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A QUANTITATIVE REPRESENTATION OF THE TRADEOFF BETWEEN PRODUCT COMMONALITY AND VARIETY IN PRODUCT FAMILY DESIGN

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ABSTRACT

Product family design and platform-based product development have garnered much attention over the last decade. They have been used to provide nearly customized products to satisfy individual customer requirements and simultaneously achieve economies of scale during production. The inherent challenge in product family design is to balance the tradeoff between product commonality (how well the components and functions can be reused across a product family) and variety (the range of different products in a product family). Quantifying this tradeoff at the product family planning stage, in a way that supports the engineering design process, has yet to be accomplished. Responding to this need, we have developed a graphical evaluation method, the Product Family Evaluation Graph (PFEG), that allows designers to choose the 'best' product family design option among sets of alternatives based on their performance with respect to the ideal commonality/variety trade off, given a company's competitive focus. One of the necessary supporting pieces for the PFEG is to develop a quantitative representation of the ideal tradeoff between commonality and variety in a product family based on the elements that characterize a company's competitive focus. In this paper, we develop the commonality/variety tradeoff angle, α, ranging from 0° to 90°, as a quantitative representation of the ideal commonality/variety tradeoff in product families based on a company's competitive focus and their industry-wide competitors' information. α is defined as a function of the weighted sum of the strategic factors' quantitative impact on commonality and variety (S) in a product family. These factors cover five categories - market, product characteristics, life-cycle processes, government and industry regulations and/or standards, and organizational capabilities. In this paper, we analyze whether each of these factors causes an increase or decrease in commonality or variety to better understand their impacts. The factors and their categories are admittedly incomplete and the analyses of the factors' impact are subjective. A more accurate factor identification and impact analysis will be necessary in the near future as the number of companies using the product family strategy increase. We intend for this paper to serve as a basis for that expansion. In this paper, we propose a three-step approach to estimate this angle for a given company using the linear regression model. The angle can then be used with the PFEG to help designers evaluate a product family or compare product family design alternatives. The proposed angle is illustrated with an application to four families of power tools.

Keywords: commonality, variety, product family design, product family evaluation graph

1 INTRODUCTION

Today's marketplace is characterized by rapid innovation, globalization, customization, and market fragmentation. The emergence of these characteristics has fundamentally altered the way many manufacturing companies do business [1]. However, many manufacturing companies still typically design new products one at a time. Meyer and Lehnerd [1] found that "the focus on individual customers and products often results in a failure to embrace commonality, compatibility, standardization, or modularization among different products or product lines." Hence, to remain competitive in the marketplace, many manufacturing companies are investing in product family development to provide useful external variety (differentiation of product functionality that is appreciated by customers) [2] to satisfy individual customer requirements and simultaneously achieve economies of scale and scope within their manufacturing capabilities [3].

A product family is a group of similar products that are derived from one or more product platform(s), but possess specific features/functionalities to satisfy different customer needs [1]. Each product variant shares some common features and product technologies that come from the product platform of the product family [4]. The core of a product family is therefore the product platform [5], which can be broadly defined as the collection of assets (components, processes, knowledge, and people/relationships) shared by a group of products and from which a stream of derivative products can be "efficiently developed and launched" [3]. Product family design and development methods have been tackled from various perspectives, including the areas of business strategy, marketing, manufacturing and production, customer engineering, information technology, and general management. A comprehensive review of the recent advances in product family design can be found in Simpson, *et al*. [6].

Both commonality and variety can offer competitive advantages to a company. Product commonality refers to how well components and functions are reused across a product family, and product variety refers to the diversity of products that a company provides to the marketplace [1]. Achieving greater commonality across a family usually entails sacrificing some degree of performance (and/or variety) for individual products. Likewise, increasing product variety may make it difficult to share common functions and/or components across a product family. Consequently, there is an inherent tradeoff between commonality and variety within any product family [7]. The ideal product family would have complete commonality within its non-differentiating components and functions, while the differentiating components and functions are employed to satisfy all of the necessary variety for the marketplace. According to Porter [8], companies can achieve competitive advantages by following one of three generic strategies - differentiation, cost leadership, or focus. However, a company should only focus on one of the competitive advantages (cost or differentiation), because being 'all things to all people' is a recipe for strategic failure and below-average performance – it typically means that a company has no competitive advantages at all [8]. If a company wants to have a competitive advantage over a number of segments (a broad target), the company can either aim at achieving cost leadership while simultaneously providing differentiation relative to its competitors, or aim at achieving differentiation while simultaneously remaining price competitive with its competitors [9]. Therefore, to maximize the combination of commonality and variety a product family can achieve, designers should successfully balance between commonality (cost) and variety (differentiation) based on the company's intent for the particular product family.

Although the importance of resolving the tradeoff between commonality and variety in product family design has been addressed, quantifying this balance at the product family planning stage, in a way that supports the engineering design process, has yet to be accomplished. Responding to this need, we have previously developed a graphical evaluation method, the Product Family Evaluation Graph (PFEG) [10, 11], to allow designers to compare sets of product family design options with respect to the commonality/variety tradeoff specific to a company's competitive focus, and to choose the 'best' product family design. The PFEG, supported by either of two sets of commonality and variety indices [CMC_C, CMC_V] and [CDI_C, CDI_V] [11], is a single quadrant graph of the measured commonality and variety of each product family under evaluation. One of the necessary supporting pieces for the PFEG is to develop a quantitative representation of the ideal tradeoff between commonality and variety in a product family, determined by the elements that characterize a company's competitive focus. In this paper, we develop the commonality/variety tradeoff angle, ranging from 0° to 90°, as a quantitative representation of the ideal tradeoff for a particular product family based on a company's competitive focus and products' competitive pressures.

2 QUANTITITATIVE TRADEOFF BETWEEN COMMONALITY AND VARIETY

Porter [8] stated that companies can achieve competitive advantage either through differentiation or cost leadership. Companies have taken many different approaches in product family design that can be classified as either process-based strategies (focused on increasing the flexibility of manufacturing and logistics processes to accommodate high levels of external variety at a reasonable cost) or product-based strategies (focused on decreasing component variety and process complexity by increasing the level of commonality) [12]. In this paper, we define a product family's competitive focus is characterized by the strategic life-cycle factors influencing the commonality/variety tradeoff. These factors span five categories - the market, product characteristics, life-cycle processes, government and industry regulations and/or standards, and organizational capabilities - and their cumulative impact determines whether a company should focus more on product differentiation or cost leadership in a product family. However, when facing a set of product family design options in the conceptual design phase with a product family's competitive focus, no existing method can assist designers in evaluating these design options with respect to the commonality/variety tradeoff. The PFEG aims at filling this void. One of the supporting pieces for the PFEG, the commonality/variety tradeoff angle developed in this paper, can be used to quantitatively represent the ideal tradeoff between commonality and variety determined by the competitive focus, which serves as a basis for evaluating sets of existing product family design options. The development of the quantitative representation begins with the identification of the factors influencing this tradeoff in product family design throughout the product life-cycle and the analysis of whether each factor causes an increase or decrease in commonality or variety. Such analysis is shown in Table 1 and detailed in the following sections.

Table 1. Impact and factors table

Category	**Strategic Impact Factors**		**Factor States**	**Commonality-Variety Tradeoff**		
				↑C	**↑V**	**Neutral Impact**
Market	**Demands factors**	*Stability and predictability of demand levels*	Stable and predictable	+		
			Unstable and unpredictable		+	
		Customer needs characteristics	Basic	+		
			Exlusive		+	
		Customer needs	Easily defined	+		
			Uncertain		+	
		Price consciousness	Yes	+		
			No			-
		Quality consciousness	High		+	
			Low	+		
		Fashion/style consciousness	Yes		+	
			No	+		
		Level of pre- and post-sales service	High		+	
			Low	+		
	Structural factors	*Buyer power*	High	+	+	
			Low	+		
		Competitive intensity	High		+	
			Low			-
		Vulnerability to substitute products	Strong		+	
			Weak			-
Product characteristics	*Unique sets of customer requirements*		Yes		+	
			No	+		
	Development time		Long			-
			Short	+		
	Product life-cycle length and predictability		Long and predictable	+		
			Short and unpredictable		+	
Life-cycle processes	*Maintenance and service*		Fast	+		
			Slow			-
	Automation rate		High	+		
			Low			-
	Recycling		Required	+		
			Not required	+		-
Government/industry regulations and/or standards			Strong	+		
			Weak			-
Organizational capabilities	*Financial condition*		Enough investment		+	
			Investment limited	+		
	Distribution and supply channel		Complex	+		
			Simple			-

2.1 Factors identification

Many researchers have begun to develop taxonomies to classify the factors encountered in product family design [1, 2, 8, 13-17]. Our literature review revealed that there are several different types of factors that impact the commonality/variety tradeoff in product family design. To this end, we identified five categories of factors (market, government/industry regulations and/or standards, product characteristics, life-cycle processes, and organizational capabilities) that, taken together, determine the relative importance of product commonality and variety in product family designs (Table 1). In addition, each of those factors has a potential state that may impact the tradeoff between commonality and variety by causing a need for increased commonality ('+' in the C column), causing a need for increased variety ('+' in the V column), or having a neutral impact ('-' in the Neutral Impact column) as shown in Table 1 and detailed in Section 2.2. The list of factors is based on experience from existing product families and extensive literature review. The completeness of this list can be improved through empirical studies.

2.2 Factor's impact on the tradeoff between commonality and variety

In this section, we aim to define each of the factors listed in Table 1 and describe how they affect the tradeoff between product commonality and variety in product family designs. We admit that the factors' impact is subjective, and we invite researchers in the field to create more objective and verified impact analysis utilizing this list as a starting point. We would assume that any industrial use of this information would start with the following as a guideline for developing their own list of relevant factors.

Market

Understanding a company's market environment has became more and more important for determining its competitive focus [1, 2, 8, 13, 17]. The factors under the market category describe the market environment where a firm stands. Typically, they are divided into two types: demand factors and structural factors [17].

<u>Demand factors</u>

Demand factors include the stability and predictability of demand levels, customer needs characteristics, customer needs, price consciousness, quality consciousness, fashion/style consciousness, and pre- and post-sales service [17]. These factors indicate the degree of control that a company has over the market. The higher the controllability of the market, the less the impact that the market has on a company's product decisions. Descriptions of each of these factors and how they influence the tradeoff between commonality and variety are given in the following paragraphs.

Stability and predictability of demand levels (stable and/or predictable vs. unstable and/or unpredictable): The demand levels in a market could be stable and predictable or unstable and unpredictable. A stable and predictable market is a perfect market environment for the mass production paradigm characterized by standardization, batch production, and low prices [17]. In such a marketplace, the only competitive advantage is a lower price. Stable and predictable demand levels cause a need for increased commonality. On the other hand, unstable and/or unpredictable demand levels indicate fragmentation in demand that is "a key characteristics of market customization" [17]. In the late 1970's, the automobile market became very unstable. In only 10 years, the minivan market segment has fragmented into "car-like minivan," "van-like minivan," "tall cars," and "compact sport wagon." As a result, there is much less demand stability for automobiles and much more variety is available to customers [17]. Unstable and unpredictable demand levels lead to a need for increased variety. A company can compensate for the losses caused by demand fragmentation by expanding the breadth of useful external variety.

Customer needs characteristics (basic vs. exclusive): Products that fulfil exclusive customer needs naturally tend to be more "distinctive, higher priced, and unique," while products that fulfil basic needs are more likely to be standardized [2, 17]. A simple example is luxury handbags that require much more external variety (the definition should not just be limited as the number of unique products offered to the marketplace, but can be expanded to all of the different elements that customers may notice) than basic handbags. Exclusive customer needs cause a need for increased variety, while basic customer needs cause a need for increased commonality.

Customer needs (easily defined vs. uncertain): If customer needs are uncertain, a company is more likely to launch a number of different products to blanket the marketplace and then try to find the ideal market niche. The uncertainty of customer needs causes a need for increased variety. For example, in the rapidly changing electronics industry, Japanese companies like Toshiba usually develop a diversity of products for the marketplace since they are not sure about their customer needs [17]. On the other hand, easily defined customer needs are a characteristic of the mass production paradigm and cause a need for increased commonality.

Price consciousness (yes vs. no): Within a market segment (e.g., low end market segment), the prominent buying criterion is price. Price conscious customers are less loyal and easily switch between the brands if they could find a cheaper product in the marketplace [17]. Therefore, these customers cause a need for increased commonality to reduce costs. On the other hand, in high-end market segments, price is not the prominent buying criteria. Companies can increase their market share through either price competition or differentiation. This means that a lack of price consciousness has a neutral impact on commonality and variety in product family design.

Quality consciousness (yes vs. no): The definition of quality has changed from “meeting specifications” to “satisfying the expressed and latent needs” of customers [2, 17]. Therefore, quality consciousness forces companies to provide greater variety and customization to better meet their customers’ needs. That means that quality consciousness causes a need for increased variety. On the other hand, if there is no quality consciousness in the market, companies could sacrifice some level of customer needs to achieve more sharing (commonality) to reduce cost. Therefore, a lack of quality consciousness results in increased commonality in product family design.

*Fashion/style consciousness (yes vs. no):*Pine [17] proposes that, “few things can introduce variety in the industry than a base of customers intent on following the latest fashions.” Hence, fashion/style consciousness causes a need for increased variety. On the other hand, if customers do not care about the latest fashion/style, they could be satisfied with lower prices. This means that a lack of fashion/style consciousness causes a need for increased commonality in product family design.

*Pre- and/or post-sale service (high vs. low):*Since the levels of pre- and/or post-sale services are directly associated with how much customization customers want, companies can differentiate their standard products using different levels of service [17]. For example, customers can choose different shipping methods for the same products when shopping online. Inherently, a high level of pre- and/or post-sale service causes a need for increased variety. On the other hand, a low level of pre- and/or post-sale service causes a need for increased commonality.

<u>Structural factors</u>

Structural factors include buyer power, competitive intensity, and vulnerability to substitute products [17]. These factors characterize the structure of the industry in which a company operates. Each of these factors and how they influence the tradeoff between commonality and variety in product family design are discussed in the following paragraphs.

Buyer power (strong vs. weak): If buyer power is strong in an industry, a company has limited control over their market. This means that a company has to respond more carefully to what their customers want. If low prices are desirable to their customers, this results in significant price competition; if differentiation is desirable to the customers, this results in more variety. Simply sated, strong power causes a need for increased commonality or variety, which is dependent of the prominent market drivers. On the other hand, if in an industry, the buyer power is weak, companies control the marketplace and customers are willing to buy almost whatever is provided to the marketplace. Thus, companies would tend to standardize products to increase margins. This means that weak buyer power causes a need for increased commonality.

Competitive intensity (high vs. low): The competitive intensity in the marketplace is characterized by the number of competitors and how strongly they compete in the marketplace. A high level of competitive intensity in an industry can result in uncertain demand [17]. As we discussed before, uncertain demand causes a need for variety. For example, recent aggressive global competition has forced many companies to offer more variety to respond to uncertain global markets. On the other hand, if competitive intensity is low, companies are not motivated to change their current products. Therefore, a low level of competitive intensity has a neutral impact on commonality and variety in product family design.

Vulnerability to substitute products (strong vs. weak): If a company’s products are vulnerable to substitutes, then the company must spend more time and effort satisfying customers’ needs by offering more variety. For example, customers are more likely to shop on a website with a greater diversity of brands. This means that strong vulnerability to substitutes causes a need for increased variety. On the other hand, if a company’s products are not susceptible to substitutes, the company has little incentive to change current products. As we discussed before, this means that weak vulnerability to substitutes has a neutral impact on commonality and variety in product family design.

Product characteristics

Product characteristics include a unique set of customer requirements, development time, and the product life-cycle length and predictability [32-34]. These factors define the characteristics of the products that a company will offer to the marketplace. Each of these factors and how they influence the tradeoff between commonality and variety in product family design are detailed in the following paragraphs.

Unique set of customer requirements (yes vs. no): Products with unique customer requirements inherently require companies to provide variety. Not all customer needs can be made common if products are to be exactly what the customer wants. This means that unique sets of customer needs cause a need for increased variety. On the other hand, if companies can standardize products without constraining the unique customer requirements, then they can reduce costs and increase profit margins. This means that non-unique sets of customer needs cause a need for increased commonality.

Development time (long vs. short): Today's marketplace forces companies to compress development time to retain or increase their market share by promptly responding to market changes. One strategy to achieve this is to increase commonality across the portfolio of products. This means that short development times cause a need for increased commonality. On the other hand, if companies have more development time, they can increase their profit margins by seeking either cost leadership or differentiation. This means that longer development times have a neutral impact on commonality and variety in product family design.

Product life-cycle length and predictability (long and predictable vs. short and unpredictable): Pine [17] defines the product life-cycle length as the time from the first shipment to its replacement or withdrawal. Long and predictable product life-cycles are one of the main characteristics of mass production, which is reinforced by "stable demand and homogenous markets" [17]. Hence, it causes a need for increased commonality. On the other hand, shorter, unpredictable life-cycles indicate an uncertain demand. As we discussed previously, that uncertain demand of short and unpredictable product life-cycles causes a need for increased variety.

Life-cycle processes

Life-cycle process factors include service and maintenance, automation level, and recycling [1, 32-34]. Here we are using the term life-cycle to mean the life of an individual produced unit, as opposed the previous section where it connoted the market life of all units of product. These factors cover some of the facets influencing product family design throughout the product life-cycle. Each of these factors and how they influence the tradeoff between commonality and variety in product family design are discussed in the following sections.

Service and Maintenance (fast vs. slow): Quick service and maintenance can be a distinct competitive advantage in today's marketplace. To implement design for serviceability, engineers can group components with related service and maintenance in a single module [14, 18], and/or reduce the number of unique components and increase component sharing across products to lower service costs. Hence, fast service and maintenance causes a need for increased commonality (and modularity). On the other hand, a lesser need for service and maintenance would have a neutral impact on commonality and variety in product family design.

Automation level (high vs. low): The complexity of assembly lines increases with increased variety. This complexity results in increased assembly cost. High automation levels indicate that most of the components in a product can be automatically assembled. This requires more standard and/or common components to reduce the complexity of the assembling process. Therefore, a high automation level causes a need for increased commonality. On the other hand, a low automation level denotes that few components in products can be automatically assembled, and most of the components need assembling by hand. Assembling either the standard components, common components, or unique components by workers does not result in significant differences on assembly cost. Therefore, a low automation level has a neutral impact on commonality and variety in product family design.

Recycling (required vs. not required): In today's marketplace, recycling has become the responsibility of the manufacturers in more and more industries; it can also be used as a competitive advantage. To enable low cost recycling, a common strategy is to reduce the material inventory [14]. Reducing the material inventory or material diversity requires increased material sharing among products. Therefore, required recycling causes a need for increased commonality. On the other hand, if companies are not required to recycle their products, either they could choose to increase commonality to implement recycling as a competitive advantage, or they could remain with their current products. Not having required recycling therefore has a neutral impact on commonality and variety in product family design.

Government/industry regulations and/or standards (strict vs. lenient)

Companies must of course make sure that all the applicable regulations and standards are satisfied by their products [2, 16]. If the government/industry regulations and standards are very strict for a particular product category, companies might group components in a product based on the regulations and standards to which they must adhere, creating separate modules and thus improving their agility in response to changing regulations and standards. Alternatively, a company might look to improve material or component commonality specific to reduce the variability in impact of the regulations and standards. For example, Kodak significantly reduced the number of different types of plastics used in its single-use camera family in response to stricter government standards on plastics recycling. On the other hand, companies might leave current products as they are if the standards and regulations are lenient. This means that lenient government/industry regulations and standards have a neutral impact on commonality and variety in product family design.

Organizational capabilities

Organizational capability factors include the company's financial condition and their distribution and supply channel. Porter [8] and Anderson [2] address how organizational capacities constrain the product commonality and variety that a product family can achieve. Financial conditions and distribution and supply channels and how they influence the tradeoff between commonality and variety in product family design are discussed next.

Financial condition (sufficient investment vs. limited investment): If a company's financial condition is good, then they could invest more money in product development to realize the needs of additional customer niches and choose differentiation as their competitive focus. Hence, being in a solid financial condition causes a need for variety. On the other hand, generally, offering variety is associated with increased costs. With limited investment in product development, the only way for companies to improve their profit margins is to reduce costs by increasing commonality and sacrificing some degree of variety. Therefore, a bad financial condition causes a need for increased commonality.

Distribution and supply channels (complex vs. simple): The complexity of distribution and supply channels is characterized by the number of suppliers and their different locations. If companies have complicated distribution and supply channels, the costs associated with that complexity are high. To reduce the logistics costs, one product-based strategy is to increase component sharing across products. Complicated distribution and supply channels therefore cause a need for increased commonality. On the other hand, if companies have few suppliers and/or different locations, then standardizing or commonizing products might not significantly reduce the logistics costs. Therefore, companies could be content to remain with their current distribution and supply channel. This means that simple distribution and supply channels have a neutral impact on commonality and variety in product family design.

2.3 Quantitative representation of the tradeoff in product family design

The commonality/variety tradeoff angle, α, ranging from 0° to 90°, quantitatively represents the commonality/variety tradeoff in a product family. Different companies strive for different competitive foci when developing product families. As a result, the angle can vary from one industry to another, from one company to another, and from one product family to another. When the competitive focus for a product family is addressing cost leadership (commonality), α should be within the range of 0° to 45°. In this case, commonality is more important than variety. When the competitive focus for a product family is addressing differentiation (variety), α should be within the range of 45° to 90°. In this range, variety is more important than commonality. Companies would aim to achieve complete commonality without any constrains if α equals 0°, while companies would be striving for complete differentiation without any constraints if α equals 90°.

In our approach, we define α as a function of the weighted sum of the strategic factors' quantitative impact on commonality and variety in a product family as shown in Equation 1.

$$\alpha = f(S) \tag{1}$$

where:

S = The weighted sum of the factors' impact on commonality and variety in a product family design such that:

$$S = \sum_{i=1}^{n} (w_i \times I_{f_i}) \tag{2}$$

n = The total number of the relevant factors influencing the tradeoff between commonality and variety in a product family design

f_i = The i^{th} relevant factor in a product family design, $i = 1, 2, \ldots, n$

I_{fi} = Indicator for the i^{th} relevant factor's impact on the relative importance of commonality and variety in a product family design

I_{fi} = 1 if f_i causes a need for an increased variety in a product family design

I_{fi} = -1 if f_i causes a need for an increased commonality in a product family design

I_{fi} = 0 if f_i has a neutral impact on commonality and variety in a product family design

w_i = The relative importance of the i^{th} relevant factor in a product family design

To evaluate this weighted sum, the cross-functional product platform design team uses its expertise and judgement to rate each relevant factor's importance based on the company's competitive focus for a product family. A 9/6/3/1 rating system is used to assign these weights (see Table 2). Similar rating system has been used in engineering design literature such as the one used in the Analytic Hierarchy Process (AHP) [19].

Table 2. Factor importance rating system (w_i)

Factor importance rating system (w_i)	
Rating	Description
9	A factor is extremely important for a company in product family designs
6	A factor is strongly important for a company in product family designs
3	A factor is important for a company in product family designs
1	A factor is slightly important for a company in product family designs

To calculate the commonality/variety tradeoff angle, there are at least two scenarios.

- Scenario A: A company launches a new product family into the marketplace where no competitor exists. Such methods to help develop this type of product family are discussed by Alizon *et al*. [20], Thevenot *et al*. [21]. In our analysis, we do not consider this scenario.
- Scenario B: A company launches a new product family into the marketplace where more than one competitor exists. Our analysis will focus on this scenario. In such a scenario, it is possible to obtain a commonality/variety tradeoff angle, α_c, for a single competitor or multiple competitors using Equation 3.

$$\alpha_c = \arctan\left(\frac{\text{VI}}{\text{CI}}\right) \tag{3}$$

where:

VI = The degree of variety of a competitor's product family, which can be obtained using either CMC_V or CDI_V

CI = The degree of commonality of a competitor's product family, which can be obtained using either CMC_C or CDI_C

We have detailed how to calculate the degree of commonality and variety using [CDI_C, CDI_V] and [CMC_C, CMC_V] and then how to calculate the commonality/variety angle for each competitor in Ref. [11]. In addition, for each competitor, analysis of the weighted sum of factor's impact can be carried out separately using equation 2 and Table 1. In this paper, we quantitatively characterize the commonality/variety tradeoff angle based on a company's competitive focus and their industry-wide competitors' information. Typically, the empirical models including linear regression, response surface models, and/or neural networks are used to approximate the relationships between x (inputs) and y (outputs). Hence, to establish the relationship between S (the weighed sum of the factor's impact) and α (the commonality/variety tradeoff angle), we use a linear regression model with a and b as the best linear fit coefficients, as defined in Equation 4.

$$\alpha = aS + b \tag{4}$$

There are three steps to estimate the commonality/variety tradeoff angle for a given company using the linear regression model (Figure 1). The angle can then be used with the PFEG to help designers evaluate a product family or compare product family design alternatives with respect to the tradeoff between commonality and variety supported by the [CMC_C, CMC_V], or the [CDI_C, CDI_V].

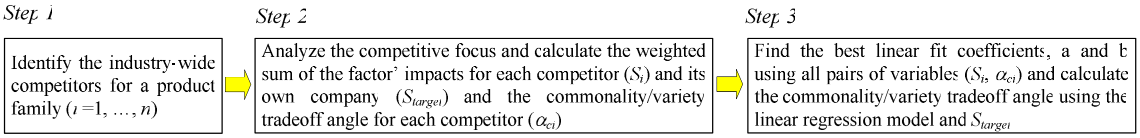

Figure 1. Three steps to calculate the commonality/variety angle

3 CASE STUDY

A case study is presented in this section to demonstrate how to obtain the commonality/variety tradeoff angle for a given company based on its competitive focus and how this angle can be combined with the PFEG to help product family redesign. We use a Delta® power tool family and three competitors' power tool families to illustrate this method (see Figure 2).

Figure 2. Delta® and its competitor cordless power tool families

3.1 Setting α for a Delta® power tool family

In our approach, we use the three-step approach shown in Figure 1 to obtain the commonality/variety angle α.

Step 1: Identify the industry-wide competitors for a product family

Delta®machinery plans to launch a 14.4v cordless power tool combo kit for today's do-it-yourself market segment. In today's marketplace, DeWALT®, Black & Decker®, and Skil® (see Figure 2) provide cordless power tool combo kits with the same voltage. We admit there are more than these three manufactures producing power tool combo kits; however, in this paper, we use these three companies as the industry-wide competitors to illustrate how to use the proposed approach to calculate the commonality/variety tradeoff angle.

Step 2: Analyze the competitive focus and calculate *S* and α_c

As we described in the previous section, once analyzing the strategic factors, these manufactures can determine using either cost leadership or differentiation as their competitive focus. This process starts with choosing the relevant factors for the particular product family design from Table 1, assigning weights for each relevant factor based on their judgments and expertise using Table 2, and then calculating the weighted sum (S) using Equation 2. Note that the identification of the relevant factors identification and the assignment of their weights are not based on corporate information in this illustrative example. We have made estimates based on our own knowledge of these companies and of power tool families. For example, from Table 1, quality consciousness in Black & Decker® is identified as a relevant factor in this product family, its state is high, and its indicator for the impact on the relative importance of commonality and variety is 1 since this factor causes a need for increased variety. We then assign a weight of 9 to this factor. Hence, the product of weight and indicator of quality consciousness is 9. The other relevant factors in this product family can be analyzed using the same method. As a result, the weighted sum of this family's relevant factors' impact on commonality and variety is 5 using Equation 2. Using the same analysis, the weighted sum for the three other product families is obtained. The results of this analysis are shown in Table 3. The CDI_C and CDI_V for the Black & Decker® family are 0.424 and 0.576, respectively, as calculated using the method in Ref. [11]. Based on Equation 3, the commonality/variety tradeoff angle is 53.67°. The angle in the Skil® family and DEWALT® can be computed similarly. The results of the analysis are shown in Table 4. Hence, Delta® machinery sets its competitive focus as being the overall cost leader in the do-it-yourself market segment. Skil® is also trying to beat its competitors using a low cost strategy. DEWALT® uses differentiation as its competitive focus. Black & Decker® uses differentiation as its competitive focus as well.

Table 3. S calculation for Black & Decker®, Delta®,DEWALT®and Skil® product families

Factor	Black & Deck®			Dewalt®			Skil®			Delta®		
	weight (w_i)	I_{fi}	S_i	weight (w_i)	I_{fi}	S_i	weight (w_i)	I_{fi}	S_i	weight (w_i)	I_{fi}	S_i
Stability and predictability of demand levels	6	-1	-6	3	-1	-3	3	-1	-3	6	-1	-6
Customer needs characteristics	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1
Customer needs	3	-1	-3	3	-1	-3	3	-1	-3	3	-1	-3
Price consciousness	3	-1	-3	3	-1	-3	9	-1	-9	9	-1	-9
Quality consciousness	9	1	9	9	1	9	9	1	9	9	1	9
Level of pre- and post sales service	6	1	6	6	1	6	6	1	6	6	1	6
Buyer power	9	1	9	6	1	6	6	1	6	3	1	3
Competitive intensity	6	1	6	9	1	9	6	1	6	6	1	6
Unique sets of customer requirements	1	-1	-1	1	-1	-1	1	-1	-1	3	-1	-3
Development time	6	-1	-6	3	-1	-3	3	-1	-3	6	-1	-6
Product life-cycle length and predictability	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1
Maintenance and service	3	-1	-3	3	-1	-3	3	-1	-3	3	-1	-3
Automation level	1	-1	-1	1	-1	-1	1	-1	-1	3	-1	-3
Recycling	6	-1	-6	1	-1	-1	3	-1	-3	1	0	0
Financial condition	9	1	9	6	1	6	6	1	6	6	1	6
Distribution and supply channel	3	-1	-3	3	-1	-3	3	-1	-3	3	-1	-3
Sum =			5			13			2			-8

Table 4. Results of α_c and S calculations

Competitors	CDI_C	CDI_V	α_c	S
Black and Decker®	0.424	0.576	53.67°	5
DEWALT®	0.324	0.676	64.42°	13
Skil®	0.438	0.562	52.10°	2

Step 3: Find the best linear fit coefficients, *a* and *b*, and calculate the α

Using the linear model (Equation 4) and data (S_i, α_{ci}) in Table 4, the best linear fit coefficients, *a* and *b*, and α can be obtained. The results of such analysis are shown in Table 5 and Figure 3.

Table 5. Parameters for the linear regression model to predict α

Company	S_{target}	a	b	α
Delta®	-8	1.17	48.95	39.61°
	α = -8×1.17+48.95 = 39.61			

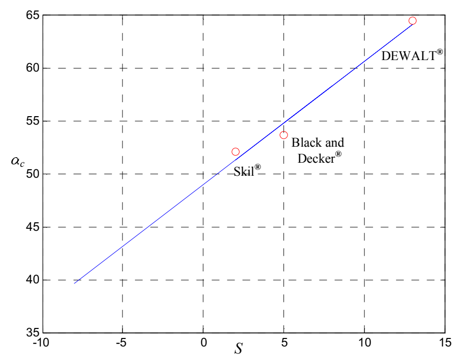

Figure 3. Linear regression model for α

3.2 Combining α with the PFEG

As we stated before, the PFEG can be used to help designers evaluate a set of product family design options and choose the best option based on a competitive focus when designing a new product family, or it can be used to help designers decide if there is a need to improve the commonality or variety of an existing product family. The first use of the PFEG has been addressed in previous papers [10, 11]. The use of PFEG for redesign is illustrated in this paper using the Delta® power tool family.

By comparing the difference between the actual commonality/variety tradeoff angle obtained using Equation 3 and the ideal commonality/variety tradeoff angle determined using the approach proposed in the Section 3, designers can decide if the existing product family needs increased commonality or variety in the redesign. Many bottom-up product family design approaches that appear in the literature are only focused on maximizing commonality in a product family, without considering if it could undermine the company's competitive focus. In the PFEG, we believe it is unnecessary to improve commonality or variety when redesigning product families if this move does not add value to the company's competitive focus.

For the existing Delta® power tool family (Figure 2), the analysis of the actual and ideal commonality and variety tradeoff angle is shown in Table 6. Moreover, the PFEG construction for Delta® power tool family is shown in Figure 4.

Table 6. α result for Delta® power tool family

	CDI_C	CDI_V	α_{actual}	α_{ideal}
Delta®	0.22	0.78	74.3°	39.6°

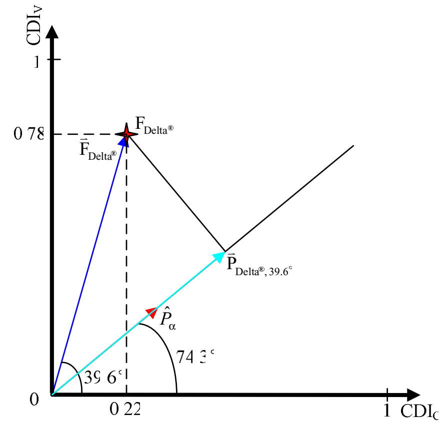

Figure 4. PFEG for the Delta® power tool family

Based on the results in Figure 4, to minimize the difference between the actual commonality/variety angle and ideal commonality/variety tradeoff angle when redesigning the Delta® power tool family, designers need increase the CDI_C score of this family. This means that designers should improve the commonality in this family to make the family's α_{actual} fit better the company's competitive focus. The detailed redesign recommendations are beyond the scope of this paper. However, designers could use the approaches developed by Alizon *et al*. [20] and Thevenot *et al*. [21] to improve the degree of commonality in a product family through reducing unnecessary differentiation across this product family.

4 CONCLUSIONS

Although many product family design and evaluation methods proposed in the literature have addressed the importance of the tradeoff between commonality and variety, no methods can quantitatively characterize the tradeoff to be very useful during product family (re)design. The commonality/variety tradeoff angle (α) developed in this paper quantitatively represents the commonality/variety tradeoff based on a company's competitive focus for a product family (i.e., focusing more on commonality or variety). The commonality/variety tradeoff angle can be applied to the product family evaluation graph (PFEG) to help designers evaluate product family design alternatives and then choose the best product family design or redesign product family. A table of tradeoff influencing factors and their impacts has been proposed as well. However, the approach proposed in this paper is only a starting point in quantitatively solving the central problem of developing product families - the tradeoff between commonality and variety. At this point, the factors and their categories are admittedly incomplete and the analyses of the factors' impact are subjective. Our intent is to initiate a conversation on these important factors by suggesting a starting point, developing a representation, and illustrating their use in product family (re)design using the PFEG. Future work includes developing ontology of the factors and their relative impact on the balance between commonality and variety.

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