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STRATEGIC DESIGN OF BUNDLED PRODUCTS CONSIDERING RETAIL CHANNEL STRUCTURE

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ABSTRACT

Modern retailers now control in excess of 70% of many markets thereby controlling the access manufacturers have to the end customer. Success of a product design therefore depends upon acceptance of the product by the powerful retailer as well as the end customer. Manufacturers should take this market asymmetry into account in developing product designs. One prevalent approach to increasing the attractiveness of a product offering to end customers and therefore to retailers is to bundle related items together for one price. A bundled purchase is attractive to retailers and manufacturers because it can result in greater revenues by enticing consumers to purchase more products at a presumed discount. To be most effective, bundled products require design integration to achieve synergies of utility (value) for the end customer. Design integration can only be performed by the manufacturer and requires consideration early in the design process. We propose an approach for manufacturers to develop bundled product design within a modern retail environment that takes into account strategic reactions of retailers. The design approach accounts for the demand dependencies between bundled and unbundled goods to reflect the impact of any such product design. A bundled product design case study is presented for two complimentary power tools that offer a synergy in value. Manufacturer profit and market share are optimized within two strategic retail environments (monopoly and duopoly) and we find that optimal bundle designs increase profits for both retailers and manufacturers.

Keywords: Product Bundling, Channel Based Strategic Design, Dynamic Competition, Decision Based Design

1 INTRODUCTION

A massive consolidation of retail channel power has been underway for several decades in the United States. From this consolidation and explosive growth in national chains the modern retailer has emerged as a dominating force in many North American markets [1]. In fact accounting for just 7 select retailer revenues revealed a total revenue in excess of $500 Billion in 2005 (see Table 1) [2].

Table 1: Dominant Retailers

Retailer	Wal-Mart	Target	Home Depot	Lowes	Best Buy	Circuit City	Toys R' Us	Total
Revenue ($B)	$285	$52	$82	$43	$28	$11	$11	$512

This revenue total is nearly 4% of the U.S. gross domestic product and higher than the 2007 U.S. Department of Defense Budget ($502 Billion) [3]. While these figures convey the consolidated nature and sheer size of modern retailers they do not express the drastic power shift between retailers and manufacturers. For most of the 20th century the manufacturers capable of developing and distributing products were the larger of the two parties involved in the retail channel (manufacturer and retailer). One need not search too hard to observe the reversal of this relationship. Examples of retailers greatly overshadowing manufacturers include Home Depot's $82 Billion in revenue vs. $5 Billion for its largest power tool supplier or Toys "R" Us $11 Billion vs. Mattel's less than $5 Billion [2]. Even more importantly, some retailers are controlling up to 70% of the market, in effect acting as gatekeepers to end customers [1]. Manufacturers are already forced to take this retailer power into account in the area of pricing and marketing. In this paper, we extend this to an overall product design approach and claim that manufacturers should be proactive in their engineering design considerations as they price and market their products.

Numerous approaches have been reported for developing new products to address customer needs with engineering design. These methods focus on capturing customer needs and preferences which have become the focus of product design processes. For the most part, the methodologies developed have been improvements in engineering design and assume that the manufacturer or producer interacts directly with the consumer in the marketplace, see e.g., [4],[5],[6],[7]. These recent 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 using models that are, for example, based on a discrete choice model and a cost model. The extant work thus far has assumed that manufacturers have direct access to the end customers and that products are considered only within a single product category (e.g. power drills only) although there has been some recent work on product design diversity and commonality in product families from primarily an engineering design perspective [8]. Modern retailers can react to product offerings by providing or denying shelf space and by setting the retail price which ultimately effects manufacturer market share. The approach developed in this paper will expand upon the discrete choice design approaches to include these retailer reactions.

The design of products taking into consideration the retail channel structure is an overarching theme for this paper and has been rarely broached as a topic in the literature [9]. In this paper, we narrow the focus to the increasingly pervasive practice of product bundling in the retail sector which has been studied by economists and marketing researchers [10],[11],[12],[13],[14]. Bundling is a practice where value is added to the product offering by combining multiple complimentary products for a single price. Bundling creates greater profits for manufacturers and retailers alike by convincing customers to spend more during one transaction. Manufacturers that carefully design desirable bundles for end customers will have greater access to retail markets due to the retailer’s interest in increased revenues as a result of larger purchases.

Two sub-categories of bundling exist: (1) Price and (2) Product [15]. Price bundling is simply the offering of two or more separate but independent products for one price. An example might be the selling of a corded power drill with a corded angle grinder. Product bundling, on the other hand, requires some level of product integration and dependency. An example is the selling of a cordless angle grinder with a cordless power drill where both rely on the use of the same battery pack included in the bundle. Price bundling can be easily achieved by retailers while product bundling requires action on the part of manufacturers to integrate the products at the design stage. Researchers generally agree that product bundling provides the greatest opportunity for increased profits [11],[15]and is therefore a prime candidate for design consideration.

An additional distinction is made in the bundling literature between *pure* and *mixed* strategies for bundling. A pure bundle is the simplest form where products can only be purchased as a bundle. A mixed bundle allows for the purchase of the products as a bundle or separately. Extant literature has examined conditions under which pure or mixed bundling is better for manufacturers [12],[13],[17], with the consensus that mixed offering provides optimal profit in more situations as compared to pure bundling. Shortcomings that have been exposed [15] in the bundling literature as a whole include the lack of credible cost models that include economies of scale and scope as well as secondary objectives such as market penetration.

Although examples abound in the retail marketplace, the extant literature has not considered the role of bundling early in the product design process. Ideally, a design process would take into account the possibility of bundling by incorporating efficiencies of quantity and scope (i.e. costs) from the bundle as well as any market share gained from the added value to customers. Less obviously, the design approach should also take into account the effects of design integration on the individual products (e.g. each tool must use the same battery), the cannibalization (lost manufacturer sales) for existing products, and the effect of the bundle on the retailer’s profit. Finally, regardless of the bundling strategy a retailer chooses to use, if products are made more complementary in the design stage itself both manufacturers and retailers can benefit from higher sales, which makes it easier for the manufacturer to convince the retailer to carry its products. The existing engineering design methods have not taken product bundling into account during the product design stage though the prevalence of the strategy in retail markets warrants it.

2 APPROACH TO BUNDLED PRODUCT DESIGN

We approach this problem from the perspective of the manufacturer who is considering the design of multiple individual products and their possible bundle. Our example is presented with only two products but can easily be extended to multiple products by evaluating the bundle market share within each product category. Our approach is formulated with three key goals in mind: (1) the effect of bundled products should be accounted for in calculating all product category market share and profits (e.g. cross category effects), (2) the approach should be capable of optimizing multiple firm objectives (e.g. profit and market share), and (3) the possible strategic moves of retailers that result from the channel structure should be modelled and taken into account in the design process.

2.1 Discrete Choice Modelling of Bundles

Manufacturers are concerned with profit which is a function of production costs, wholesale price, and market share. In the context of a bundled product the manufacturer is concerned with the profit generated by the original unbundled products as well as the bundle. When designing for a single product category the discrete choice approaches are used to transform a set of engineering design variables into intermediate product level attributes where market share and costs are calculated [4],[5],[6]. For a bundled product design we propose a modified approach where the bundle is considered in two separate product categories. Consider the mixed bundling strategy presented in Figure 1 where all of the activities are performed by the manufacturer. First the manufacturer collects survey data from likely users about the relevant product categories (Products 1 and 2). In our approach a conjoint analysis of the surveys is employed to estimate the value or utility that customer segments assign to product attributes. These are high-level attributes like battery life, or weight. Commercially available marketing software (e.g. Sawtooth Software Market Research Tools [18]) can be used to perform these conjoint utility estimates for each market segment [7] and is again suggested for this application. The software estimates customer utility for attributes by repeatedly presenting potential customers with two products with varying levels of attributes. The customer choices are decomposed into attribute utilities using maximum likelihood estimation and ultimately used to calculate market share.

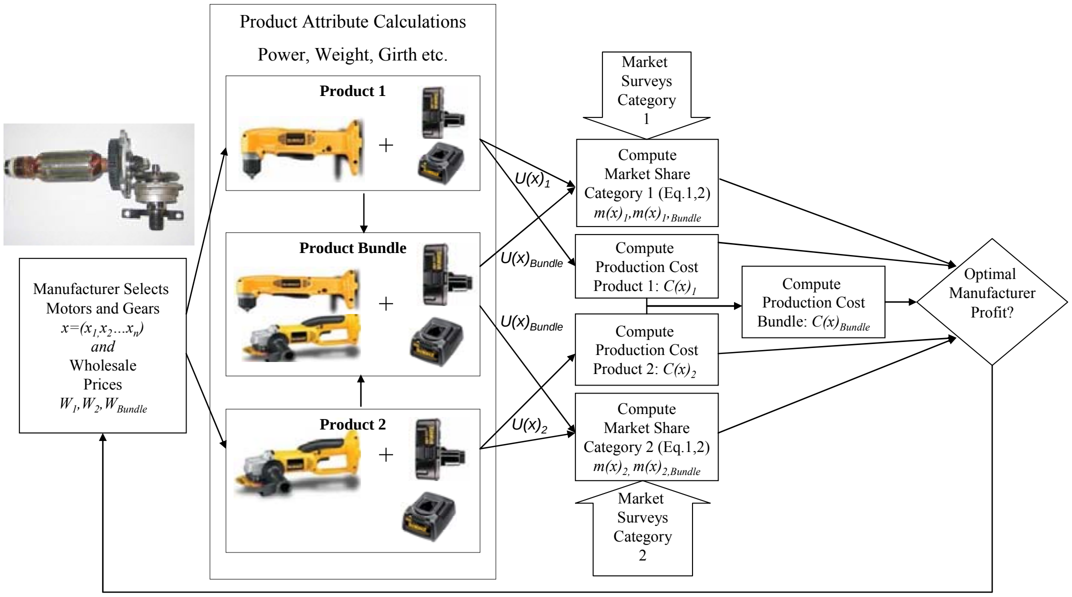


Figure 1: Discrete Choice Design for Product Bundling

In parallel the manufacturer can develop engineering models (e.g. motor and bevel gears depicted on the far left of Figure 1 that directly affect the high level customer relevant attributes. For a conventional discrete choice approach only one product need be designated in the design variables. For our approach we concatenate the design variables for two different products which are passed in to the model. For example, our approach designs one version of Product 1, one version of Product 2 and a bundle of the two products that consists of both products. In this case, as shown in Figure 1, the synergy of the two products is evident in the fact that one battery can be used in bundling the two products together. This is considered a *product bundle* because a dependency exists between the two products in the form of a battery although the approach could be used for *price bundles* as well. Once a design is selected for the two products the high level product attributes must be estimated through intermediate engineering design computations intrinsic to the product in question. Now that the product attributes are known for both products, the value of the bundle market shares for each product category can be computed using any discrete choice model. In our case we use a latent class multinomial logit (MNL) model [19].

$$U_{ik} = \sum_{j=1}^{J} u_{ijk} \tag{1}$$

U_{ik} is the utility for product i to customers in segment k. It is computed by summing the attribute utilities u_{ijk} over all j product attributes. The market share m_{ik}(%) of product i in segment k (Eqn. 2) is approximated from the logit model with:

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

U_{nc} denotes the customers utility for choosing not to buy any of the options, i.e. nc = no choice or no purchase. As mentioned previously we need to account for cross category effects through the inclusion of the product bundle offering (see [20] for a detailed treatment). We simplify our approach as an initial foray into bundled product design. To do so, a market share is calculated for the product bundle under evaluation in each product category's logit model. Thus $m_{1,Bundle}$ denotes the market share of the bundle in category 1. A binary (dummy) variable is used in the conjoint study for whether or not the product includes an additional tool as a bundle. It is logical for customers to assign a positive utility to the inclusion of the extra tool provided all other attributes of the original product remain the same (including price). By introducing the product bundle into each of the categories the pre-existing market share of individually offered products will actually be lower because the bundle is an alternative under consideration in the denominator of Eqn. 2. As such, the overall profit and market share objectives must include the individual product market shares (m_1,m_2) and the market share of the bundle in each of the product categories ($m_{1,Bundle}$, $m_{2,Bundle}$). This accounts for the cross category effects and substitution of the bundle into the existing product categories. Profit Π which is the manufacturer's first objective is calculated by summing the product of the offering market shares *m,* manufacturer margin (*W*-*C*), and the market size (possible customers) *M* for product category 1 and 2:

$$\begin{aligned}\Pi = &\left(m_1(W_1 - C_1) + m_{1,Bundle}(W_{1,Bundle} - C_{1,Bundle})\right)M_1 \\ &+ \left(m_2(W_2 - C_2) + m_{2,Bundle}(W_{2,Bundle} - C_{2,Bundle})\right)M_2\end{aligned} \tag{3}$$

As mentioned previously this first objective (Eqn. 3) can easily be extended to *G* product categories by calculating market shares m_G, $m_{G,Bundle}$ and the associated wholesale and production costs. Employing a profit function such as this allows the manufacturer to evaluate the cannibalized revenue from the individual product offerings in light of the increased revenue from the bundle. Additionally, it should be noted that the approach is flexible in terms of being a pure or mixed strategy. The manufacturer can simply set the wholesale design variable for any product to an excessively high value. This results in a higher retail price which drives the market share to zero for any single product or bundle offering that is unprofitable. This might occur when a bundle offers higher overall profit and competes too closely with the manufacturer's non-bundled model or it is simply more profitable to force customers to buy added features. Examples of this type of bundling abound in the retail sector where frequently it is impossible or quite difficult to buy an individual part of a bundle without purchasing the whole, e.g. wrench sets, computer bundled with a monitor and keyboard, car with multiple options, etc.

Objectives other than profit may be of interest to manufacturers. As such, we formulated our approach to handle multiple firm objectives within the design optimization framework. Several researchers [15] have pointed out that in addition to profit, market share or market penetration may be equally important in new product introductions. Market penetration *P* (units) is defined as the number of units sold by the manufacturer and serves as our second objective:

$$P = \left(m_1 + m_{1,Bundle}\right)M_1 + \left(m_2 + m_{2,Bundle}\right)M_2 \tag{4}$$

The upper bound on this function is of course M_1+M_2. This objective can also easily extended to include additional products by calculating m_G, $m_{G,Bundle}$. An inherent conflict exists between the two objectives (Eqns. 3 and 4) though it is possible for the manufacturer to increase attributes (increased cost) or reduce price to the point where the margin is negative and maximum market penetration is achieved. This can result in a large negative profit. These negative profits have been observed for several product introductions (e.g. the X-box where maximum market share is of primary consideration in the hopes of future profits on software sales [16]) and can be presented to the eventual decision maker for consideration.

2.2 Retailer's Strategic Moves

Depending upon the strategic environment of the retailer and the assortment offered at the retailer a variety of pricing situations can unfold. Because the retailer actually sets the price encountered by the customer we propose that a dynamic model for retail prices should be placed in a manufacturer's decision process between design generation and market share evaluation. This appears as the "Retailer Sets Retail Prices" block in grey. Engineering decisions, strategic pricing moves are shown in grey to highlight the multiplayer aspect of this approach, as shown in Figure 2.

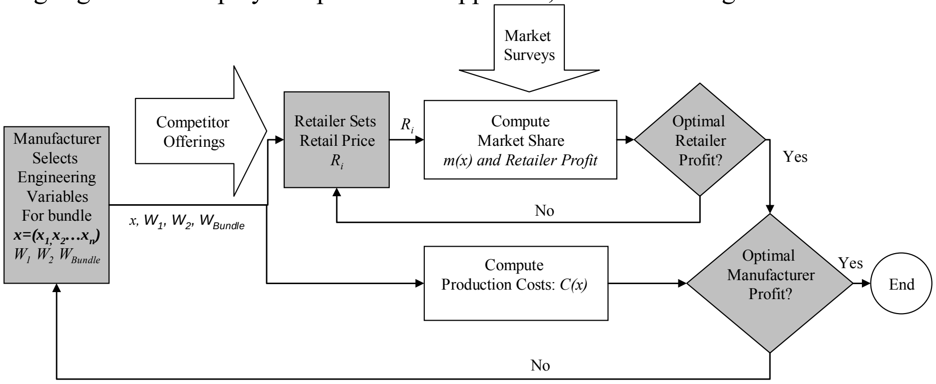


Figure 2: *Bundle Design for Retail Environment*

The retail price will directly impact the market share of a product through utility derived from the product (Eqn. 1,2). In the case of a monopolistic retailer the manufacturer should expect the retailer to set retail prices so that the category profit is maximized:

$$\max_{R_i} \sum_{i=1}^{n} m_i (R_i - W_i) \tag{5}$$

Thus as the manufacturer sets the wholesale price *W,* he should expect the retailer to set R_i for the $i=1,\ldots,n$ products in the category such that the retailers profit is maximized. Because market share m_i is a function of this retail price the manufacturer cannot know the market share achieved until the retailer reaches a pricing decision. This decision (Eqn. 5) is reached through an inner optimization comprised of the inner loop between the nodes "Retailer Sets Price" and "Optimal Retailer Profit". The manufacturer's decision is an outer optimization of selecting design variables and wholesale prices that maximize Eqns. 3 and 4 and is comprised of a loop between the nodes "Manufacturer selects…" and "Optimal Manufacturer Profit".

We also investigated a duopoly pricing scheme between two retailers (A and B) to determine a competitive environment's effect on the design performance. Our duopoly pricing scheme at the retailer level relies upon the concept of the *Nash Equilibrium* [21]. An equilibrium price is achieved at the retail level when none of the competitors can be made better off by changing their price (i.e. first derivatives of profit functions with respect to own price must be zero). For the existence of a unique equilibrium the profit function must be quasi-concave which is true for logit profit functions such as ours [22],[23] . Thus, to find the *Nash Equilibrium* we minimize the following equation:

$$\min_{R} \left(\sum_{i=1}^{n} \left(\frac{dP_A}{dR_i} \right)^2 + \sum_{i=n}^{N} \left(\frac{dP_B}{dR_i} \right)^2 \right)^{.5} \tag{6}$$

Where P_A, P_B are the profits of retailer A with products from $i=1,...,n$ and retailer B with products $i=n,...,N$. Each derivative is squared to ensure that negative derivatives do not cancel out positive derivatives in finding an equilibrium point. Because the manufacturer first sets his price (outer optimization) and the retailer responds (inner optimization) this is said to be a situation of Stackelberg leadership (leader-follower which is for manufacturer-retailer) which mimics reality [24]. It is worth noting that the retailer still has significant power regardless of whether or not he sets prices first. This is because the retailer has no maximum on what retail price to set. For example if the retailers perceive difficulty in creating value (profit) from a product they can simply raise the price of the product until no market share is achieved. Essentially, the product is then considered blocked from access to the market. As explicated in the introduction, this blocking power of retailers of increasingly grave concern to manufacturers and is endogenous to our model through inner optimization of retail price.

3 CASE STUDY

3.1 Marketing Model

We developed a bundled product engineering design for notional customer segments based on historical data as a case study for our approach. A *product bundle* of a cordless angle grinder and a cordless right angle drill is proposed as a bundle that is likely of interest to customers. Each product comes with a battery pack and charger when sold separately and share a battery/charger when sold together in a drill/grinder bundle. The two cordless tool engineering models were developed from our previous work in tool design on a motor-bevel gear assembly [9]. An explanation is in order as to why a manufacturer might bundle these two products together. An angle grinder is a tool commonly used in many trades for removal of material or cutting while a right angle drill is frequently used for drilling in cramped spaces due to its reduced horizontal clearance. A combination of these tools would be especially attractive to plumbers, electricians, or even the weekend hobbyist. The combination or bundle of these tools is considered a product bundle because both tools must rely on the same battery pack and charger. The user can expect to receive a reduced price by using the same supporting components (battery pack and charger in Figure 1). This complicates the overall design as the battery pack design must consider the preferences of the shoppers principally interested in the right angle drill and shoppers principally interested in the angle grinder.

Table 2: *Grinder and Drill Category Utilities*

Grinder Category Utility Estimates

Segment	One	Two	Three	Four
Share	37.8%	24.8%	12.1%	25.3%
	μ	μ	μ	μ
Bundle				
Yes	0.1	0.5	1.1	1.8
No	-0.1	-0.5	-1.1	-1.8
Price				
$99.00	4	3	2	2
$199.00	0.1	0.1	0.1	0.1
$299.00	-4	-3	-2	-2
Volts				
10	-1.25	-0.45	-1.5	-0.5
25	0.13	0.1	-0.65	-0.38
40	1.2	1	2.13	2.82
Life (min)-operating time				
4	-1.4	-1.12	-1.71	-0.8
10	0.5	-0.47	-0.82	0.74
16	0.9	1.57	2.53	1.54
Girth				
Small	2.5	0.7	1.5	2.4
Large	-2.5	-0.7	-1.5	-2.4
Weight				
16lbs	-0.3	-1.2	-0.5	-1.5
9 lbs	-0.5	0.4	-0.1	0.5
6 lbs	0.8	0.8	0.6	1
No Choice	-2	-2	-2	-2

Drill Category Utility Estimates

Segment	One	Two	Three	Four
Share	22.4%	21.20%	34.40%	22.00%
	μ	μ	μ	μ
Bundle				
Yes	0.2	0.7	2.5	1.8
No	-0.2	-0.7	-2.5	-1.8
Price				
$99.00	2	3	2	3
$199.00	0.1	0.1	0.1	0.1
$299.00	-2.1	-3.1	-2.1	-3.1
Volts				
10	-2.25	-1.45	-2.5	-2.5
25	-0.13	-0.1	-0.65	-0.38
40	2.38	1.55	3.15	2.88
Life (min)-operating time				
4	-0.8	-0.5	-0.7	-1.2
10	-0.3	-0.5	0.2	0.3
16	1.1	1	0.5	0.9
Girth				
Small	2.5	0.7	1.5	2.4
Large	-2.5	-0.7	-1.5	-2.4
Weight				
16lbs	-2.3	-1.8	-2.5	-1.5
9 lbs	-0.5	-1.2	-1.5	-0.5
6 lbs	2.8	3	4	2
No Choice	-2	-2	-2	-2

Each tool uses a bevel gear set and universal motor to transfer power and torque. Cordless angle grinders are operated for long periods (minutes at a time) at high RPM (10,000 RPM) while drills are operated for much shorter periods at higher torque (up to 600 in-lbs) and lower RPM (less than 1,750). Due to the nature of these two operating environments one can expect the voltage requirements (directly impact torque) for each tool and battery capacity (amp-hrs) to be somewhat different for each tool. For example, buyers of angle grinders want longer battery life due to the high RPM and longer tasks while the users of drills are particularly interested in light weight designs. As such, we developed two notional sets of conjoint marketing data derived from real historical data that provide plausible customer preferences for this academic case study of cordless power tools (see Table 2).

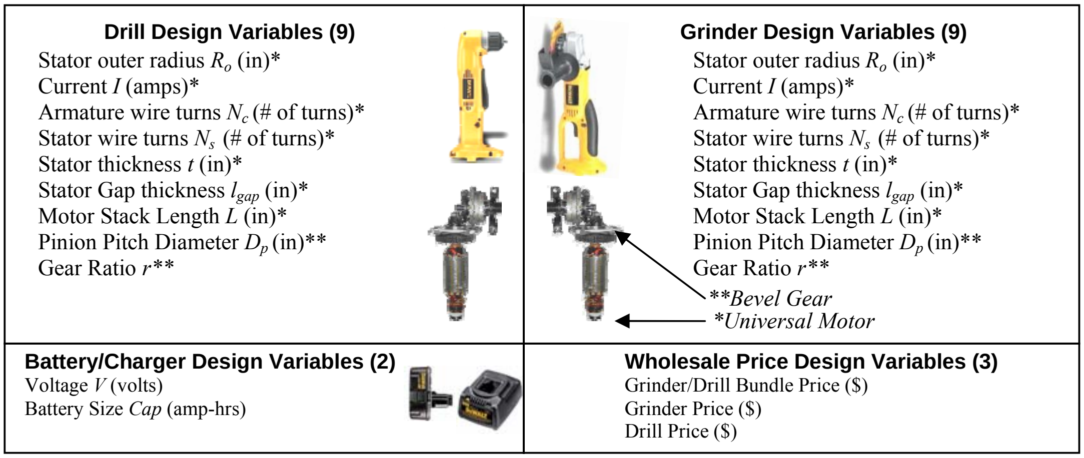
We assume that each category has a market size of 10 million units and that our subject manufacturer is offering 1 of 3 drills in the product line and 1 of 3 grinders along with the bundle of the two products. It is worth noting that a few general trends can be observed in each of the product categories. First it can be noted that both categories have relatively similar preference for bundling, price, and tool girth. The categories differ in their preference for voltage, life, and weight. This will be important to selecting an optimal design as buyers who are principally grinder buyers will want longer life batteries which will result in heavier weight. Grinder buyers are less sensitive on the weight attribute than drill buyers and therefore would be open to a heavy but high operating time battery in their bundle or even in an individual grinder purchase. In contrast, drill buyers are less concerned with battery life and more concerned with weight as indicated by the high utility preference for the 6 lb tool. Additionally, drill buyers are sensitive to voltage as they are aware that voltage directly impacts torque which is a critical performance component for drilling large holes.

Table 2 serves as an intermediate performance evaluation for engineering designs. Computation of the attributes relevant to Table 2 will be presented in the next section. An attribute generated by an engineering design is transformed to utility with a piecewise linear interpolation which is ultimately reflected in market share.

3.2 Engineering Performance Model

3.2.1 Engineering Design Variables

A general universal motor and bevel gear design was adapted for the cordless right angle drill and angle grinder. In designing the two tools the proposed approach was restricted to offering just one drill and one grinder so that the bundled set could not be different in characteristics of the individual tool designs. In the design of electric power tools we have identified 9 design variables that impact higher level attributes. Because we are designing two different motors (one for each the grinder and the drill) we have 18 design variables related to motor and bevel gear set alone (Figure 3). Variables related to the motor are annotated "*" while those related to the bevel gear are annotated with "**".



Drill Design Variables (9)
Stator outer radius R_o (in)*
Current I (amps)*
Armature wire turns N_c (# of turns)*
Stator wire turns N_s (# of turns)*
Stator thickness t (in)*
Stator Gap thickness l_{gap} (in)*
Motor Stack Length L (in)*
Pinion Pitch Diameter D_p (in)**
Gear Ratio r**

Grinder Design Variables (9)
Stator outer radius R_o (in)*
Current I (amps)*
Armature wire turns N_c (# of turns)*
Stator wire turns N_s (# of turns)*
Stator thickness t (in)*
Stator Gap thickness l_{gap} (in)*
Motor Stack Length L (in)*
Pinion Pitch Diameter D_p (in)**
Gear Ratio r**

Battery/Charger Design Variables (2)
Voltage V (volts)
Battery Size Cap (amp-hrs)

Wholesale Price Design Variables (3)
Grinder/Drill Bundle Price ($)
Grinder Price ($)
Drill Price ($)

Figure 3: *Design Variables*

There are also two shared design variables that affect all product offerings from the manufacturer: voltage (volts) and battery size (amp-hrs). Finally, three wholesale prices were also set as design variables, one for the grinder, drill and bundle.

3.2.2 Computation of Customer Level Attributes

The engineering design variables were transformed to intermediate customer relevant variables that are then transformed to utility using linear interpolation of the customer level attributes in Table 2. One of the simplest examples of this transformation is the operating time or battery life of the tool:

$$Life(\min) = 0.7 \times \frac{Cap}{I} \tag{7}$$

where I is the design variable for motor current and Cap is the Battery size and an efficiency factor of 0.7 is applied [25]. Similarly the girth attribute G of the design is calculated as:

$$G(in) = 2 \times (R_o + .5) \tag{8}$$

where R_o is the outer radius of the stator in inches and ½ inch is added to the radius to account for the plastic body of the tool and an air gap for cooling the motor. The weight of the tool is a somewhat more complicated approximation from the design variables and is presented in Table 3.

Table 3: *Mass Computations*

Density Steel ρ_s (lbm/ in^3)	$\rho_s = 0.283 (lbm/in^3)$
Density of Copper ρ_{copper} (lbm/ in^3)	$\rho_{copper} = 0.297 (lbm/in^3)$
Face Width b (in)	$b = 0.3\ in$
Gear Pitch Diameter D_g (in)	$D_g = D_p \cdot r$
Armature Diameter l_r (in)	$l_r = 2(R_o - t - l_{gap})$
Wrap length l_{rw} (in)	$l_{rw} = 2l_r + 2L$
Stator Mass M_s (lbm)	$M_s = (\pi(R_o)^2 - \pi(R_o - t)^2) \cdot L \cdot \rho_{steel}$
Armature Mass M_a (lbm)	$M_a = A_r \cdot L \cdot \rho_s$
Windings Mass M_w (lbm)	$M_w = l_{rw}(N_c + 2N_s)A_w \cdot \rho_{copper}$
Motor Mass M_m (lbm)	$M_m = M_s + M_a + M_w$
Pinion Mass M_p (lbm)	$M_p = (\pi \cdot D_p^2 \cdot b \cdot \rho_{steel}) / 4$
Gear Mass M_g (lbm)	$M_g = (\pi \cdot D_g^2 \cdot b \cdot \rho_{steel}) / 4$
Bevel Gears Mass M_{bg} (lbm)	$M_{bg} = M_p + M_g$
Battery Mass M_{bat} (lbm)	$M_{bat} = Cap + 0.5$
Fixed Mass M_f (kg)	$M_f = M_{commutar} + M_{Arbor} .... = 1.2(lbm)$
Total Mass M_t (kg)	$M_t = M_{bg} + M_m + M_f + M_{bat}$

The mass of the battery M_{bat} is an approximation based upon a survey of commercially available replacement batteries for power tools. Mass increases linearly with the capacity at a rate of roughly 1 lbm per amp hour. It is important to note that the battery weight impacts two performance attributes in the design: weight and battery life. Additionally, weight and battery life are valued differently in utility estimates of the two different categories presented in Table 2. Thus the selection of the battery design variables has wide ranging impacts throughout the rest of the model.

Table 4: *Common Constraints*

Integer Turns	$N_c, N_s = \text{int}$
Length to Diameter Ratio	$L / G \le 5$
Flux Density armature B_r (Tesla)	$B_r = \phi / ((\pi \cdot l_r^2) / 4) \le 1.5 Tesla$
Flux Density Stator B_s (Tesla)	$B_s = \phi / (2 \cdot L \cdot l_r) \le 1.5 Tesla$
Flux Density Air Gap B_g (Tesla)	$B_g = \phi / (L \cdot l_r) \le 1.5 Tesla$
Armature Heat Flux K_s (A/m)	$K_s = \frac{N_c \cdot I}{\pi \cdot l_r} \le 10000$
Stator Heat Flux K_s (A/m)	$K_s = \frac{N_s \cdot I}{\pi(l_r + t)} \le 10000$
Contact Stress σ_f (Pa)	$\sigma_f = Z_H Z_e \sqrt{\frac{K_a K_m F_i (d_v + D_v)}{(d_v D_v)}} \le 720 MPa$
Bending Stress σ_b (Pa)	$\sigma_b = (K_a K_m F_i) / (m \cdot J) \le 145 MPa$
Armature Tip Velocity v_a	$v_a = \pi \cdot N_{motor} \cdot l_r \le 10000\ (ft/s)$

Like in any engineering design problem, there are constraints considered for this case study. A set of constraints is implemented for each class of power tool though the universal motor and bevel gear overall design is general in nature. This is because the usage scenario of each motor is far different (e.g. high torque necessary for drill, high RPM necessary for grinding). The constraints are presented as three separate tables to highlight the differences and similarities between the motor/bevel gear designs (Tables 4-5).

The common constraints (Table 4) are implemented for each design while Table 5 constraints are product category specific. In total there are 24 constraints for the overall engineering design $\left(2 \cdot 10(common) + 2(drill) + 2(grinder)\right) = 24$. Due to space constraints it was not possible to demonstrate all intermediate computations. For details on calculating the following intermediate design variables (flux ϕ, module (pinion) m, motor RPM N_{motor}, torque T, gear cone depth D_v, pinion cone depth d_v, tooth loading intensity F_i, zone factor Z_H) and selection of design constants (Z_e, K_a, K_m, J) see Williams et al., 2006 [9]. The common constraints ensure that for each motor design physical limits such as bending stress in the bevel gears, heat flux in the stator and armature tip velocity are not exceeded.

For the grinder, two unique constraints were implemented to ensure safe operating speeds and adequate grinding RPM. The range of output RPM was limited from 8000 to 10000. 10000 RPM is the upper limited allowed by the manufacturers of the grinding disks that are commonly sold for the angle grinder while 8000 RPM under no-load conditions ensures adequate operation in comparison to the corded alternatives and competitors. Torque is less of a concern for the angle grinder as the user is expected to back off the pressure when the motor begins to slow down. Additionally, it was necessary to limit the RPM of the motor to a safe operating speed (less than 40000) for the quality of motor expected for this application.

Table 5: Grinder and Drill Performance Constraints

Motor RPM N_{motor}	$N_{motor} \le 40000$
Grinding Wheel RPM $N_{out\text{-}grinder}$	$8000 \le (N_{out-grinder} = N_{motor} / r) \le 10000$
Torque T (lbf-in)	$T \ge 500\ (lbf - in)$
Drill Output RPM $N_{out\text{-}drill}$	$N_{out-drill} = N / r \le 1750$

Right angle drills are used to bore large holes through wall studs for routing plumbing and electrical services. The large drill bits require significant torque so the output was constrained to greater than 500 lbf-in which is appropriate for high quality consumer grade power tools. In addition, the no-load output RPM was limited to less than 1750 to ensure a reasonable operating range for drilling in wood.

Finally, a battery cost model was added to the motor-bevel gear cost model [9] based upon a market survey of battery costs and a simple multi-regression of two coefficients: voltage and battery size.

$$BatteryCost(\$) = 1.51 \cdot V(Volts) + 10.3 \cdot BatterySize(Amp - hrs) \tag{9}$$

The battery design (cost) is then very important along three attributes as the customer segments are sensitive to the performance (i.e. voltage and battery life) as well as have significant utility for lower prices. The tension between these performances attributes, engineering design constraints, and strategic interplay makes for an interesting case study and test bed for our proposed methodology.

4 OPTIMIZATION APPROACH

We used Matlab's Genetic Algorithm and Direct Search Toolbox (GADS) to develop a multi-objective genetic algorithm (MOGA) to simultaneously optimize market share and profit for the subject manufacturer using a non-dominated sorting algorithm for design ranking [26]. The 23 design variables were encoded in a binary format with lower and upper bounds specified. The wholesale prices were allowed to increase to \$2,000 each as a method to eliminate any unprofitable product from the manufacturer's product line. Such a price would result in a miniscule market share that would be truncated from consideration by a decision maker. The design variables were encoded as 200 bit binary strings and run with a population size of 200 for 200 generations. Additionally, the MOGA was set to terminate if objective function values change less than 10^{-6} over 50 generations or change less than 10^{-6} or a time period of 600 seconds. Constraints were handled using the "Feasible Over

Infeasible Approach" [26] where violated designs are set equal to the worst function call plus a penalty. Additionally, a crossover fraction of 0.6, a mutation rate of 0.1 and an elite fraction of 1/3rd were used. The inner optimization for retail price setting is quasiconcave [23] for monopoly and duopoly price setting (See Equations 5 and 6). We implemented this in Matlab's minimization routine "fmincon" where retail prices were constrained to being greater than wholesale prices.

5 RESULTS

One case was run for both the monopoly (one retailer) and duopoly (two retailers) channel structure. Figure 4 shows the Duopoly Pareto Frontier (non-dominated solutions) with blue diamonds and the Monopoly Pareto Frontier as magenta squares. Both results show that a wide range of optimal market penetration and profit results are possible along the Pareto Frontier. First, these plots confirm the tension between market share and profit as objectives. Market share can be gained at the expense of profit and vice versa. We also see that market share and profit can only be traded against one another to a limited extent. This is because market share is a component of the overall profit equation. Once market share falls to the point where it is more detrimental to profit than the increase in margin the extreme solutions become dominated and thus are not Pareto optimal (see Design 7 taken from the raw monopoly data on Figure 4). Interestingly, the practice of offering products at a loss to achieve market penetration (e.g. X-box, inkjet printers) is confirmed in the negative profit regions of Figure 4 where the market share realized nearly reaches 100% or 20M units for the monopoly channel. This result is possible because the customers are sufficiently elastic (sensitive) to price and the wholesale pricing was allowed to reach values far below marginal cost. This result can also be achieved by designing extremely high quality goods (i.e. greater utility) and offering these goods at below cost. It need not be a situation where a mediocre good is offered at an extremely low price. Both types of solutions exist along the Pareto front. This is a business model akin to that employed for the X-box and inkjet printers where manufacturers accept loses to achieve future revenue streams on software and ink.

Finally, we are able to see the impact that the channel structure has on the profitability of designs along the Pareto Frontier by overlaying the Pareto curves on Figure 4. This figure shows that the increased competition observed by adding a competitor results in downward pressure on wholesale margins. The manufacturer is still able to achieve very large values of market penetration but the peak profit is roughly 2/3rd of what could be achieved in the monopoly situation. Comparing single optimal designs in terms of only profit is another way to perform this comparison but the fact that the duopoly Pareto lies almost entirely below that of the monopoly lends credibility to the belief that monopolies improve the chance of increased profits when manufacturers are *Stackelberg leaders* (set prices first).

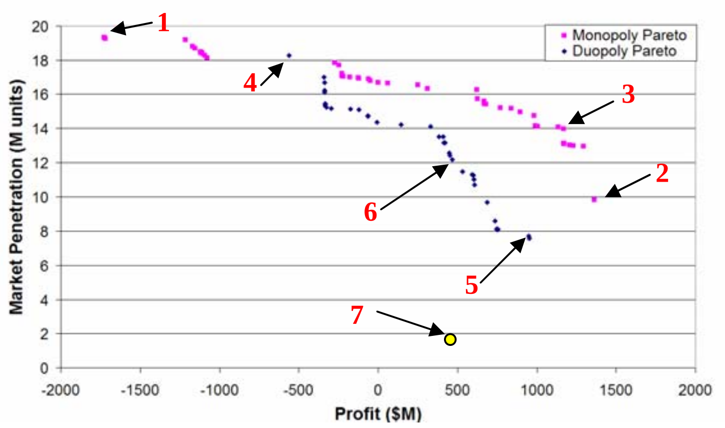


Figure 4: *Monopoly/Duopoly Pareto Comparison*

To demonstrate how designs along the Pareto curve can be achieved we present 6 designs (as indicated on Figure 4) in Tables 6 and 7. Design 1 and 4 are highly unprofitable yet capture high levels of market share by offering better attributes at higher production costs yet with low wholesale prices or a negative margin. The profitable designs (2, 3, 5 and 6) have much lower voltage designs and lower battery capacities in general which results in a lower production cost. It appears that given the assumed utility for price for customers that low cost/lower performance strategies are better given the assumed strategic framework and assortment.

Table 6: Sample of Optimal Designs

	Monopoly						Duopoly					
	Design 1		Design 2		Design 3		Design 4		Design 5		Design 6	
	Grinder	Drill	Grinder	Drill	Grinder	Drill	Grinder	Drill	Grinder	Drill	Grinder	Drill
N_c (turns)	114	125	114	98	114	109	131	94	111	116	117	102
N_s (turns)	40	15	39	17	38	16	26	21	37	15	32	29
R_o (in)	0.53	0.67	0.94	0.69	0.97	0.69	0.86	1.19	0.54	1.19	0.59	1.11
T (in)	0.15	0.26	0.15	0.22	0.15	0.25	0.36	0.19	0.24	0.28	0.22	0.27
l_{gap} (mil)	2.35	2.32	1.86	2.29	1.86	2.31	2.07	1.46	2.07	2.10	2.33	1.00
L (in)	2.563	2.880	4.030	1.571	4.030	1.571	2.465	1.720	1.934	1.762	2.257	3.830
r (ratio)	2.245	2.877	3.148	2.890	3.120	2.875	3.643	2.832	3.618	4.155	3.993	4.195
D_p (in)	0.764	0.686	0.799	0.686	0.799	0.686	0.629	0.788	0.711	0.728	0.728	0.706
V (Volts)	40.277	40.277	14.272	14.272	14.0528	14.05	29.193	29.19	14.4124	14.412	21.358	21.36
Cap (amp-hrs)	1.89588	1.15319	1.1501	1.1135	1.1146	1.115	2.0155	2.015	1.46595	1.4659	2.5348	2.535
Girth (in)	2.06	2.33	2.88	2.37	2.93	2.38	2.7134	3.37	2.0713	3.37	2.18	3.22
Mass (lbm)	6.53	6	9.95	5.6	10.39	5.52	7.0298	8.98	7.233	8.26	7.64	11.62
Duration (min)	4.1	1.55	2.4	1.73	2.69	1.65	3.44	7.39	4.0418	3.63	4.02	3.9
Prod. Cost ($)	$105.6	$116.6	$24.7	$30.3	$26.8	$29.9	$51.5	$79.2	$50.9	$29.7	$43.6	$57.6
Bundle Cost ($)	$172.37		$34.93		$37.05		$91.36		$58.87		$67.17	

In addition it is worth noting that retailer profits benefit from the product bundle design optimization. Otherwise the designs would be rejected through the dynamic pricing mechanism (Eqn. 5 and 6). A reference or comparison design (Table 7) was chosen for the subject manufacturer that contained no product bundles and retailer profits were computed. These profits and markets shares are shown in the last line of each of the monopoly and duopoly sections. Clearly the retailer profit improves considerably with the inclusion of product bundles regardless of the channel structure for our case study thus making the manufacturer's job of convincing the retailers to carry the new products easier.

Table 7: Manufacturer and Retailer Profit

		WholesalePrices			MFR Profit ($M)	MFR Market Share (M Units)	Total Retailer Profit ($ M)
		Grinder	Drill	Bundle			
Monopoly	Design 1	$84.48	$112.34	$53.43	-1728	19.34	2001
	Design 2	$117.02	$144.08	$100.30	1362.9	9.79	1943
	Design 3	$117.02	$126.52	$60.30	1167	13.97	1745
		Comparison Design			102	5.12	642
Duopoly	Design 4	$69.94	$91.73	$48.39	-562.1	18.27	2158
	Design 5	$44.06	$148.38	$108.24	950.1	7.73	1979
	Design 6	$78.46	$112.09	$88.16	466.76	12.17	1702
		Comparison Design			82	3.47	1073

6 CONCLUSION

We have presented a new and novel approach to developing bundled product designs within a retail channel setting under two different pricing frameworks: monopoly and duopoly. Bundling product categories is increasingly prevalent and has important design implications as evidenced by the power tool case study relying upon the same battery pack that would likely be suboptimal for either as individual tools. We have shown that the bundled product offering increases profits for both the retailer and manufacturer by convincing consumers to make larger purchases (bundles) due to their added utility. Our approach is distinct as a design methodology in that we take into account the strategic interactions of retailers in the design process which we demonstrate as an important factor in calculating profit and market share.

Many extensions to this new area of research can be pursued. First the uncertainty in customer preferences and cost models has not been accounted for in the proposed approach. Additionally, we did not allow the algorithm to design the individual products differently from the bundle. It would be useful to incorporate a profit function that increases fixed costs whenever the individual product differs from the bundle due to the necessity of running separate production runs. Finally, an extension of the proposed approach in the context of product line design will be useful.

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