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Retail Channel Structure Impact on Strategic Engineering Product Design

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We examine, in a strategic setting, the broad issue of how retail channel structures—retail monopoly versus retail duopoly—impact a manufacturer's optimal new product design, both in terms of engineering design specifications as well as manufacturer and retailer profits. Our strategic framework enables manufacturers in specific contexts to anticipate the reactions of the retailers and competitive manufacturers to new designs in terms of the retail and wholesale pricing and to understand how different channel structures and channel strategies (such as an exclusive channel strategy) impact the engineering design of the new product, conditional on consumer preference distributions and competitor product attributes. Based on a simple numerical and a power tool design example, we illustrate how the insight from the framework translates to design guidelines; specifically, understanding which designs are optimal under differing channel structure conditions, and which design variables need precise targeting given their profit sensitivity.

Key words: new product design; engineering design; research and development; retail channels; marketing; game theory; genetic algorithms; latent class models; structural models
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1. Introduction

The product development process has been defined as the transformation of a market opportunity into a product available for sale and involving disciplines of marketing, operations management, organizational management, and engineering design with each discipline focusing on critical decisions (Krishnan and Ulrich 2001). These critical product decisions are ultimately realized as product attributes and features that are important to the market. The realization that the decision for many of these attributes and features is made early in the design stage and cannot be changed significantly later in product development to enhance the marketability of the product or its economic success has led to cross-disciplinary approaches in many of these related fields (Ulrich and Eppinger 2004). To that end, many approaches have been developed in extant literature to collect and integrate customer preferences in the early stages of design, aiming to provide the manufacturer flexibility in designing products that are market focused. Some of these approaches focus on the information sharing and coordination aspects across disciplines (e.g., Terwiesch et al. 2002); others propose specific design methodologies that consider cross-disciplinary impact and synergies (Morgan et al. 2001). In the engineering design literature, the methodologies developed have been improvements in engineering design aspects and assume that the manufacturer or producer interacts directly with the consumer in the marketplace (e.g., Li and Azarm 2000, Wassenaar and Chen 2003, Luo et al. 2005, Besharati et al. 2006, Luo 2011). These approaches rely on the estimation of customer utility for high-level product attributes that are the result of engineering design decisions. These high-level product attributes are translated into market share and profit with implications focusing on competitive draw or market expansion using a discrete choice model and generally a cost model (e.g., Ramdas and Sawhney 2001).

With the emerging dominance and clout of retailers (Cappo 2003), recent approaches have started examining and accounting for the impact of retail channels in manufacturers' new product design in addition to customer preferences. For example, from an analytical viewpoint, a number of game theoretic frameworks have been developed to understand strategic interactions in retail environments (monopolies—Dewan et al. 2003; duopolies—Savin and Terwiesch 2005, Klastorin and Tsai 2004). From an empirical viewpoint, Luo et al. (2007) examined the issue of how manufacturers can design new products strategically in a specific retail monopoly setting in order to maximize manufacturer profits, and Shiau and Michalek (2009) examined vertical Nash structures with symmetric competition at the retail and manufacturer level. Williams et al. (2008) analyzed how manufacturers can increase the acceptance of their new products by a retail monopolist through a mix of design options and slotting allowances. In this paper, we examine, in a strategic setting, the important issue of how retail channel structures itself (retail monopoly versus retail duopoly) and the specific channel strategy (e.g., exclusive or nonexclusive) impact of a manufacturer's optimal new product design, both in terms of engineering design specifications as well as manufacturer and retailer profits. Specifically, we propose a framework that enables manufacturers, in specific institutional settings and under certain market assumptions, to anticipate the reactions of the retailers and competitive manufacturers to new designs in terms of the retail and wholesale pricing under different structures and channel strategies. In such a setting, the framework allows the manufacturer to determine the quality (the specific attributes) of the new product that the retailer(s) would prefer most to carry in their assortment given the specific distribution of consumer preferences and competitive product attributes. Based on numerical examples, including an application to power tool design, we illustrate how the insight from the framework—the increased competition in duopoly/oligopoly retail settings allows manufacturers to target the design preferences of the more price sensitive consumer segments more profitably as compared to the retail monopoly case—translates to specific design guidelines. Collectively, our paper provides important insights and testable hypotheses into how the downstream channel structure and the exclusive/nonexclusive strategy followed by a manufacturer will shape the optimal design characteristics of a new product as well as manufacturer/retailer profits, as the following overview highlights.

In evaluating a new product to carry in their assortment, retailers typically use revenue per square foot or revenue per shelf space as metrics (in addition to customer preferences). The inclusion of the new product has to lead to an increase in overall category profit. For example, Home Depot will only carry in their assortment the 5 out of 20 available drills that generate the greatest revenue for the drill category. Additionally, in the presence of retail competition, this assortment composition is particularly important in maximizing the retailer's market share vis-à-vis their competition. Given these considerations and the fact that the retailers' shelf space is limited, manufacturers have to strategically consider the attributes and features of their product vis-à-vis the assortment (i.e., competing manufacturers' product features and attributes) the retailers carry. This must all be done at the early design stage so as to maximize the chances of the new product being carried by one or more retailers and being successful in the market.

In considering the powerful retailers and their interactions, and the competitive manufacturers' products and their designs, a manufacturer cannot afford to take a "myopic" perspective in the design decisions by considering only its technical design and its impact on the customers. Given that engineering design decisions determine product cost and attribute positioning at the foundation of the development process, it is logical to conclude that engineering design decisions of a manufacturer are transmitted to competitors and retailers as strategies to which they are forced to counteract. For example, just as a manufacturer considers retailers' assortment, profit criteria, and competitors' existing products in designing a new product, other competitors may anticipate this strategy and make their own move to influence the retailers. They might, for example, reduce their wholesale prices to the retailers to make the retailer margins more attractive. Retailers, on the other hand, may also consider such dynamics in new product offerings and wholesale prices in making their own assortment decisions considering the extent of retail competition. Thus, "games" in the marketplace calls for the manufacturers to be "strategic" in their design decisions. This is a key assumption of our approach that has considerable support in practice (Montgomery et al. 2005).

Using the strategic approach proposed in this paper, a designer would be able to develop a scenario that if a product is designed with engineering design variables $\mathbf{x}$, which result in customer level product attributes $\mathbf{y}$, then an equilibrium price vector P would appear in the retail environment as a result of strategic interactions by competing retailers and manufacturers. The retail price vector P determines the market shares m and manufacturer profitability Π of the design that the manufacturer wants to maximize. Thus, using our approach, a manufacturer is able to determine the optimal new product design under different structures characterizing the retail channel, specifically, how the optimal engineering design variables $\mathbf{x}$ and manufacturer and retailer profits vary under different channel structure scenarios. Additionally, in the case of retail duopoly structures, our strategic approach enables consideration of the specific channel strategy early in the design process to determine the optimal new product design. It is important to note that our approach is appropriate in specific institutional settings where the model assumptions we make are valid. In market settings that are different, our framework can be used as a heuristic to develop hypotheses that could be tested using other approaches.

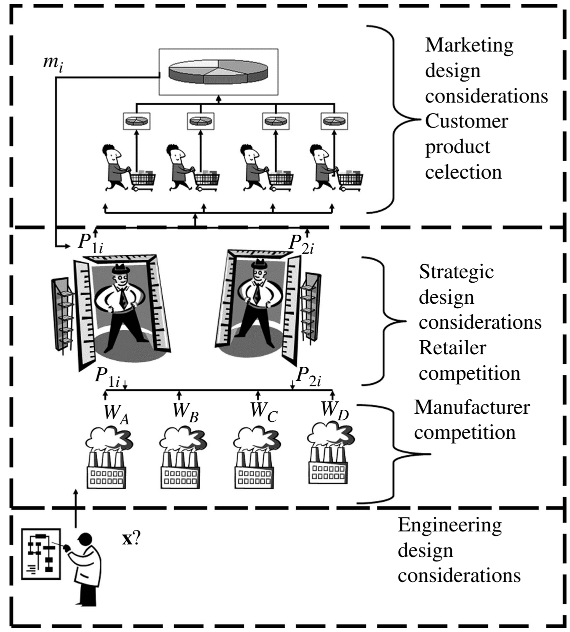
With respect to the extant literature in the product development area, our area of focus—downstream channel structure, strategies, and product design decisions—has seen limited research (see Krishnan and Ulrich 2001, Krishnan and Loch 2005). Whereas early work has focused on upstream channels in explaining product variety in the market as a function of supply chain structure (Randall and Ulrich 2001) and in exploring the impact of supply chain configuration/coordination in a manufacturer–retailer competitive setting on product design/product variety in the market (Subramanian and Kapuscinski 2002, Subramanian et al. 2008), only recently have Luo et al. (2007), Williams et al. (2008), and Shiau and Michalek (2009) incorporated downstream channel considerations in an empirical setting to determine optimal product designs. However, these papers consider the design issue either only in the retail monopoly setting or in an analytical setting. Our approach focuses on understanding (in addition to customer-facing attributes and price) the variations in engineering design attributes and, more importantly, physical feasibility along with related costs within multiple channel structures (retail monopoly versus retail duopoly—identical versus differentiated) and channel cooperation strategies (exclusive versus nonexclusive strategies). In addition, our approach provides insights into which design variables need to be right on target and where variations in design variables can be tolerated under different channel structures.

In §2, we provide an overview of our proposed framework along with model assumptions and justifications. In §3, we discuss the numerical examples and analysis that provide an illustration of our methodology, along with the different cases and results. We highlight the managerial implications and the challenges in generalizing the approach in §4. We conclude in §5 by presenting the contributions, limitations, and extensions of our approach and directions for future work.

2. Market Structure and Proposed Framework

The product market that we consider is one characterized by manufacturers reaching out to customers indirectly through a retail channel consisting of powerful retailers (monopoly or duopoly). The manufacturers differentiate themselves with strong brands in a mature market and compete with other man-

Figure 1 **Strategic Design Framework**



ufacturers for retail shelf space. When they introduce new products, they set wholesale prices for the retailers who choose to either carry the product or not carry the product. Retailers set their own retail prices, which along with the wholesale price is taken into account for the carry or carry-not decision. This product market is characteristic of many consumer durables that are engineered and marketed to customers through retailers (e.g., power tools, household appliances, electronics, etc.). The multilevel strategic design framework is shown in Figure 1 for a retailer duopoly (which can be simplified to the monopoly channel by removing one retailer) with four manufacturers and four consumer segments. Table 1 provides the nomenclature we use in presenting the multitiered design framework.

The product design problem will be analyzed from the perspective of the manufacturer firm (i.e., the perspective of a product designer in the firm—bottom level in Figure 1) who is interested in maximizing profit and can be described as follows. In a competitive market of i products, manufacturer A (the focal manufacturer) designs a candidate product with engineering design variables $\mathbf{x}$ that must take into account the strategic response of other manufacturers. We assume that the other manufacturers B, C, and D have only the strategic move of altering their wholesale prices W_B, W_C, and W_D, respectively. This is a standard assumption (Luo et al. 2007) because other responses in attributes are difficult to achieve in the short term. For manufacturers to set wholesale prices, they must know the effect on market share, which can only be determined after retailers set their retail prices (e.g., $P_{ri} = P_{1i}, P_{2i}, \ldots, P_{Ri}$; middle level in

Table 1 Nomenclature

Engineering design variables (e.g., current, diameter, length, etc.)	**x**
Customer level product attributes[a] (e.g., weight, amp rating, etc.)	**y**
Intermediate level variables (attributes not evaluated by customers)	**z**
Engineering constraints	$g(\mathbf{x}) \leq b$
Product index for an n product assortment	$i = 1, \ldots, n$
Production cost of the ith product ($)[a]	C_i
Wholesale price ($) of the ith product[a]	W_i
Utility for attribute j of product i in segment k[a]	u_{ijk}
Total product utility for a product i in segment k[a]	U_{ik}
Market share of the ith product in segment k (%)[a]	m_{ik}
Market segment size (%)	S_k
Overall market share of the ith product (%)[a]	m_i
Market size (units)	N
Retailer index for R retailers	$r = 1, \ldots, R$
Retail price ($) of the ith product[a] of retailer r	P_{ri}
Profit of Retailer r on product i ($)[a]	π_{ri}
Profit of manufacturer on product i ($)	Π_i

[a]Functions of engineering design variables.

Figure 1). We assume that both retailers and manufacturers are fully informed about customer preferences (top level in Figure 1), which is a valid assumption in mature markets (e.g., Villas-Boas and Zhao 2005). The market provides feedback to the retailers' actions in the form of product market shares m_i. The retailers choose their retail prices to maximize profits in the monopoly case or to reach price equilibrium in the duopoly/oligopoly case. Considering the retail price responses at the retail level, manufacturers can determine equilibrium wholesale prices. Given price equilibrium at the two levels (manufacturer and retail levels) the manufacturer is able to determine the efficacy of any candidate design **x**. The focal manufacturer can, thus, perform a strategic scenario analysis with retail profits and manufacturer profits as outcomes given any design candidate. Thus, the framework provides a rich and realistic environment for evaluating engineering design decisions because it accounts for the power of retailers and the strategic responses available to competitors. We expand on the links between engineering design, strategy, and marketing in the next subsection.

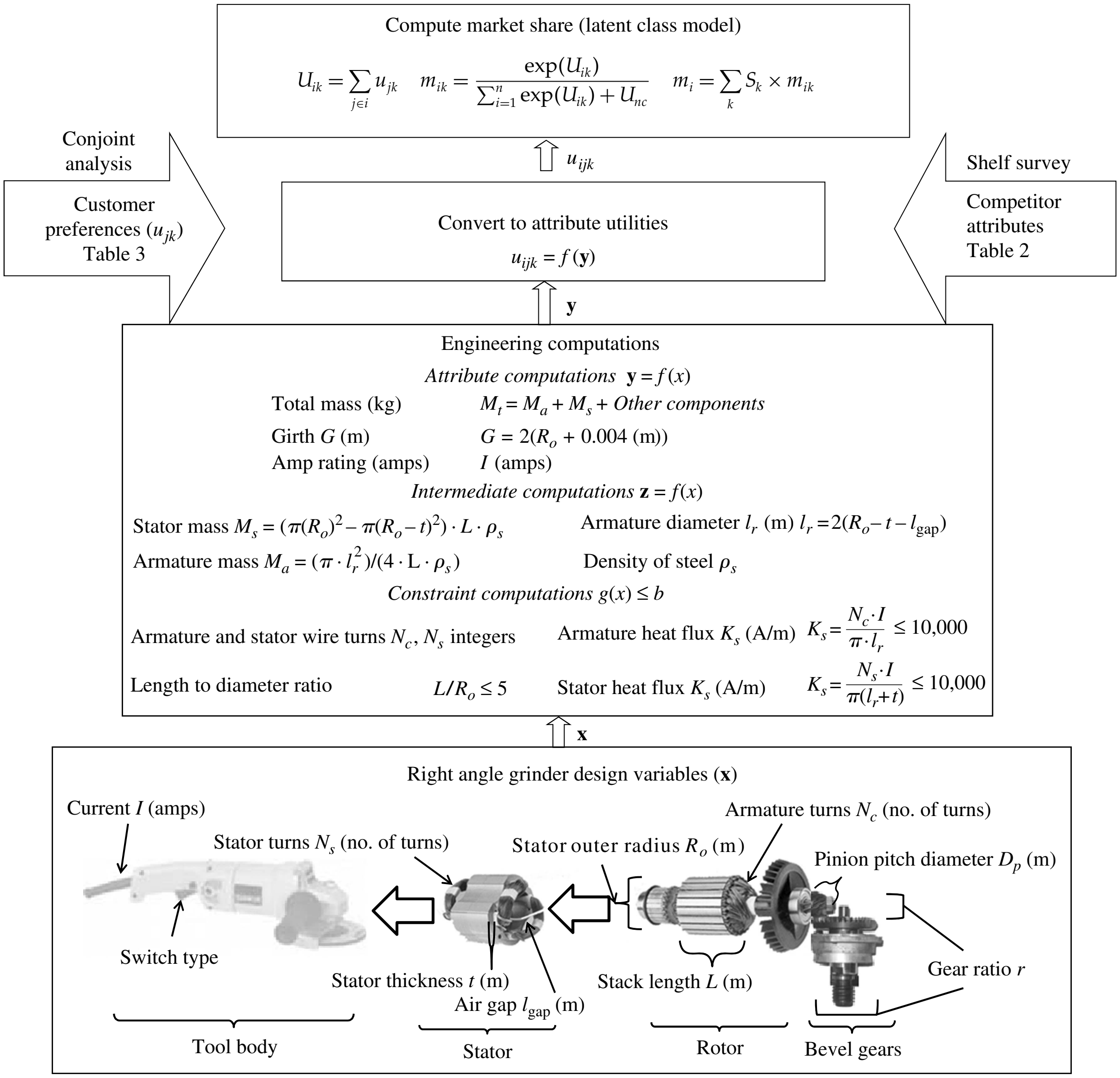
2.1. From Product Design to Market Share

Before discussing the strategic interactions in any design evaluation, we present the mapping process for turning engineering design **x** into product attributes **y**, which are then used to determine market share m_i. This process is depicted in Figure 2 for a hand-held power tool—a right angle drill. We assume that market information—competition and their offerings—is already available, through shelf surveys of assortments at the retailers. In the short term, we assume that the product attributes (except price) of competitor products, **y**, are fixed (e.g., the weight of competitor product). Each power tool's attributes in the assortment are recorded as the existing competitor's product attributes that are critical to the positioning of any new design. Customer preference data can be in the form of survey data or choice-based conjoint data. The customer preference data is analyzed using finite mixture estimation techniques to identify distinct latent class segments to capture the heterogeneity in customer preferences.[1] This latent class conjoint estimation along with the shelf survey allows our design approach to search for gaps in the competitive landscape that are weak in terms of competitive offerings as well as find customer segments whose preferences are currently underserved. The integration of this information with a bottom-up translation of engineering designs into customer relevant product attributes is presented in Figure 2.

The design process starts with an instance of design variables **x**, which are then transformed to product attributes **y** for the focal manufacturer through appropriate engineering computations and determination of intermediate variables **z**, which are frequently used for constraints (see the bottom two blocks in Figure 2). For example, the weight of product is calculated from the density and volume of its constituent components. Similarly, power and torque of a product will be functions of gear ratios, current, and voltage. Engineering constraints such as gear stresses, heat flux, armature velocity, and others are calculated at this point to determine if the candidate design is feasible before proceeding to market share estimate determination. Design variables and engineering functions (constraints or attribute functions) need not be continuous as we will employ a genetic algorithm (Deb 2001) to find optimal designs. It is worth noting that the marketing and engineering should collaborate (e.g., Morgan et al. 2001) to determine which product attributes and intermediate variables are most relevant in investigating for optimization (i.e., they must matter to customers or affect the production cost). For example, marketing communicates to engineering that weight is one of the important evaluation criteria to customers and should be an output of the design model. Similarly, if engineering and manufacturing have determined that revolutions per minute (RPM) is an important driver of cost in the past because of higher stresses and heat dissipation requirements, it should be communicated to marketing for inclusion in the conjoint study in an appropriate way. Even if customers place little value on such attributes, this knowledge will be important to the overall design optimization because designers can

[1] Alternatively, a hierarchical Bayes conjoint estimation can also be used to capture heterogeneity.

Figure 2 Product Design to Market Share



relax preconceived notions for minimum RPM values (a constraint) and possibly reduce production costs without affecting overall product performance and utility. Thus, an early concurrent consideration of all the relevant criteria (engineering design and customer preference) by the product development team gives a significant advantage in avoiding the costly mistake of performing customer studies that do not contain all of the relevant attributes that are cost or performance drivers in the engineering model (see Loch and Terwiesch 1998).

Once product attribute variables $\mathbf{y}$ are determined from intermediate engineering design computations, one can estimate the utility of each attribute $\mathbf{y}$ (with a piecewise interpolation of utility values assigned to attribute levels, if needed) based on the conjoint analysis estimates for each segment by summing the utilities u_{jk}, in segment k, of all attributes j that appear in product i resulting in

$$U_{ik} = \sum_{j \in i} u_{jk}. \tag{1}$$

The same procedure is repeated for each of the n competing products in the assortment. We estimate the segment share of product i in segment k as follows while taking into account the utility of the no-choice (or no-purchase) option U_{nc}:

$$m_{ik} = \frac{\exp(U_{ik})}{\sum_{i=1}^{n} \exp(U_{ik}) + U_{nc}}. \tag{2}$$

The total market share (%) of a given product i is computed by summing over the segment size S_k (%) estimated using the finite mixture estimation techniques

(Sawtooth 2001) and the market share within each segment m_{ik} (%) as

$$m_i = \sum_k S_k \cdot m_{ik}. \tag{3}$$

Given that retailers have increasingly consolidated power and control of the retail channel (i.e., access to consumers), evaluating the manufacturer's design in the context of the effect it has on retailer profit is an important consideration, even with our primary objective being to maximize the manufacturer profit. Clearly, if the manufacturer is concerned with a possibility of being denied shelf space by the retailer, he or she would prefer to select a design that is much more profitable for the retailer than the existing assortment it carries. At the same time the manufacturer's profit and the retailer's profit are competing objectives so a manufacturer would benefit from being able to choose from an optimal set of designs with respect to each of these objectives. The formulation presented in this paper is such an approach to setting the manufacturer's design strategy given a specific channel structure. As such, in addition to maximizing manufacturer profit we add a constraint to our formulation where the manufacturer also wishes to increase retailer profitability so as to ensure market access. Thus, the focal manufacturer's objective (when facing a monopolist retailer) can be stated as

$$\begin{aligned} \max_{x_i}: \quad & \Pi_i = m_i(W_i - C_i) \\ \text{s.t.} \quad & g(\mathbf{x}) \le b \\ & \sum_{i=1}^{n} \pi_i^{\text{new}} \ge \sum_{i=1}^{n} \pi_i^{\text{old}} \\ & C_i,\, m_i = f(\mathbf{x}). \end{aligned} \tag{4}$$

The focal manufacturer's profit Π_i is maximized by altering engineering design variables $\mathbf{x}$ so as to satisfy engineering constraints $g(\mathbf{x}) \le b$, realizing that market share m_i is largely a function of $\mathbf{y}$ and therefore $\mathbf{x}$. In addition to focusing on optimizing retailer profit we constrain the design search space to only those designs that improve the retailer's category profit (i.e., $\pi_i^{\text{new}} \ge \pi_i^{\text{old}}$).[2] Production costs C_i can be modeled as a function of the engineering design variables $\mathbf{x}$ or can be estimated from product attributes $\mathbf{y}$, like those shown in Figure 2 (U.S. Department of Defense 1999, Scanlan 2002). We have chosen to use the latter approach in our application, which is based on historical prices of products in a category. The formulation presented above may appear simple until one considers that market share is also significantly dependent on retail price P_i (as shown in Figure 2), which is also dependent upon the wholesale price W_i. The prices W_i and P_i are not under the manufacturer's control because of competitor manufacturer and retailer reactions, which require us to develop a more nuanced framework that endogenize price equilibrium models.

An equilibrium framework that analytically captures the interactions of Figure 1 is presented in Figure 3 for both monopoly (one retailer) and duopoly (two retailers) channels with an oligopoly of manufacturers competing with the focal manufacturer. The framework incorporates the layers of strategic pricing moves available to competitors under the classical game theory assumptions (Osbourne and Rubinstein 1994), assuming that players are rational and fully informed of each other's possible strategic moves (i.e., perfect information).

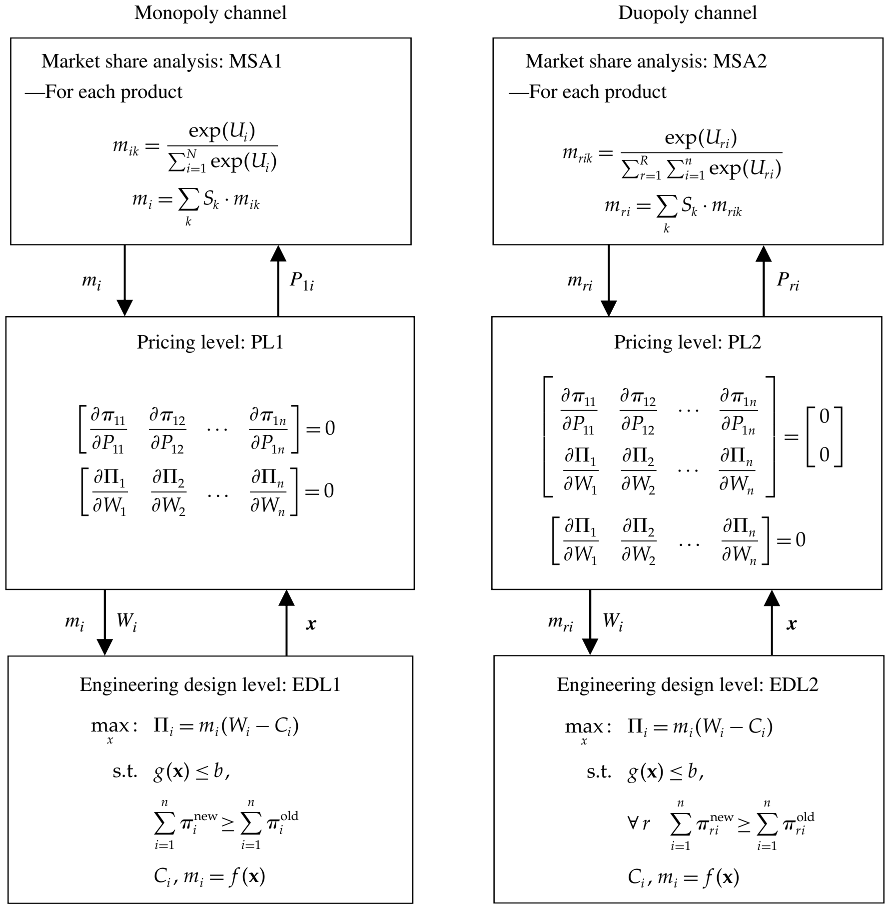
2.2. Equilibrium Framework

The focal manufacturer (manufacturer A) develops a new product A in the assortment $i = 1, \ldots, n$, which has engineering design variables $\mathbf{x}$ (bottom layer, Figure 3) with an objective to maximize profit. In the short term (one quarter to one year) the competing manufacturers will be unable to change product designs because of the manufacturing line and supply contract modifications that would be necessary. However, they can alter their wholesale prices and do so under the assumption that their competitors will attempt to make a "best response" to any W_i decision (manufacturer layer, Figure 3). The retailers also select retail prices P_{ri} that will maximize their profit under a "best" response assumption from their competitive retailer (in the case of a duopoly retail channel) or simply maximize profit (in the case of the monopoly channel). The retail prices and product designs affect each consumer segment depending on its specific preference structure, which the finite mixture latent class model estimates based on the conjoint analysis. These determine the segment sizes and the market shares (top layer, Figure 3).

The strategic aspects of retailers and manufacturers selecting retail and wholesale prices based on Nash equilibria makes the problem of optimizing product design computationally intensive. Following Luo et al. (2007), we solve the layered equilibrium conditions as a nested algorithm where the pricing level optimization is the selection of retail prices P using the Nash equilibrium of profit for retailers. The setting of wholesale prices is also based on the concept of Nash equilibrium. Simultaneously (with retail price setting), we minimize the sum of the squares of the first derivatives of manufacturer profit functions with respect to wholesale prices W_i to solve the manufacturer first-order conditions (FOC) in the middle layer of Figure 3. This structure creates a vertical

[2] This channel profit constraint is deterministic although a stochastic or "chance constrained" approach has been developed for a single-objective model in previous work (Williams et al. 2008). However, they do not consider this in a strategic context, that is, they do not consider the (re-) actions of other manufacturers or retailers.

Figure 3 Equilibrium Framework



Nash equilibrium for the manufacturers and retailers in setting prices. The details of the optimization methodology are provided in the online appendix (provided in the e-companion),[3] where we also provide proofs that optimal engineering design is dependent on the channel structure.

3. Numerical Examples and Analyses

In this section, we provide two numerical illustrations to highlight how channel structure impacts optimal engineering design. The first example involves a very simple design problem to highlight the intuition behind different optimal designs for different structures and how they are related to customer preferences. The second example is a power tool design problem based on some customer preferences and firm and market data.

3.1. Impact of Channel Structure on Engineering Design: A Simple Numerical Example

Let us assume we focus on a single design variable x (say, product life expressed in number of years).

[3] An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

Consider the manufacturer profit maximization problem of Equation (4) determining the optimal x_i of product i, with the overall market share m_i being the sum of market shares from each retailer r, m_{ri}. Then Equation (4) without the retailer constraint can be rewritten as

$$\begin{aligned} \max_{x_i}: \ & \Pi_i = \sum_{r=1}^{R} m_{ri}(W_i - C_i) \\ \text{s.t.} \ & g(x) \le b \\ & C_i, m_i = f(x). \end{aligned} \tag{5}$$

Expressing the market shares derived for product i from each retailer using a logit expression and the cost function to be a quadratic function of x with coefficient c and intercept C, the above maximization problem can be written (dropping the subscript i) as the sum of profits derived from each retailer r:

$$\max_x \Pi := N \sum_{r=1}^{R} \frac{(W - c((x-1)^2 + x) - c)\exp(bx - (P/\mu) + U)}{\exp(bx - (P/\mu) + U) + U_{tot} + U_{nc}}, \tag{6}$$

where N is the total market size. The designer/manufacturer's margin is the difference in wholesale

Table 2 Example Problem Settings

	Focal product	Competitor
Competitor specific parameters		
U^a (segment 1)	6.5	6
U^a (segment 2)	5	6
Common parameters		
C	1/3	
N	1,000,000 units	
U (no choice)	−1.1	
	Segment 1 (50%)	Segment 2 (50%)
μ	10	12
B	1/5	8/15

[a] U does not contain x (quality) or price utility.

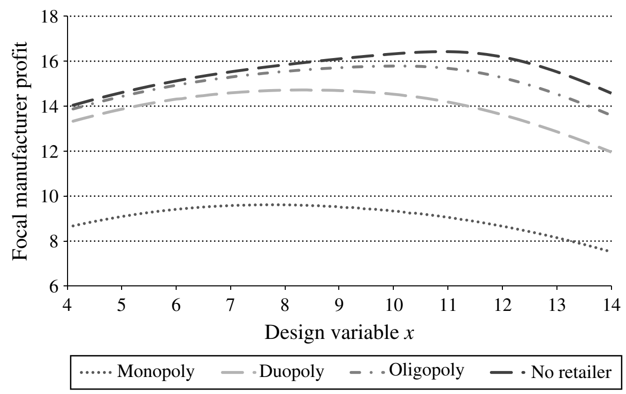
price W and the quadratic cost function with coefficient c and intercept of C. Utility increases linearly in x at the rate of b and utility decreases linearly in retail price P at a rate of $1/\mu$. We consider one other competing product in the market place and between zero and three retailers so profits are summed across the index r as well as segments k, which is suppressed (see Equations (2) and (3)). The total utility of competing product in this case is represented by U_{tot}, and U_{nc} is the utility of the no-choice option. The competitor has a design of $x = 9$ and identical cost structure to the focal manufacturer (see Table 2).

Even with such a simple problem, an infinite number of analysis scenarios are possible, so we focus on realistic problem parameters that were robust in converging to pricing equilibria as shown in Figure 3.

We analyze four simple cases: (1) no retailer (i.e., the manufacturers sell directly to market); (2) monopolist retailer; (3) duopolist retailers; and (4) a three-member oligopoly of retailers. Prices for the competing manufacturer and the retailers are calculated using a nested optimization using FOC for retailers and manufacturers as shown in Figure 3. The no-retailer case is important because if one is to believe that channel structure is important then we should see a difference between optimal design without retailers and those taking into account retail pricing. The cases are exhaustively analyzed for design optimality by parameterizing x between 2 and 15. Our aim is to see how optimal design changes according to market structure and examine why that is so.

One can see in Figure 4 that the optimal design varies markedly by virtue of the channel structure. The optimal design (i.e., product life, which is a measure of design quality) for the monopoly case $x_m^* = 7.8$ is significantly lower than the other three cases. From there the duopoly structure has the next lowest optimal design ($x_d^* = 8.4$), followed by the three retailer oligopoly ($x_o^* = 10$) and finally when retail competition is neglected we have the highest quality design ($x_{nr}^* = 10.9$). The difference between the monopoly case and the competitive retail case is the most striking and is largely explained by the equilibrium pricing as shown in Figure 5.

Figure 4 Channel Structure Effect on Optimal Design



Clearly, in the monopolist case, equilibrium retailer markup increases significantly as quality is increased and the monopolist retailer prices the products much higher in general (an average of \$133 for all products and \$103 for the optimal product). The higher monopolist markup and prices are anticipated (see, e.g., Andersen et al. 1992) because of lack of a strong no-choice option. In contrast, average and optimal retail prices for the duopoly across all retailers (average \$120, optimal \$89) and oligopoly (\$118, \$98) cases are much lower, which is also consistent with expectations as retail competition rises.

In examining Equation (6), costs increase quadratically in quality (left side of numerator) and utility increases linearly in quality so one would expect a trade-off to exist. The design variable equilibrium for the monopoly is reached much quicker (lower) in the parametric study because the comparative utility with the no-choice option is reached much more quickly with the higher markup from the retailer. At this point, subsequent increases in quality add insufficient utility to overcome the subsequent increase in price

Figure 5 Average Equilibrium Retailer Markup as a Function of Focal Design

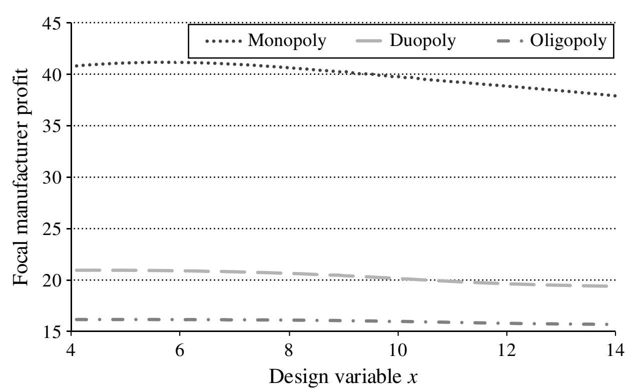
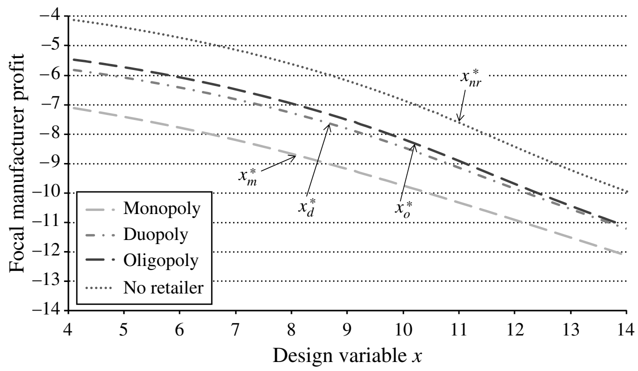


Figure 6 **Pricing Change with Respect to** x



and loss of utility. We can see this by analyzing the inner focal manufacturer component of Equation (6). If we assume wholesale margins (first parenthetical in numerator of Equation (6)) have reached an equilibrium, changes in profitability can only be accomplished by the focal manufacturer changing x in the second numerator parenthetical in Equation (6): $x + (P_r/\mu) + U$. Let $A = (bx + (P_r/\mu) + U)$; the following identity should be true at equilibrium when a solution is focused largely on one segment: $dA/dx = b - (1/\mu)(dP_r/dx) = 0$ if we take an economic interpretation that the gain in utility for quality should be equal to the loss of utility for cost at equilibrium. Thus, the design equilibrium for a given strategic case is realized when the utility coefficient b is equal to the change in price with respect to quality dP_r/dx after being scaled by the price scaling factor μ. We numerically observe that each of the strategic cases converged to a slope similar to b for segment 2 (see Figure 6). The slope for the monopoly and duopoly cases (change in P_r/μ with respect to x) is nearly equal to 8/15 at the optimal design that equates to the second segment's quality sensitivity (b).

The monopolist case, not surprisingly, converges to a design/price equilibrium that equates to the second segment's price elasticity where consumers are least price sensitive. The second segment is the least sensitive to price increases and yet places more value on design improvements by virtue of the coefficient μ and b, respectively (see Table 2). Clearly, the monopolist is less interested in increasing quality because maximal profits can be made off of the second segment with very little penetration into the first segment (less than 17%). The remainder of the cases also have low penetrations in segment 1 (relative to segment 2), which were 30%, 22%, and 19% for duopoly, oligopoly, and no-retailer, respectively. These cases converge to slopes of 0.5 to 0.7, which is closer to the b attribute of segment 2 than that of segment 1 as expected.

This numerical study suggests that retail pricing in the monopolist case will have significant effects on optimal design. Specifically, the monopolist retailer has incentive to select products to take advantage of its strategic position, so it forces the focal manufacturer to produce lower/medium quality and price it high enough to skim the market. As more retailers enter the market prices get more competitive. As the monopolist retailer relinquishes control to a duopoly/oligopoly, the focal manufacturer starts to focus on increasing quality to capture market share from the higher-quality competitor as the price utility of all products increases. As quality increases, the products with lower prices reach more of the low-end, price-sensitive consumers. It is also worth noting that as more retailers are added to the channel the difference between the no-retail and oligopoly structures start decreasing. So, if the number of retailers is very high (fragmented channel) then manufacturers can totally disregard the impact of retailers in their design as that impact will be very minimal (it is as if there were no retailers).

The results we discuss in this example are consistent with the analytical result (in Online Appendix B) that product quality tends to be higher, given the preferences of the consumer segments, and prices decrease with retail competition. Additionally, optimal designs are shown to be dependent on channel structure as shown analytically in Online Appendix B. Somewhat specific to this numerical example (i.e., both consumer segments value higher quality) quality increases with retail competition, as a focal product design gets closer to consumer segment preferences given the underlying settings and assumptions (e.g., that costs are a function of design and utility is mildly increasing in quality for both segments). Costs as a function of production run volumes, and higher-order utility functions may yield different results but one can make the firm conclusion that monopoly and duopoly retail pricing can affect design significantly—retail competition tends to increase product qualities, lowers prices, and allow offerings to reach the more price-sensitive consumers—and so the market structure should be taken into consideration by the designers. If the number of segments increase, the larger of the more price-sensitive segments' preferences will have a greater impact on the optimal design. It should also be noted that consistent with the numerical nature of the previous example, the observations are only locally valid though consistent with extant economic/game theoretic literature and the analytical results in Online Appendix B. These results are functions of many parameters (segment sizes, cost coefficient, price sensitivity, quality sensitivity of segments, and the utility of no choice, etc.) and so are valid within close vicinities of these parameter values and thus cannot be generalized when one or more parameters change significantly.

Table 3 Example Assortment at a Retailer

				
Tool	A	B	C	D
Brand	W	X	Y	Z
Amps	8.00	12.00	6.00	9.00
Life (hrs)	80	110	150	110
Switch	Paddle	Trigger	Side	Side
Girth (in)	2	4	2	2.5
Weight (lbs)	6.00	16.00	5.00	6.00

3.2. A Power Tool Design Example

In this section, we present a practical engineering design example using four cases of varying retail channel structures to show the effect of taking into account the channel's competitive structure on optimal engineering design based on an actual product-market. We consider four manufacturers (A–D) and two retailers (1 and 2) (see Table 3). The channel structure cases are as follows:

Case 1: Retailer Monopoly/Manufacturer Oligopoly. In this case, given the one retailer, strategic interactions occur only at the manufacturer level in setting wholesale prices that impact the engineering optimization. This is the baseline case that extends the prior work in the retail monopoly setting (Luo et al. 2007) to include engineering design optimization.

Case 2: Retailer Duopoly/Manufacturer Oligopoly—Identical Retailers. In this case, each retailer carries the same assortment and consumers across all segments are indifferent as to which retailer to buy from, so the retailers compete only on price. This case is more complex than Case 1 because it also has strategic interactions at the retailer level. The formulation for setting retailer prices takes into account wholesale prices as before but now is formulated as an equilibrium optimization where retail prices are adjusted to minimize the square of the first derivatives of the duopoly retailers' profits with respect to price. Although somewhat unrealistic, such a case should demonstrate downward pressure on retail prices and therefore wholesale prices relative to the monopoly case. This will also serve as a baseline to examine Case 3 and Case 4 results.

Case 3: Retailer Duopoly/Manufacturer Oligopoly—Differentiated Retailers. This case is more realistic because it accounts for the differentiated preference of consumers for the retailers themselves. For example, Lowe's targets female customers with wider, brighter isles and a greater emphasis on decorating. A conjoint study can easily include samples where product i is offered at retailer r and then assess the value that consumers place on the "retailer attribute." In Table 4 we show that three out of four customer segments prefer one retailer over the other.

Case 4: Retailer Duopoly/Manufacturer Oligopoly—Exclusive Retailer Strategy. This models the case where manufacturers and retailers seek exclusive channel relationships (Moner-Coloques 2006) as a means to secure access to market (manufacturer's perspective) and as a means to differentiate an assortment for greater profits (retailer's perspective). We model this arrangement in a manner similar to Case 2 except that the focal manufacturer decides to go to the market through only one of the two identical retailers as an exclusive retailer strategy. This approach where one retailer is allowed to fulfill all demand has been shown to theoretically improve profits for both parties in the exclusive channel (Tsay and Agrawal 2004). The retailer chosen for the exclusive relationship will carry the new product offered by the manufacturer as long as its profits improve relative to the original assortment just as in the previous cases. The competing retailer not chosen for exclusivity with our manufacturer simply offers the original assortment.

Table 4 Utility Estimates for Four Latent Segments

	Segment							
	1		2		3		4	
Share (%)	36.40		26.62		13.17		23.81	
	μ	σ	μ	Σ	μ	σ	μ	σ
Brand								
W	−0.5	0.1	0.5	0.1	2.2	0.05	−0.2	0.1
X	0.2	0.1	1.1	0.1	−2.4	0.06	−0.2	0.1
Y	0.8	0.1	0.1	0.1	−1.5	0.1	1.2	0.1
Z	−0.5	0.1	−1.6	0.1	1.7	0.06	−0.8	0.1
Price								
$60.00	2.38	0.1	2.83	0.05	2.12	0.09	1.87	0.1
Slope (*u*/$)	−0.06	0.001	−0.045	0.002	−0.035	0.001	−0.04	0.001
Amps								
6.0	1.3	0.1	0.5	0.1	−1.5	0.06	−0.5	0.1
9.0	0.1	0.1	−1.4	0.1	−0.7	0.1	−2.4	0.1
12.0	−1.4	0.1	1.0	0.1	2.1	0.1	2.8	0.2
Life (hrs)								
80.0	−0.9	0.1	−0.1	0.1	−4.7	0.08	0.8	0.1
110.0	1.3	0.1	−0.5	0.0	−5.8	0.03	0.7	0.1
150.0	−0.4	0.1	0.6	0.1	10.5	0.04	−1.5	0.1
Switch type								
Paddle	0.4	0.1	0.3	0.1	−3.3	0.05	−0.7	0.1
TopSlider	−1.0	0.1	−0.7	0.1	−3.0	0.04	0.4	0.1
SideSlider	2.4	0.1	−0.1	0.0	2.5	0.05	0.6	0.0
Trigger	−1.8	0.1	0.4	0.1	3.9	0.04	−0.3	0.1
Girth								
Small (1.5 in)	0.5	0.1	0.7	0.1	1.5	0.03	2.4	0.1
Large (4 in)	−0.5	0.1	−0.7	0.1	−1.5	0.03	−2.4	0.1
Weight								
16 lbs	−2.3	0.0	0.8	0.0	−1.5	0.02	1.5	0.1
9 lbs	0.5	0.1	1.2	0.0	0.5	0.01	0.5	0.0
6 lbs	1.8	0.1	−2.0	0.0	1.0	0.04	−2.0	0.1
Retailer								
One	0.5	0.1	0.7	0.1	−1.5	0.05	1.4	0.1
Two	−0.5	0.1	−0.7	0.1	1.5	0.05	−1.4	0.1

We apply Cases 1–4 to a previously developed design problem. Although the channel structure of the case is characterized by a differentiated duopoly, we analyze an assumed monopoly structure (with the more dominant of the two retailers as the monopolist), an identical duopoly, and the possibility of the manufacturer going into an exclusive channel contract

Figure 7 Optimization Formulations

Monopoly

$$\max_{x, W_i}: \quad \Pi_i = m_i(W_i - C_i)$$
$$\max_{x, W_i}: \quad \sum_{i=1}^{n} \Pi_i$$
$$\text{s.t.} \quad g(\mathbf{x}) \le b, \quad \sum_{i=1}^{n} \pi_i^{\text{new}} \ge \sum_{i=1}^{n} \pi_i^{\text{old}}$$
$$C_i, m_i = f(\mathbf{x})$$

Duopoly

$$\max_{x, W_i}: \quad \Pi_i = m_i(W_i - C_i)$$
$$\max_{x, W_i}: \quad \sum_{r=1}^{2}\sum_{i=1}^{n} \pi_{ri}$$
$$\text{s.t.} \quad g(\mathbf{x}) \le b, \quad \forall r \sum_{i=1}^{n} \pi_i^{\text{new}} \ge \sum_{i=1}^{n} \pi_i^{\text{old}}$$
$$C_i, m_i = f(\mathbf{x})$$

Exclusive

$$\max_{x, W_i}: \quad \Pi_i = m_i(W_i - C_i)$$
$$\max_{x, W_i}: \quad \sum_{i=1}^{n} \pi_{1i}^{\text{new}}$$
$$\text{s.t.} \quad g(\mathbf{x}) \le b, \quad \sum_{i=1}^{n} \pi_{1i}^{\text{new}} \ge \sum_{i=1}^{n} \pi_{1i}^{\text{old}}$$
$$C_i, m_i = f(\mathbf{x})$$

with one of the retailers. The monopoly case forms the baseline to examine the impact of duopoly, and the identical duopoly is used as a baseline to compare the exclusive channel contract. These comparisons provide better insights into how the channel structure impacts design decisions, which is quite useful for the focal manufacturer as the channel structures do vary across different categories of tool manufacturers. A detailed engineering design structure and conjoint data (Williams et al. 2008) were available for common small angle grinders and an ideal candidate application for the case studies as they are typically sold in a strong retailer channel environment. A brief shelf survey of the channel controlling retailers would reveal an assortment similar to that shown in Table 3.

For the four strategic cases considered, our model replaces tool A with a new product when the channel constraint is met in Equation (4). The assortment is the same for the retailers under the monopolist and duopolist cases in that they carry the new product and products B–D. For the fourth (exclusive retailer channel) we assume that retailer 1 carries the new product and that the competing retailer carries the existing product (i.e., product A from Table 3).

3.2.1. Estimating Number of Segments and Market Shares. The latent class segmentation module (Sawtooth 2001) of the Sawtooth Software Market Research Tools (SMRT) was used to perform a conjoint analysis for small angle grinders (Figure 7) reanalyzing the customer response data from Williams et al. (2008) treating price as a continuous attribute and the other attributes as discrete levels. The results of the conjoint analysis are tabulated in Table 4. Each segment has an estimate of utility mean (μ) and standard deviation (σ) for several possible alternatives of product attributes. The utilities are normalized using Sawtooth Software. For the application we assume that prices are set by players (retailers and manufacturers) based upon the mean value for attribute utilities. A linear interpolation of utilities from Table 4 is used for any product attribute along with Equations (1)–(3) to determine the segment and market share of any given design.

3.2.2. Engineering Model. An engineering model is necessary to produce feasible designs that generate product attributes that are evaluated at the customer level on the basis of the finite mixture latent class model estimates. These attributes will impact production costs as well as the strategic pricing of any product. We employ a detailed engineering model that provides direct links from design variables to customer conjoint attributes in Table 4. The components that are the greatest drivers for tool cost are shown in Figure 2 with the associated engineering design variables at the bottom of the figure. One can see that the rotor and bevel gear assembly slip inside of the stator that is then encased in the plastic body of the tool. The engineering design variables shown are evaluated to ensure feasibility as well as calculate product attributes (weight and girth) prior to utility conversion and ultimately calculation of market share as explained in §2.1 (see Williams et al. 2008 for all computations; also included in the online appendix).

Stator and armature mass make up a large component of the motor mass M_m presented in Figure 2 that is then used to compute the designs' utility from Table 4 using piecewise linear interpolation. Like any engineering problem it is necessary to satisfy constraints to ensure that the product will operate safely under a variety of conditions as well as be durable and reliable. These are shown in detail in the online appendix, Table E1, and ensure that the design selection process does not produce motors that will exceed constraints such as heat flux limits or the recommended slenderness ratio L/R_o. These constraints are evaluated before any pricing algorithm is run as developed in §2.2. Thus, we are able to reject infeasible engineering designs prior to the computation cost of reaching wholesale and retail prices.

Production cost is a critical component in our strategic framework because an increase in cost puts upward pressure on wholesale and retail prices for any competitor. We model cost C_i as a function of product attributes that takes the form presented in Equation (10):

$$C_i = \beta_0 + \beta_1 I + \beta_2 (I \cdot V / M_t) + e, \tag{7}$$

where β_1 and β_2 are the multiple regression coefficients with estimates of 3.6160 and 0.1865, respectively; the estimate of intercept β_0 is found to be −29.294; I is the current of the tool in amps; and IV/M_t is the power to weight ratio in watts/kg, where V is voltage and M_t is the total weight. For a detailed development of the multiple-regression cost model, see Williams et al. (2008). Finally, the example is implemented within our framework whereby engineering design variables (Figure 2) are optimized while taking into account engineering constraints and production costs (Equation (10)) all within the strategic pricing topology presented in Figure 3.

3.2.3. Analysis Details. We used Matlab's Genetic Algorithm and Direct Search Toolbox (MathWorks 2007) to develop a multiobjective genetic algorithm to simultaneously optimize focal manufacturer profit (manufacturer A) and retailer profit. Although our focus (Equation (4)) is to maximize the focal manufacturer's profit while ensuring that retailer makes at least as much profit as he was making with the existing assortment, an extension to finding the Pareto solutions for manufacturer and retailer profits helps to understand design impacts within a channel better, as we show subsequently. Additionally, one could argue that the increase in the retailer's profitability above the prior assortment profit would strengthen the manufacturer's case to obtain shelf space. Thus, we formulate the manufacturer's decision as two objectives: (1) maximizing his own profit, and (2) maximizing the channel partner's profit (monopolist, duopolist, or exclusive retailer). This can be described mathematically by adding the retailer profit maximization objective to the engineering design level (Figure 3). (In the retail duopoly, retail profits are the sum of the two retailers.) Three optimization formulations that we evaluate at the engineering design level are shown in Figure 7.

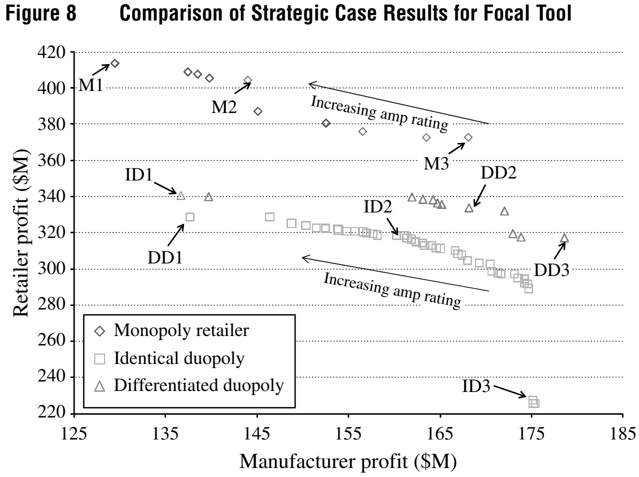
A nondominated sorting algorithm (Deb 2001) is employed to find a Pareto frontier for each strategic situation (monopoly, duopoly with identical retailers, and duopoly with differing retailers, and the exclusive retailer). The inner optimizations for retail price setting and wholesale price setting are strictly quasiconcave for monopoly and duopoly price setting (see the proofs in Online Appendix B) and as such are amenable to gradient based optimizers such as Matlab's fmincon (MathWorks 2007). The computational issues involved in our methodology are discussed at length in Online Appendix C.

3.3. Results of Numerical Analysis

The results focus on manufacturer A's design strategy in developing a new design to replace the existing product A design in the market under different channel structures. We assume that the competitor products remain in the market with their existing attributes but possibly changing wholesale prices, which is taken into account in developing the new design scenarios using strategic analyses. Because our numerical results are a function of (a) the relative utilities of consumers in the different segments, (b) the competitive product attributes and positioning in the market, and (c) competitor actions, we graphically provide the impact of these interactions by considering changes in design attributes as functions manufacturer and retail profits under the different channel structures and strategies.

3.3.1. Impact of Channel Structures: Monopoly, Identical Duopoly, and Differentiated Duopoly. The optimal design solution set of each of the strategic cases presented in Figure 8 are unique and are a function of the specific channel structure. All designs have a high probability of acceptance by the retailers because they satisfy the profitability improvement constraint from Figure 7, but, of course, those designs that provide higher retailer profitability provide an extra incentive for the retailers to carry the product (i.e., designs M1, ID1, DD1). The Pareto frontier (rather than analyzing a single design) is interesting in that manufacturers can analyze a trade-off between retailer incentives and their own. Strategies can even be developed from this information. For example, under the monopolist setting the manufacturer might propose a \$5 million slotting allowance to the retailer to carry M3 instead of M1. Clearly, the manufacturer is expected to be better off under that choice than designing M1. Similarly, the design ID3, although is Pareto optimal, is an exceedingly poor choice for the manufacturer if we do not consider the retailer profit as an objective. In this case the manufacturer can select design ID* with relatively little loss in profit but a significant improvement in retailer profitability. Figure 8 also provides those designs that provide significant profits to the manufacturer while

Figure 8 Comparison of Strategic Case Results for Focal Tool



ensuring that the retailer profits are high (designs M2, ID2, and DD2). These designs can be considered as "optimal" designs under each channel structure and are included in the table in Online Appendix C.

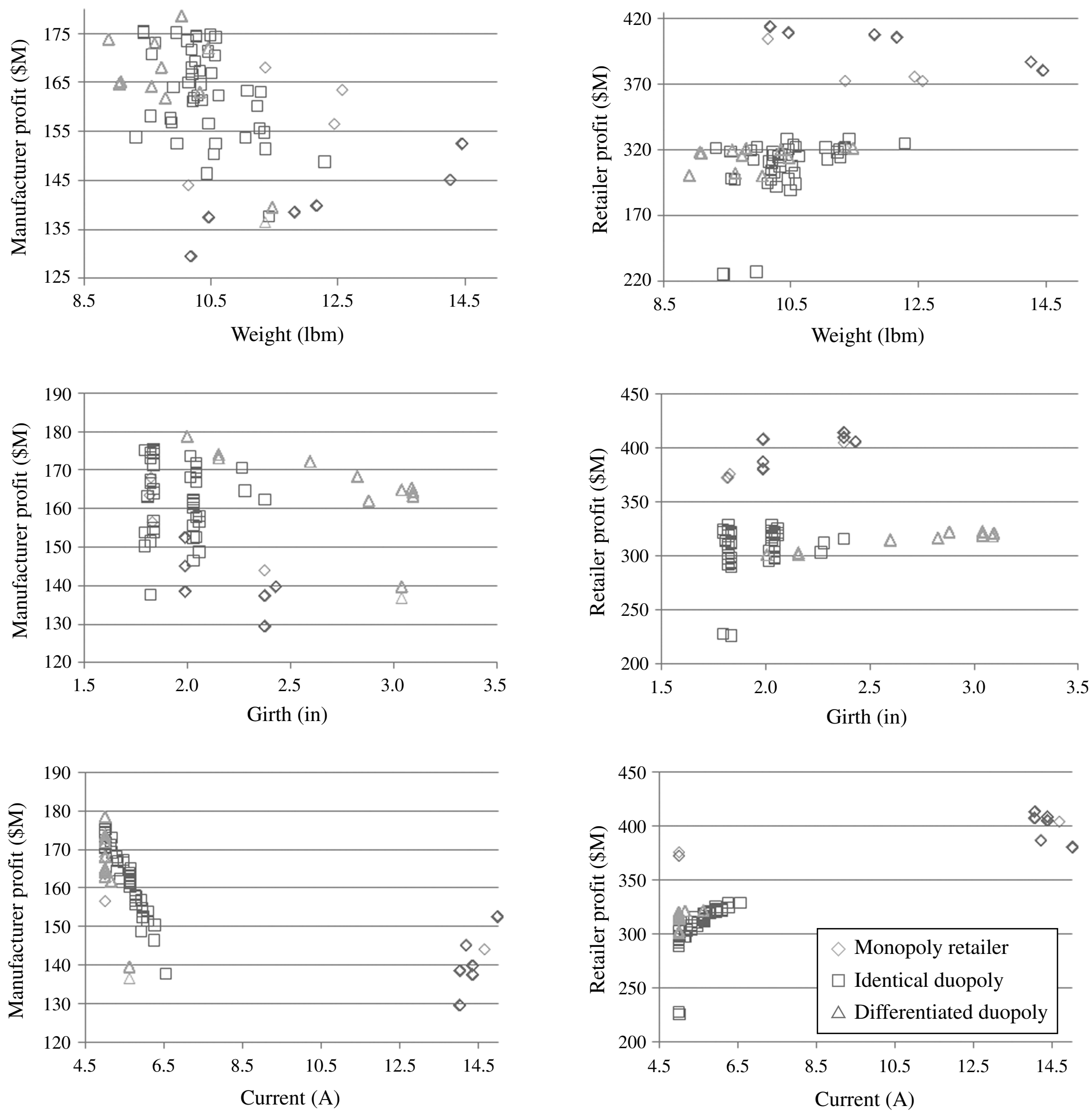
The monopoly Pareto frontier spans the lower profit regions for manufacturers—both duopoly cases have solutions acceptable to the retailers that have higher profits than the monopoly solution with the greatest manufacturer profit. In addition, monopoly retailer profits exceed profits of either of the duopoly cases, which is consistent with the extant literature (Anderson et al. 1992) given that the monopolist does not have competitive pressure to shift prices lower. In Figures 8–10 duopoly profits are the sum of the two retailers' profits.

The increased price competition in the two duopoly retailer cases (identical and differentiated) allows for the possibility of greater manufacturer profits. Retail prices are significantly lower for the duopoly cases as expected (Andersen et al. 1992; and as in the previous numerical example) which increases the overall market penetration and profitability for the focal manufacturer by reducing the number of consumers who do not participate in the market (choosing no-choice option) and focusing on the more price-sensitive consumers and their preferences. To reduce these retail prices for the duopoly cases the optimization feedback from the retailers suggests that lower production cost and lower wholesale prices are preferable (even though the best assortment fit lies in the high performance/high retail price strategy as evidenced by the monopoly results). The lower production cost has important implications for the optimal designs. Specifically, they drive down the current rating. This is precisely what we see in Figure 9, which shows that the duopoly case designs tend to be characterized by lower current rating and weights as compared to the monopoly case. For example, none of the competitor products (Table 3) can compare on amp rating to the monopoly designs that reach 14.5+ amps nor the extremely low performing solution at 4.5 amps (see Figure 9, bottom panels). In addition to a high current rating, the focal manufacturer has chosen to largely pursue designs in the 2.5 in to 3 in girth range and 10 to 14 lb range for the powerful monopolist models, which is significantly smaller in girth and lighter than the competing powerful product (product B) and larger/heavier than all of the rest of the competing products.

However, these results are also easy to explain when one examines the customer preferences in Table 4. From Table 4 we can infer that segments 2 and 4, which together make up 50% of the market, prefer heavier and more powerful tools. They are also not as price sensitive as segment 1. Therefore, in the monopoly case, the retailer prefers to carry a high performance, more expensive assortment of tools with higher margins and focus on the relatively price-insensitive and quality-sensitive segments to skim the market (the segments make up 50% of the market). Hence, the optimal design for the focal manufacturer tends to be the heavier and higher price tool. However, when the channel structure changes to duopoly and price competition starts to overwhelm the other attributes as competition forces prices lower, the more price-sensitive segment 1 (with a market size of 36%) suddenly becomes more important to the retailers competing for marker shares and profits as more consumers participate in the market moving away from the no-choice option lured by lower prices. Given this fact, the focal manufacturer starts to focus on designs that are lower in prices, lower in power (amperage), and lighter in weight (see Table 4) catering to the needs of the more price-sensitive segments. This is precisely what we observe in Figure 9, where the duopoly solutions tend to align more with the more price-sensitive segment 1 preferences. The insight that emerges from this analysis is similar to the one from the numerical analysis in §3.1—under the monopolist condition, the retailer targets the price-insensitive segment to make more profits—this results in higher prices than otherwise for the consumers targeted and depending on quality preferences for this segment and the location of competitive products, the segment may or may not get the quality they most prefer. Under duopoly with more price competition, the retailer has an incentive to target the more price-sensitive segments with products they prefer the most. In this case, it is the segment 1 preferences that determine the optimal design to a great extent.

The plots in Figure 9 also show that the tool attributes affect the players (retailers or focal manufacturer) differently depending upon the strategic case. The most drastic example is the effect of increased current rating on the duopoly cases. Even minor increases in current appear to drive manufacturer profitability sharply lower. This is because higher values of current are farther away from the ideal values for segment 1 and also lead to higher manufacturing costs. Thus, increased cost causes the manufacturer to lose profits in the environment of stiff price competition. A weaker trend can be seen in the decreased manufacturer profits associated with heavier tools for the duopoly cases. The opposite is true for the monopoly case where the monopoly retailer is able to encourage the design of the tool that fits his or her assortment (heavier and more powerful) without regard to price competition. Just as importantly optimal profits of all parties are relatively insensitive to girth and some strategies are distinctly absent for design considerations. For example there are no large

Figure 9 Focal Tool Attribute Correlations with Manufacturer and Retailer Profit



girth tools (above three inches in diameter) and no tools that are simultaneously light with low amperage. All tools are at least medium in weight, which implies that under no circumstances is the increased cost of higher power to weight ratios sufficiently offset by increased utility for higher-power, lower-weight tools. (Table D1 in the online appendix provides the details of the designs shown in Figure 8 by selecting a design from each end of the strategic case Pareto frontiers and also the optimal for each strategic case.)

The insights from these results are very instructive. Under a monopoly structure, retailer steers the new design to align with the segment that is least price sensitive and, in this case, the segment that prefers higher power and heavier tools. Under duopoly the assortments cover a wider spectrum of market preferences and the more price-sensitive segments. Thus, in our power tool design example, the optimal designs for the manufacturer under duopoly include light tools with low amperage as the manufacturer would be best served in designing cost reductions into the manufacturing process rather than increasing amperage (i.e., production cost is very important under these more price-sensitive environments). Given the distribution of customer preferences, overall manufacturer profits are extremely sensitive to current rating and somewhat sensitive to weight, and only smaller girth products were found acceptable. This provides designers specific targets for improvements in manufacturing and suggestions for successful designs.

What if the manufacturer does not take into account the channel structure in such design decisions? Figure 10 provides the scenario of how designs developed under the assumption of a specific channel structure would fare if the retail structures were different. It also shows the performance of the opti-