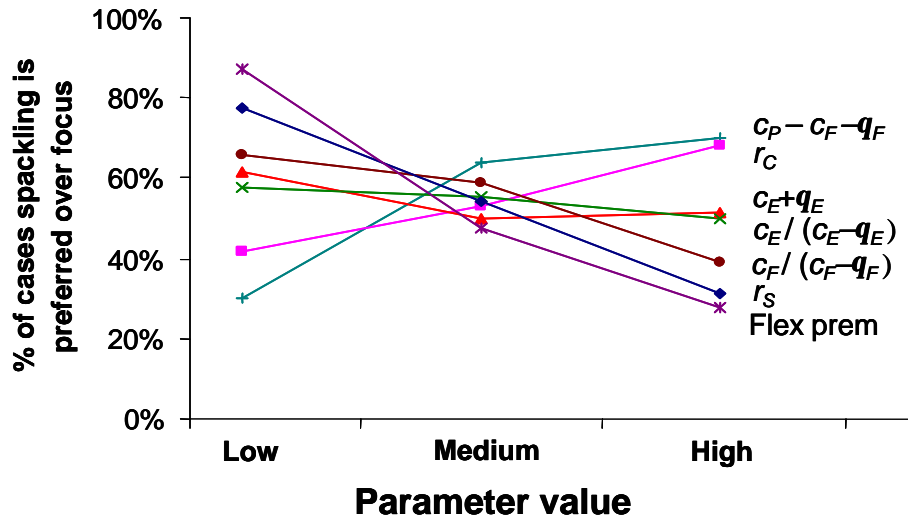
In the optimal results, spackling outperforms focus in 55% of the experiments. Importantly, if managers consider only the direct benefits of lower unit costs from efficient capacity, focused production in separate facilities will be chosen in every case, while in our experiments spackled production in a single facility is optimal in over half the cases. In the cases where spackling outperformed focus, spackling’s average profit gain was 2.58% (in some cases it was significantly more), in spite of the penalty the firm pays for expensive flexible capacity. In those cases where focus did better it similarly yielded an average benefit of 2.68%.

Figure 4 further summarizes the experimental results. The joint model is consistent with the insights from Theorem 2 in that spackling is particularly attractive when the premium for flexible capacity  $(c_F + q_F) / (c_E + q_E)$  is low, when shortage cost premium  $c_P - (c_F + q_F)$  is high, and when there is significant demand for custom products relative to standard products, as indicated

by the drop in spackling’s attractiveness with an increase in  $r_S$  and by the increase in spackling’s attractiveness with an increase in  $r_C$ .

It is worth noting that spackling remains an attractive alternative in over 20% of the cases even when the cost premium for flexible capacity is at the high level of 10%. This provides a key managerial insight. For example, say that efficient capacity involves a move to off-shore production. Our results suggest management should include an analysis of spackling benefits in determining the attractiveness of such a move. (In addition, there may be other benefits from maintaining production in a domestic flexible facility that we have not accounted for, such as shorter lead times for standard products, or the marketing advantages of domestic production.)

**Figure 4. The Attractiveness of Spackling as Determined by Parameter Levels**



## 5.2. Timbuk2 Analysis

We describe briefly the Timbuk2 analysis as it relates to the choice of spackling versus focus. For further details of the study, refer to Cattani, et al. (2003).

Timbuk2’s customer-related data were acquired in a three-stage study. In stage one, 297 MBA students at MIT participated in an adaptive conjoint survey, as described by Toubia, et al. (2003). The conjoint survey involved price plus nine other attributes, including size (medium or large), color (red or black), type of closure of the laptop sleeve (a full flap or a small tab), and six “on-off” attributes (either the bag included the attribute or lacked it), namely, an MIT logo, a holder for a cell phone, a holder for a personal digital assistant, a laptop sleeve, a mesh pocket, a bottom boot, and a carrying handle separate from the shoulder strap. From the conjoint study we

were able to determine dollar-scaled part-worth for each attribute. In the second stage, each student was given \$100 to spend on a self-configured customized bag. If the student configured a bag priced below \$100, she received the difference in cash. The third stage consisted of a follow-up survey in which the student indicated the probability that she would have actually purchased her customized bag, and identified her delay penalty for having to wait for the MTO bag.

We followed the iterative approach of §4.3 to determine the CT solution for Timbuk2 under spackling using its existing flexible manufacturing capacity in San Francisco, and under focus taking advantage of less expensive off-shore production for sourcing of standard products. We used the three-stage data to find  $r_j^i$ , customer  $i$ 's reservation price for bag  $j$ ,  $j \in \{c, s\}$ , scaled into dollars, and customer  $i$ 's price sensitivity,  $\mathbf{b}^i$ . Given that we had the distributions of  $\mathbf{b}^i$  and  $d_j^i$  for the Timbuk2 data, we did not use the representative customer approach. Instead, we used heterogeneous individual responses and searched numerically for the optimal markups  $m_S^*$  and  $m_C^*$  to solve the marketing problem.

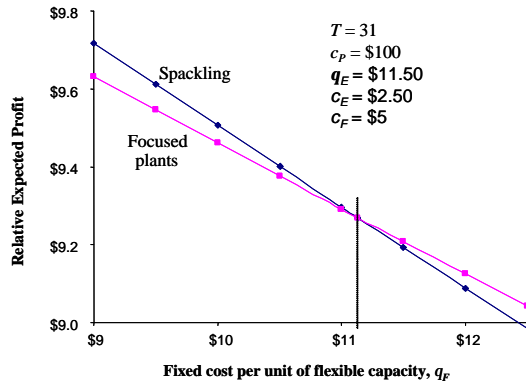
Efficient off-shore production has estimated costs of  $\mathbf{q}_E = \$11.50$  and  $c_E = \$2.50$ . We assumed a subperiod to be one day and a period to be one month ( $T = 31$ ). Given  $\mathbf{q}_E + c_E = \$14$ , we examined how the cost of domestic flexible production impacts the choice of spackling versus focus. In all our scenarios, results converged to within \$0.01 in 3 or fewer iterations.

First we examined whether Timbuk2 should spackle or focus as a function of the fixed cost of flexible capacity,  $\mathbf{q}_F$ . Figure 5 shows expected profits. In this case, spackling is preferred (Timbuk2 will still be better off sourcing all products from its domestic flexible facility ) as long as the sum of fixed plus variable costs for flexible capacity is no more than about 15% higher than that for efficient capacity. At this point of indifference, cost  $c = \$16.23$  for spackling and cost  $c_C = \$16.88$  (with  $c_S = \$14$ ) for focus. Spackling increases utilization of the flexible capacity, reducing the combined per-unit costs of overage and underage from 75 cents to 10 cents.

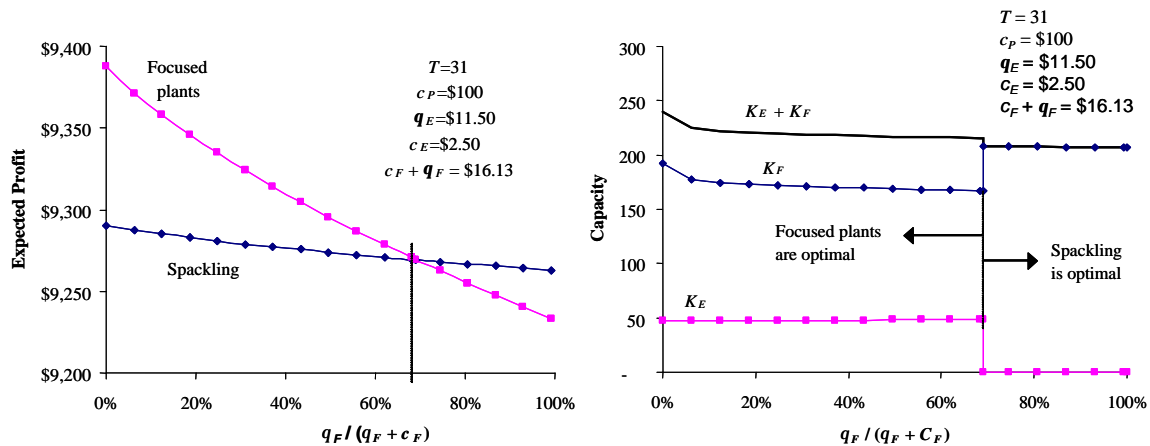
Continuing to assume  $\mathbf{q}_E = \$11.50$  and  $c_E = \$2.50$ , we examined the choice of spackling versus focus as a function of how much of the cost of flexible production is fixed, i.e., the ratio  $\mathbf{q}_F / (\mathbf{q}_F + c_F)$ . Figure 6 shows profits and optimal capacities given  $\mathbf{q}_F + c_F = \$16.13$ . Note in the second frame of Figure 6 that total capacity is lower under spackling, as one might expect, due to

the pooling effects. Spackling facilitates greater capacity utilization, but this is of lesser advantage if most of the cost is variable (the cost is not incurred unless demand materializes). If a high % of cost is fixed, spackling becomes more attractive than a set of focused facilities.

**Figure 5. Effect of the Fixed Cost of Flexible Capacity**



**Figure 6. Profits and Capacities as Determined by How Much of the Cost is Fixed**



We also performed comparative statics associated with the parameters  $T$ ,  $c_P$ , and the magnitude of the  $b$ 's. In summary, we found that spackling becomes more beneficial as  $T$  and  $c_P$  increase, but with diminishing effects (this is intuitive due to the “square-root law” of pooling efficiencies). Changing the price sensitivities (the  $b$ 's) had a relatively minor effect.

## 6. Conclusion

Motivated by the experiences of Timbuk2, a manufacturer of messenger bags, we gain insight as to when the practice of spackling, involving the use of a flexible production facility to produce both standard and customized products, is preferred to focus, where an efficient resource

makes the standard items and a flexible factory focuses on the custom units. We show that the capacity acquisition question is intertwined with product pricing. While an operations model typically takes demand variability as given, our work suggests the firm impacts variability through its pricing. In turn, variability impacts the capacity decision made by operations, which impacts product cost. The marketing/operations loop is closed by the impact of cost on pricing, pointing to the importance of an integrated marketing and operations approach.

Our model suggests spackling is the preferred strategy as long as the cost premium of the flexible resource is not too high: for example, Timbuk2 should spackle as long as the cost premium is less than about 15%. While the benefits of going to efficient production are often visible and easy to calculate, our analysis highlights some of the hidden offsetting factors. In other words, if unaware of the benefits of spackling, senior management could in a case like this be falsely attracted by a phantom savings.

The basic concept of spackling is currently employed by some of the firms that successfully implement mass customization, although not always precisely in the fashion presented in our paper. For example, Dell uses flexible manufacturing systems in its U.S. factories to assemble desktop computers to the customer's exact configuration and is able to deliver within a few days. Even though Dell assembles to order (and not to stock), not all orders are equally time sensitive. Within the factory, which is local and flexible, orders can be scheduled in such a way that time-sensitive orders get first priority, and then the schedule can be spackled with less time-sensitive orders. For example, the schedule might proceed in the following order: (1) First priority goes to time sensitive customers (who ideally are charged a premium). (2) Spackled on top are normal customers, with about a 5 day lead time. (3) Another spackled layer consists of a class of customers who specify delivery on an exact date (and perhaps pay more for it) – these units could be built after receipt of the order but in advance of the specified delivery date and held as FGI for that customer. (4) The final layer is a class of customers that gets a discount for being flexible on lead time and delivery date. Through such a spackling strategy, Dell can most efficiently use its capacity while meeting the expectations of each class of customers.

In our Timbuk2 example, we found greater demand for custom products than for standard products. In the reverse situation, where demand for standard products dominates that for customized configurations, one might envision a more elaborate multi-layered spackling

strategy. Here the firm would start with a layer of efficient capacity to produce most of the standard products in a constant stream (for example, sourcing them off-shore). On top of this focused, efficient capacity, the firm would add a layer of spackled (local) production to meet the periodic (say, daily) MTO orders for custom products. As in the case of “traditional” spackling that we described here, it would also use the local flexible capacity to produce standard products when capacity is available, such that its flexible facility also runs at near-full capacity utilization. We leave the determination of optimal capacity levels under this strategy to future work. We also leave to future work extensions of our model that address some of our simplifying assumptions.

On the one hand, there seems to be heightened interest in customized products, possibly due to the successes of companies such as Dell, as well as to the spread of the Internet. The Internet facilitates customization because it allows rapid, two-way communication between the firm and its customers, facilitating product configuration and pricing, and media-rich conceptualization of product alternatives by customers (Dahan and Hauser (2002)). This attracts customers who can thus attain a better product fit or who simply prefer to configure their own products, despite having to wait for delivery and/or pay a higher price.

On the other hand, some customers still prefer to buy standard products off-the-shelf. As mentioned earlier, the “five-day car” has yet to materialize in the automotive industry in a significant way, although there has been much interest in such a concept. Clearly, there are trade-offs involved in offering standard versus custom products. We offer senior management a new way of analyzing some of these trade-offs in the case where both types of products are offered.

## Appendix I: Proofs

### Proof of Theorem 1.

We apply the technique of Anderson, et al. (1992) to our context.

Given  $w$  products, the firm maximizes its profit,  $\boldsymbol{p}$ , given by:

$$\pi = \boldsymbol{m} \sum_{i=1}^w m_i q_i \tag{16}$$

Note that  $\frac{\partial q_i}{\partial m_i} = -\boldsymbol{b} q_i (1 - q_i)$  and  $\frac{\partial q_i}{\partial m_j} = \boldsymbol{b} q_i q_j$  for  $i \neq j$ . The first order conditions (FOC), with

respect to  $m_i$ , result in:

$$\frac{\partial \mathbf{p}}{\partial m_i} = \mathbf{m}q_i \left( 1 + \mathbf{b} \sum_{j=1}^w m_j q_j - \mathbf{b} m_i \right) = 0 \quad \forall i. \quad (17)$$

Noting  $\mathbf{m}q_i \neq 0 \quad \forall i$ , manipulation of (17) yields:

$$m_i^* = \frac{1}{\mathbf{b}} \left( 1 + \mathbf{b} \sum_{j=1}^w m_j q_j \right) \quad \forall i. \quad (18)$$

From (18),  $m_i = m_k \equiv m^* \quad \forall i$ . Replacing  $m_i$  with  $m^* \quad \forall i$  in (18),  $m^*$  is the solution to:

$$m^* = \frac{1}{\mathbf{b} \left( 1 - \sum_{j=1}^w q_j \right)} \quad (19)$$

Note that the left side of (19) is linearly increasing in  $m^*$  while the right side is strictly decreasing, so there exists a unique solution.

To see that the FOC result in a globally optimal solution, note that there exists, for each possible markup  $m_i$ , a lower boundary at  $m_i = 0$  where profit is everywhere strictly increasing in

$m_i$ , that is,  $\left. \frac{\partial \mathbf{p}}{\partial m_i} \right|_{m_i=0} = \mathbf{m}q_i \left( 1 + \mathbf{b} \sum_{j=1}^w m_j q_j \right) > 0$ , and note that (as we show in the next paragraph)

there exists, for each possible markup  $m_i$ , an upper boundary at  $m_i = \bar{m}$  where profit is strictly decreasing in  $m_i$  as long as  $m_j \leq \bar{m}$  for  $j \neq i$ ; that is, there exists an  $\bar{m}$  such that  $\left. \frac{\partial \pi}{\partial m_i} \right|_{m_i=\bar{m}} < 0$  for

all  $m_j \leq \bar{m}$  where  $j \neq i$ . Thus the globally maximizing set of markups must lie strictly within the interior defined by these lower and upper boundaries, i.e., all optimal markups must be strictly greater than zero and strictly less than  $\bar{m}$ . Since  $m_i = m_j \equiv m^* \quad \forall i, j$  is a solution, and the only solution, to the FOC, it must lie within this interior and must be globally optimal.

To show that  $\bar{m}$  exists, let  $\hat{m} \geq m_j \quad \forall j$ , and  $\hat{m} > \frac{1}{\mathbf{b} \left( 1 - \sum_{j=1}^w q_j \right)}$  and let  $m_i = \hat{m}$ . Then

$$\left. \frac{\partial \mathbf{p}}{\partial m_i} \right|_{m_i=\hat{m}} = \mathbf{m}q_i \left( 1 + \mathbf{b} \sum_{j=1}^w m_j q_j - \hat{m} \mathbf{b} \right) \leq \mathbf{m}q_i \left( 1 + \mathbf{b} \hat{m} \sum_{j=1}^w q_j - \mathbf{b} \hat{m} \right) = \mathbf{m}q_i \left( 1 - \mathbf{b} \hat{m} \left( 1 - \sum_{j=1}^w q_j \right) \right) < 0. \quad \text{Note}$$

that  $0 < \mathbf{b} \left( 1 - \sum_{j=1}^w q_j \right) < \mathbf{b}$ . Then  $\bar{m}$  is any number  $> \hat{m}$ .

**Proof of Corollary 1.**

Define the base unit to be any product  $j$  with cost  $c_j$ . Consider any other product  $k$  with cost  $c_k$ . By Lemma 1,  $m^* = p_j^* - c_j = p_k^* - c_k$ . Thus  $p_k^* - p_j^* = c_k - c_j$ . That is, the optimal incremental price for the feature set that transforms product  $j$  into product  $k$  equals the incremental cost of that feature set.

**Proof of Theorem 2.**

Total expected overage and underage costs over the period for the case of focus are:

$$\begin{aligned} C(K_E) &= T[\mathbf{q}_E K_E] + (c_P - c_E) \int_{TK_E}^{\infty} (x_P - TK_E) f_P(x_P) dx_P \\ &= T[\mathbf{q}_E K_E] + (c_P - c_E) n_P(K_E), \text{ and} \end{aligned}$$

$$\begin{aligned} C(K_F) &= T\left[\mathbf{q}_F K_F + (c_P - c_F) \int_{K_F}^{\infty} (x_C - K_F) f_C(x_C) dx_C\right] \\ &= T\left[\mathbf{q}_F K_F + (c_P - c_F) n_C(K_F)\right] \end{aligned}$$

Total expected costs over the period for the spackled-production case are:

$$\begin{aligned} C(K) &= T\mathbf{q}_F K + (c_P - c_F) \int_{TK}^{\infty} (x_T - TK) f_T(x_T) dx_T \\ &= T\mathbf{q}_F K + (c_P - c_F) n_T(K). \end{aligned}$$

The functional form of  $C(K_E)$ ,  $C(K_F)$  and  $C(K)$  is the traditional newsvendor equation from which the optimal values for the capacities are readily derived:

$$K_E^* = \frac{1}{T} F_P^{-1} \left[ (c_P - c_E - \mathbf{q}_E) / (c_P - c_E) \right] = \mathbf{m}_S + (1/\sqrt{T}) z_E^* \mathbf{s}_S$$

$$K_F^* = F_C^{-1} \left[ (c_P - c_F - \mathbf{q}_F) / (c_P - c_F) \right] = \mathbf{m}_C + z_F^* \mathbf{s}_C$$

$$K^* = \frac{1}{T} F_T^{-1} \left[ (c_P - c_F - \mathbf{q}_F) / (c_P - c_F) \right] = \mathbf{m}_C + \mathbf{m}_S + (1/T) z_F^* \mathbf{s}_T$$

where  $z_i^* = F^{-1}((c_P - c_i - \mathbf{q}_i) / (c_P - c_i))$ , the standardized variate for the given fractile, with  $i \in \{E, F\}$ .

To find the lower bound for  $c_E$  and spackled production, we note that spackled production will be preferred when  $C(K_E^*) + C(K_F^*) > C(K^*)$ , or  $C(K_E^*) + C(K_F^*) - C(K^*) > 0$ .

Since  $C(K_E^*) + C(K_F^*) - C(K^*)$

$$\begin{aligned}
&= T \left[ \mathbf{q}_E K_E^* \right] + (c_P - c_E) n_P (K_E^*) \\
&+ T \left[ \mathbf{q}_F K_F^* + (c_P - c_F) n_C (K_F^*) \right] \\
&- T \mathbf{q}_F K^* - (c_P - c_F) n_T (K^*) \\
&= T \mathbf{m}_S (\mathbf{q}_E + c_E - \mathbf{q}_F - c_F) \\
&+ (c_P - c_F) T \mathbf{s}_C L(z_F) + (c_P - c_E) \sqrt{T} \mathbf{s}_S L(z_E) - (c_P - c_F) \mathbf{s}_T L(z_F) \\
&+ \sqrt{T} z_E \mathbf{q}_E \mathbf{s}_S + T z_F \mathbf{q}_F \mathbf{s}_C - z_F \mathbf{q}_F \mathbf{s}_T
\end{aligned}$$

this difference is greater than zero when

$$(c_F + \mathbf{q}_F) - (c_E + \mathbf{q}_E) >$$

$$\frac{1}{T \mathbf{m}_S} \left[ (c_P - c_E) \sqrt{T} \mathbf{s}_S L(z_E^*) + (c_P - c_F) T \mathbf{s}_C L(z_F^*) - (c_P - c_F) \mathbf{s}_T L(z_F^*) + \mathbf{q}_E \sqrt{T} z_E^* \mathbf{s}_S + \mathbf{q}_F T z_F^* \mathbf{s}_C - \mathbf{q}_F z_F^* \mathbf{s}_T \right] \equiv V$$

## References

- Anderson, S. P., A. De Palma and J. F. Thisse. 1992. *Discrete choice theory of product differentiation*. The MIT Press. Cambridge, MA.
- Arreola-Risa, A. and G. A. DeCroix. 1998. Make-to-order versus make-to-stock in a production-inventory system with general production times. *IIE Transactions*. **30** 705-713.
- Aydin, G. and E. L. Porteus. 2003. Inventory, pricing and supply chain coordination for multiple competing products under logit demand. *Working Paper*. Stanford University, Stanford, CA.
- Ben-Akiva, M. and S. Lerman. 1985. *Discrete choice analysis*. MIT Press. Cambridge, MA.
- Cattani, K. D., E. Dahan and G. M. Schmidt. 2003. A framework for assessing the desirability of multi-channel markets. *Working Paper, The University of North Carolina at Chapel Hill*.
- Chase, R. 1996. The mall is my factory: Reflections of a service junkie. *Production and Operations Management*. **5** (4) 298-308.
- Dahan, E. and J. R. Hauser. 2002. The virtual customer. *Journal of Product Innovation Management*. **19** (5) 332-353.
- Eliashberg, J. and R. Steinberg. 1993. Marketing-production joint decision making. J. Eliashberg and G. L. Lilien, eds. *Handbooks in operations research and management science: Marketing*. Elsevier Science Publishers B. V., Amsterdam, 827-880.
- Eynan, A. and M. J. Rosenblatt. 1995. Assemble to order and assemble in advance in a single-period stochastic environment. *Naval Research Logistics*. **42** 861-872.

- Fisher, M. and A. Raman. 1996. Reducing the cost of demand uncertainty through accurate response to early sales. *Operations Research*. **44** (1) 87-99.
- Fudenberg, D. and J. Tirole. 1991. Perfect bayesian equilibrium and sequential equilibrium. *Journal-of-Economic-Theory*. **53** (2) 236-60.
- Graman, G. A. and M. Magazine. 2000. An analysis of capacitated postponement. *Working Paper*. University of Cincinnati, Cincinnati, OH, 45221.
- Guadagni, P. M. and J. D. C. Little. 1998. A logit model of brand choice calibrated on scanner data. *Journal of Forecasting*. **17** 303-326.
- Gupta, D. and S. Benjaafar. 2001. Make-to-order, make-to-stock, or delay product differentiation? - a common framework for modeling and analysis. *Working Paper*. The University of Minnesota, Minneapolis, MN.
- Karmarkar, U. S. 1996. Integrative research in marketing and operations management. *Journal of Marketing Research*. **33** 125.
- Lancaster, K. R., Brian T. 1990. The economics of product variety: A survey; marketing applications of the economics of product variety. *Marketing Science*. **7** (3) 189-211.
- Li, L. 1992. The role of inventory in delivery-time competition. *Management Science*. **38** (2) 182-197.
- Lovejoy, W. S. 1998. Integrated operations: A proposal for operations management teaching and research. *Production and Operations Management*. **7** 106-1124.
- Muckstadt, J. A., D. H. Murray and J. A. Rappold. 2001. Capacitated production planning and inventory control when demand is unpredictable for most items: The no b/c strategy. *Working Paper*. Cornell University, Ithaca, NY.
- Rajagopalan, S. 2002. Make to order or make to stock: Model and application. *Management Science*. **48** 241-256.
- Rudi, N. 2000. Dual sourcing: Combining make-to-stock and assemble-to-order. *Working Paper*. University of Rochester, Rochester, NY.
- Schmidt, G. and E. L. Porteus. 2000. The impact of an integrated marketing and manufacturing innovation. *Manufacturing and Service Operations Management*. **2** (4) 317-336.
- Toubia, O., D. Simester, J. R. Hauser and E. Dahan. 2003. Application and test of web-based adaptive polyhedral conjoint analysis. *forthcoming in Marketing Science*.
- Van Mieghem, J. A. 1998. Investment strategies for flexible resources. *Management Science*. **44**

(8) 1071-1078.

van Ryzin, G. and S. Mahajan. 1999. On the relationship between inventory costs and variety benefits in retail assortments. *Management Science*. **45** 1496-1509.

Verma, R., G. M. Thompson, W. L. Moore and J. J. Louviere. 2001. Effective design of products/services: An approach based on integration of marketing and operations management decisions. *Decision Sciences*. **32** (1) 165-193.