International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713696255

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First Published:January2009

To cite this Article Ye, Xiaoli, J. Thevenot, Henri, Alizon, Fabrice, Gershenson, John K., Khadke, Kiran, Simpson, Timothy W. and Shooter, Steven B.(2009)'Using product family evaluation graphs in product family design',International Journal of Production Research,47:13,3559 — 3585

To link to this Article: DOI: 10.1080/00207540802183646

URL: http://dx.doi.org/10.1080/00207540802183646

International Journal of Production Research
Vol. 47, No. 13, 1 July 2009, 3559–3585

Using product family evaluation graphs in product family design

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(*Received 10 October 2007; final version received 21 March 2008*)

Product family design and platform-based product development have garnered much attention. They have been used to provide nearly customised 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 trade-off between product commonality (how well the components and functions can be shared across a product family) and variety (the range of different products in a product family). Quantifying this trade-off at the product family planning stage in a way that supports the engineering design process has yet to be accomplished. In this paper, we introduce 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 an ideal commonality/variety trade-off determined by a company's particular competitive focus, and guides designers towards a more desirable trade-off between commonality and variety in an existing product family. Two necessary supporting pieces for developing the PFEG are also proposed. One piece is the development of commonality and variety indices to quantitatively capture the degree of commonality and variety in a product family and its functions and components. We introduce two sets of commonality and variety indices – the CDI (commonality versus diversity index) for commonality (CDI_C) and variety (CDI_V), and the CMC (comprehensive metric for commonality) for commonality (CMC_C) and variety (CMC_V) – to achieve this. The other supporting piece is the development of a quantitative representation of the ideal trade-off between commonality and variety in a product family, known as the commonality/variety trade-off angle α, based on the elements that characterise a company's competitive focus and their industry-wide competitors. A linear regression model is used to link the qualitative competitive focus to a quantitative engineering perspective, and then to estimate the ideal trade-off angle. The commonality/variety trade-off angle can then be applied to the PFEG to help designers evaluate a product family or compare product family design alternatives. Most importantly, the PFEG is not just the graph of the two sets of indices; it is the representation of the commonality/variety trade-off relative to the desired competitive focus. Four families of power tools are used to illustrate how the computation of such indices supports product family design evaluation in the PFEG. In this paper, we only use the CDI in the example application, but the CMC can be computed using the same approach.

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ISSN 0020–7543 print/ISSN 1366–588X online

DOI: 10.1080/00207540802183646
http://www.informaworld.com

Keywords: product family; product platform; commonality index; variety index; product family evaluation

1. Introduction

Today's market place is characterised by rapid innovation, globalisation, customisation, and market fragmentation. The emergence of these characteristics has fundamentally altered the way many manufacturing companies do business (Meyer and Lehnerd 1997). However, many manufacturing companies still typically design new products one at a time. Meyer and Lehnerd (1997) found that 'the focus on individual customers and products often results in a failure to embrace commonality, compatibility, standardisation, or modularisation among different products or product lines'. Hence, to remain competitive in the market place, many manufacturing companies are investing in product family development to provide useful external variety (differentiation of product functionality that is appreciated by customers) (Anderson 1997) to satisfy individual customer requirements and simultaneously achieve economies of scale and scope within their manufacturing capabilities (Robertson and Ulrich 1998).

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 (Meyer and Lehnerd 1997). Each product variant shares some common features and product technologies that come from the product platform of the product family (Erens and Verhulst 1997). The core of a product family is therefore the product platform (Simpson *et al.* 1999), 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'. 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.* (2005).

Commonality and variety can both offer competitive advantages to a company. Product commonality refers to how well components and functions are shared across a product family, and product variety refers to the diversity of products that a company provides to the market place (Meyer and Lehnerd 1997). All of the benefits of product commonality result in reduced costs. However, 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 trade-off between commonality and variety within any product family (Simpson *et al.* 2001). The ideal product family would have complete commonality within its non-differentiating components and functions, while the differentiating components and functions satisfy all of the necessary variety for the market place. According to Porter (1985), companies can achieve a competitive advantage by following one of three generic strategies – differentiation, cost leadership, or focus. However, a company should only emphasise one of these 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 (Porter 1985). If a company wants to have a competitive advantage over a number of segments (a broad target), then the company can either aim to achieve cost leadership while simultaneously providing differentiation relative to its competitors, or aim to achieve differentiation while simultaneously remaining price competitive with its competitors (Kristjansson and Hildre 2004). Therefore, to maximise the combination of commonality and variety a product family can achieve, designers should successfully balance between commonality (cost) and variety (differentiation) based on a company's intent for a particular product family.

Even with the ability to design a product family and product platform, there is still a glaring need to quantitatively evaluate product family design options to determine which one better satisfies the ideal trade-off for a particular product family based on a company's desirable competitive focus and the products' competitive pressures. A product family's competitive focus is characterised by the strategic life-cycle factors influencing the commonality/variety trade-off. These factors span five categories – the market, product characteristics, life-cycle processes, government and industry regulations and/or standards, and organisational capabilities – and their cumulative impact determines whether a company should focus more on product differentiation or cost leadership in a product family. Responding to the need, we have previously developed a graphical evaluation method, the product family evaluation graph (PFEG) (Ye *et al.* 2005), to allow designers to compare sets of product family design options with respect to the commonality/variety trade-off specific to a company's competitive focus, and to choose the 'best' product family design. The PFEG is a single quadrant graph of the measured commonality and variety of each product family under evaluation as described in the next section. As discussed in Section 3, two necessary supporting pieces for the PFEG are to characterise the commonality and variety of product family design options directly, and to develop a quantitative representation of the ideal trade-off between commonality and variety in a product family, determined by the elements that characterise a company's competitive focus. The PFEG qualitatively links a company's competitive focus (represented by the strategic life-cycle factors) and the measured quantities of commonality and variety (based on product functions and components) through an initial regression model. In this paper, we propose two sets of commonality and variety indices – the CDI (commonality versus diversity index) for commonality (CDI_C) and variety (CDI_V), and the CMC (comprehensive metric for commonality) for commonality (CMC_C) and variety (CMC_V). In addition, we develop the commonality/variety trade-off angle α, ranging from 0° to 90°, as a quantitative representation of the ideal trade-off for a particular product family based on a company's competitive focus and the products' competitive pressures. Section 4 presents an example involving four families of power tools to demonstrate the PFEG and these two supporting pieces. Section 5 discusses future research for PFEG.

2. Product family evaluation graphs (PFEG)

The ideal product family has complete commonality within its non-differentiating components and functions, while its differentiating components and functions specifically satisfy the necessary variety for the market. Achieving greater commonality within a family usually means sacrificing some degree of performance (and/or variety) for individual products; however, increasing product variety could make it difficult to share common functions, components, or manufacturing processes across a product family. Therefore, to obtain a better product family design, designers need to successfully navigate the trade-off between product commonality and variety based on the focus of a given company's competitive advantage (e.g. commonality or distinctiveness). A graphical evaluation method, the product family evaluation graph (PFEG), developed previously by the authors (Ye *et al.* 2005), provides a structure to support product family design through identifying the best ('best' here is based on our model/criteria and is not intended to be objective) product family design option among a set of design candidates during new product family design or redesign based on the competitive focus. The PFEG is the first step in linking the competitive focus from the marketing domain to the engineering side (component and/or function).

In the PFEG, a single evaluation criterion (typically the maximal combination of commonality and variety a product family can achieve given particular resource constraints) is employed to determine the best product family design. The PFEG is a two-dimensional graph with the horizontal axis referring to a commonality index (CI) and the vertical axis referring to a variety index (VI). Typically, graphs can be used either for the spatial positioning/location or the relationship/trade-off assessment. Since our goal is trade-off assessment, independence of the two axes in the PFEG is unnecessary. Moreover, the PFEG is generic to any commonality indices or variety indices only if they can be split into two parts (commonality and variety) to separately evaluate the degree of commonality and variety in a product family. We will split the CMC (Thevenot and Simpson 2006b) and the CDI (Alizon *et al.* 2006) into the constitutive axes in the next section for use in the PFEG. Both of these indices are novel in that they consider the trade-off between commonality and variety simultaneously (Thevenot *et al.* 2007).

When using the PFEG (see Figure 1) to assess and compare product family design options, the first step is to set the commonality/variety trade-off unit vector, $\hat{P}_\alpha$, at the commonality/variety trade-off angle, α, ranging from 0° to 90° to quantitatively represent the relative importance of product commonality and variety given a company's competitive focus for a product family. Further development of α will be introduced in Section 3.2. $\hat{P}_\alpha$ represents the ideal combination of the commonality and variety in a product family with respect to a particular α. Ideally, more variety and more commonality are both better; however, the combination is limited by a company's focus for a product family and its available design resources. Hence, based on the single evaluation criteria in the PFEG, the best product family design among a set of candidates with respect to a specific α is the one with the longest projection along the unit vector.

The second step in creating a PFEG is to measure the degree of commonality and variety using commonality and variety indices for each of n product family design options ($i = 1, 2, \ldots, n$), and then locate a point, F_i, for each family option at (CI_i, VI_i). Further development of the two sets of direct commonality and variety indices are introduced in Section 3.1. The accuracy of the assessment of the design by the indices is based on the type of data and its availability. We know that the sets of indices that we are using consider a limited number of parameters; the assessment can be refined using additional information or types of information. Again, the focus on the paper is not to develop a comprehensive set of metrics to fully assess the design of a product family, but to show more detailed and refined models to be used when more information is available.

The third step in creating a PFEG is to draw the commonality/variety positioning vector, $\vec{F}_i$, from the origin to the product family point, F_i. This vector represents the combination of commonality and variety that the product family design option, F_i, can achieve. The last step in creating a PFEG is to project $\vec{F}_i$ onto $\hat{P}_\alpha$ to create the trade-off

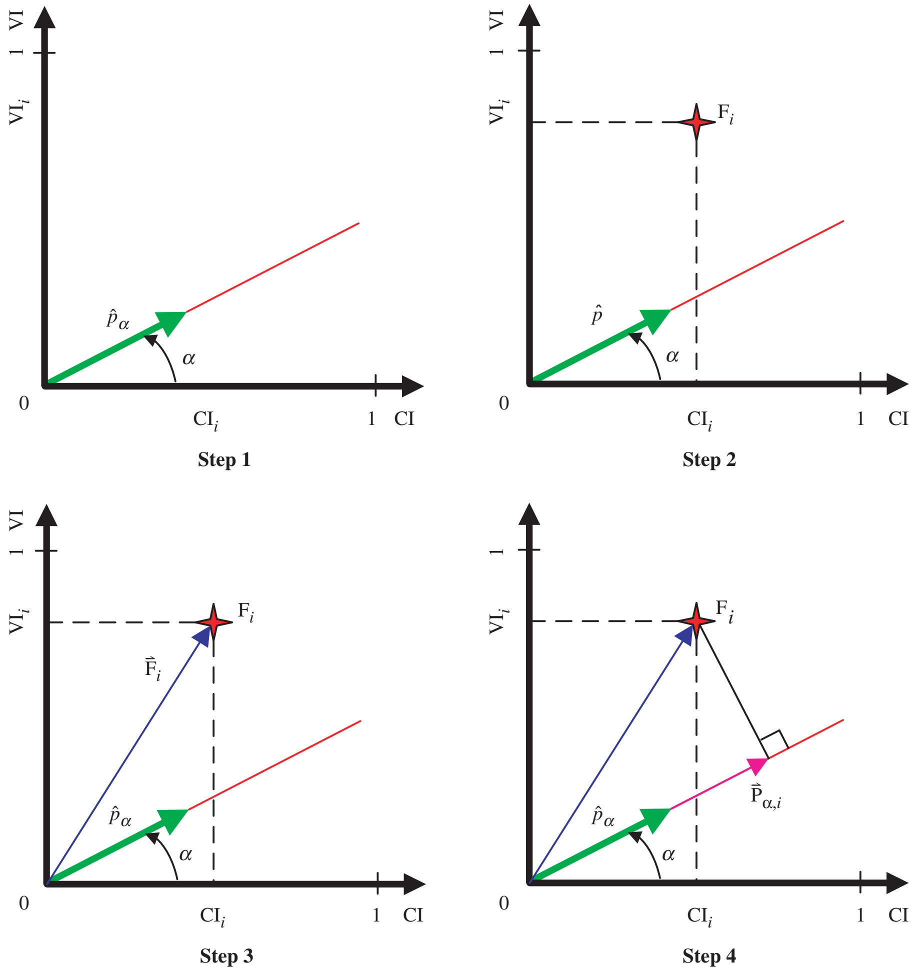

Figure 1. Four steps in PFEG construction.

achievement vector, $\vec{P}_{\alpha,i}$, of F_i. This is shown graphically in Figure 1 and can be calculated by Equation (1).

$$\left|\vec{P}_{\alpha,\,i}\right| = \left|\vec{F}_i \bullet \hat{p}_\alpha\right| \tag{1}$$

At this point, designers only need to analyse the scalar value of the trade-off achievement vector, $|\vec{P}_{\alpha,i}|$, to assess the set of product family design options. The best product family design option identified in the PFEG is the alternative with the maximal value of $|\vec{P}_{\alpha,i}|$.

3. Two supporting pieces for developing the PFEG

As stated in the previous section, the PFEG is not just a graph of the indices as measured; rather, it is the representation of the commonality/variety trade-off relative to the desired competitive focus for a particular product family. However, to realise this concept, two supporting pieces are necessary. One is a pair of indices to characterise the degree of commonality and variety in a product family, and the other is a method to obtain the ideal commonality/variety angle determined by the competitive focus of a company. These are both introduced in this section.

3.1 *Characterisation of product family commonality and variety*

Commonality indices and variety indices are frequently addressed in the literature to characterise the degree of commonality and variety in product families. Researchers have developed multiple indices for assessing commonality and variety. The PFEG is generic to any commonality index or variety index that can be used to represent the quantitative aspect from functions and components provided that they can be split into two parts, namely, commonality and variety. In this section, we separate the CMC (Thevenot and Simpson 2006b) and the CDI (Alizon *et al.* 2006) into their constitutive commonality and variety components. In this paper, the aim is to develop the two sets of indices and then to illustrate how the computation of such indices supports the product family design evaluation.

3.1.1 *Existing commonality and variety metrics*

The challenge of finding the optimal trade-off between commonality and variety during product family design has led to the development of many component-based commonality indices (the comprehensive metric for commonality (Thevenot and Simpson 2006b), the commonality and diversity index (Alizon *et al.* 2006), the degree of commonality index (Collier 1981), the total constant commonality index (Wacker and Trelevan 1986), the commonality index (Martin and Ishii 1996, Martin and Ishii 1997), the percent commonality index (Siddique *et al.* 1998), the component part commonality index (Jiao and Tseng 2000), the product line commonality index (Kota *et al.* 2000), and the total commonality index (Blecker and Abdelkafi 2007) and a few variety indices (the non-commonality index (Simpson 1998), the performance deviation index (Simpson 1998), and the generational variety index (Martin and Ishii 2002)). Generally, a commonality index is a metric for assessing the degree of commonality within a product family based on different parameters such as the number of common components, component costs, manufacturing processes, and so on. These indices often provide a surrogate for estimating manufacturing cost savings within a family and are often the starting point when designing a new product family or when analysing an existing family. An extensive review of commonality indices can be found in Thevenot and Simpson (2006a).

The issue of variety in a product family has been addressed as well. Ulrich (1995) defines product variety as the diversity of products that a production system provides to the market. Jiao *et al.* (1999) classify two more focused types of variety – functional variety and technical variety. Functional variety, any differentiation of product functionality, is used to satisfy customer requirements. Technical variety, including various design methods, components, assemblies, etc., is used to realise the functions required by customers. Simpson (1998) develops two indices to measure the product variety of a product family. The non-commonality index is a weighted sum of average relative variations in design variables across a family of products to evaluate whether products meet their targeted performance. The performance deviation index measures a weighted sum of deviations from performance targets across a family of products. The generational variety index developed by Martin and Ishii (2002) indicates the amount of redesign required for a component to meet the future market requirements and captures the changes among product family generations.

One main limitation of most of the previously mentioned indices is the fact that they ignore the commonality/variety trade-off in product family design. To address this need, Thevenot and Simpson (2006b) and Alizon *et al.* (2006) recently developed the comprehensive metric for commonality (CMC) and the commonality versus diversity index (CDI), respectively. The CMC extends the percent commonality index to assess the impact of each component on the overall level of commonality and variety in the product family. The CDI, with three levels of analysis (function, component, and family), scores both the commonality and variety within a family of products to decide what should be common-variant-unique (function specification) and what is the real trade-off (component specification).

Not only do both the CDI and CMC show promising results on the assessment of commonality and variety in a product family, but they combine commonality and variety aspects into a single measurement (Thevenot *et al.* 2007). Hence, to apply these two indices to the PFEG to directly capture the degree of commonality and variety in a product family, a slightly refined formulation of these two indices is needed. The next section describes a classification of components that is employed in the paper to support the following introduction of the two sets of indices derived from the CMC (Thevenot and Simpson 2006b) and the CDI (Alizon *et al.* 2006).

3.1.2 *Differentiating and non-differentiating components*

The classification of the components in a product family is a key element of the two indices. Within a given product family, the products' components can be classified into two groups: non-differentiating or differentiating. Differentiating components are ones that are intended to differentiate the products aesthetically or that provide unique functions to the product. For example, when considering a family of single use cameras, the 'identification label' (aesthetic differentiation, Figure 2(a)) and the 'APS film' (functional differentiation, Figure 2(b)) are the differentiating components. On the other hand, non-differentiating components are not used to differentiate products, neither

(a) (b) (c)

Identification label, differentiating component (aesthetically)

APS film, differentiating component (functionally)

Flash, non-differentiating component

Figure 2. Example of differentiating and non-differentiating components in a single use camera family [photographs: Authors' own].

aesthetically nor functionally. As an example, the 'flash' is a non-differentiating component in the single use camera family (Figure 2(c)). All of the unique components in a product are considered to be differentiating; the common components are assumed to be non-differentiating.

The development of the $\mathrm{CMC_C}$, $\mathrm{CMC_V}$, $\mathrm{CDI_C}$, and $\mathrm{CDI_V}$ is based on this classification. Hence, these indices are orthogonal because commonality and variety are antagonistic (components and functions can be either common to more than one product or specific to one product). The $\mathrm{CMC_C}$ and $\mathrm{CDI_C}$ consider non-differentiating components and/or functions, while the $\mathrm{CMC_V}$ and $\mathrm{CDI_V}$ consider differentiating components and/or functions in a product family.

More specifically, differentiating and non-differentiating components in the CDI and CMC can be categorised into common, variant, and unique. A common component is the exact same component shared by some or all of the products in the family. A variant component has the same function across some or all of the products in the family, but characteristics such as the shape and/or material differ slightly from one product to the next across some or all of the products in the family. A unique component is a component used by only one product in the family. The term component refers to the entities obtained after the lowest level of disassembly possible, i.e. to the point where the products cannot be divided further and still be re-assembled into a functioning product. In our work, all unique components are considered to be differentiating; the common components are non-differentiating, and the variant components can be either differentiating or non-differentiating.

3.1.3 *The CMC for commonality (CMC_C) and variety (CMC_V)*

The CMC, as an extension of the product line commonality index (Kota *et al.* 2000), stresses production volume and costs, and the commonality/variety aspect of each component. The CMC assesses the design of a product family based on the ratio of the current component commonality and variety and the level of commonality and variety that is desired (Thevenot and Simpson 2006b). It considers all of the components across all products in the family in one measurement, yielding a global assessment of the product family. In this paper, we have broken the CMC into two components – the $\mathrm{CMC_C}$ and the $\mathrm{CMC_V}$ – to assess commonality and the variety, respectively. As described previously, we can divide the set of all components in a product family into two subsets – non-differentiating components (*ND*) and differentiating components (*D*). The $\mathrm{CMC_C}$ defined in Equation (2) weights the non-differentiating components in the products based on their cost, as well as their size and geometry, their material, their manufacturing process, and their assembly scheme using four separate ratios. Similarly, the $\mathrm{CMC_V}$ defined in Equation (3) weights the differentiating components in the products. Thus, the $\mathrm{CMC_C}$ and $\mathrm{CMC_V}$ are more comprehensive than the $\mathrm{CDI_C}$ and $\mathrm{CDI_V}$ with their inclusion of these four ratios.

$$\mathrm{CMC_C} = \frac{\sum_{i \in ND} n_i * \left(C_i^{\max} - C_i\right) * \prod_{k=1}^{4} f_{ki}}{\sum_{i \in ND} n_i * \left(C_i^{\max} - C_i^{\min}\right)} \tag{2}$$

$$\mathrm{CMC_V} = \frac{\sum_{i \in D} n_i * \left(C_i^{\max} - C_i\right) * \prod_{k=1}^{4} f_{ki}}{\sum_{i \in D} n_i * \left(C_i^{\max} - C_i^{\min}\right) * \prod_{k=1}^{4} f_{ki}^{\max}} \tag{3}$$

where:

- I Total number of components in the family.
- ND Set of indices of the non-differentiating components in a product family (e.g. if only component$_1$, component$_3$, and component$_5$ are non-differentiating in a particular family, then $ND = \{1, 3, 5\}$).
- D Set of indices of the differentiating components in a product family (e.g. if only component$_2$ and component$_4$ are differentiating in a particular family, then $D = \{2, 4\}$).
- n_i Number of products in the product family that have component i.
- f_{ki} $\{f_{1i}, f_{2i}, f_{3i}, f_{4i}\}$.
- f_{1i} Ratio of the greatest number of products that currently share component i with identical size and shape to the number of products that have component i (n_i).
- f_{2i} Ratio of the greatest number of products that currently share component i with identical materials to the number of products that have component i (n_i).
- f_{3i} Ratio of the greatest number of products that currently share component i with identical manufacturing processes to the number of products that have component i (n_i).
- f_{4i} Ratio of the greatest number of products that currently share component i with identical assembly and fastening schemes to the number of products that have component i (n_i).
- $f_{ki}^{\max}$ $\left\{f_{1i}^{\max}, f_{2i}^{\max}, f_{3i}^{\max}, f_{4i}^{\max}\right\}$.
- $f_{1i}^{\max}$ Ratio of the greatest number of products that could share component i (this number is determined by the market, designer expertise, available technologies, etc.) with identical size and shape to the number of products that have component i (n_i).
- $f_{2i}^{\max}$ Ratio of the greatest number of products that could share component i with identical materials to the number of products that have component i (n_i).
- $f_{3i}^{\max}$ Ratio of the greatest number of products that could share component i with identical manufacturing processes to the number of products that have component i (n_i).
- $f_{4i}^{\max}$ Ratio of the greatest number of products that could share component i with identical assembly and fastening schemes to the number of products that have component i (n_i).
- C_i Current total cost of component i in a product family as in Equation (4).

$$C_i = \sum_{j=1}^{n_i} V_{ij}, \quad \text{and } V_{ij} = Q_{ij} \times v_{ij} \tag{4}$$

where:

- V_{ij} Total cost of component i in variant j.
- Q_{ij} Quantity of component i in variant j.
- v_{ij} Unit cost of component i in variant j.

Two cost models can be used to estimate the unit cost, v_{ij} (the choice of the cost estimate is independent of the CMC_C and CMC_V formulation).

(1) For the components produced in-house, v_{ij} is given by:

$$v_{ij} = v_{ij}^a + \frac{v_{ij}^b}{Q_{ij}} \tag{5}$$

where:

- v_{ij}^a Material and processing cost (further estimated using component volume material and processing cost per unit volume)
- v_{ij}^b Setup cost (e.g., for plastic injection components, this will be the cost to produce the mold)

(2) For purchased components, an appropriate cost estimate should be considered, with decreasing costs as quantity increases due to volume discounts.

- $C_i^{\min}$ Minimum total cost of component i that could be obtained if component i was common across all of the products having component i as in Equation (6).

$$C_i^{\min} = v_{ij}^{\min} \times \sum_{j=1}^{n_i} Q_{ij} \tag{6}$$

where:

- $v_{ij}^{\min}$ Minimum unit cost of component i in variant j that is equal to the minimum value among all of the cost of the components i in the product family.
- $C_i^{\max}$ Maximum total component cost that could be obtained if component i was different in each of the products having component i as in Equation (7).

$$C_i^{\max} = \sum_{j=1}^{n_i} Q_{ij} \times v_{ij}^{\max} \tag{7}$$

where:

- $v_{ij}^{\max}$ Maximal unit cost of component i in variant j computed using the most expensive variant and the most expensive materials.

For the CMC_V, it is assumed that the current design possesses more variety than it should; in other words, the CMC_V does not penalise increased commonality when more variety is desired. To counter this, the CDI_V (described in the next section) was formulated. In addition, when the desired variety is achieved, the formulation of the CMC_V given in Equation (3) is not valid, since $C_i^{\min} = C_i^{\max} = C_i$. The CMC_V should then be taken as 1. The CMC_C and the CMC_V range from 0 to 1. $CMC_C = 1$ is obtained when all of the non-differentiating components are common across all of the products; $CMC_C = 0$ is obtained when all of the non-differentiating components vary in size, geometry, manufacturing process, assembly, and material. $CMC_V = 1$ is obtained when the desired variety in a product family is obtained; $CMC_V = 0$ is obtained when all of the differentiating components vary in size, geometry, manufacturing process, assembly, and material across all of the products (except where the desired variety requires that all of the components are different). A limitation of the current formulation of the CMC_V is that it does not penalise unnecessary variety. The CMC_C and CMC_V may also be very information-intensive if the necessary data is not readily available. However, the CMC formulation is very flexible, and if some of the previously mentioned data is not available, then the CMC_C and CMC_V can be adapted to use whatever information is available at that point in the design process. Moreover, the CMC_C and CMC_V can be used at different levels of granularity. In the formulation above, the CMC_C and CMC_V is computed at the component level, but if the number of components becomes too large, the CMC_C and CMC_V can be computed at the module level, where each module is considered as a single entity rather than multiple components.

3.1.4 *The CDI for commonality (CDI_C) and variety (CDI_V)*

The CDI developed by Alizon *et al.* (2006) quantifies the difference between an existing product family design and an ideal product family design for different levels of analysis (function, component, and family). For the CDI, an ideal design with respect to the market specified design requirements has:

(1) Common functions (the same function and relevant functional attributes across products) that use the same components to increase similarity.
(2) Unique functions (different functions across products) that use unique components.
(3) Variant functions (the same function across multiple products with different functional attributes in each product) that use the same components and/or different components where necessary to create functional variety.

In general, each function can be decomposed into its functional attributes and assigned functional attribute values (given the function 'Store Image' for a single-use camera, one of the relevant functional attributes is the 'F-stop' that can take the values of ISO100, ISO200, ISO400, etc. in each product having this function). As a result, it is easy to identify common, variant, and unique functions based on products' functions and functional attributes. Given the functional requirements for the various market segments, it is possible to establish the ideal design for the CDI more objectively than with other indices. The CDI takes into account that a component can be used by several functions even if a one-to-one correspondence between components and functions is a design goal (in violation of Suh's independence axiom (Suh 2001)). In such a case, the CDI analyses a component for each of its functions. Moreover, the CDI_C and CDI_V are novel in that they penalise the 'inappropriate' commonality and variety of components in terms of the ideal design of a product family. 'Inappropriate commonality' refers to the case in which common components across a product family should not be made common according to the ideal design, while 'inappropriate variety' refers to that case in which the unique components across a product family should not be made specific according to the ideal design.

In this paper, the original CDI (Alizon *et al.* 2006) is split into two indices – commonality and variety – for use with the PFEG. Commonality is measured with the CDI_C and variety is measured with the CDI_V. The calculation process is the same – as the CDI always managed commonality and variety independently – the only change is that we calculate two indices (CDI_C and CDI_V) instead of one.

For the mathematical formulation, let $P = \{P_1, \ldots, P_N\}$ be a family of N products that has F functions, f_i ($i = 1, \ldots, F$). Each function, f_i, in the product family is achieved by K_i components, c_{ik} ($k = 1, \ldots, K_i$). For example, in a single-use camera, the function 'Display Information' is realised by three different components – 'Counter wheel', 'View finder', and 'Flash'. For a given k, c_{ik} refers to a generic component for function f_i (e.g. 'View finder' for the function 'Display information'). The physical representations or instances of the generic component c_{ik} in the products $P_1, \ldots, P_N$ are denoted as $c_{ik}^j (j = 1, \ldots, N)$. $c_{ik}^j =$ null if the component c_{ik} is not present (has no instance) in product j. Such definitions are shown in Table 1.

We use the term 'instance' to indicate the physical representation of a generic component. For example, for the generic component 'Film' for the function 'Store image' for the single-use camera family, the instances could be 35 mm colour film, 35 mm black and white film, and 25 mm colour film. The ideal instances of a generic component are related to the ideal design with respect to the market-specified functional design requirements, while the actual instances are related to the current/existing design. In the example shown in Table 2, one of the generic components for function 1, c_{1k}, has three ideal physical representations/instances (O, Δ, and $\square$) across the six products. The instance O is ideally common across three products, P_1, P_2, and P_3, Δ is ideally specific to P_4, and $\square$ is ideally common between P_5 and P_6.

Table 1. Example of the generic components and related instances for the 'Display Information' function in a single-use camera family.

Components				Single-use camera family			
				Zoom	Plus digital	Max HD	Outdoor
Function (f_1)	k	Generic component (c_{1k})		Instances (c_{1k}^j)			
Display information	1	Counter wheel	c_{11}	c_{11}	c_{11}^2	c_{11}^3	c_{11}^4
	2	View finder	c_{12}	c_{12}^1	c_{12}^2	c_{12}^3	c_{12}^4
	3	Flash information	c_{13}	c_{13}^1	c_{13}^2	c_{13}^3	null

Table 2. Example of ideal and actual instances for a generic component for Function 1.

Functions	Products	Generic component (c_{1k}): Actual instance	Ideal instance
Function 1	P_1	Φ	O
	P_2	O	O
	P_3	Θ	O
	P_4	Δ	Δ
	P_5	$\square$	$\square$
	P_6	$\square$	$\square$

Let c_{ik}^{j} denote the ideal instance of the generic component c_{ik} in the ideal design of product j and $c_{ik}^{\prime j}$ denotes the actual instance of the generic component c_{ik} in product j. To evaluate the 'inappropriate commonality' and 'inappropriate variety' for a generic component, we first define the commonality indicator (I_c) and the variety indicator (I_v) as shown in Table 3.

For each generic component c_{ik}, the *Inappropriate_com* then equals the sum of the commonality indicators and the *Inappropriate_var* equals the sum of the variety indicators as in Equations (8) and (9).

$$Inappropriate\_com_{ik} = \sum_{j=1}^{N} I_C \tag{8}$$

$$Inappropriate\_var_{ik} = \sum_{j=1}^{N} I_V \tag{9}$$

For each generic component, c_{ik}, the ideal maximum variety, denoted by $Var_{ik}^{\max}$, equals the number of components in a product family minus 1. The $\mathrm{CDI_C}$ and $\mathrm{CDI_V}$ scores for the generic component c_{ik} of the function i in the product family can then be calculated using Equations (10) and (11).

$$\mathrm{CDI}_{\mathrm{C}_{\mathrm{Component}_{ik}}} = 1 - \frac{Inappropriate\_var_{ik}}{Var_{ik}^{\max}} \tag{10}$$

$$\mathrm{CDI}_{\mathrm{V}_{\mathrm{Component}_{ik}}} = 1 - \frac{Inappropriate\_com_{ik}}{Var_{ik}^{\max}} \tag{11}$$

The $\mathrm{CDI_C}$ and $\mathrm{CDI_V}$ scores of the function f_i can then be calculated using Equations (12) and (13).

$$\mathrm{CDI}_{\mathrm{C}\,\mathrm{Function}_{i}} = \frac{1}{K_i}\sum_{k=1}^{K_i}\left(1 - \frac{Inappropriate\_var_{ik}}{Var_{ik}^{max}}\right) \tag{12}$$

$$\mathrm{CDI}_{\mathrm{V}_{\mathrm{Function}_{i}}} = \frac{1}{K_i}\sum_{k=1}^{K_i}\left(1 - \frac{Inappropriate\_com_{ik}}{Var_{ik}^{max}}\right) \tag{13}$$

Table 3. Commonality indicator and variety indicator.

Component		I_C	I_V
		$c_{ik}^{j} = c_{ik}^{\prime j}$	$c_{ik}^{j} = c_{ik}^{\prime j}$
Common		0	1
Unique		1	0
Variable	Variable_common	0	1
	Variable_unique	1	0

Finally, the CDI_C and CDI_V scores of a product family can be calculated using Equations (14) and (15).

$$\mathrm{CDI_C}_{\mathrm{Family}_P} = \frac{1}{F}\sum_{i=1}^{F}\frac{1}{K_i}\sum_{k=1}^{K_i}\left(1 - \frac{Inappropriate\_var_{ik}}{Var_{ik}^{max}}\right) \tag{14}$$

$$\mathrm{CDI_V}_{\mathrm{Family}_P} = \frac{1}{F}\sum_{i=1}^{F}\frac{1}{K_i}\sum_{k=1}^{K_i}\left(1 - \frac{Inappropriate\_com_{ik}}{Var_{ik}^{max}}\right) \tag{15}$$

3.1.5 *Using CMC and CDI in product family design*

The two proposed sets of indices, while focusing on capturing the trade-off between commonality and variety, have slightly different foci, making them relevant at different stages of the product design process (Thevenot *et al.* 2007). In the early stages of the design process, the CDI_C and CDI_V can help designers focus on which components should be made common, variant, or unique across a product family. In the detailed design stage, both sets of indices can be used to ensure that the functions and the corresponding components still possess the appropriate variety and commonality and then help designers improve the commonality between components without sacrificing variety in the product family. Hence, when to use the CDI_C and CDI_V or the CMC_C and CMC_V in the PFEG will depend upon in which design stage the designers are using it. If designers use the PFEG at the early stage of the design process to preliminarily evaluate a set of product family design options, designers should use the CDI_C and CDI_V. However, if designers use the PFEG at the detailed design stage, either the CDI_C and CDI_V or the CMC_C and CMC_V can be used in the PFEG. Regardless of which pair of indices is used, the quantitative representation of commonality and variety enable us to compute the trade-off angle within PFEG for each product family option as described next.

3.2 *Quantitative representation of the trade-off in product family design*

Typically, Pareto optimality (Fudenberg and Tirole 1983) is used to solve trade-offs. However, in the PFEG, we intend to solve the trade-off between commonality and variety in terms of different factors that characterise a company's competitive focus rather than solve it using an established ratio in the Pareto approach. Therefore, we develop the commonality/variety trade-off angle, α the second supporting piece for the PFEG. This angle can be used to quantitatively represent the ideal trade-off between commonality and variety determined by the competitive focus, which serves as a basis for evaluating sets of existing product family design options. The commonality/variety trade-off angle is based on the qualitative competitive focus, a very sophisticated topic. In this paper, we identify the factors that could characterise the competitive focus throughout the product life-cycle and then analyse whether each factor causes an increase or decrease in commonality or variety. Such analysis is shown in Table 4, and further details can be found in Ye *et al.* (2007).

Many researchers have begun to develop taxonomies to classify the factors encountered in product family design (Porter 1985, Anderson 1997, Meyer and Lehnerd

Table 4. Impact and factors table adapted from Ye *et al*. (2007).

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		+	

(*continued*)

Table 4. Continued.

Category	Strategic impact factors	Factor states	Commonality-variety tradeoff ↑C	↑V	Neutral impact
		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			–

1997, Ericsson and Erixon 1999, Martin 1999, Juuti 2004, Allada *et al.* 2006). Our literature review revealed that there are several different types of factors that impact the commonality/variety trade-off in product family design. To this end, we identified five categories of factors

(i) market,
(ii) government/industry regulations and/or standards,
(iii) product characteristics,
(iv) life-cycle processes, and
(v) organisational capabilities

that, taken together, determine the relative importance of product commonality and variety in product family designs (see Table 4). In addition, each of those factors has a potential state that may impact the trade-off between commonality and variety by causing a need for increased commonality (plus (+) in the 'C' column), causing a need for increased variety (plus (+) in the 'V' column), or having a neutral impact (minus (−) in the 'Neutral impact' column) as shown in Table 4 and detailed in Ye *et al.* (2007). The factors and their categories are evolving, and the analysis of each of the factor's impact is subjective. The current list of factors is based on our collective experience with existing product families and an extensive literature review, and it provides a useful starting point for understanding the commonality/variety trade-off angle that is central to this paper. The list will continue to be refined over time through empirical studies and new industrial cases.

3.2.1 *The commonality/variety trade-off angle*

In this paper, the commonality/variety trade-off angle, α, is developed to quantitatively represent the desired commonality/variety trade-off in a product family. Since different companies strive for different competitive foci when developing product families, this 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 (where commonality is more important than variety), α should be within the range of 0° to 45°. When the competitive focus for a product family is addressing differentiation (where variety is more important than commonality), α should be within the range of 45° to 90°. 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 (16).

$$\alpha = f(S) \tag{16}$$

where:

S The weighted sum of the factors' impacts on commonality and variety in a product family design as in Equation (17).

$$S = \sum_{i=1}^{n} (w_i \times I_{f_i}) \tag{17}$$

Table 5. 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

n The total number of the relevant factors influencing the trade-off between commonality and variety in a product family design.

f_i The ith relevant factor in a product family design ($i = 1, \dots, n$).

I_{fi} Indicator for the ith 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 ith relevant factor in a product family design.

To evaluate this weighted sum, the cross-functional product platform design team uses its expertise and judgment 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 (Table 5). Similar rating systems have been used in engineering design literature such as the one used in the analytic hierarchy process (Saaty 1990).

To calculate the competitor commonality/variety trade-off angle, α_c, there are at least two scenarios to consider:

(1) *Scenario A:* A company launches a new product family into the market place where no competitive offerings exist. In our analysis, we do not consider this scenario since there is no competition in the market place, and it happens so infrequently. Alizon *et al*. (2006) and Thevenot *et al*. (2007) discuss methods to help develop this type of product family.

(2) *Scenario B:* A company launches a new product family into the market place where more than one competitor exists. Our analysis focuses on this scenario, which happens more frequently in practice. In such a scenario, it is possible to obtain the competitor commonality/variety trade-off angle, α_c, for a single competitor or multiple competitors using Equation (18).

$$\alpha_c = \arctan\left(\frac{\mathrm{VI}}{\mathrm{CI}}\right) \tag{18}$$

where:

VI The degree of variety of a competitor's product family, which can be obtained using either $\mathrm{CMC_V}$ or $\mathrm{CDI_V}$.

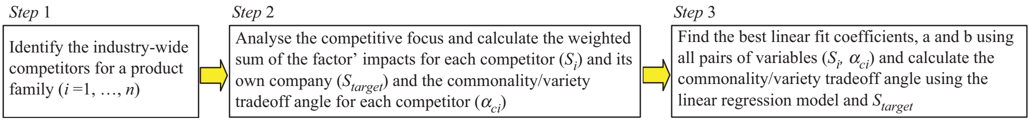

Figure 3. Three steps to calculate the commonality/variety angle.

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 either the CDI_C and CDI_V or the CMC_C and CMC_V. In addition, for each competitor, analysis of the weighted sum of factor's impact can be carried out separately using Equation (17) and Table 4. In this paper, we empirically characterise α based on a company's competitive focus and its industry-wide competitors' information. Typically, empirical models use linear regression, response surface models, and/or neural networks to approximate the relationships between x (inputs) and y (outputs). Hence, to establish the relationship between S (the weighed sum of the factors' impacts) and α (the commonality/variety trade-off angle), we use a linear regression model with a and b as the best linear fit coefficients, as defined in Equation (19).

$$\alpha = aS + b \tag{19}$$

There are three steps to estimate the commonality/variety trade-off angle for a given company using the linear regression model (see Figure 3). First, the industry-wide competitors for the product family need to be identified. Next, all of the competitive foci including both the competitors and its own company should be characterised by analysing the relevant impact factors. Then, each competitor's α should be calculated by dissecting and analysing their products. Finally, through the linear regression model, α for the particular product family can be obtained and used with the PFEG to help designers evaluate a product family option or compare product family design options with respect to the trade-off between commonality and variety supported by the CMC_C and CMC_V or the CDI_C and CDI_V. An example involving four families of power tools follows in the next section to demonstrate the proposed approach.

4. Example application

Four families of power tools are used to illustrate how the computation of the indices (CDI_C and CDI_V or CMC_C and CMC_V) supports product family design evaluation in the PFEG. The scope of the paper is not to show how to combine both indices *per se* or to show how to use each of these indices during product family development. In addition, we only use the CDI_C and CDI_V in the example application, but the CMC_C and CMC_V can be computed using the same approach. In the example application, we use a Delta® power tool family and three competitors' power tool families (see Figure 4). First, we set the α for the Delta® power tool family based on the company's competitive focus and its industry-wide competitors' information. There are, of course, additional competitors in the market place for Delta®, but to simplify the illustration, we picked a few key competitors. We had no access to information from Delta® or any of the other three companies – all information is obtained from either product dissection or

Figure 4. Delta® and its competitor cordless power tool families [photographs: Authors' own].

corporate websites. Next, we make use of the α in the PFEG to show how designers can redesign existing power tool families based on the commonality/variety trade-off angle.

4.1 *Setting α for a Delta® power tool family*

We use the three-step approach (see Figure 3) to obtain the commonality/variety angle α for the Delta® power tool family by analysing its own and its three competitors' competitive focus, calculating the trade-off angles for the competitors, and then obtaining the trade-off angle for Delta® using the linear regression model.

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

Delta® machinery plans to launch a 14.4 v cordless power tool combo kit for today's do-it-yourself market segment. In today's market place, DeWALT®, Black & Decker®, and Skil® (see Figure 4) provide cordless power tool combo kits with the same voltage. Admittedly, there are more than these three manufacturers 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 trade-off angle.

Step 2: Analyse the competitive focus and calculate S and α_c

By analysing their strategic factors, each manufacturer has determined their competitive focus for their product family, which entails some aspect of cost leadership or differentiation. To apply PFEG, we start by choosing the relevant factors for the particular product family design from a list such as Table 4, assigning weights for each relevant factor based on their judgments and expertise as in Table 5, and then calculating the weighted sum (S) of the factors' impact using Equation (17). For example, from Table 4, 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, yielding a weighted quality consciousness value of 9. The other relevant factors in this product family can be analysed 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 (17). Using the same analysis, the weighted sum for the three other product families is obtained based on our analysis of their product offerings, corporate websites, and advertisements. The results of this analysis are shown in Table 6. Note that the identification of the relevant factors and the assignment of their weights do not represent actual corporate policy; they are simply used for illustrative purposes.

Table 6. *S* calculation for Black & Decker®, Delta®, DEWALT®, and Skil® product families.

Factor	Black & Decker®			Dewalt®			Skil			Delta®		
	w_i	I_{ft}	S_i	w_i	I_{ft}	S_i	w_i	I_{ft}	S_i	w_i	I_{ft}	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 7. 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

The CDI_C and CDI_V for the Black & Decker® family are 0.424 and 0.576, respectively, as calculated using the method in Section 3.1.4. Based on Equation (18), the commonality/variety trade-off angle is 53.67°. The angle in the Skil® family and DEWALT® are computed similarly, and the results listed in Table 7. Hence, Delta® 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.

Step 3: Find the best linear fit coefficients, a and b, and calculate α
Using the linear model in Equation (19) and data for S_i and α_{ci} in Table 7, the best linear fit coefficients, a and b, and α can be obtained. The results of such analysis are shown in Table 8 and Figure 5.

4.2 *Combining* α *with the PFEG*

As we stated earlier, the PFEG can be used in a new product family to identify which product family design option best satisfies the trade-off determined by the competitive focus in the early stage of the design process. Designers can then realise the best design option in the downstream design stages. The PFEG can also be used in the redesign process. Designers can be guided if they need to increase the commonality or variety based on the determined trade-off. The first use of the PFEG has been addressed in previous papers. The use of PFEG for redesign is illustrated in this paper using the Delta® power tool family. Keep in mind, however, that the PFEG can only be used in design and redesign scenarios where there are market place competitors to the product family under consideration.

By comparing the difference between the actual commonality/variety trade-off angle obtained using Equation (18) and the ideal commonality/variety trade-off angle determined using the approach proposed in Section 3.2, designers can decide if the existing product family would benefit from increased commonality or variety in the redesign. Many bottom-up product family design approaches that appear in the literature only focus on maximising commonality in a product family, without considering if it could undermine the company's competitive focus on differentiation. In the PFEG, we believe it is unnecessary to improve commonality or variety when redesigning product families if it does not add value to the company's competitive focus.

For the existing Delta® power tool family (see Figure 4), the analysis of the actual and ideal commonality and variety trade-off angle is given in Table 9. Moreover, the PFEG construction for Delta® power tool family is shown in Figure 6.

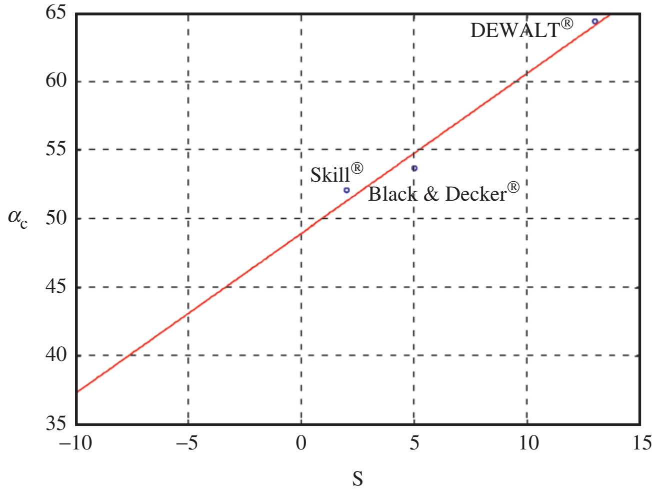

Figure 5. Linear regression model for α.

Table 8. Parameters for the linear regression model to predict α.

Company	S_{target}	a	b	α
Delta®	−8	1.17	48.95	39.61°
		$\alpha = -8 \times 1.17 + 48.95 = 39.61$		

Table 9. α result for Delta® power tool family.

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

Based on the results in Figure 6, to minimise the difference between α_{actual} and α_{ideal} for the Delta® power tool family, designers need to 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} better match the company's desirable competitive focus given the competition in the market place. The next step is to redesign the product family to improve its commonality accordingly, and designers can use the approaches developed by Alizon *et al*. (2006) and Thevenot *et al*. (2006b) to achieve this by reducing unnecessary differentiation within the product family.

5. Conclusions

The product family evaluation graph (PFEG) provides a structure to support product family design by identifying the best (based on our model/criteria and not best by itself)

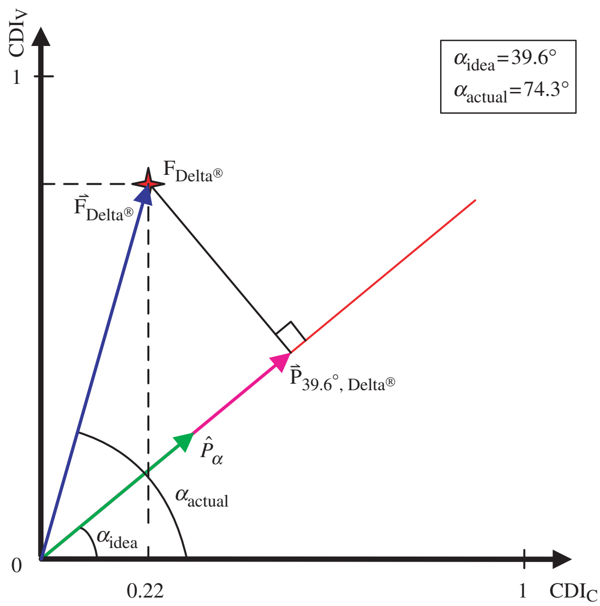

Figure 6. PFEG for the Delta® power tool family.

product family design option among a set of candidates in new product family design and by guiding designers in better matching a product family's competitive focus during redesign. The product families considered in the PFEG are only those with competition in the market place, whether they are new families or families to be redesigned. This paper is a first step in linking the competitive focus of the marketing domain with the component and/or function focus of the engineering domain.

In this paper, we characterise a product family's competitive focus using the strategic factors. We model the qualitative competitive focus as the commonality/variety trade-off angle (α), which quantitatively represents the commonality/variety trade-off in a product family using the CDI or CMC indices and a linear regression model. The mathematical link between the qualitative competitive focus and the indices measured, using functions and components, is not defined at this time. Instead, we use a regression model to obtain the trade-off angle. A table of some potential strategic factors and their potential impact on α is proposed as well. We identified five categories of factors (market, government/industry regulations and/or standards, product characteristics, life-cycle processes, and organisational capabilities) that, taken together, determine the relative importance of product commonality and product variety in a product family. We believe that a generalised accounting of the factors and their impacts is not possible, as every product family, company, industry is different.

In addition, we develop two sets of direct commonality and variety indices – the CMC for commonality (CMC_C) and variety (CMC_V) and the CDI for commonality (CDI_C) and variety (CDI_V) – to support the evaluation in the PFEG and the calculation of the commonality/variety trade-off angle. The two sets of the indices are separated components of the original CMC and CDI indices. Both the CDI and CMC have shown promising results on the assessment of commonality and variety in product families, and they account for both commonality and variety aspects in their measurement. We do not intend to say that only these two sets of indices can be used in the PFEG – any index can be applied to the PFEG provided that it can be split into two parts to capture the degree of commonality and the degree of variety separately. The indices as we are using them consider a limited number of parameters; however, the assessment can be refined using case-specific information, and application of the method would not change.

Four families of power tools are used to demonstrate the computation of the indices (CDI_C and CDI_V in particular) supports product family design evaluation in the PFEG. The scope of the paper is not to show how to combine both indices *per se* or to show how to use each of these indices during product family development. In addition, we use only the CDI_C and CDI_V in the example application, but the CMC_C and CMC_V can be computed using the same approach. Most importantly, the PFEG is not just the graph of the two sets of indices; it is the representation of the commonality/variety trade-off relative to the desired competitive focus.

We will consider how to use both indices during the product family development and test the sensitivity and accuracy of the PFEG when using the different indices in future work. Additional case studies will also be investigated to substantiate the use of PFEG and examine the utility of the proposed approach.

Acknowledgements

The authors would like to acknowledge the support of the National Science Foundation through Grant numbers DMI-0323497, DMI-0133923, IIS-0325321, and IIS-0325402. Any opinions, findings and conclusions or recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation. We also acknowledge the Sustainable Future Institute at Michigan Technological University for enabling this research.

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