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MODULARIZATION TO SUPPORT MULTIPLE BRAND PLATFORMS

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ABSTRACT

Methods to determine acceptable architecture for multiple platforms supporting multiple brands must represent both platform cost saving commonization as well as revenue enhancing brand distinctions. Functional architecting methods determine modularization based upon functional concerns. Brand identity is additionally determined by sensory aesthetics. We introduce three architecting rules to maintain brand identity in platforms. A dominant theme must be ensured on each product of a brand, and this must be transferred to each product's specifications and aesthetics. Elements critical to brand identity must be made common across all products in a brand. For any platform, brand specific elements must be maintained unique on each product variant. The set of elements not identified as a brand carrier can be made common to a platform. A matrix representation of each platform and its supported brand variants is useful as an architecting tool.

NOMENCLATURE

Aesthetic Forms: industrial design / human factors aspects of a product

Brand differentiation: concept of maintaining common expectations to a brand's offerings, and distinct from others

Brand identity: the desired expectation of any product offered within a brand

Brand module: a module that is used within many/all offers within a brand, to maintain brand identity

Brand platform: the set of shared brand signatures and modules

Brand signature: a function or aesthetic element made common to a brand's offerings, to maintain brand identity

Dominant theme: the particular brand identity description

Functions: what a product does

Module: a pair of both grouped functions and associated grouped physical systems as a subset of a product

INTRODUCTION

Determining product architecture is one of the key activities of any industrial product development activity. Volkswagen claims to save \$1.7 billion annually on development and production costs through effective product architecture (Bremmer, 1999, 2000). Volkswagen is able to take advantage of platform and component commonality by sharing between its four major brands, namely VW, Audi, Skoda, and Seat. These different automobiles share car platforms, which in Volkswagen's case includes front axles, rear axles, front ends, rear ends, exhaust systems, brake systems, and numerous other elements (Bremmer, 1999, 2000). However, Volkswagen also claims that all vehicle on this shared common platform, each of different brand, can be effectively differentiated in the eyes of the customer. Interestingly, Ford Motor Company has similar shared platform ambitions within its new Generic Architecture Process program. However, Ford defines its platform, which will be shared between several car models and brands, to consist of common locator points among the three major units of the underbody framing. Ford has similar expectations of large monetary savings in development and production costs while maintaining the ability to effectively differentiate the platformed cars in price and performance. Both comprise associated common processes to the shared parts and systems. Surprisingly, though, Volkswagen and Ford's definitions as to what constitutes a platform were vastly different.

This example highlights the fact that the product architecting process, despite being a key determining factor in both cost savings and in the ability to offer product variety, is not well understood. System engineering and architecting remains an activity relegated to heuristics. Such activities are often only completed by experienced systems engineers who have gained an understanding of the various objectives that must be considered when architecting a product line. In past work, we have been developing tools and methods to support systematic architecting of product portfolios. A very important aspect of

product platforms, though, occurs when the different products on the platform come from different brands that the company owns. Black and Decker has the DeWalt, Firestorm®, Quantum, VersaPak® and standard brand of power tools, all models built off the same platforms. Ford Motor Company has vehicle platforms that encompass Jaguar, Mazda, Volvo and Ford brands.

Platform decisions are difficult – to decide what can be platformed and common to all products, no matter the brand, and what should be unique to each product. Brand differentiation also brings additional problems, however. Specifically, just as there ought to be common systems to a product platform no matter the brand, there ought to be common systems to a brand, no matter the product. There are distinct features that must be maintained to instill a sense of the brand gestalt. DeWalt drills must be industrial strength, and all are yellow. Jaguar vehicles must be sport–luxury, and “British”: leather seats, and include the special Jaguar J-pattern shifter, for example. From an engineering viewpoint, there is a brand platform that also must be maintained. In this paper, we present a methodology to operate with these two distinct forms of platforms – brand platforms and product platforms. We present modularization rules to build a brand platform, and present rules to enable maintaining the distinct brand of each product variant built upon a product platform.

RELATED WORK

The development of product families built on product platforms and shared modules has been the subject of much recent research. Much research has shown different approaches on managing the planning and use of platforms (Meyer and Lehnerd, 1997, Wheelwright and Clark, 1992; Erens and Verhulst, 1996; Robertson and Ulrich, 1998; Pedersen, 1999; Pulkkinen et al., 1999). Baldwin and Clark (2000) present six “rules” or observations on how modules arise. These are not rules for partitioning a system as presented here, but rather observations of how engineering teams can form modules from a system or from other modules. Basically, a non-modular system can be partitioned to form new modules, modular designs can have new modules developed stand-alone, or modules can be transformed from other pre-existing systems or into new more complex systems. Means to do this from an engineering viewpoint, though, are not developed.

In the product design literature, one can find several design and manufacturing strategies for offering variety that begin with commonality metrics (Martin and Ishii, 1997; Kota and Sethuraman, 1998, Maupin and Stauffer, 2000). There are also several model-based approaches to designing different kinds of product platforms. Simpson et al. (1999) and Conner et al. (1999) use a Decision Support Problem formulation to design families of products based on scalable platforms. A similar approach is used by Ortega et al. (1999) to show tradeoffs among multiple life-cycle objectives for a product family. Krishnan et al. (1998) developed network models to design families of products that are measured along a single performance criterion. Siddique and Rosen (2000) developed a

“product-family reasoning system” to design commonality into a family of products, where they represent the products and assembly constraints using graphs, and solve for system modules that satisfy all constraints. Finally, optimization approaches have been developed by Gonzalez-Zugasti et al. (2000) and Nelson et al. (1999) to design product platforms and families of variants. Another optimization approach is used by Fujita et al. (1999) for designing a family of products from catalogs of existing swappable modules. Eppinger, Whitney and colleagues have pursued the Design Structure Matrix as an approach to partition groups in the design process (1994), and is now extending these thoughts to product architecture, to compare process and product architectures (Sosa et al, 2000).

Less work has been done to develop tools to help the system engineer systems into sets of common modules. Reichtin and Maier (1997) have developed many architecting heuristics and checks for system engineers to consider when partitioning systems. We have found that these rules of thumb are all often true and all often conflict, making their systematic use limited. Nonetheless, the ideas are sound and influential in practice.

In this paper, we present a method for partitioning a product into modules based in part upon functional modeling. Function structures developed by Pahl and Beitz (1996) are used to model the product. Starting with a functional model, we then make use of single product architecting rules as developed by Stone et al. (1998). Note that using function structures for product architecting in this way is a different use of function structures from that commonly assumed. We are not using function structures to develop a form independent description of a product for the purposes of conceiving new concepts, technologies, or physical principles for the product. This work has already been done at the point at which we operate. For example, corporate research and development may have developed a new technology that is now ready to be deployed as a product. A function structure can be developed for that technology as a new product. This still leaves open the question of how it should be modularized.

Related to Stone et al.’s work are extensions to analysis of platformed product families. Similar to Stone et al.’s function structure partitioning rules for single products, Zamirowski and Otto (1999) develop portfolio-wide partitioning rules. The analysis and selection of candidate architectures using function structures is presented in Dahmus et al. (2000), through a *modularity matrix* that succinctly represents the shared portfolio architecture and each product variant’s product architecture. The result is a set of possible product portfolio architectures. These fit into the categorization of portfolio architectures shown by Yu et al. (1999). In summary, these works provide an architecting process based upon technical factors. The method developed here will provide a means to also consider brand identity.

A second body of literature important to our study considers methods to define and maintain brands. Aaker (1996) presents the basis for segmentation using customer descriptors. The Gestalt nature of customer perceptions and aesthetic form decompositions are discussed by Veryzer, (1993) and Schmitt

and Simonson (1997). Bloch (1995) proposed a model of customer responses as the basis for product differentiation. Berkowitz (1987) presents work on how product shape can also create effective brand differentiation. We make use of these works here.

In the next section, we discuss how to develop a modular product portfolio architecture in the context of a brand portfolio. This includes the development of a set of heuristics to complement the above modular product portfolio architecture approach. This framework is crucial to bridge gaps between brand management and product portfolio architecture development, i.e., to maximize synergies across brands during product development while preventing products from being perceived as too much alike by their customers. The proposed set of principles and the framework will be evaluated using several Black and Decker's brands and products. See (Sudjianto, 2001), for other brands and product applications, including a Ford vehicle platform and a Hamilton Beach / Proctor Silex platform.

BRAND IDENTITY

Brand positioning is about creating customer perceptions of a particular brand among other brands (including competitors and other brands offered by a company). Companies strive to avoid product positioning overlap and brand dilution. The process of brand positioning starts with market segmentation, dividing the market into sub-categories and pursuing different offers for each category. The underlying belief for market segmentation is that customer preferences are heterogeneous: tastes and preferences differ among people. The basis for segmentation is often down the following descriptors (Aaker, 1996):

1. *Geographic*: cultural differences among customers living in different locations.
2. *Demographic*: gender, age, education, occupation, income, marital status, or household size.
3. *Psychographic*: attitudes, beliefs, lifestyles, or personality.
4. *Behavioral*: usage situation or frequency.

The first two are more easily quantified through marketing statistics. The latter two, however, are more difficult to ascertain, and yet most often provide the richest brand positioning opportunities by taking advantage of unique product attributes/benefits and product forms. Though many elements in marketing (price, promotion, and placement) are crucial for successful brand positioning, here we focus on product design attributes.

Here, we consider design attributes of both function and aesthetic form. Function decomposition of a product is well described in the literature, we will make use here of function structures. Aesthetic form decomposition is also well described in the literature (Veryzer, 1993; Schmitt and Simonson, 1997), though perhaps not in the engineering literature. We will make use here of a sensory element decomposition, also called *product aesthetics*.

Product aesthetic forms are composed of four primary sensory elements: *visual*, *auditory*, *olfactory*, and *tactile*. These

elements come together to create multi-sensory experiences when customers consume products. The visual element is the most prevalent element in the eye of customers. From product point of view, the major visual elements consist of *shapes* and *colors*. While shape can be very complex, there are four basic elements of shape: size (volumetric), angularity (round, sharp), symmetry, and proportion (long, short). The tactile element is the feel of *touch*. Material and textures of material create a certain feel and sensation for a product because they carry a strong association with strength, warmth, and naturalness. The sound element is characterized by *intensity* (or loudness) and *frequency content*. Sound can trigger very sensitive reactions of customers, it creates an impression of quality. A soft clicking sound provides impression of refined and quality while loud sound provides impression of strength and power. The smell element is also important, as it can evoke a strong memory and create desired perception and feeling which can be used to enhance identity. For example, automotive companies pay significant attention to the smell of a new car and its leather interior.

Dominant Theme

The reason to establish a set of distinct brands by a single company is that each brand must own distinct associations and offerings reflected by each brand identity, to thereby more closely target consumers in a wide market and thereby increase value to all customers. There are two viewpoints on how to construct such a brand identity, the *atomistic view* and the *gestalt view*. The atomistic view considers most products to consist of easily identifiable parts, each perceived independently by consumers. Therefore the effect of the element to brand differentiation is additive. The *gestalt view*, on the other hand, argues that congruity among elements (how they relate to each other) is beyond mere chance and as a result brand identity comes about through part interactions with each other – there are super-additive effects (Veryzer and Hutchinson, 1998).

Whether atomistic or gestalt, we call the summary perception of a brand by a consumer group the *dominant theme*. This is the overall aesthetic that a brand is to have. From an engineering perspective, the dominant theme is to aesthetics what an overall function is to a function tree. However, beyond that, the analogy breaks down, as decomposition of the dominant theme include functional and aesthetic forms. Elements of function can contribute to the dominant theme. For example, some product brands are known for its products having large secondary functions, adjustments, and extras. These extras are additional functionality that such a brand infuses into its products to maintain its dominant theme.

An example of dominant themes is well demonstrated by Black and Decker's brand lines. The VersaPak®, Firestorm®, and DeWalt brands exhibit very distinct dominant themes, though many of the products share many parts. The VersaPak® has a dominant theme of inexpensive cordless household, Firestorm® of high performance (male) enthusiast, and DeWalt of professional contractor quality.






					
Dominant Theme	Versatile, Household	Portable, Household	High Performance, Option Laden	High Value	High Quality, Professional
Brand Signatures	Color: Blue Touch Color: Orange Battery Pack: VersaPak® Selections: None Quality: Household Power: Low	Color: Blue Touch Color: Orange Battery Pack: 9.6, 14.4, 18 V Selections: Adequate Quality: Adequate Power: Adequate	Color: Red Touch Color: Black Battery Pack: 9.6, 14.4, 18 V Selections: Many Quality: Good Power: High	Color: Green Touch Color: Yellow Battery Pack: 9.6, 14.4 V Selections: Adequate Quality: Good Power: High	Color: Yellow Touch Color: Black Battery Pack: 14.4, 18, 24 V Selections: Adequate Quality: Outstanding Power: High

Figure 1: Black and Decker Brand Differentiation Matrix.



Figure 2: Cordless Drill Platform.

Brand Signatures

Given the overall brand dominant theme, the next question is what constitutive aesthetic elements come together to form the dominant theme. Of all the aesthetic elements, only a subset is critical to convey the brand identity. We call these brand-critical atomistic elements the *brand signatures*. They can be functional or aesthetic, but they are to aesthetics what primary sub-functions are to function trees or function network decompositions.

For example, Black and Decker applies a select set of aesthetic elements as brand signatures. All VersaPak® products, for example, are blue with orange triggers, are comparatively inexpensive and lower durability, and make use of the VersaPak® battery. All Firestorm® products are red with sculpted black hand-grips, have many options and settings (e.g., 22 versus 6 drill chuck slip torque settings), yet are not comparatively expensive nor inexpensive. All DeWalt products are yellow with black handle-grip features, have sufficient options and settings for perceived professionals, are high quality, durable and long-life, and are expensive. The brand signatures for all of Black and Decker's brands are therefore housing colors, hand interface colors and tactile feel, durability, and option content.

For any set of product platforms, the aesthetic elements that should form the set of brand signatures can be determined through marketing techniques such as conjoint analysis. The aesthetic elements that are important to the customer should form the brand signatures. Conversely, the aesthetic forms that are not important to the customer can form elements that can be

safely made common across brands, should several brands be built upon common product platforms.

Brand Differentiation Matrix

To help allocate and differentiate brands, we introduce the *Brand Differentiation Matrix*. This is a matrix with each supported and contested brand as a column, and each brand signature as a row. Within each matrix cell are entered the aesthetic form targets for each brand on each brand signature. The following table shows an example of Black & Decker brand differentiation matrix, highlighting brand differentiation, for VersaPak®, Black and Decker, Firestorm®, and DeWalt products.

The task of a company with multiple products is to formulate and ensure the brand identities. Translated on the brand differentiation matrix, the task is to enter values into the matrix that distinguish the brands and profitably target the market segments.

ENGINEERING PRODUCT PLATFORMS

A product platform is a set of shared functionality across multiple products. In the context here, a product platform is a set of functions shared across multiple products each within a different brand. For example, Figure 2 shows the Black and Decker's cordless drill platform, each drill from a separate very different brand. Nonetheless, there are shared modules across all of the drill variants, as will be shown.

Otto and Wood (2000) and Dahmus et al. (2000) introduced functional architecting of product family by developing possible function structures for each product variants and merge them into a common function structure. The

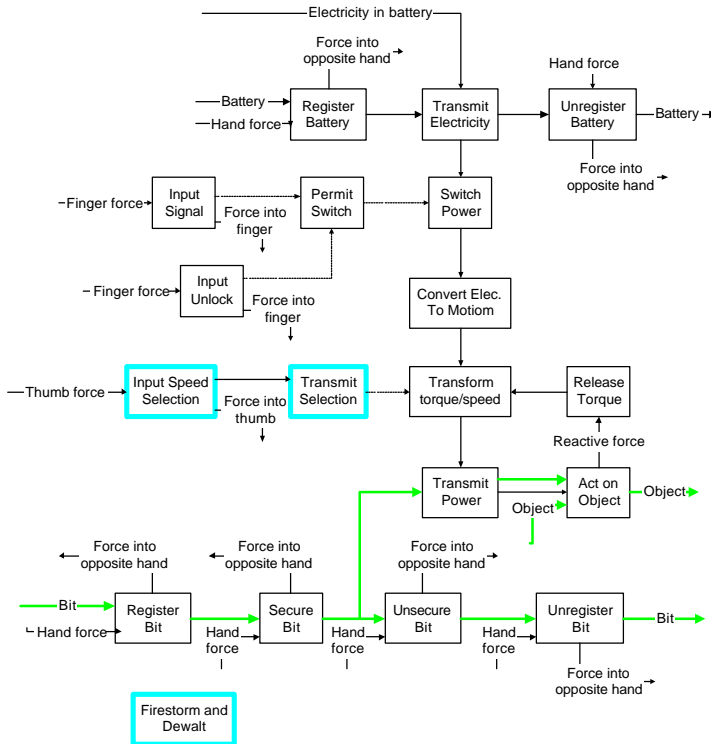


Figure 3: Cordless drill family function structure.

result is a family function structure which highlights *shared functions* among variants in a product family. Subsequently, a collection of these shared functions is used as a platform for a product family. Dahmus et al. (2000) demonstrate the use of family function structure complemented with a modularity matrix to consider redesigns of the Black & Decker VersaPak product family.

Functional Modularization

A function structure for multiple products in a product family can be constructed by overlaying individual product function structures into a single function structure (Zamirowski and Otto, 1999; Otto and Wood, 2000; Dahmus et al., 1999). The union of all product variant function structures is a single diagram of product family function structure that has every function in every product variant including all the flows. A product family function structure is useful to investigate opportunity for possible commonality among product variants to develop a product platform as a building block foundation for a product family.

In exactly the same way, a family function structure can be constructed for a product family where each variant also carries a brand. As an example, Figure 3 shows the family function structure for Black & Decker and Firestorm® cordless drills/drivers. All functions depicted by unshaded boxes are shared between the two brands, and functions denoted by shaded boxes are exclusive to Firestorm® only.

Over the family function structure, modules can be considered through application of modularization rules (Stone et al, 1998, Zamirowski and Otto, 1999). These consist of the following:

- R1. *Dominant Flow Rule*. A module can be formed by grouping a set of functions for which a flow passes through them from the start to the exit of the flow in the system.
- R2. *Branching Flow Rule*. Modules can be formed by grouping sets of functions that make up branches in the function structure. All modules (one per branch) must interface at the last function before the flow branches.
- R3. *Conversion-Transmission Rule*. A module can be formed by grouping a pair of functions that performs conversion of flow (information, energy, or material) from one to another type and transmission of the flow.
- R4. *Function Sharing Rule*. A platform module can be constructed from a set of functions that are shared among variants in a product family.
- R5. *Unique Function Rule*. Conversely to the function sharing modularity, a module may be formed from a set of functions that is unique to a single product variant.

Application of these rules to a family function structure leads to alternative modularizations and product platforms.

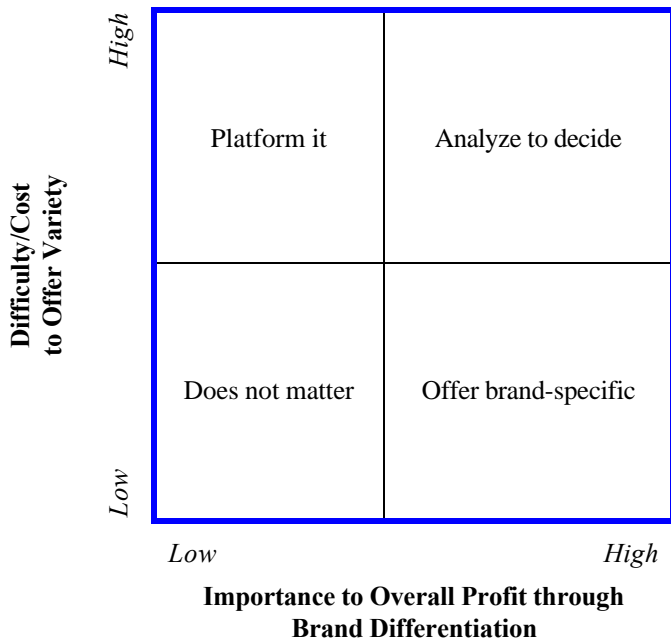
Modularity Matrices

A family function structure is an effective tool to visually identify interactions of functions by tracing the flows and thus lead to candidates for modular partitions. However, it is difficult to simultaneously visualize alternative partitions of a product family using the single function structure. Additionally, as functions are achieved and delivered at different quality levels or embodied differently for different brands, a family function structure is not capable of capturing all of this information without becoming unwieldy.

To represent the alternative modularizations considered on the family function structure during subsequent evaluation and selection discussions, Dahmus and Otto (2000) introduced the modularity matrix. This is a matrix with each product variant represented as columns, and each function in the family function structure represented as a row. Each cell in the matrix is a representative specification for the product variant on the function. These specifications are choice variables for the design team. Making like-values across different products on the same function enables that function to be platformed. Within-product modules are diagrammed as rectangles on the matrix, and across-product shared platformed modules as common colored cells. We will make use of the modularity matrix here as well, but augment it with brand aesthetic specifications.

ENGINEERING MULTI-BRAND PRODUCT PLATFORMS

Developing product platforms requires consideration of modules that will be used by multiple products. The shared platformed modules must be designed compatible with all of the supported product variants, an expansion of the difficulty facing development teams. Factoring brand identity into the platform design problem brings a similar expansion of the difficulties to a



development team. In particular, the brand signatures must be maintained common across all products within a brand. This is perpendicular to the platform design problem, which seeks to make the shared functions of a platform common across brands, all within a product platform.

One can express the problem within the syntax of family function structures and modularity matrices. Conceptually, first one constructs a function structure for the product to be platformed. For example, with battery powered tools, one would construct function structures for cordless drills, cordless circular saws, cordless jigsaws, etc. One must then ensure that the function structure is comprehensive of each product variant's functions, should some of the products have added functionality. For example, the Firestorm® drill has a two speed transmission which the standard Black and Decker drill does not. This added function of changing speed must be incorporated, to form a platform family function structure. This should be completed for the several product platforms that each brand will have a product within. With multiple platform family function structures, the subsets of the functions can be made brand specific within each platform, but identical across the platforms.

Brand Differentiation

Brand modularity rules are especially important to establish product platforms that support multiple brands. Special attention is paid on how to develop brand differentiation using a gestalt product dominant theme. This is the overall integration of aesthetics and functionalities that a brand is to have. Family function structure and brand modularity matrix methodologies are proposed to aid in the application of the brand modularity rules to architect a product platform. Jointly, the rules and the

modularity matrix can be used as a framework to analyze and synthesize a product platform to support multiple products and multiple brands.

Brand differentiation entails product variety with its complexity of costs for product development, manufacturing, marketing, and sales, as well as post-sale maintenance. On the other hand, product commonization may cause a loss of profit opportunity as products become too similar and weaken profitable brands. Brand differentiation is important in generating profits by creating a premium price, however product commonization is important in generating profits by creating a lower development cost. For any component, the decision to apply brand differentiation or to apply platform commonization is summarized in Figure 4 as follows:

1. *Platform component.* When a component is not important for brand differentiation, and the difficulty or cost to create variety is high, then the component is a candidate to be included in a product platform. The decision to select a platform often requires a trade-off between cost of the variety and *giveaway / loss of opportunity* costs. Giveaway cost is a cost due to the use of a higher end platform in a lower end product to satisfy high end product requirements while the loss of opportunity cost is the opposite condition.
2. *Brand-specific component.* When a component is important for brand differentiation or identity, and the difficulty (or cost) to provide variety is low, then the component should be made brand-specific.
3. *Does not matter component.* When a component is not important for brand differentiation, and the cost or difficulty to provide variety is low, then it does not matter for either brand differentiation or commonization. There are two ways to take advantage of this component: (1) Make the component a part of the product platform or (2) Find a way to use component variety to enhance brand differentiation, i.e., one should always change “does not matter” components into either platform components or brand-specific components.
4. *Analyze and decide component.* When a component is important for brand differentiation, but the cost to provide variety is high, then one must complete some further analysis to decide whether the component should be included as part of the product platform or made brand-specific. In this situation, modular architecture may be considered so that brand differentiation can be made while maintaining a low difficulty or cost condition, i.e., one should change the product architecture to make a component in the *Analyze and Decide* quadrant move into the *Offer brand-specific* quadrant.

Figure 4 forms general guidelines that can be applied for an individual firm. They are, of course, guidelines which requires careful consideration. For example, if the development and production processes are very separate, then additional process related concerns can enter which may guide the architecting to weigh on differentiating the items.

To implement these concepts, one must have a modular product architecture. For example, Black & Decker uses a



(a) Black & Decker cordless drill housing



(b) Firestorm® dual speed gearbox

Figure 5: Slot modularity in the Black & Decker cordless drill housing. The separation of the top section of the housing allows Black & Decker to use the same housing for both Firestorm® and basic Black & Decker products.

product modularization strategy to create brand variety, as illustrated in the Black & Decker and Firestorm® cordless drills shown in Figure 5. A slot modularity approach is employed to separate the housing of the drill to enable Firestorm, the high performance brand, to offer a dual-speed transmission for high speed/high torque capability not available on the basic brand.

The decision table shown in Figure 4, however, does not provide guidelines whether a component is important or not for brand differentiation profitability. The next section presents answers to this question.

Brand Differentiation Rules

One of the most difficult question to answer in developing a platform to support multiple brands is what should be differentiated among brands and what can be made the same so that customers perceive multiple brands developed from the same platform as distinct products consistent with their individual brand positioning. Bloch (1995) proposed a model of customer responses as the basis for product differentiation. His model can be applied as principles for brand differentiation as follows:

- *Distinct product-related beliefs.* Products derived from the same platform must generate different belief characteristics, as indicated by distinctive brand personalities.
- *Distinct categorization.* Multiple brands derived from the same platform must be classified into different product categories (i.e., segments) by their consumers.

For designing a product platform architecture, however, this high level principle of customer responses must be made more concrete into product related characteristics.

The following rules work to formally state the brand differentiation and commonization concepts using a product-characteristics viewpoint. These are additional rules, in extension to those presented earlier, R1-R5. Each is discussed in turn.

R6. Dominant theme rule. Brands derived from the same platform must have a distinctive dominant theme.

A dominant theme generally follows the Gestalt law, i.e., the whole (product congruity and unity) is more than the summation of the individual elements. See, for example, (Sudjianto, 2001) for experimental evidence of gestalt responses of dominant theme in the cordless drill market. A dominant theme must be created from an integration of distinct customer-perceived functional characteristics (i.e., features or quality of functional performance) and product aesthetic forms. The basic Black & Decker and high performance Firestorm® drill/driver illustrate their dominant theme primarily based on functional characteristic distinctions. The speed switch and slip clutch offer more levels on the Firestorm® than the basic Black and Decker, and the Firestorm also offers a gear reduction transmission for higher torque applications. Note that these are functional differentiators, Black & Decker chose not to use major product aesthetic forms (e.g., shape) as part of its dominant theme differentiation between Black and Decker and Firestorm®, rather minor aesthetic forms were applied (e.g., color).

On the other hand, Berkowitz (1987) demonstrated that product shape exploitation can also create effective differentiation. When differentiation of functional characteristics are almost indistinguishable, a dominant theme must be made from product aesthetic forms of the most frequent product-user interface or usage areas using the integration of visual (shape and color) and tactile elements supported with auditory and olfactory elements.

This case is illustrated by the differentiation between Firestorm® and DeWalt drills/drivers. Both Firestorm® and DeWalt have identical product functionality: continuous speed wicking, fine grid clutch slip, gear reduction, and high power. Therefore to create a distinctive dominant theme, Firestorm® and DeWalt share no common aesthetic forms. The casings, colors, sounds, feel and quality (time to failure of the parts and systems) are distinct.

Maintaining brand distinction within any particular platform is only half of the problem. At the same time, each brand must maintain unity across the different platforms that a company may offer. To do this, the set of elements that define the dominant theme may be considered a “module” for brand-



Figure 6. Common parts in Black & Decker and Firestorm® drills/drivers.

specific products. This modularization view resembles the Unique Function Modularity Rule (R5) introduced by Zamirowski and Otto (1999).

R7. Brand signature rule. The selected few design elements that are identified as brand signatures, either functional characteristics or aesthetic forms, should be repeated exclusively across products and over time (i.e., product generations) only within a brand. This repetition of brand signature establishes memorable brand identity. Unique product forms, or cues, should be employed, maintained exclusively, and shared among products only within a brand.

For example, Black and Decker applies the brand signature rule using aesthetic color. All Firestorm® power tools use an orange and black color combination, all Black & Decker VersaPak® tools use a blue and orange color combination, while all DeWalt products use yellow and black. No other brands use those brand signatures. Note that brand signatures are often very important to a company to establish and protect. Often they are trademarked, to reinforce the brand and prevent knock-offs.

A final brand modularization rule is a corollary to the previous two rules.

R8. Brand platform rule. Any element that is neither part of a dominant theme nor part of a brand signature may be commonized into a product platform.

This rule resembles the Function-Sharing Modularity Rule (R4) proposed by Zamirowski and Otto (1999). The case for the platform rule is illustrated by commonization between Black & Decker and Firestorm® drills/drivers as shown in Figure 6. Many internal unnoticed systems are shared.

Modularity Matrices

Modularization of a product family as previously proposed by Zamirowski and Otto (1999), Dahmus et al. (2000), Otto and Wood (2001) was strictly function-based, as indicated by the inclusive use of the family function structure to construct possible modules. While all of these modularization approaches are applicable, the approach is incomplete because it does not

address the need of brand differentiation to support multiple brands. Because both product functions and aesthetic forms are crucial ingredients to develop a platform to support brand differentiation, brand modularization must address both of these elements, i.e., brand identity or differentiation should be created using a minimum set of combinations of product functions and aesthetic forms constituting a dominant theme while other, less brand-sensitive elements, may be used to develop a platform for all brands. To concisely represent a product family architecture's function and form, the family function structure and a new expanded form of a modularity matrix is employed.

To apply this approach for brand differentiation on product platforms, matrix entries are augmented with brand signatures to describe specific brand attribute information. This is usually in terms of product aesthetic forms, such as shapes and colors. To do this, we expand the specification entries entered on the modularity matrix. In addition to a functional specification on each function for each product, we also enter a possible aesthetic specification for the functional carrier. For example, an "Input Signal" might be done with a finger with a function specification of a trigger. We might decide also to ensure it carries a brand identity by making an aesthetic specification of "orange" in color on all of our products within a brand. This is shown in the entries of Figure 7 for the Black and Decker drill platform. To indicate the brand signatures, those aesthetic specifications that are brand signatures – important aesthetic elements that identify the product as being part of its brand – are highlighted. In Figure 7, the brand signatures are shown in outlined fonts.

The specification values and brand differentiation attributes entered in each matrix represent targets for functions and their associated brand identity for each product. These various values establish the architecting space that will define a product portfolio architecture to support multiple brands. The design team must select specification values for the functions and necessary attributes that are likely to carry (or not to carry) brand differentiation. The extent to which a product specification and attributes is compatible defines how well the individual product will work and possess a distinct dominant theme. The extent to which a function has the same targets established across brands defines how well the function can be shared across brands in the family. That is, when the function does not carry brand differentiation attributes, this function can be shared for all brands as a part of the elements in the product family platform. The degree to which multiple products and multiple brands can be satisfied define how well the functions can be shared across products and brands. All of these concerns are made clear on the modularity matrix. Presenting this information in a matrix allows commonality and differentiation to be identified easily. The commonalities and uniqueness can, in turn, be identified as modules. A row-wise grouping identifies the same function targets into possible modules shared across brands, i.e., a platform module. In Figure 7, platform modules are shown with the same shaded entries across columns. A column-wise grouping that incorporates multiple functions in a product leads to the identification of possible product modules, which can be

	Dewalt	Firestorm®	Quantum	Black & Decker	VersaPak®	
						
Dominant Theme	Heavy Duty	High Performance	High Value	Standard	Multi-purpose	
Functions	Input Signal	<i>Black</i> Trigger	<i>Black</i> Trigger	<i>Yellow</i> Trigger	<i>Orange</i> Trigger	
	Switch Power	□ <i>Variable speed</i>	□ <i>Variable speed</i>	□ <i>Variable speed</i>	2 speed	2 speed
	Unlock Switch	<i>Black Oval</i> Button	Black Button	Black Button	Black Button	Black Button
		Convert Elect	<i>Powerful</i> 300	220	220	220
	Transform τ, ω	<i>Quiet 2 Sp</i> Box	<i>2 speed</i> Box	1 speed Box	1 speed Box	1 speed Open
		Switch Speed	□ Fine Ring Gear	□ <i>Ring Gear</i>	□ □	□ □
	Transmit Power	<i>Embosses</i> 16 Slip Clutch	<i>Cut outs</i> <i>22 Slip Clutch</i>	<i>Lines</i> 6 Slip Clutch	<i>Lines</i> 6 Slip Clutch	<i>Solid</i> Shaft
	Input Speed	Thin Button	<i>Wide</i> Button	□ □	□ □	□ □
		Act on Object	Bit	Bit	Bit	Bit
	(Un) Register Bit	□ Chuck Teeth	□ Chuck Teeth	□ Chuck Teeth	□ Chuck Teeth	□ Chuck Teeth
		(Un) Secure Bit	<i>Wide Lines</i> Chuck	<i>Thin Lines</i> Chuck	<i>Thin Lines</i> Chuck	<i>Thin Lines</i> Chuck
	Transmit Electricity		<i>Square</i> 9.6 V, 2pt	<i>Open</i> 9.6 V, 2 pt	<i>Open</i> 9.6 V, 2pt	<i>Open</i> 9.6 V, 3pt
		(Un) Register Battery	<i>Bevel</i> 2 point	<i>Straight</i> 2 point	<i>Straight</i> 2 point	<i>Straight</i> 3 point
	Permit Positioning	<i>Rough</i> Palm	<i>Padded</i> Palm	Diamond Palm	Diamond Palm	Diamond Palm
		Encase	<i>Yellow</i> 2 piece	<i>Red</i> 3 piece	<i>Green</i> 3 piece	<i>Blue</i> 3 piece

Figure 7: Cordless Drill Family Modularity Matrix. For each function, technical specifications are given on the lower line and aesthetic specifications given on the upper line. Product modules are shown by shared colors across functions within a product (column). Platform modules are shown by shared colors across products. Brand signatures are shown as highlighted text (shared within a brand, platform to platform). Complete brand signature modules are outlined (shared within a brand, platform to platform).

selected by applying modularity rules such as dominant flow, branching flow, and conversion-transmission (Stone et al, 1998). In Figure 7, such product modules are shown as entries that are shaded the same within a product column. A column-wise grouping (product module) that incorporates brand differentiation attributes identifies a module that is important for establishing the dominant theme of a brand.

The modularity matrix in Figure 7 provides an example of some of the functions shown in the family function structure of Black & Decker and Firestorm® cordless drills. Row-wise observations in the modularity matrix show that the “Convert Electricity” functions (i.e., DC motor) are common between the two brands. On the other hand, the “Transform Torque (τ) and Speed (ω)” (i.e., transmission) as well as “Transmit Power”

(e.g., clutch) functions are unique for each brand because these functions are brand-differentiation carrying functions – the DeWalt transmission is very smooth and of high quality. Column-wise observations, in conjunction with modularity rules, reveal possible modules as exemplified by “Transform $\tau\omega$ ” and “Switch Speed.” The combination of “Transform $\tau\omega$,” “Switch Speed,” and “Transform Power” functions create a unique dominant theme for each brand and thus they are used to support brand differentiations. The case of the Black & Decker brand family will be discussed further.

The modularity matrix in Figure 7 presents concise descriptions of the functionality targets and brand differentiations among the products. The specification values and brand differentiation attributes entered in each matrix represent targets for functions and their associated brand identity for each product that was selected by the Black & Decker design team.

The row-wise grouping of the same function targets across multiple brands indicates shared modules that can serve as the platform. The exact shared modules are depicted by shaded boxes whereas shared modules with distinct brand appearances are depicted by diagonal lines. For example, the “Input Signal” function is shared across all products but is differentiated from each brand by its color. Note that to deliver “Input Signal” functionality, DeWalt and Firestorm® share exactly the same component, as does Black & Decker and VersaPak®. On the other hand, the module that consists of “Transform $\tau\omega$,” “Switch Speed,” and “Transmit Power” is unique for each brand except for Quantum and Black & Decker brands. The column-wise grouping incorporates these multiple functions into a module and is identified by applying the conversion-transmission modularity rule. The utilization of a unique module for each brand reflects the selection of the module as part of a dominant theme of a brand. Here, the Black & Decker design team applied the dominant theme rule. That is, distinct functionalities as well as aesthetic form presentations distinguish the module for each brand.

The modularity matrix shows that there is very little sharing of modules between DeWalt and the rest of the Black & Decker brands. A distinct quality achievement level of the functionalities (e.g., more powerful motor, quieter gears) accomplishes the dominant theme differentiation of “heavy duty” in the DeWalt brand, as well as a distinct product aesthetic

form. On the other hand, there are many shared modules among the Black & Decker, Quantum, and Firestorm® brands. Other than distinct colors, the incremental performance targets solely differentiate the brands, from basic to high performance. The Black & Decker and Quantum brands are differentiated by dual, versus variable, speeds, while the Quantum and Firestorm® brands are differentiated by the number of slips in the clutch and the high speed/torque selection in the Firestorm® brand.

It is interesting to note that the Black & Decker design team used primarily product functionality and not the product shape aesthetic to form the dominant themes. While this approach may be justified given cost factors, one may question the approach given the dominant theme rule’s suggestion of using both functionality and aesthetic form to create differentiation. In conjoint studies, some of the brands were perceived too much alike, especially the Quantum brand (Sudjianto, 2001). This example demonstrated the power of brand modularity matrix to highlight the strength and weakness of the product portfolio to support multiple brands.

The modularity matrix also depicts the complexity of a product platform in the Black & Decker brand portfolio, as there is no single platform that is shared among all of the brands other than “Trigger,” “Chuck,” and “Bit”. Each of these uses identical modules, with slight differences that can be easily accommodated – the trigger is molded with different color plastics, and the chuck has slightly different casing rings. The use of these shared modules indicates that they are not considered part of any brand’s dominant theme, and thus they are commonized for the entire portfolio – an example of the platform rule application. There are three distinct “motors” in the portfolio to deliver the “Convert Electricity” function, as this component is crucial for making a differentiation for some brands, especially to the DeWalt brand. As a result, this component cannot be commonized for the entire portfolio. A similar situation happens to the “gear box” module to deliver “Transform $\tau\omega$,” “Switch Speed,” and “Transmit Power” functions. Yet, as will be discussed later, the commonization of the drill platform is not as comprehensive as it might be, even without loss of brand identity.

		Dewalt	Firestorm®	Quantum	VersaPak®
					
Dominant Theme		Heavy Duty	High Performance	High Value	Multi-purpose
Functions	Input Signal	<i>Black</i> Trigger	<i>Black</i> Trigger	<i>Yellow</i> Trigger	<i>Orange</i> Trigger
	Switch Power	□ <i>Variable Speed</i>	□ <i>Variable Speed</i>	□ <i>Variable Speed</i>	□ 2 speed
	Unlock Switch	<i>Oval Black</i> Horz. Hold Button	<i>Thin Black</i> Vert. Hold Button	<i>Oval Black</i> Horz. Hold Button	<i>Orange</i> Horz. Hold Button
	Convert Elect	<i>Powerful</i> 450	330	330	120
	Transmit Power	□ Shaft	□ Shaft	□ Shaft	□ Shaft
	Position Object	<i>Silver, Large</i> <i>Adjustable Shoe</i>	<i>Black, Large</i> <i>Adjustable Shoe</i>	<i>Steel, Large</i> <i>Adjustable Shoe</i>	Steel 90° Shoe
	Act on Object	<i>5 3/8"</i> Circular Blade	<i>5 3/8"</i> Circular Blade	<i>5 3/8"</i> Circular Blade	<i>3 3/8"</i> Circular Blade
	(Un) Register Tool	□ Shaft Taper	□ Shaft Taper	□ Shaft Taper	□ Shaft Taper
	(Un) Secure Tool	Hex Clamp	Hex Clamp	Hex Clamp	Hex Clamp
	Transmit Electricity	<i>Square</i> 14.4 V, 2pt	Open 14.4 V, 2pt	Open 14.4 V, 2pt	<i>VersaPak</i> 7.2 V, Round
	(Un) Register Battery	<i>Bevel</i> 2 Point	Straight 2 Point	Straight 2 Point	<i>VersaPak</i> Round
	Accept Hand	Rough Palm	<i>Padded</i> Palm	Diamond Palm	Diamond Palm
	Encase	<i>Yellow</i> 4 Piece	<i>Red</i> 3 Piece	<i>Green</i> 4 Piece	<i>Blue</i> 2 piece

Figure 8: Circular Saw Family Modularity Matrix. For each function, technical specifications are given on the lower line and aesthetic specifications given on the upper line. Product modules are shown by shared colors across functions within a product (column). Platform modules are shown by shared colors across products. Brand signatures are shown as highlighted text (shared within a brand, platform to platform). Complete brand signature modules are outlined (shared within a brand, platform to platform).

Architecting Multiple Platforms with Multiple Brands

As a brand typically encompasses multiple products (e.g., a cordless drill and a cordless circular saw, etc.), there is a need for simultaneously architecting the platforms to support multiple brands and multiple products. For example, Black and Decker's battery packs can be used across many of these platforms. Therefore, developing a product platform in the context of multiple products and multiple brands requires the consideration of modules that will be used by multiple products and multiple brands. Modules in a platform design must be made compatible with all of the supported product variants as

well as brand identity. The family function structure and brand modularity matrix can be expanded to guide the architecting process of a platform to support multi-products and multi-brands.

In this case, two perpendicular dimensions of brands and products must be simultaneously captured. To consider this, Figure 8 presents the modularity matrix for Black and Decker's cordless circular saw family, similar to the cordless drill family of Figure 7. Here we have multiple (two) platforms with multiple (five) brands that must be architected to share as many modules as possible to save development, production and

distribution costs. Yet, Black and Decker must also maintain brand identity.

The modularity matrix for any platform as developed so far is equipped to do this, with the addition of one additional set of information. Entire modules that operate as brand signatures and are shared across a brand must also be highlighted, termed *brand modules*. We denote these here with outlined boxes on each platform's modularity matrix. For example, the orange trigger module is shared across many of the products in the VersaPak® brand. The VersaPak® battery is shared across all VersaPak® products. These shared systems help form the brand identity, and go beyond the brand signatures. Brand signatures are the form manifestation of targeted brand performance or customer requirements. For example, the DeWalt brand signatures include their drills having a gear reduction for high torque applications, and their saws have an adjustable shoe. These forms implement the DeWalt brand signature of "Adequate Selections." These brand signatures are not shared modules. Shared modules exist on the product form space. For example, all DeWalt cordless products, including the drill and saw, share the same battery pack as a brand module.

Examining the two product platform's modularity matrices, one can make observations of the Firestorm® and DeWalt brands. The matrices suggest that there is almost no commonality between the two brands (as a result, the two product platforms exhibit strong dominant theme differentiation between the two brands). Comparing multiple products within a brand, the matrices provide evidence that the Black and Decker design team employed brand signatures to support the brand dominant theme. Firestorm, for example, uses strong brand signature elements to deliver "Transmit Electricity," "Register Battery," "Unregister battery," "Accept Hand," "Encase," and "Switch Power" functionalities, in particular applying the product aesthetic form of the orange-black colors and the padded-palm. Similarly, DeWalt uses strong brand signature elements that are distinct from Firestorm®. At the expense of the platform strategy, the design team chose to excel in dominant themes to provide a gestalt distinction within a platform, as well as strong brand signatures to reinforce the distinct expression of dominant themes.

Process

Given these representations of brands, platforms, modules, functional performance and aesthetic attributes, how can they be applied to create products from common platforms with distinct brand identities? In practice, we have considered two approaches. A team can either start with an existing product and expand it into multiple products, or a team can start with distinct unique products, and work to merge them into a common platform.

Since gestalt interaction effects occur, we have found that, in practice, starting from a common product platform and expanding the variety one feature at a time to create brand differentiation, generally, will not be successful (Sudjianto, 2001). Instead, we have found more success when starting with distinctive product elements that maximize brand

differentiation, and then merge them to create a product platform using a *subtract and analyze* approach. That is, instead of started from a common product platform to create brand differentiation, one should start from distinctive products and perform a one-at-a-time element commonization approach, ensuring that one maintains brand differentiation. An element is included in the platform when commonization of this element does not reduce brand differentiation by reducing the dominant theme of any of the supported product variants. A product platform is the result of the common elements identified by such an iterative subtract and analyze process. The remaining brand differentiation carrying features set up a dominant theme and brand signatures. The importance of this approach should not be underestimated; our experience is that poor platforms result from processes that start with a common platform and work to differentiate it into brands. Instead, one should start with the brand positions and an architecture, such as represented by a family function structure. Then one should work to identify the portions of the architecture that can be made common to some/all of the brands, and the portions of the architecture to keep as unique brand signatures.

Opportunities for platform commonization can be explored in the modularity matrix by following the "subtract and analyze" process, i.e., each function is analyzed, and possible commonization among brands is investigated, to merge the product platform while maintaining brand differentiation. The following questions need to be asked to commonize an element: Is the element a brand signature that must be maintained across products within a brand? Should the element be differentiated (i.e., in terms of either function achievement or product aesthetic forms) among brands to maintain the current dominant theme of each brand? Will giveaway/loss opportunity costs due to commonization exceed the cost of variety? If the answer to any of these questions is substantially yes, then the element should not be commonized.

CONCLUSION

This paper presented material to answer a major challenge in designing a product platform that must support multiple brands. The problem is to design necessary differentiation among brands in the portfolio and at the same time to utilize acceptable brand parity as a common product platform. Functional architecture based on a function structure methodology and a brand modularity matrix were proposed to provide a concise representation of a product portfolio architecture and to facilitate the applications of modularity rules to investigate possible modules for a product family. The proposed representation and framework provides a systematic and practical approach to consistently develop successful platforms.

Several brand specific architecting rules (i.e., dominant theme of product functions and aesthetic forms, brand signature, and platform rules) for product modularization were introduced to guide the development of a product platform to support multiple brands. One of the important principles in developing a platform that supports multiple brands is the gestalt nature of

products. As a result of this finding, the dominant theme and brand signature rules have been proposed to ensure that brands developed from the same platform will have sufficient differentiation. The complementary result of these rules is the emergence of modules that can be commonized as the product platform. The proposed methodology is useful in deciding necessary brand differentiation and platform commonization to promote brand positioning. It helps to identify the modules and components that can be commonized and those that must be unique so that each brand's platformed products are perceived differently by their respective customers.

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REFERENCES

- Aaker, D., (1996). *Building Strong Brands*, The Free Press, New York.
- Baldwin, C. and Clark, K., (2000). *Design Rules: The Power of Modularity*, MIT Press, Cambridge, MA.
- Berkowitz, M., (1987). "Product Shape as a Design Innovation Strategy," *Journal of Product Innovation Management*, 4:274:283.
- Bloch, P., (1995). "Seeking The Ideal Form: Product Design and Consumer Response," *Journal of Marketing*, 59:16-29.
- Bremmer, R., (1999). "Cutting-Edge Platforms," *Financial Times Automotive World*, June, pp. 30-41.
- Bremmer, R., (2000). "Big, Bigger, Biggest," *Financial Times Automotive World*, June.
- Conner, C., De Kroon, J. and Mistree, F. (1999). "A Product Variety Tradeoff Evaluation Method for a Family of Cordless Drill Transmissions," *ASME Design Engineering Technical Conferences*, Las Vegas, Nevada. DAC-8625.
- Dahmus, J., Gonzalez-Zugasti, J.P. and K. Otto, (2000). "Modular Product Architecture," *ASME Design Engineering Technical Conferences*, Baltimore, MD, DETC2000/DTM-14565.
- Erens, F. and K. Verhulst, (1996). "Architectures for product families," *WDK workshop on Product Structuring*, Delft University of Technology.
- Eppinger, S., Whitney, D., Smith, R. and D. Gebala, (1994). "A Model-based Method for Organizing Tasks in Product Development," *Research in Engineering Design*, 6(1)1-13.
- Fujita, K., Sakaguchi, H. and Akagi, S. (1999). "Product Variety Deployment and its Optimization under Modular Architecture and Module Commonalization," *ASME Design Engineering Technical Conferences*, Las Vegas, NV. DFM-8923.
- Gonzales-Zugasti, J., and K. Otto, (2000). "A Method for Architecting Product Platforms with an Application to Interplanetary Mission Design," *Research in Engineering Design*, 12:61-72.
- Kota, S. and K. Sethuraman, (1998). "Managing Variety in Product Families through Design for Commonality," *ASME Design Engineering Technical Conferences*, Atlanta, Georgia. DTM-5651.
- Krishnan, V., Singh, R. and Tirupati, D. (1998). "A Model-Based Approach for Planning and Developing A Family of Technology-Based Products." The University of Texas at Austin Management Department. April 1998. Working Paper.
- Martin, M. and Ishii, K. (1997), "Design for Variety: Development of Complexity Indices and Design Charts," *ASME Design Engineering Technical Conferences*, Sacramento, CA, DFM-4359.
- Maupin, A. and L. Stauffer. "A Design Tool to Help Small Manufacturers Reengineer A Product Family," *Proceedings of DETC 00: ASME Design Engineering Technical Conferences*, Baltimore, Maryland. DETC/DTM-14568.
- Meyer, M.H. and Lehnerd, A.P. (1997), *The Power of Product Platforms: Building Value and Cost Leadership*, Free Press, N.Y.
- Nelson, S., Parkinson, M. and P. Papalambros, (1999). "Multicriteria Optimization in Product Platform Design," *1999 ASME Design Engineering Technical Conferences*, Las Vegas, Nevada. DAC-8676.
- Ortega, R., Kalyan-Seshu, U. and B. Bras, (1999). "A Decision Support Model for the Life-Cycle Design of a Family of Oil Filters," *1999 ASME Design Engineering Technical Conferences*, Las Vegas, Nevada. DAC-8612.
- Otto, K. and Wood, K. (2000), *Product Design*, Prentice Hall, Englewood Cliffs, N.J.
- Pahl, G. and Beitz, W. (1996), *Engineering Design: A Systematic Approach*, Springer Verlag, N.Y.
- Pedersen, P., (1999). "Organisational Impacts of Platform Based Product Development," *International Conference on Engineering Design*, Munich.
- Pulkkinen, A., Lehtonen, T. and A. Riitahuhta, (1999). "Design for Configuration - Methodology for Product Family Development," *International Conference on Engineering Design*, Munich.
- Rechtin, E. and M. Maier, (1997). *The Art of Systems Architecting*. Boca Raton, CRC Press.
- Robertson, D. and K. Ulrich, (1998). "Planning for product platforms," *Sloan Management Review* 39(4): 19-31.
- Schmitt, B. and A. Simonson, (1997). *Marketing Aesthetics*, The Free Press, N.Y.
- Siddique Z. and D. Rosen (2000). "Product Family Configuration Reasoning Using Discrete Design Spaces," *Proceedings of DETC 00: ASME Design Engineering Technical Conferences*, Baltimore, Maryland. DETC/DTM-14666.
- Simpson, T., Maier, J. and Mistree, F. (1999). "A Product Platform Concept Exploration Method for Product Family Design." *ASME Design Engineering Technical Conferences*, Las Vegas, Nevada. DTM-8761.

- Sosa, M, Eppinger, S. and C. Rowles, (2000). "Designing Modular and Integrative Systems," *Proceedings of DETC 00: ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conferences*, Baltimore, Maryland. DETC/DTM-14571.
- Stone, R., Wood, K. and R. Crawford, (1998). "A Heuristic Method to Identify Modules from a Functional Description of a Product," *ASME Design Engineering Technical Conferences*, Atlanta, Georgia. DTM-5642.
- Sudjianto, A. (2001). "Platform Development to Support Multiple Brands," M.S. Thesis, Massachusetts Institute of Technology.
- Veryzer, R.W. (1993), "Aesthetic Response and the Influence of Design Principles on Product Preferences," in *Advances in Consumer Research*, Vol. 20:224-231, Leigh McAllister and Michael Rotschild, eds., Association for Consumer Research, Provo, UT.
- Veryzer, R.W. and Hutchinson, J.W. (1998), "The Influence of Unity and Prototypicality on Aesthetic Responses to New Product Designs," *Journal of Consumer Research*, 24: 374-394.
- Wheelright, S.C. and Clark, K.B. (1992), *Revolutionizing Product Development: Quantum® Leaps in Speed, Efficiency, and Quality*, Free Press, N.Y.
- Yu, J., Gonzalez-Zugasti, J. P. and Otto, K. N. (1999). "Product Architecture Definition Based Upon Customer Demands." *Journal of Mechanical Design* 121(3): 329.
- Zamirowski, E. and Otto, K. (1999), "Identifying Product Portfolio Architecture Modularity Using Function and Variety Heuristics," *ASME Design Engineering Technical Conferences*, Las Vegas, Nevada, DTM-8760.