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A VARIATION-BASED METHODOLOGY FOR PRODUCT FAMILY DESIGN

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ABSTRACT

In recent years, considerable research has been directed towards the development of methods for designing families of products. In this paper, we present a Variation-Based Platform Design Methodology (VBPDM), which aims to satisfy a range of performance requirements using the smallest variation of the product designs in the family. In the first stage of the VBPDM, the common product platform around which the product family is to be developed is identified. A ranged set of solutions is found, represented by the mean and standard deviation of the input design variables, to meet a range of the different performance requirements for the product family. During this first stage, a compromise Decision Support Problem (DSP) is used to optimize the commonality goal that seeks to minimize the deviation of the input design variables, while satisfying the range of performance requirements. Those design variables that show small deviations are held constant to form the product platform. In the second stage of the VBPDM, each individual product is designed around the common platform such that the functional requirements of the product are best satisfied. As an example, the proposed method is used to develop a family of universal electric motors designed to meet a range of torque requirements. The results are compared against previous work.

Keywords: Product family, Product platform, Commonality, Solution Set, Universal electric motor

NOMENCLATURE

DSP	Decision Support Problem
VBPDM	Variation-Based Platform Design Methodology
PPCEM	Product Platform Concept Exploration Method
μ_{x_n}	Mean of the nth design variable in the product family
σ_{x_n}	Standard deviation of the nth design variable in the product family
μ_{b_i}	Mean of the ith desired performance in the product family
σ_{b_i}	Standard deviation of the ith desired performance in the product family
μ_{h_i}	Mean of the ith actual performance in the family
σ_{h_i}	Standard deviation of the ith actual performance in the family
X	Vector of all the design variables for a product
$h_{ij}(\mathbf{X})$	The i^{th} performance of the j^{th} product
b_{ij}	The i^{th} performance requirement of the j^{th} product
W_t	Weights for the different objectives in the compromise DSP

1. INTRODUCTION

In this age of a "buyer's market" in which manufacturing firms must satisfy individual customer requirements, many of the current management strategies address developing single products as rapidly as possible. Meyer and Utterback (1993) argue for a broader approach to managing new products. According to them, concentrating the design efforts at the level of the product family, and on the development and sharing of key components and assets within a family, is of vital importance. This approach is in keeping with the evolving paradigm of mass customization (Pine, 1993; Kotha, 1995).

Meyer and Utterback (1993) give the following definitions of *Product Platform* and *Product Family*. A

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product platform encompasses the design and components shared by a set of products. An effective platform is the core of a successful product family, and serves as the foundation for a series of closely related products. Products that share a common platform but have specific features and functionality required by different sets of customers form a *product family*. A product family typically addresses a market segment, while specific products within the family target niches within that segment.

It becomes clear from the above definitions that a product family should be designed to satisfy a range of functional requirements, and the ideal product platform should include all of the non-differentiating features of the products in the family. In other words we should attempt to standardize all those components that need not be essentially varied to satisfy the varying functional requirements of the products in the family (cf., Kota and Sethuraman, 1998). Selection of a good platform the first time is very important since it provides the foundation for the product family and changing a platform can involve significant capital expenditure, as companies have to redesign their existing products (cf., Meyer and Lehnerd, 1997). For example, Sanderson and Uzumeri (1995) discuss how Sony has managed to effectively design and develop three Walkman® platforms to maintain dominance of the portable audio stereo market.

More and more engineering tools and methods are being developed for designing product families. In the modular design approach to product family design, standardization of component parts and sub-assemblies across different products in the product family is attempted by focusing on developing modular product architecture. Ulrich and Eppinger (2000) define an integral architecture to have a complex mapping between functions and components, whereas a modular architecture exhibits one-to-one mapping between functions and components. Along the same lines, Pine (1993) suggests that the best method to achieve maximum individual customization while minimizing cost is through creation of modular components that can be configured into a wide variety of end products and services. Stone, et al. (1998) propose a heuristic method to identify modules from a functional description of a product. McAdams, et al. (1998) introduce a method that uses customer needs across a range of products, translated into functional requirements, to explore design solutions at a functional level. Such an approach allows design synthesis of modules, which are independent of and prior to the existence of form and structure of a particular product. Allen and Carlson-Skalak (1998) develop a methodology for designing modular product, which involves identification of modules of a previous generation of product. While most of the product family design concepts are applicable to products that are modular with respect to functions (cf., Siddique, et al. 1998), Kota and Sethuraman (1998) note that generally, a modular design tends to have more components than a multi-functional design performing the same overall function. An "optimum" balance between the functional content that each part should have and the level of commonality that should exist within a product family needs to be addressed.

In developing design metrics for tradeoff analysis when designing a product family, Martin and Ishii (1996, 1997) develop the method of Design for Variety that uses quantitative tools to estimate manufacturing costs of providing variety and qualitative tools to increase managers' and engineers' understanding of how to reduce costs and to determine customer preference for variety. Gonzalez-Zugasti, et al. (1999) develop a quantitative measure of the value to the company for different family designs and apply it to select the most appropriate design from a set of possible alternatives.

In the category of model-based product family design approach, Simpson, et al. (1999) use the Product Platform Concept Exploration Method (PPCEM) for designing a common product platform. In the PPCEM, the market segmentation grid is employed to help identify suitable scale factors around which the common product platform is "scaled" or "stretched" to satisfy a range of performance requirements. Robust design principles are used to facilitate the design of the common platform by minimizing the sensitivity of the performance to variations in the scale factor(s). The variations of the scale factor(s) reflect the amount of product variety within the product family. Based on the similar principle as that of the PPCEM, the Product Variety Tradeoff Evaluation Method (PVTEM) is presented by Conner, et al. (1999) to assess appropriate product family tradeoffs using the commonality and performance indices developed in (Simpson, 1998). In each of the above model-based approaches, the set of the scale factor(s) and that of the common platform parameters are pre-selected, and the selection is independent from the commonality and performance tradeoff evaluation model.

Our interest in this paper is to *integrate the selection of the common platform parameters and the non-platform variables (scale factors) as a part of the commonality and performance tradeoff procedure.* In particular, we ask the following question:

> Given the performance desired from individual products of a family, how can we design the common product platform and the individual products in the family to maximize the commonality within the product family as well as to best satisfy the design requirements of each product?

The foundations for our proposed approach are the representation of flexible design specifications (i.e., a range of solutions) embodied in the Robust Concept Exploration Method (RCEM) (Chen, et al., 1997) and the compromise Decision Support Problem (DSP) (Mistree, et al., 1993) for multiobjective decision-making. The next section explains how we extend the concepts of these two techniques to develop our Variation-Based Platform Design Methodology.

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2. VARIATION-BASED PLATFORM DESIGN METHODOLOGY (VBPDM)

Product family design involves satisfying a range of functional requirements with a range of products. To design a product family, the conventional approach would be to design each of the products of the family independently of the others in a way that satisfies the needs and requirements for each product. As Meyer and Lehnerd (1997) note, the focus on individual customers and products often results in "a failure to embrace commonality, compatibility, standardization, or modularization among different products or product lines." The end result is a proliferation of product variety, increasing costs and lowering margins. The proposed approach is to first identify a common product platform designed to maximize the standardization of components across the product family, taking into account the overall range of functional requirements that must be satisfied. The individual products are then subsequently designed around this common platform to satisfy their functional requirements. This results in a range of products that satisfies a range of requirements with maximum standardization.

2.1 Technology base

The RCEM and the compromise DSP form the technology base for the VBPDM. In the DSP technique, design is defined as *the process of converting information that characterizes the needs and requirements for a product into knowledge about a product* (Mistree, et al., 1990). This definition is extended to describe product family design, as the process of converting information that characterizes the needs and requirements for a product family into knowledge about a product family. The compromise DSP (Mistree, et al., 1993) formulated in terms of the keywords "Given," "Find," "Satisfy," and "Minimize", provides a domain independent framework for grouping information, and solving multiobjective, nonlinear, optimization problems. In this paper, the compromise DSP is used to assess the tradeoffs related to product family and platform design.

The compromise DSP is used to determine the values of the design variables that satisfy a set of constraints and bounds and achieve as closely as possible a set of conflicting goals. The compromise DSP is solved using the Adaptive Linear Programming (ALP) algorithm based on sequential linear programming and is part of the DSIDES (Decision Support in Designing Engineering Systems) software (Mistree, et al., 1993). In this work the set of conflicting goals in the compromise DSP are weighted in an Archimedean solution scheme. A solution to the compromise DSP is called a satisficing solution (cf., Simon, 1996). If we expand this idea of a satisficing solution, we can envision a set of satisficing solutions that satisfy a range of system requirements. The efficacy of the compromise DSP in creating ranged sets of top-level design specifications has been demonstrated by earlier work in this area (Lewis, et al., 1999; Simpson, et al., 1996).

Greater design flexibility can be achieved during the design process by generating a range of solutions rather than a single point solution; this is the basis for the RCEM. The RCEM (Chen, et al., 1996) facilitates quick evaluation of design alternatives and generation of top-level design specifications with quality considerations in the early stages of design. It classifies the design parameters as noise and control factors and uses the compromise DSP to determine the solution in which the range of control factors satisfy the system requirements within an allowable performance variation, contributed by the deviations of both control and noise factors. Thus robust and flexible top-level design specifications can be developed for a product. We extend the above concepts here to develop the VBPDM that will address the research question raised earlier.

2.2 Extending our technology base to develop the VBPDM

Figure 1 shows a schematic representation of the VBPDM. The first stage of the VBPDM is the selection of the common product platform. In the second stage, each individual product is designed around the common platform. The details of these two stages are elaborated in the following two sub-sections.

2.2.1 Platform selection in VBPDM

In the platform selection stage, a *single* compromise DSP (see Figure 2) is formulated to determine which variables should be selected as the common platform variables and the optimal values for these variables. To consider all of the products in this single compromise DSP, the variation among the family of products is captured by the deviations of the input design variables and the resulting performance deviations. For the ease of computation, a probabilistic representation is adopted. The design variables of the product are modeled to follow uniform probability distributions, represented by two variables - the mean and the standard deviation. The resulting variations of performance parameters are desired to match with the desired ranges of performances across the product family.

The compromise DSP in Figure 2 is formulated to find the mean and standard deviation of the design variables that result in a desired range of performance. Constraints and goal targets are imposed on the mean and standard deviation of the performance so as to satisfy the range of performance requirements of the product family. On the other hand, the need for standardization requires the use of a minimum set of design variables (non-platform variables) whose deviations help satisfy the range of requirements. Thus one objective in the compromise DSP is to find the smallest set of design variables whose deviations satisfy the range of performance requirements as best as possible. This is accomplished by creating a goal of minimizing the total deviations in as many design variables as possible. We call this goal the

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commonality goal. Because there is a tradeoff between achieving standardization across the different products and satisfying the functional requirements of each product, an Archimedean formulation is used in the compromise DSP in which weights are assigned to the different goals to make the tradeoffs. Here we assume there is no correlation among the different performances. After solving the compromise DSP, if the standard deviation of a design variable is found to be very small relative to its mean value, it indicates that this parameter has very little contribution to achieving the range of performance, and it is then taken as a common platform parameter. On the other hand, the set of design parameters that has significant variations in the result cannot be held common for the family and are used as the non-platform variables (or scale factors) in the second stage of the VBPDM.

We now provide some mathematical details of formulating the compromise DSP.

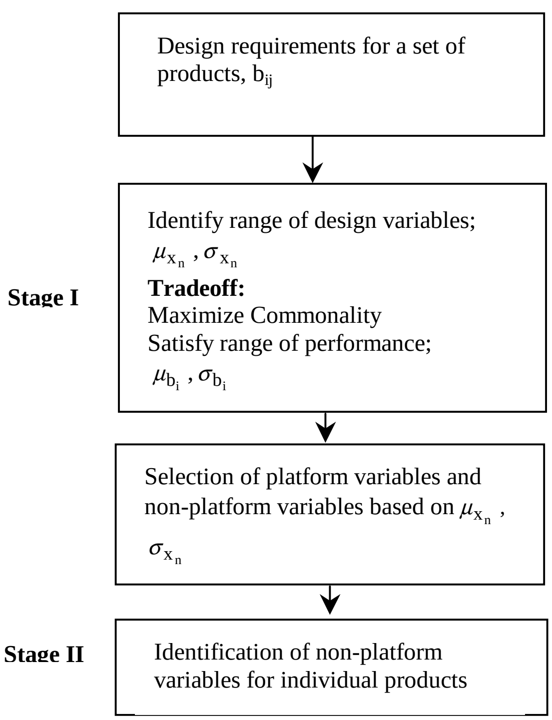

Figure 1 Schematic representation of the VBPDM

In Figure 2, the mean and standard deviation of design variables across all the products are represented as μ_{x_n} and σ_{x_n} (n = 1, 2,…, k), respectively. In the same figure, $h_{ij}(\mathbf{X})$ represents the function value of the i^{th} performance of the j^{th} product ($\mathbf{X}$ is the vector of design variables). A critical element of our proposed approach is to match the resulting performance distributions (captured by μ_{h_i} and σ_{h_i}) caused by the deviations of design variables, with the desired range of design requirements (represented by μ_{b_i} and σ_{b_i}). The modeling of this part depends on whether a design requirement is considered as a constraint or a goal, and whether the desired value or limiting value is the same or different for all the products. As shown in Equations 2.1 through 2.6, the constraints/goals for meeting a range of performance are classified into six different categories that include:

a. Equality constraints on performance with different desired values from product to product,
b. Equality constraints on performance with the same desired value from product to product,
c. Inequality constraints on performance with different limiting values from product to product,
d. Inequality constraints on performance with the same limiting value from product to product,
e. Goal targets on performance, with different values for each product of the family, and
f. Goal targets on performance, with the same target value from product to product.

For category (a) design requirements, two sets of equality constraints are imposed to achieve the mean location and the dispersion of the performance (Equation 2.1). The modeling of category (b) requirements is identical to category (a) but with the dispersion set as 0 because the desired values of all of the equality constraints are the same in this case (Equation 2.2). For category (c) design requirements, only the mean performance is modeled (Equation 2.3). When the limiting values of all the products are the same in category (d), the worst case among all of the products is identified to satisfy the constraint (Equation 2.4). For design requirements that are considered as goals (categories (e) and (f)), either the target or the mean of the different targets are modeled (Equations 2.5 and 2.6). The distribution of a target is not important because goals represent designer' wishes and the targets are used to express the aspiration levels but not necessary the true levels of performance. Finally, equation 2.7 is used to model the commonality goal. The evaluations of the worst case, the mean and standard deviation of performances can be implemented based on data sampling or simplified approach such as Taylor expansion.

2.2.2 Designing individual products of the family

Once the common platform parameters and their values are determined in the first stage of the VBPDM, we seek the values of the non-platform variables to best satisfy the functional requirements of the individual products during the second stage of the VBPDM. One compromise DSP is formulated for each individual product in the family to optimize its non-platform variables. In each of these compromise DSP, we are "Given", the settings of the common platform design variables identified from the first stage. "Find", the values of the non-platform design variables (i.e., scaling factors). The "constraint" and "goals" are appropriately modeled to satisfy the functional requirements

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specified for a particular product in the family. This process is also referred to as the instantiation of the product family.

Given
Mathematical relationships, and constants
System constraints and goals
Find
μ_{x_n} n = 1,…..,k
σ_{x_n} n = 1,…..,k k is the number of design variables
Satisfy
The *system constraints* that must be satisfied can be classified as follows:
Equality constraints on performance with different desired value for each product of the family $h_{ij}(\mathbf{X}) = b_{ij}$

This constraint is modeled as $\mu_{h_i} = \mu_{b_i}$ and $\sigma_{h_i} = \sigma_{b_i}$ **(2.1)**

Equality constraints on performance with same desired value for each product of the family $h_{ij}(\mathbf{X}) = b_i$

This constraint is modeled as $\mu_{h_i} = b_i$ and $\sigma_{h_i} = 0$ **(2.2)**

Inequality constraints on performance with different limiting value for each product of the family $h_{ij}(\mathbf{X}) \le b_{ij}$

This constraint is modeled as $\mu_{h_i} \le \mu_{b_i}$ **(2.3)**

Inequality constraints on performance with the same limiting value for each product of the family $h_{ij}(\mathbf{X}) \le b_i$

This constraint is modeled as $h_i(\mathbf{X})_{worst\text{-}case} \le b_i$ **(2.4)**

The *system goals* that must achieve a specified target as far as possible:
Goal targets for performance, with different value for each product of the family $h_{ij}(\mathbf{X})/T_{ij} + d_{ij}^- - d_{ij}^+ = 1$

This goal is modeled as $\mu_{h_i} / \mu_{T_i} + d_i^- - d_i^+ = 1$ **(2.5)**

Goal targets for performance, with the same target value for each product of the family $h_{ij}(\mathbf{X})/T_i + d_{ij}^- - d_{ij}^+ = 1$

This goal is modeled as $\mu_{h_i} / T_i + d_i^- - d_i^+ = 1$ **(2.6)**

The commonality goal for minimizing the deviation of the system variables, and thus helps in standardization

$(\sigma_{x_1}/a_1 + \ldots\ldots\ldots + \sigma_{x_k}/a_k)/k + d^- - d^+ = 0$ **(2.7)**

where $a_1, \ldots\ldots, a_k$ are the normalizing factors
Minimize

$$Z = \sum_{t=1}^{i+1} W_t (d_t^- + d_t^+);\ \ \Sigma W_t = 1;\ W_t \ge 0$$

Figure 2 Compromise DSP for determining the product family platform

To illustrate the applicability of our approach, we adapt an example from Simpson, et al. (1999) involving the design of a family of universal electric motors. In Simpson, et al. (1999), a universal electric motor family is developed using the Product Platform Concept Exploration Method (PPCEM). We use this product family as a benchmark for comparing the product family developed using our proposed methodology.

3. EXAMPLE PROBLEM

The fundamentals of universal electric motor operation and performance are described in detail in Simpson, et al. (1999). The analytical model is based on equations given in Chapman (1991). The requirements of the product family are described below. The design problem is to develop a family of ten universal electric motors to satisfy a range of torque (T) requirements. The other motor performance parameters are the masses of the motors (M), their efficiency (η), their power (P), and their magnetizing intensity (H). In the following, issues related to the above performances are discussed.

1. Magnetizing intensity (H): The design of the motor should ensure that the magnetizing intensity be below 5000. This is to ensure that the magnetizing flux within the motor does not exceed the physical flux carrying capacity of the steel.
2. Power (P): The desired power for each motor in the family is 300 W.
3. Efficiency (η): The goal target for maximizing efficiency for all the motors is 70%.
4. Mass (M): A maximum allowable mass of 2.0 kg is assumed to define a feasible motor. The goal target for minimizing mass for all the motors is 0.5 kg.
5. Torque (T): The desired torque requirement for the ten motors {0.05, 0.1, 0.125, 0.15, 0.2, 0.3, 0.35, 0.4, 0.5}N-m.

Each motor has eight design variables that need to be determined during the design process for satisfying the needs and requirements of the product; they are:

1. Number of turns of wire on the motor armature, N_c
2. Number of turns of wire on each field pole, N_s
3. Cross-sectional area of the wire on the armature, A_{wa}
4. Cross-sectional area of the wire on the field poles, A_{wf}
5. Radius of the motor, r
6. Thickness of the stator, t
7. Current drawn by the motor, I
8. Stack-length of the motor, L

The current I drawn by the motor is treated as a state variable in the system, i.e., it is the amount of current which is drawn by the motor such that the given torque and power requirements are met for a given motor configuration.

3.1 Designing the common platform of the universal motor family

The first stage in the VBPDM is to design the platform for the motor family. We formulate a compromise DSP for the product family as discussed in Section 2.2.1. The compromise DSP formulation used for designing the motor family platform is particularized and shown in Figure 3. The torque requirements of the motor family are modeled as equality constraints on performance with different desired values from product to product (category (a), Equation 2.1). The constraints on the magnetizing intensity (H) and mass (M) are modeled as inequality constraints on performance with the same limiting value from product to product (category (d), Equation 2.4). The constraint on power (P) is formulated as an equality constraint on the performance with the same desired value for all the products (category (b), Equation 2.2). The constraint ($\sigma_{h_{power}} = 0$), as per the generic formulation, is not included because the current (I), being a state variable,

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satisfies the constant power requirement for all the motors without requiring an additional constraint. The mass and efficiency goals are incorporated into the compromise DSP, as goals on performance with the same target value from product to product (category (f), Equation 2.6). The commonality goal is to minimize the normalized standard deviation of the system variables with a target of zero. The normalization value is approximately at the middle of the specified bounds for the standard deviations in the optimization process. The extent to which the commonality goal is achieved for a particular system variable gives us an indication whether or not the system variables can be held constant (i.e., made part of the common platform) for the product family. The goals on efficiency, mass, and commonality are assigned equal weights.

The mean of the performance is assumed to be at the mean of the design variables. The standard deviation of the performance is calculated using the Taylor series approximation. Thus for a general function:

$$h = f(x_1, x_2, \ldots\ldots\ldots\ldots, x_k) \tag{3.1}$$

mean of h is

$$\mu_h = f(\mu_{x_1}, \mu_{x_2}, \ldots\ldots\ldots\ldots, \mu_{x_k}) \tag{3.2}$$

and the standard deviation of h is

$$\sigma_h = \sqrt[2]{\left(\frac{dy}{dx_1}\right)^2 \sigma_{x_1}^2 + \ldots\ldots\ldots + \left(\frac{dy}{dx_k}\right)^2 \sigma_{x_k}^2} \tag{3.3}$$

where μ_{x_n} is the mean of the n^{th} design variable, and σ_{x_n} is the standard deviation of the n^{th} design variable. It should be noted that, for better accuracy, we could use sampling methods such as Monte Carlo simulation. However in this case, since the deviation of torque requirements is not large, the Taylor series approximation is good enough.

The results of the compromise DSP formulation discussed above are tabulated in Tables 1 and 2, in which the identified mean and the standard deviation of the design variables and resulting performance variations are provided, respectively. The different degrees to which the *commonality goal* is satisfied by the different system variables, provides an indication about the system variables that should compose the product platform. The decision on how much variation is negligible is specific to the problem. The value of the standard deviation as a percentage of the mean value can provide a good indication. For this problem we consider standard deviations, less than 10% of the mean value, to be small enough for the corresponding design variable to be considered a common platform variable.

Given:
All information necessary for assessing the achievement of goals and constraints (i.e., constants, mathematical relationships, goal targets).
Find:
The mean and standard deviation of the design variables:
Number of turns on the armature, N_c
Number of turns on each pole on the field, N_s
Area of the wire on the armature, A_{wa}
Area of the wire on the field, A_{wf}
Thickness of the stator, t
Radius of the motor, r
Stack length, L
State variable: Current drawn by the motor, I
Satisfy:
The *system constraints* that must be satisfied for feasible solution:
Equality constraints on torque with different desired values from product to product; $\mu_{h_{torque}} = \mu_{b_{torque}}$ and $\sigma_{h_{torque}} = \sigma_{b_{torque}}$
where $\mu_{b_{torque}} = 0.2325$, $\sigma_{b_{torque}} = 0.13675$
Equality constraints on power with the same desired value for all products in the family; $\mu_{h_{power}} = \mu_{b_{power}}$ where $\mu_{b_{power}} = 300$
Inequality constraints on mass and magnetic intensity (H);
$\mu_{h_{mass}} \leq 2$ kgs and $\mu_{h_H} \leq 5000$

The *system goals* that must achieve a specified target as far as possible:
Goal targets for mass and efficiency with the same target value from product to product;
$\mu_{h_{mass}}/0.5 + d_1^- - d_1^+ = 1$ and $\mu_{h_\eta}/0.7 + d_2^- - d_2^+ = 1$
Commonality goal:
$$(\sigma_{N_c}/a_{N_c} + \sigma_{N_s}/a_{N_s} + \sigma_t/a_t + \sigma_r/a_r + \sigma_L/a_L + \sigma_{Awa}/a_{Awa} + \sigma_{Awf}/a_{Awf})/7.0 + d_3^- - d_3^+ = 0$$
Minimize:
$$Z = \sum_{t=1}^{3} W_t(d_t^- + d_t^+); \quad W_t = 0.3333$$

Figure 3 Compromise DSP for determining motor family platform

Table 1 Identified Mean and Standard deviation of design variables

Design Variable	Mean	Standard deviation	Ratio
A_{wa} [mm^2]	0.280	0.0	0.0
A_{wf} [mm^2]	0.384	0.0	0.0
t [mm]	7.15	1.74	24%
r [cm]	2.38	1.13	47%
N_c	1120	122	10%
N_s	72	6	8%
L [cm]	2.51	0.17	6%

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Table 2 Performance parameters of the product family

Response	Mean	Standard deviation
Power [W]	300	-
Efficiency	0.71	-
Mass[kg]	0.72	-
Torque[N-m]	0.2235	0.1354
H	4168	-

Based on the results in Table 1, we form the product platform comprising the armature wire area (A_{wa}), field wire area (A_{wf}), the number of turns of field wire (N_s), and the stack length of the motor (L). The radius of the motor (r), thickness (t), number of turns of the armature wire (N_c), and current (I) are allowed to vary from motor to motor within the family. From Table 2, we see that the power requirement is satisfied for each product at μ_{power} = 300W and σ_{power} = 0. The product family platform also satisfies the target for the mean efficiency; however, the target of 0.5 kg for the mean mass is not achieved. The constraint on mean torque is satisfied with a violation of 3.8%, which is within the specified tolerance range. The constraint on standard deviation of the torque is better satisfied with a violation of only 0.9%. The constraint on the magnetic intensity is satisfied at this stage of the design.

3.2 Instantiation of the individual products in the family

The next stage of the VBPDM is to instantiate the individual motors of the product family using the product platform specifications. The compromise DSP formulated for designing the individual motors is shown in Figure 4. While the common platform variables determined from stage I, are fixed as constant parameters, the to-be-identified variables are the four non-platform variables. The constraints and goals are related to the design requirements originally stated at the beginning of Section 3. The product family thus developed, represented by the values of all design variables and the resulting performance, is listed in Table 3.

Given:
Platform settings for A_{wa}, A_{wf}, L, and N_s (Table 1)
Find:
Number of turns on the armature, N_c
Thickness of the stator, t
Current drawn by the motor, I
Radius of motor, r
Satisfy:
The system constraints:
Magnetizing intensity, H $\leq$ 5000
Power, P = 300 W
Mass, M $\leq$ 2.0 kg
Individual torque requirements:
T = {0.05, 0.1, 0.125, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5} N-m

The *system goals* that must achieve a specified target as far as possible:
Goal targets for mass and efficiency
$M / 0.5 + d_1^- - d_1^+ = 1$ and $\eta/0.7 + d_2^- - d_2^+ = 1$
Minimize

$$Z = \sum_{t=1}^{2} W_t (d_t^- + d_t^+); \quad W_t = 0.5$$

Figure 4 Compromise DSP for design of each motor

Table 3 Universal motor product family instantiations by the VBPDM

Motor	Product Specifications (Design Variables)								Responses			
	Nc	Ns	Awf [mm^2]	Awa [mm^2]	I [A]	R [cm]	t [mm]	L [cm]	T [N-m]	P [W]	η	M [kg]
1	374	72	0.280	0.384	2.92	2.32	4.05	2.51	0.05	300	.89	.50
2	731	⇓	⇓	⇓	3.16	1.99	3.19	⇓	0.1	⇓	.82	.50
3	906	⇓	⇓	⇓	3.29	1.83	2.85	⇓	0.125	⇓	.79	.50
4	1068	⇓	⇓	⇓	3.42	1.70	2.69	⇓	0.15	⇓	.76	.50
5	1183	⇓	⇓	⇓	3.65	1.82	2.97	⇓	0.2	⇓	.71	.57
6	1260	⇓	⇓	⇓	3.85	1.95	3.79	⇓	0.25	⇓	.67	.63
7	1295	⇓	⇓	⇓	4.06	2.06	3.92	⇓	0.3	⇓	.64	.67
8	1297	⇓	⇓	⇓	4.29	2.16	4.00	⇓	0.35	⇓	.60	.72
9	1297	⇓	⇓	⇓	4.49	2.27	4.37	⇓	0.4	⇓	.58	.76
10	1269	⇓	⇓	⇓	4.89	2.49	4.99	⇓	0.5	⇓	.53	.83

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4. VERIFICATION

Our proposed approach is verified from two aspects. First, the results obtained using the VBPDM are compared to those from PPCEM where the common platform variables are pre-specified. This is to show that by choosing the best set of common platform variables instead of using the pre-specified ones, our approach provides more flexibility when designing the platform and is therefore expected to yield better overall performance of the product family. Second, the mathematical structure of the example problem is studied in more thorough detail to verify whether the results obtained from our proposed approach are consistent with the physics of the problem.

4.1 VBPDM vs. other approaches

In (Simpson, et al., 1999), the motor stack length (L) is pre-selected as the scale factor. The variation of the stack length is expected to result in the desired variation of the motor torque while the other design variables form the common platform. We believe that the approach described in this paper removes the trial and error process involved in deciding the product platform.

A comparison of the product family developed using the PPCEM by selecting the stack length as the scale factor, with the product family developed using the VBPDM is presented in Table 4. To improve the product family obtained by the PPCEM, Simpson, et al. (1999) also developed another product family with reduced standardization, by assuming a platform of constant radius of motor (r), and constant thickness (t). Table 5 contains the comparison of this product family with the VBPDM family.

Table 4 Comparison of the performance between the VBPDM motors and the PPCEM motor family with only stack length varying

Motor	VBPDM motors		PPCEM motor		% difference	
	η	M[kg]	η	M[kg]	η	M
1	.89	.50	.768	.380	Equiv.	Equiv.
2	.82	.50	.722	.520	Equiv.	-3.9
3	.79	.50	.700	.576	Equiv.	-13.2
4	.76	.50	.679	.625	+11.9	-20.00
5	.71	.57	.639	.703	+11.11	-18.92
6	.67	.63	.602	.759	+11.30	-17.00
7	.64	.67	.568	.797	+12.68	-15.93
8	.60	.72	.536	.820	+11.94	-12.20
9	.58	.76	.505	.830	+14.85	-8.43
10	.53	.83	.448	.820	+18.30	+1.22
Average change:					+13.15	-12.04

Table 5 Comparison of the responses between the VBPDM motors and the PPCEM motor family with a platform of radius and thickness

Motor	VBPDM motors		PPCEM motor		% difference	
	η	M[kg]	η	M[kg]	η	M
1	.89	.50	.747	.397	Equiv.	Equiv.
2	.82	.50	.721	.456	Equiv.	Equiv.
3	.79	.50	.711	.477	Equiv.	Equiv.
4	.76	.50	.701	.499	Equiv.	Equiv.
5	.71	.57	.675	.568	+5.19	+0.3
6	.67	.63	.646	.646	+3.72	-2.48
7	.64	.67	.622	.712	+2.89	-5.9
8	.60	.72	.599	.774	+0.17	-6.9
9	.58	.76	.577	.833	+0.52	-8.76
10	.53	.83	.538	.941	-1.49	-11.8
Average change:					+1.83	-5.9

All the motor families in Tables 4 and 5 meet their goals for both power and torque; however, their response for efficiency and mass differ, hence we can use these two parameters to compare the product families. Tables 4 and 5, list the percentage difference of each response from the VBPDM to the PPCEM. For efficiency, a positive change denotes an improvement from the PPCEM to the VBPDM; while, a negative change denotes an improvement in the mass. A motor which has achieved its target mass (0.5 kg) and efficiency (70%) is considered equivalent to a motor with a mass which is lower than the target or an efficiency which is higher than the target. From Tables 4 and 5, we observe that the product family obtained using the VBPDM is better than the PPCEM product family in terms of achieving both the mass and efficiency goals. Results in Table 5 indicate that we can achieve a high degree of standardization while providing sufficient variety by proper selection of the platform variables.

4.2 Verification based on model behavior

To have a better understanding of the physical behavior of our example problem, we develop response surface models (RSM) (see, e.g., Myers and Montgomery, 1995) of the different motor performance using the OPTIMUS® software. The response surface models are developed for the torque (T), power (P), efficiency (η), and mass (M) of the motor in the neighborhood of the optimum solution obtained by the VBPDM (see Table 1). The RSM is developed for a small range of $\pm$ 5 % around the mean values for the design variables in Table 1.

The contribution plots indicate the importance of the different design terms for the design output. The coefficients are calculated in a normalized design space, such that they can

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be compared. The contribution plot for torque (see Figure 5) shows that the radius (r) is the most dominant term. This matches with the deviation of variables obtained from the VBPDM in Stage 1 (see Table 1), which indicates that the radius (r) of the motor has the greatest contribution towards satisfaction of the range of performance requirements. Note in this case, torque is the only performance for which the standard deviation has to meet the target, for achieving a range of performance within the product family. However, in general cases, the variation of the different design variables obtained by the VBPDM for satisfying the range of performance requirements depends on the different competing objectives. Contribution plots were also generated for power, mass and efficiency. Contribution plots of these performance measures indicate the changing importance of the variables in the different responses.

We are also interested in whether the deviations of design variables based on the instantiated individual products at the end of Stage 2 are consistent with those determined in Stage 1. Table 6 lists the mean and standard deviation of the non-platform variables obtained in the actual product family developed Stage 2. We notice that there is a significant difference from the ratio of standard deviation to the mean, obtained in the platform design stage (see Table 1). One of the reasons for this difference is the existence of multiple equivalent solutions for this particular problem, and the other reason is that the mass and efficiency goals are satisfied to different extents in the final product family. This causes a change in the deviation of the variables from the first stage where the deviation of the variables only satisfies the range of torque requirements. In future work, introducing elements of cost and manufacturing convenience into the model should serve to eliminate some of the multiple equivalent solutions.

We should also note that the maximum contributing variable for a performance is not an obvious or automatic choice for satisfying the range of performance when we have competing objectives. Therefore sensitivity analysis is not sufficient enough to identify what should be the common platform variables or non-platform variables. We need the platform design optimization process in Stage 1 to find the best set of design parameters to vary, considering all of the objectives and the desired range of performance.

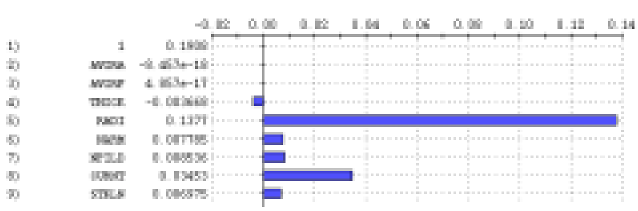

Figure 5 Contributions of different variables for torque

Table 6 Mean and Standard deviation of design variables for the product family

Variables	Mean	Standard deviation	Ratio
N_c	1068	295	27.6%
R [cm]	2.1	0.24	11.4%
T [mm]	3.68	0.69	18.7%

5. CLOSURE

In this paper, the Variation-Based Platform Design Methodology (VBPDM) is proposed to identify the common platform parameters and the non-platform variables (scale factors) in a tradeoff between the standardization requirement and the need for satisfying a range of performance requirements during product family design. The VBPDM uses a two-stage process to design and develop a product family. In the first stage, the VBPDM uses the compromise DSP to make tradeoffs between commonality and individual product performance within the product family and identify the product family platform that is defined by the common platform parameters. We extend the concept of a ranged set of solutions, which is the basis of the RCEM concept, to obtain a satisficing range of solutions for the corresponding range of performance requirements of the product family. We presented the compromise DSP formulation to show how one optimization formulation can be used to model the needs for a range of products using variation-based representations. In the second stage of the VBPDM, the common product platform is used as the core to develop the individual products of the family, i.e., determine the values of non-platform variables.

A family of ten universal electric motors with a range of torque requirements is used to illustrate the proposed method. The product family developed by the PPCEM method (Simpson, et al., 1999) with pre-specified platform variables is used for comparison to illustrate the advantages of our approach. We then use the response surface models to study the effect of the contributing design variables to confirm further the validity of the results obtained. These verification studies illustrate the advantages of our proposed approach as well as the potential challenges associated with solution search due to the existence of multiple equivalent solutions.

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