Proceedings of DETC'99
1999 ASME Design Engineering Technical Conferences
September 12-15, 1999, Las Vegas, Nevada, USA

DETC99/DAC-8675

CATALOG-BASED CUSTOMIZATION

Bala Chidambaram
The Boeing Company
2401 East Wardlow Road, Mail-code: C160-0307
Long Beach, California 90807
Email: bchidamb@gte.net

Alice M. Agogino
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California 94720
Email: aagogino@me.berkeley.edu

ABSTRACT

This paper develops a new method for implementing mass-customization, namely, the customization around standard products, or catalog-based customization. The method addresses the customization requirements of a class of products that are complex in configuration, multi-functional and structurally similar. We formulate catalog-based customization as an optimization problem consistent with the manufacturer's goal of incurring minimal costs in the redesign of existing standard components, while meeting customer specifications and satisfying design constraints. The 'catalog-based' nature of the formulation raises concomitant issues of cost function development and problem simplification/solution. We identify the generational structure as best suited to exploit the cost data in existing catalogs and construct a product cost function. The cost-estimation methods used by the generational structure in the construction are identified as weight-based—for modeling the material costs, and methods based on similarity principles and regression analyses—for the production costs. The optimization formulation of catalog-based customization may be simplified by an a priori identification of a standard catalog design as the customization basis. This is accomplished with function costing—a cost-estimation hypothesis that uses product functionality to develop an approximate cost-estimate. The function-costing estimate is also used to abstract features from the standard base design into the optimization formulation. The preferred solution strategy for the optimization formulation is identified as genetic algorithms. We apply the customization method developed to Brushless D.C. Permanent Magnet (BDCPM) motors and obtain optimal minimal cost custom designs (from the standard designs of a BDCPM motor family) for different sets of customer requirements.

Keywords: Customization, Optimization, Electric Motors

1 INTRODUCTION

The economic landscape of the 1990's has been subject to fundamental changes from a manufacturing viewpoint—from mass production to mass customization. This new model of customized production was anticipated by Toffler (1970). In 1987, Davis coined the word mass-customization to describe it. This paper develops a new method for implementing mass-customization, namely, the customization around standard products, or *catalog-based customization.* The method addresses the customization requirements of a class of products that are complex in configuration, multi-functional and structurally similar. We formulate catalog-based customization as an optimization problem consistent with the manufacturer's goal of incurring minimal costs in the redesign of existing standard components, while meeting customer specifications and satisfying design constraints. The 'catalog-based' nature of the formulation raises concomitant issues of cost function development and problem simplification/solution and these are discussed.

Section (2) describes the problem of catalog-based customization that we are addressing in this paper. Commonly used mass customization techniques are reviewed and their inadequacy in dealing with the customization of complex, multi-functional and structurally similar products is noted. In Section (3), the problem is formulated as an optimization problem guided by the manufacturer's objective to minimize the cost of the customized design for a set of customer specifications. A solution framework is presented. Features of catalog-based customization that make it different from a standard optimization problem are identified and solution techniques to address these are discussed. Section (4) develops a mathematical model, i.e., design variables and constraints, for Brushless D.C. Permanent Magnet (BDCPM) motors, the domain of application of our methodology. This model describes the family of eight standard BDCPM motors listed in a manufacturer's catalog and forms the bases for our study of catalog-based customization. In Section (5), we review commonly used cost structures and cost-estimation methods and identify those cost analyses techniques that are most suitable to catalog-based customization. We also develop the cost function for the BDCPM motor family that we are studying. We apply the customization methodology developed to obtain optimal custom-designs (from a cost perspective) from the standard designs of the BDCPM motor family for different sets of customer design specifications in Section (6). Insights obtained from solving these problems and some general observations about our formulation of catalog-based customization are summarized in Section (7).

2 PROBLEM STATEMENT

In this section, we begin with a review of mass-customization methods. A customization scenario which is inadequately addressed by existing methods is then described. Related work that partially addresses this customization scenario is reviewed and the rationale underlying our study of catalog-based customization is presented.

The reasons for the paradigm shift from mass-production to mass-customization have been well-studied. There has been renewed interest recently in formally studying mass-customization methods. Pine (1993) identifies four implementations of mass-customization, namely, 1) create customizable products, 2) provide point-of-delivery customization, 3) provide quick response throughout the links of the value chain, and 4) modularize components to customize end-products.

These methods work on the four fundamental links in an organization's value-chain, namely, development, production, marketing and delivery. A brief description of these implementations is now presented. Creation of customizable products involves the creation of products that are customizable by the customer, for e.g., computers. Ellis (1990) provides some good model-based approaches to this implementation of mass customization. Point-of-delivery customization is based on the philosophy that the best way to instantly provide what a customer wants is to produce it at the point of sale and delivery, for e.g, sporting goods. Complexity limits the applicability of both the above methods. Providing quick response throughout the value-chain is basically time-based competition and its power and benefits have been well-studied (Peters (1987), Stalk (1990)). Design for Manufacture, Quality Functional Deployment, Design for Assembly are some common enabling technologies for 'quick response' implementations of mass customization. While these techniques have proven effective in developing a quality product at a low cost, they don't address the need to optimize the costs of producing a variety of products. Modularization of components for customization is another popular implementation of mass customization. Customization is gained by the variety with which the components can be configured into products. The primary draw-back here is that the performance of a product can always be optimized and its manufacturing costs lowered by reducing or eliminating modularity.

Let us now consider the following scenario: A manufacturer produces a (closely related) family of products that realize multiple customer design specifications that may vary continuously. The products are complex configurations of component parts and their assemblies and require a substantial infrastructure for their production. Typical examples of this class of products may be found in manufacturers' product catalogs. The selection of a standard product from a manufacturer's product catalog by a customer, based on his/her needs, is frequently employed in design. Product catalogs offer the customer the advantages of convenience and low cost. There are, however, situations when existing standard products don't meet the customer specifications. The question we then pose is as follows:

How does a manufacturer create a custom-design that is feasible (with regard to a set of design specifications) for a class of products that are complex, multi-functional and structurally similar?

Modularizing of components does provide a partial solution to this question but it isn't an effective strategy as it doesn't expoit the similarity between the products. In the context of modularity, it is worth our while to review an emerging trend in manufacturing systems, namely Design for Variety. Design for Variety (DFV) refers to product and process design that meets the market demand for product variety with the best balance of design modularity, component standardization, late point differentiation and product offering (Martin (1996)). While DFV expands the range of available products, we are concerned with customization that is *necessary*—DFV is essentially an a priori customization approach.

3 OPTIMIZATION FORMULATION

We begin by defining the attributes of the customization problem. Design variables are the independent variables that a manufacturer can alter in his/her attempts to meet design specifications. The design specifications are the desired behavior of the product and are provided by the customer. Performance variables evaluate the product's performance. They may be direct design variables or may be functions of the direct design variables. Performance variables are evaluated against the design specifications to ensure that the product satisfies requirements. Indeed, it is the violation of some of these 'performance-exceeds-specification' or acceptability constraints that motivates the customization. In addition to the constraints that model the acceptability constraints, there are constraints that model the physical laws underlying the operation of the product.

Given the above definitions, the customization problem, from a manufacturer's perspective, can be stated as follows: "The manufacturer tries to minimize the cost of manufacturing a product, to meet design specifications, with respect to the design variables he/she controls, and subject to the acceptability constraints and the physical laws that model the product". The basic optimization formulation for the manufacturer is thus

Minimize	Product Cost
w. r. to Design Variables	
subject to	Acceptability Constraints Satisfied
	Physical Laws Satisfied

(1)

Equation (1) has several features that distinguish it from a standard optimization problem. These features and the 'catalog-based' nature of the problem are discussed in Section (3.1). In Section (3.2), we outline a framework to solve the customization problem. The domain of application of the customization methodology developed is Brushless D.C. Permanent Magnet (BDCPM) motors. These are briefly described in Section (3.3).

3.1 Problem Features and Solution Techniques

The primary features of the problem posed in Eq. (1)are 1) the non-availability of a well-defined functional form for the objective function, 2) the design variables are discrete-continuous and the acceptability constraints are often the results of simulations, and 3) the optimization problem exists in a space populated by existing catalog designs - this feature may be used to greatly simplify the formulation. We now discuss these features in greater detail.

The product cost function in Eq. (1) is rarely available in a closed-form. Much of the recent work in cost estimation for customization deals with approximate methods that give a rough estimate of the cost of introducing variety in a product line (Martin (1996)). For the purpose of our optimization model, however, we require a functional form for the product cost that is accurate and can be generated in a timely fashion. There are several available cost structures and cost modeling methods that could be used and these are reviewed in Section (5) from the perspective of their applicability to customization. We select a generation-based structure and use techniques that are regression-based in our development of the product cost function. The 'material' cost component of the product cost can generally be obtained analytically; however, expressions to evaluate the 'production' cost are not readily available. An important contribution of this paper is the construction of analytical expressions for the 'production' cost component. We use the principles of geometric similarity and the available manufacturing cost data of standard catalog designs to obtain analytical expressions for the production cost. Section (5) describes the methodology in greater detail and develops the product cost function of an electric motor manufacturer from available catalog motors' cost data. The product cost function development is one of the aspects in which the customization problem is catalog-based.

The design variables of the non-linear program formulation of the customization problem are discrete-valued. They basically represent the set of available component parts (that are used in the standard catalog designs) which can be configured to obtain the final product design. The discreteness of the variables precludes the application of gradient-based optimization methods. Customization often needs to be applied to products whose performance variables are dynamic. The constraints of the customization problem can thus include simulations to determine the operating conditions of the product and simulations are computationally expensive. This, coupled with the non-linearities of the constraints in general, poses problems for discrete optimization methods like, for instance, branch and bound methods. We use genetic algorithms (GAs) as the preferred optimization technique to solve the customization problem. The applicability of genetic algorithms to customization problems has been well-studied by Carlson (1996).

The customization problem may be simplified by identifying a standard 'base' design from the catalog products that 'best' satisfies the design specifications and fixing some of the design variables of Eq. (1) at the corresponding parameter values of this standard 'base' design (this design is a catalog design and is thus completely instantiated). We note that the standard 'base' design doesn't satisfy all the design specifications—indeed, this is the reason why we are developing a customization methodology. Abstracting features from the standard 'base' design would reduce the dimensionality of the customization problem and would thus offer a quicker solution and correspondingly, savings in the product development time. The issues to be addressed in this context are 1) How does one select the 'best' standard 'base' design given multiple design specifications that none of the existing catalog designs satisfy ? and 2) How does one select the features (or design parameters) of this standard design that are to be used in the design of the customized product ?

A variant of the first question, namely the selection of a catalog design that meets all design specifications (or catalog selection problem), has been widely addressed in design research (Bradley (1993, 1994)). We, however, have a situation where none of the existing catalog designs are feasible for the given design specifications. Also, intrinsic to our problem, is the notion of minimum cost and we shall use this to guide our search for the standard 'base' design. We shall estimate the minimum cost of a product given multiple design specifications using the technique of function-costing and select the nearest available catalog design (in the cost sense) as the standard 'base' design. Function-costing is a cost-estimation hypothesis that estimates the cost of a product from its primary function or performance measure. The origins of this hypothesis, its underlying assumptions and the range of its validity are explained in greater detail in Section (5). Thus, given multiple design specifications, we can identify a primary specification and obtain an estimate of the product cost using function-costing. The standard 'base' design may then be identified as the catalog design closest in cost to this estimate. It is interesting to note that the function-cost hypothesis is global in nature and can thus be applied by different manufacturers to their customization attempts.

The issue as to what feature of the standard 'base' design to abstract into the customization problem depends on the particular form of the product cost function and thus varies with manufacturer. It relates to the design variables that have the maximum impact in determining the function-cost estimate from the primary design specification. This can be determined only by a detailed analysis of the product cost structure and model function and is domain-specific. In Section (6), we provide examples that suggest the parameters of standard 'base' designs that may be used in the customization of electrical motors by a particular manufacturer given multiple design specifications.

3.2 A Framework for Customization

The preceding discussion is summarized in Fig. (1). The manufacturing infrastructure and the design specifications are imposed on the product description to obtain a particular customization model. This model may be simplified by abstracting features from a standard base design identified from the primary design specification. A product family cost function is also developed from available cost and manufacturing knowledge. Finally, a genetic algorithm is used to solve the resulting optimization problem and obtain the final customized design and its corresponding cost.

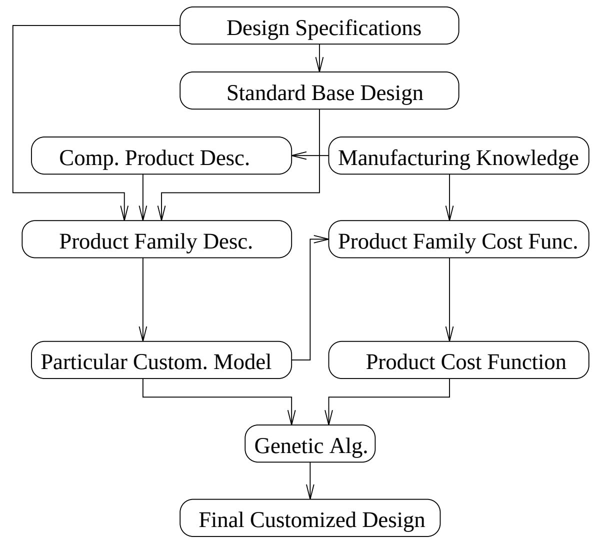


Figure 1. A Framework for Customization

3.3 Domain of Application

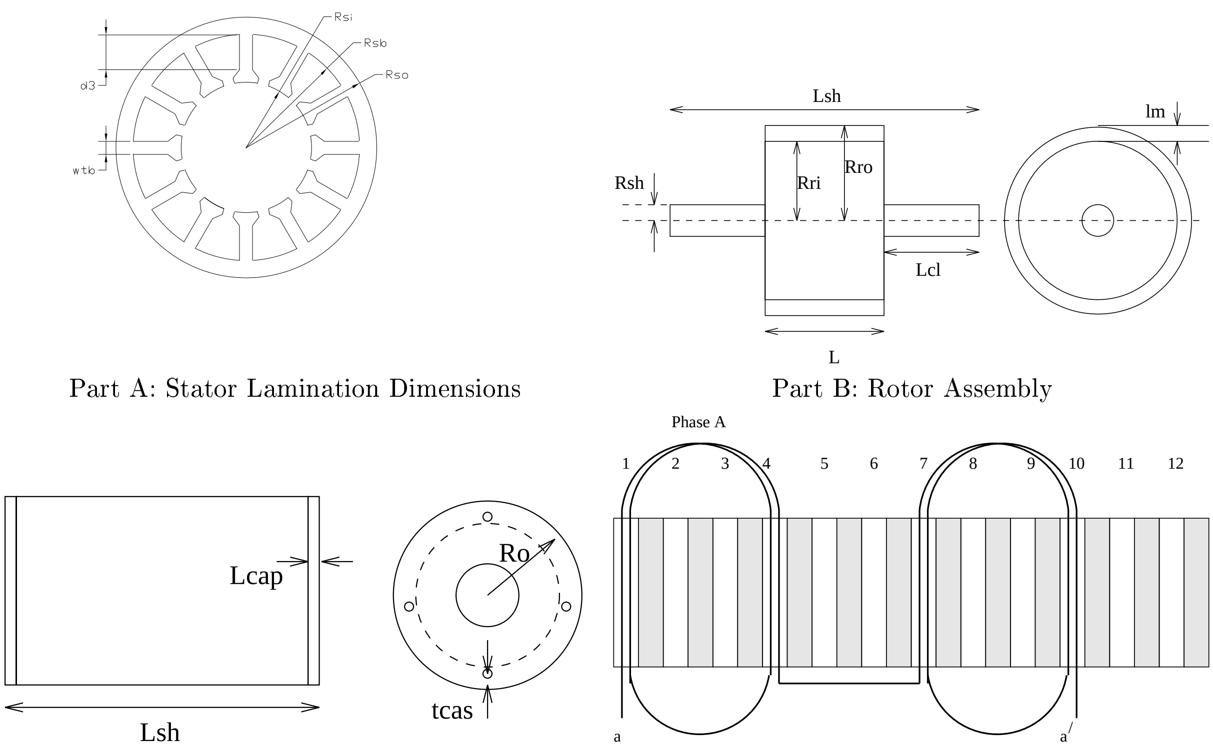
The domain of application for the customization methodology being developed is Brushless D.C. Permanent Magnet (BDCPM) motors. With the advances in permanent-magnet and power-electronic technology, BDCPM motors are fast gaining in popularity as cheap energy-efficient motors. Hendershot (1994) provides a good review on the theory and design of BDCPM motors. The motor essentially comprises an outer stator assembly (windings on a frame) and an inner rotor assembly (magnets mounted on a rotor). Several variants of this basic structure exist - Section (4) develops the mathematical model for the motor family considered in this paper.

4 BDCPMMS - MODEL DEVELOPMENT

The derivation of the mathematical model of the BDCPM motor is terse in this section (for a comprehensive exposition of the model development, the reader is refered to Chidambaram (1997a,b)).

Figure (2) summarizes the features of the 12 slot - 4 pole BDCPMM (we consider 24 slot - 4 pole machine in this paper). Part A shows a typical lamination for the 12 slot - 4 pole machine and its defining dimensions. The laminations have thickness $t = 5.8 \times 10^{-4}$ m so that the frame length $L = 5.8 \times 10^{-4} n_l$ m where n_l is the number of laminations. The laminations (and the motor frame) have $N_s = 24$ slots.

Figure 2. Features of BDCPM Motor Construction



Part A: Stator Lamination Dimensions

Part B: Rotor Assembly

Part C: Outer Casing of the Motor

Part D: A Typical Winding Pattern

Three lamination types, namely 'X', 'Y' and 'Z', are used in the frame construction of the BDCPM motor family. The semantic variable L_{type} identifies the lamination type used. The defining dimensions of these laminations are summarized in Table (1). The lamination types and the frame lengths for the eight motors comprising the BDCPM motor family are summarized in Table (2).

Table 1. Lamination Descriptors of the BDCPM Motor Family

	R_{si} (mm.)	d_3 (mm.)	w_{tb} (mm.)	w_{bi} (mm.)
$L_{type} = X$	21.90	12.0	2.39	5.23
$L_{type} = Y$	22.22	15.1	2.39	5.23
$L_{type} = Z$	25.40	15.1	2.80	5.50

The stator frame is wound with a single-layer lap winding with each coil containing N turns. Each coil encircles six stator teeth. Part D of Fig. (2) shows one phase of the winding pattern for the 12 slot - 4 pole machine. The phases may be connected in a Y or Δ configuration and the coils may be connected in series ($a = 1$) or parallel ($a = 2$). The stator teeth and slots have been shown in a linear fashion in this figure. The wire gage used in the windings is characterized by its area A_{wire}.

Table 2. Frame Descriptors of the BDCPM Motor Family

	M1	M2	M3	M4	M5	M6	M7	M8
L_{type}	X	Y	X	Z	Y	Y	Z	Z
L (cm.)	2.54	2.54	5.08	2.54	5.08	7.62	5.08	7.62

The wound stator is enclosed in a tubular shell. Part C of Fig. (2) shows two views of the casing with the tubular shell and end-caps. Part B of the figure shows the rotor assembly; a ring-magnet bonded onto a stepped shaft that fits into the bore of the stator frame assembly. The total length of the motor is L_{sh}. We observe that $L_{sh} = L + 2L_{cl}$. Here, the side-clearance L_{cl} is given by $L_{cl} = \{4.215, 4.265, 4.775\} \times 10^{-2}$m. $\cong L_{type} = \{X, Y, Z\}$.

Based on the preceding discussion, the design variables within this manufacturer's infrastructure along with their permissible ranges are now summarized.

$$n_l \in \{44,45,...,132\},\ \ L_{type} \in \{X,Y,Z\},\ \ a \in \{1,2\},$$
$$N \in \{20,21,...,80\},\ \ M_{ph} \in \{Y,\Delta\},\ \ A_{wire} \in \{16,16.5,...,24\} \quad (2)$$

We now develop the design constraints for the optimization formulation.

The lamination slot area A_s simplifies to $A_s = d_3[\frac{\pi}{12}(R_{si} + \frac{d_3}{2}) - wtb]$. The damping coefficient D and the hysteresis loss coefficient T_h for the frame are given by $D = 7.243\times10^{-4}\{\pi(2R_{so}(w_{bi}+d_3) - (w_{bi}+d_3)^2) - 24A_s\}$ and $T_h = 0.133\{\pi(2R_{so}(w_{bi}+d_3) - (w_{bi}+d_3)^2) - 24A_s\}$. The total length of wire L_{wire} used in the windings is obtained as $L_{wire} = 24N[5.8\times10^{-4}n_l + \frac{\pi}{2}\{w_{tb} + \frac{5\pi}{12}(R_{si} + \frac{d_3}{2})\}]$ so that the terminal resistance R is calculated as $R = 1.72\times10^{-8}(\frac{KC_{res}}{a})(\frac{L_{wire}}{12A_{wire}})$ where $K = \{4,2\} \cong a = \{1,2\}$ and $C_{res} = \{2,\frac{2}{3}\} \cong M_{ph} = \{Y,\Delta\}$. The expression for the thermal resistance (determined by the casing geometry) plays a key role in determining the continuous operating conditions of the motor, and is obtained as $R_{th} = \frac{1}{\{\frac{8.01}{(R_{si}+d_3+w_{bi}+0.002)}+4.8\}A_{cas}}$ where the surface area of the casing $A_{cas} = 2\pi\{(R_{si}+d_3+w_{bi}+0.002)^2 + (R_{si}+d_3+w_{bi}+0.002)(5.8\times10^{-4}n_l + 2L_{cl} + 5.08\times10^{-3})\}$. The torque constant k_t is obtained as $k_t = C_{tor}\frac{44.5\times10^{-4}NR_{si}n_l}{a}$ where $C_{tor} = \{\frac{2}{3},\frac{1}{3}\} \cong M_{ph} = \{Y,\Delta\}$.

Now, given the requirement for an operating torque of T_d at the operating speed ω_d, the torque that must be developed by the motor $T_{req} = T_d + D\omega_d + T_h$ (accounting for frictional losses). The current in the winding in order that the motor develop T_{req} is thus given by $I = \frac{T_{req}}{k_t}$ or $I = \frac{aT_{req}}{44.5\times10^{-4}NR_{si}n_lC_{tor}}$. Temperature considerations provide a bound on the operation of the motor - this constraint may be expressed as

$$\{\frac{\frac{68}{R_{th}} - D{\omega_d}^2 - T_h\omega_d}{1.72\times10^{-8}(\frac{KC_{res}}{a})(\frac{L_{wire}}{12A_{wire}})}\}^{0.5} \geq \frac{aT_{req}}{44.5\times10^{-4}NR_{si}n_lC_{tor}} \quad (3)$$

The limiting case of this inequality also helps identify the operating points corresponding to maximum continuous output power, namely ω^*_{cont} and T^*_{cont}. These points are obtained, using calculus, as

$$T^*_{cont} = k_t\{\frac{\frac{168}{R_{th}} - D{\omega^*_{cont}}^2 - T_h\omega^*_{cont}}{R}\}^{0.5} \text{ and}$$
$$\omega^*_{cont} = \frac{-3T_h}{8D} + \frac{\sqrt{9T_h^2 + \frac{1088D}{R_{th}}}}{8D} \quad (4)$$

The role played by these points is as follows: We shall assume that implicit in the requirement for an operating torque of T_d at the operating speed ω_d, is the requirement that the operating point be at maximum efficiency. Thus, we have $T_{req} = T^*_{cont}$ and $\omega_d = \omega^*_{cont}$.

The power supply for continuous operation (based on the supply voltage $V_d \geq IR + k_t\omega_d$) simplifies to

$$3.21\times10^{-7}\frac{T_{req}KC_{res}L_{wire}}{C_{tor}A_{wire}NR_{si}n_l} + C_{tor}\frac{44.5\times10^{-4}NR_{si}n_l}{a}\omega_d \leq V_d \quad (5)$$

An empirical winding constraint (that prevents magnetic saturation and demagnetization) used by the manufacturer of this motor family is $A_{wire}N \leq \{150,240,280\}\times10^{-7} \cong L_{type} = \{X,Y,Z\}$. We now develop the product cost function for the BDCPMM family.

5 DEVELOPMENT OF THE MANUFACTURING COST MODEL

Cost analysis is defined as the process of the systematic breakdown of product cost into various cost structures, depending on the sources from which they arise. A cost structure is described by the cost of components and the relationships between the components comprising the product. The component and component-relationship costs may be estimated by a variety of cost-modeling methods. We identify the cost structures and costing methods best suited to customization. The selection is driven by the following requirements on the functional form of the cost: 1) accuracy of the estimate and 2) generation of the estimate in a timely fashion. Based on these requirements, we select a generation-based and a function-based structure, and use techniques that are regression-based and similarity-based in our development of the product cost function for the BDCPMM family.

Section (5.1) reviews commonly used cost structures and methods. The rationale for our selection of the structures and methods is developed. In Section (5.2), a framework for cost analysis in customization is presented. This framework is applied to develop the product cost function of the BDCPMM family is Section (5.3).

5.1 Typical Cost Structures and Methods

Cost structures break down the product cost according to one of several criteria: type of cost, parts, functions, production processes, etc. Sheldon (1991) classifies cost structures into the following types: a) organizational—based on departments and units of the manufacturer, b) generational—based on elements and features of the product, c) functional—based on the function of the product and d) work/activity—based on the production processes.

Of these, the generational and functional structure best address the requirements of customization.

In the generational structure, the product is decomposed into sub-assemblies which are broken down into their base constituent components or primitives. The costs associated with these primitives and the costs of assembling them are summed to obtain the total product cost. Winchell (1989) provides a good review of the use of the generational structure. The generational structure allows the identification of similar primitives so that the cost of a new product similar to one whose cost structure is known may be easily deduced based on comparisons. This is precisely the requirement of the catalog-based customization paradigm and we use the generational structure as the basis for representing cost data. Section (5.3) demonstrates its use on the BDCPM motor family.

Most design practices start from product functionality. A function-based structure can be used by designers to obtain a rough estimate of product cost at the early stages of design. The approximate nature of the estimates makes function-based structure unsuitable for the cost function development of catalog-based customization. The structure however has the advantage of generating quick estimates and we would like to use this feature to simplify the optimization formulation of customization. Indeed, function-based structure forms the cornerstone of the discussion in Section (3) towards the identification of a standard 'base' design and the abstraction of features from it into the custom design. The examples of BDCPM motor redesign, presented in Section (6), explain the application of function-based structure in greater detail.

A commonly used estimation technique to determine the constituent costs of the functions is function-costing and we now provide an overview of the technique. Function-costing was introduced by French (1971). It is a hypothesis that helps estimate the costs of a product directly from its specifications. French (1993) and Pahl (1984) have applied function-costing to preliminary cost estimation at the conceptual stage of design. Function-costing proceeds on the surmise, that for a class of products, the principal cost-driver is the primary performance function of the product and that the relationship between cost and this performance function can be captured in a mathematical relation (based on regression analyses). It is based on the following assumptions: a) the technology is mature, or not rapidly developing, b) the market is free of monopolies and c) the market is large.

Having looked at cost structures, we now review cost modeling methods. The commonly used cost models during design are based on operations, weight, material, throughput parameters, regression analysis and similarity laws. Hundal (1993) provides a good review of these cost estimation models. Operation-based costing and activity-based costing are higher-level methods that are difficult to use to model customization.

Weight-based calculations for estimating manufacturing costs are particularly suited for one-of-a kind products and for mass-produced items where only size-changes are made. The production costs per unit weight of similar products are assumed to be proportional. Customization typically involves significant changes in production costs besides material-cost changes and the proportionality assumption for unit production costs thus fails to hold. However, by developing analytical expressions that accurately model the weight of the product or its components, the weight-based method could be used to develop precise cost estimates of the material costs of customization. The weight-based method has been used to develop the material costs of the components comprising BDCPM motors in Section (5.3).

Regression-based models attempt to relate the manufacturing cost to the product characteristics through statistical analyses. The premise here is that the cost can be estimated based on those product characteristics that are only analogous, and not wholly causative, to final cost. Stewart (1987) provides a good overview of regression-based parametric cost-estimation models. A functional form that is experience-based (in terms of relevant product characteristics) is first assumed for the cost-estimating relation or CER. The parameters that define the functional form are then calculated by minimizing the square of the errors between the data points, i.e., available historical cost/product characteristics information and the costs estimated by the CER. Stratification of CERs to classify data-points into families for more meaningful results is commonly implemented. Regression analysis forms the basis of the product cost function development for customization. It is used to estimate the production cost component from the existing data on the production costs of standard components. Similarity principles (described in the next paragraph) help in selecting the particular functional form of the CER as well as the relevant product characteristics that regression analysis requires. The application of CERS and stratified CERs to the cost function development of the production cost components of BDCPM motors is shown in Section (5.3). Regression analysis is also the preferred estimation method in the function-based structure that is used to simplify the customization problem by identifying the standard base design.

Similarity principles have been widely used in predicting the costs of products made in size ranges. Hundal (1993) provides an overview of the method. If a product has been made to a particular size and its cost is known, then the costs of other designs that are structurally 'similar' to the product but are of different sizes may be estimated using similarity methods. The underlying premise here is that the linear dimension ratio of two products is the primary parameter in relating their costs. The linear dimension ratio ϕ_l for say two products 'X' and 'Y' is given by $\phi_l = \frac{l_y}{l_x}$ where l_y and l_x are the 'principal' dimensions of the products. Thus, if the manufacturing cost of product 'X' is $C_{x_{pr}}$, then the manufacturing cost $C_{y_{pr}}$ of product 'Y' is estimated by $C_{y_{pr}} = C_{x_{pr}} {\phi_l}^p$. The exponent 'p' usually ranges from 1.8 to 2.2 consistent with the assumption that the manufacturing costs are determined by the surface area (approximate square of the linear dimension ratio) of the material machined.

5.2 Cost Analyses for Customization

Based on the discussions in Sections (5.1), we summarize the cost structures and cost estimating methods that are best suited for the cost analyses of catalog-based customization in Figure (3).

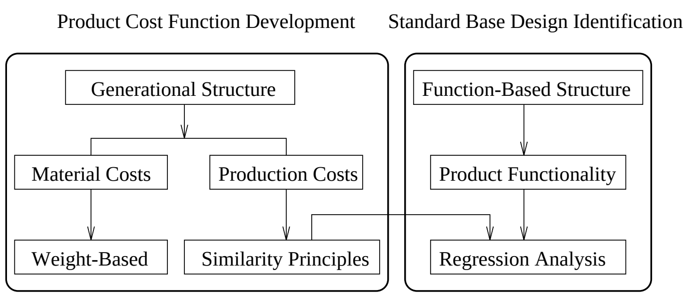


Figure 3. Cost Analysis for Customization

The generational structure is used to develop the product cost function. The material costs of the base constituent components or primitives of the product product may be computed analytically using weight-based estimation methods. The production costs associated with assembling the primitives are estimated by applying methods of similarity to the component parts of the product. The method suggests a power law for the estimation of costs. The exponents of the power law may be estimated by applying regression analyses to the data in existing standard catalog products. We observe that the similarity principle and regression analyses reinforce each other in accurately predicting the production costs associated with assembling the product. The goodness of regression analyses depends on the functional form assumed for the equation and the similarity method suggests a power law. The similarity method requires accurate values for the exponents which regression provides. In the next section, we apply these analyses tools to the cost function development of the BDCPM motor family.

The cost/performance data for the standard products in a catalog allow us to obtain the function-costing equation (in the function-based structure) using regression analysis. This equation helps identify a standard design to base the customization on. Given multiple and conflicting design specifications, if we can identify a primary specification, an estimate of the cost of the customized design may be obtained using function-costing. The standard product that is closest in cost to the estimate obtained can then be used as the standard base design. By comparing features of the standard base design obtained by function-costing with the features obtained by solving the optimization formulation of customization—for the specified primary performance measure—the features that have the maximum impact on determining product cost may be identified. Once this knowledge is available, these features may be abstracted into customization scenarios with multiple specifications, including the primary performance measure. This affords an a priori simplification of the optimization formulation to determine the cost and features of the customized design for multiple design specifications. The examples presented in Section (6) illustrate the use of function-costing for the standard base design identification and optimization formulation simplification for BDCPM motors with multiple design specifications.

5.3 Cost Function Development

The following discussion draws on prior work done by Chidambaram (1997a,b). Salient features have been reproduced to facilitate comprehension - the reader is referred to the earlier paper for a detailed discussion.

The cost structure tree for the BDCPM motor family is shown in Fig.(4).

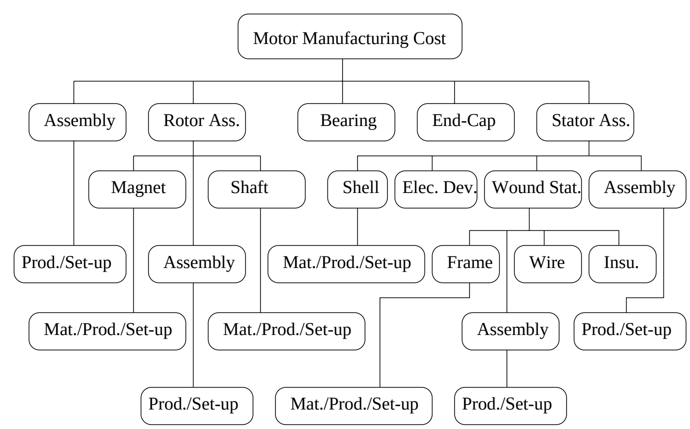


Figure 4. Cost Structure Tree for the BDCPM Motor Family

The material and production costs of the frame are summarized in Table (3) - the reader is refered to Chidambaram (1997a,b) for the other 15 (leaf) cost components of the tree. The total motor costs have also been shown. The machine set-up costs have been ignored (large production lot-sizes have allowed for amortization).

The material costs components of the component costs of the cost structure tree can be constructed analytically from the available cost data. For instance, by viewing the frame material cost $C_{fr_{mat}}(n_l)$ in the light of data presented in Table (2), we can deduce that $C_{fr_{mat}}(n_l)$ for a frame with n_l laminations is given by

$$C_{fr_{mat}}(n_l, L_{type}) = \{0.026, 0.028, 0.03\} n_l \cong L_{type} = \{X, Y, Z\} \tag{6}$$

The production costs components are approximated from the principle of similarity described in Section (5.1). For instance, let's now consider the frame production cost $C_{fr_{prod}}$. From Table (2), we observe that motors 'M1' and 'M3' are similar in their frame construction except for the frame length. Also, motors 'M2', 'M5' and 'M6' have identical lamination types and different frame lengths and motors 'M4', 'M7' and 'M8' are similarly related. The ratio of the frame-lengths is an obvious candidate for the similarity parameter ϕ_L. Figure (5) is a plot of the frame production cost $C_{fr_{prod}}$ versus the similarity parameter ϕ_L. Here, ϕ_L is the length of a particular motor frame normalized by the smallest motor frame length in that lamination type. Thus, for instance, $\phi_{L\,M5} = \frac{L_{M5}}{L_{M2}} = \frac{0.0508}{0.0254} = 2$ (we use data from Table (2) in this calculation). Cost-estimation relations have

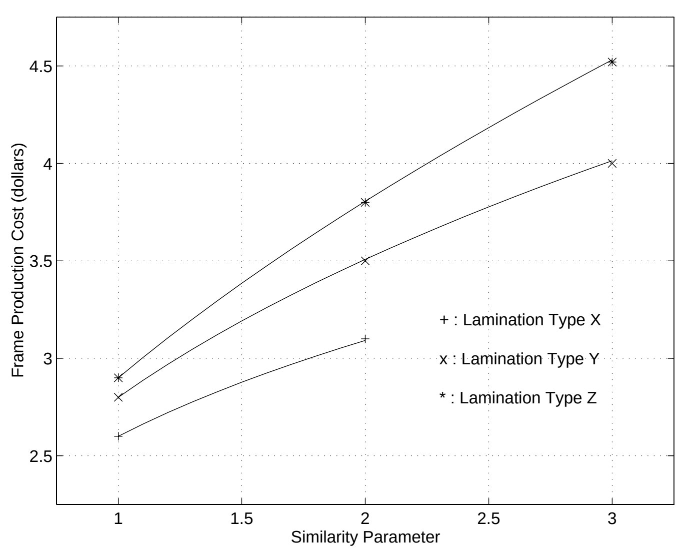


Figure 5. Frame Production Cost versus the Similarity Parameter

been fitted through the data points of Fig. (5). Assuming a power curve and stratifying the CERs by lamination type yields

$$C_{fr_{prod}}(n_l, L_{type}) = \left\{ \begin{array}{ll} 2.6(\frac{n_l}{44})^{0.25} & \text{for } L_{type} = X \\ 0.38 + 2.42(\frac{n_l}{44})^{0.37} & \text{for } L_{type} = Y \\ 1.07 + 1.83(\frac{n_l}{44})^{0.58} & \text{for } L_{type} = Z \end{array} \right\} \tag{7}$$

Following this approach for the other components of the cost structure tree, the total motor cost $C_{tot}(n_l, L_{type}, A_{wire}, N, M_{ph}, a)$ is obtained as follows (see Chidambaram (1997 a,b) for details):

$$
\begin{array}{l}
C_{tot}(n_l, L_{type}, A_{wire}, N, M_{ph}, a) = \\
\left\{ \begin{array}{ll} 2.6(\frac{n_l}{44})^{0.25} & \text{for } L_{type} = X \\ 0.38 + 2.42(\frac{n_l}{44})^{0.37} & \text{for } L_{type} = Y \\ 1.07 + 1.83(\frac{n_l}{44})^{0.58} & \text{for } L_{type} = Z \end{array} \right\} \\
+[\{0.026, 0.028, 0.03\} n_l \cong L_{type} = \{X, Y, Z\}] + \frac{n_l}{44} \\
+9.80 \times 10^5 A_{wire} N [5.8 \times 10^{-4} n_l + \frac{\pi}{2}\{w_{tb} + \frac{5\pi}{12}(R_{si} + \frac{d_3}{2})\}] \\
+0.3035 + 0.876 N [5.8 \times 10^{-4} n_l + \frac{\pi}{2}\{w_{tb} + \frac{5\pi}{12}(R_{si} + \frac{d_3}{2})\}] \\
+\pi[\{31.2(R_{si} + d_3 + w_{bi}) + 0.0312\}\{L_{sh} - 5.08 \times 10^{-3}\}] \\
+ \left\{ \begin{array}{ll} 0.7(\frac{5.8\times10^{-4} n_l + 0.0792}{0.1047})^{1.21} & \text{for } L_{type} = X \\ 0.54 + 0.26(\frac{5.8\times10^{-4} n_l + 0.0802}{0.1057})^{3.74} & \text{for } L_{type} = Y \\ 0.58 + 0.32(\frac{5.8\times10^{-4} n_l + 0.0905}{0.1160})^{4.23} & \text{for } L_{type} = Z \end{array} \right\} + 9 \\
+ \left\{ \begin{array}{ll} 1.3(\frac{5.8\times10^{-4} n_l + 0.0792}{0.1047})^{0.38} (\frac{n_l}{44})^{0.18} & \text{for } L_{type} = X \\ 1.6(\frac{5.8\times10^{-4} n_l + 0.0802}{0.1057})^{0.38} (\frac{n_l}{44})^{0.40} & \text{for } L_{type} = Y \\ 1.8(\frac{5.8\times10^{-4} n_l + 0.0905}{0.1160})^{0.41} (\frac{n_l}{44})^{0.52} & \text{for } L_{type} = Z \end{array} \right\} \\
+(1.536 R_{si} - 6.26 \times 10^{-3}) n_l + (2.014 R_{si} - 8.21 \times 10^{-3}) n_l \\
+\pi\{29.4(R_{si} - 7.25 \times 10^{-3})^2 n_l + 1.014 \times 10^5 {R_{sh}}^2 L_{cl}\} \\
+0.1862 + 5.31\pi \times 10^4 [{R_{st}}^2 L_{st} + 2{R_{sh}}^2 L_{cl} \\
-\{5.8 \times 10^4 (R_{si} - 7.25 \times 10^{-3})^2 n_l\}] + 0.01 \\
+0.1473\pi(R_{si} - 7.25 \times 10^{-3}) n_l + \left\{ \begin{array}{l} 1.2 \text{ for } T_p \leq 3.5 \\ 1.6 \text{ for } T_p > 3.5 \end{array} \right\} \\
+[\{0.5, 0.55, 0.60\} \cong L_{type} = \{X, Y, Z\}] \\
+ \left\{ \begin{array}{ll} 3.2(\frac{5.8\times10^{-4} n_l + 0.0792}{0.1047})^{-1.92} (\frac{n_l}{44})^{0.92} & \text{for } L_{type} = X \\ 3.4(\frac{5.8\times10^{-4} n_l + 0.0802}{0.1057})^{-1.92} (\frac{n_l}{44})^{1.06} & \text{for } L_{type} = Y \\ 3.7(\frac{5.8\times10^{-4} n_l + 0.0905}{0.1160})^{-3.25} (\frac{n_l}{44})^{1.60} & \text{for } L_{type} = Z \end{array} \right\}
\end{array} \tag{8}
$$

6 SOME ILLUSTRATIVE EXAMPLES

In this section, we apply the customization methodology developed to obtain optimal custom-designs (from a cost perspective) from the standard designs of the BDCPM

Table 3. Component Costs of the BDCPM Motor Family

	M1	M2	M3	M4	M5	M6	M7	M8
Frame[Matl.]	1.06	1.16	2.11	1.34	2.31	3.47	2.68	4.02
Frame[Prod.]	2.60	2.80	3.10	2.90	3.50	4.00	3.80	4.52
Ref. Chidambaram(1997)	...	...	...	...	...	...	...	...
Total Cost	35.93	40.94	43.58	44.63	47.76	55.10	54.68	63.80

motor family for different sets of customer design specifications. We addressed the issue of customization problem-simplification by the identification of a standard 'base' design and the abstraction of features from it into the custom design in Section (3). Function-costing formed the basis of the proposed simplification and the examples presented in this section provide evidence towards validating this hypothesis for BDCPM motors. The primary functional requirement for fractional horse-power BDCPM motors is to provide a continuous operating torque at a specified speed and the two examples presented are based on these. The first example has only 'the specified torque at the specified speed' requirement while the second example has an additional specification regarding the available power supply. Section (6.1) describes the first example while Section (6.2) analyzes the second customization scenario.

6.1 Customization for a Specified Operating Point

We observed in Section (4) that the specified operating point (T_d, ω_d) needs to map to the maximum continuous power coordinates on the torque-speed curve for maximum efficiency of operation and our optimization formulation will reflect this. The validation of the function-costing hypothesis for this composite power requirement is effected by comparing the cost estimates obtained through function-costing to the cost estimates obtained from the optimization formulations for different values of the requirement. Section (6.1.1) develops a cost estimate based on the optimization formulation while Section (6.1.2) uses function-costing to develop the estimate. Section (6.1.3) compares the cost estimates and validates the function-costing hypothesis for the given requirements.

6.1.1 Cost Estimate for Specified Operating Points from Optimization. The optimization problem to calculate the minimum manufacturing cost to realize a specified operating point (T_d, ω_d) is obtained as

$$
\begin{array}{ll}
\text{Minimize} & C_{tot}(n_l, L_{type}, A_{wire}, N, M_{ph}) \\
\text{w. r. to} & \{n_l, L_{type}, A_{wire}, N, M_{ph}, a\} \\
\text{subject to} &
\end{array}
$$

$$
\begin{aligned}
& h_1 : \omega^*_{cont} = \frac{-3T_h}{8D} + \frac{\sqrt{9T_h^2 + \frac{1088D}{R_{th}}}}{8D} \\
& h_2 : T^*_{cont} = k_t \{ \frac{\frac{168}{R_{th}} - D{\omega^*_{cont}}^2 - T_h \omega^*_{cont}}{R} \}^{0.5} \\
& h_3 : D = 0.000724[\pi\{2(R_{si} + d_3 + w_{bi})(w_{bi} + d_3) - \\
& \qquad (w_{bi} + d_3)^2\} - 24A_s] \\
& h_4 : T_h = 0.133[\pi\{2(R_{si} + d_3 + w_{bi})(w_{bi} + d_3) - \\
& \qquad (w_{bi} + d_3)^2\} - 24A_s] \\
& h_5 : A_s = d_3[\frac{\pi}{12}(R_{si} + \frac{d_3}{2}) - wtb] \\
& h_6 : R_{th} = \frac{1}{\{\frac{8.01}{(R_{si} + d_3 + w_{bi} + 0.002)} + 4.8\} A_{cas}} \\
& h_7 : A_{cas} = 2\pi\{(R_{si} + d_3 + w_{bi} + 0.002)^2 + (R_{si} + d_3 + w_{bi} + \\
& \qquad 0.002)(5.8 \times 10^{-4} n_l + 2L_{cl} + 5.08 \times 10^{-3})\} \\
& h_8 : k_t = C_{tor} \frac{44.5 N R_{si} n_l}{10^{-4} a} \quad h_9 : C_{tor} = \{\frac{2}{3}, \frac{1}{3}\} \cong M_{ph} = \{Y, \Delta\} \\
& g_1 : 3.21 \times 10^{-7} \frac{T_{req} K C_{res} L_{wire}}{C_{tor} A_{wire} N R_{si} n_l} + C_{tor} \frac{44.5 N R_{si} n_l}{10^{-4} a} \omega_d \leq 80 \\
& h_{10} : L_{wire} = 24N[5.8 \times 10^{-4} n_l + \frac{\pi}{2}\{w_{tb} + \frac{5\pi}{12}(R_{si} + \frac{d_3}{2})\}] \\
& h_{11} : K = \{4, 2\} \cong a = \{1, 2\} \\
& h_{12} : C_{res} = \{2, \frac{2}{3}\} \cong M_{ph} = \{Y, \Delta\} \\
& h_{13} : T_d + D\omega_d + T_h - T^*_{cont} \approx 0 \quad h_{14} : \omega_d - \omega^*_{cont} \approx 0 \\
& g_2 : A_{wire} N \leq \{150, 240, 280\} \times 10^{-7} \cong L_{type} = \{X, Y, Z\}
\end{aligned}
\qquad (9)
$$

The constraints for the problem were derived in Section (4). We use genetic algorithms to solve Eq. (9) for different operating points (T_d, ω_d) with T_d varying from 0.35 to 1.45 N-m and ω_d varying from 400 to 650 rad./sec. The constraints are incorporated using penalty methods. The parameters for the genetic algorithm are as follow: population size = 40; number of generations = 40; selection pressure = 1.3; cross-over rate = 0.7; and mutation rate = 0.035. The minimum cost solution for the operating point (T_d, ω_d) = (1.45, 400) (fitness function taken as $F = C_{tot} + h_{14}^2 + 500h_{13}^2 + 100{g_2}^2$) is obtained to be C^*_{tot} = \$62.75. The results for other operating points are summarized in Table (4).

6.1.2 Function-Costing Estimate for Specified Operating Points. We now use the function-costing method to estimate the costs for the specified operating points. We recognize that we could define a continuous power output P_d given by $P_d = T_d\omega_d$ and use this as the primary performance measure for the function-costing method.

Figure (6) is a plot of the cost C versus the maximum continuous output power $P_d^*(=T_d^*\omega_{cont}^*)$ for the eight motors comprising the motor family. We recall that the expressions for ω_{cont}^* and T_{cont}^* were stated in Eq. (4).

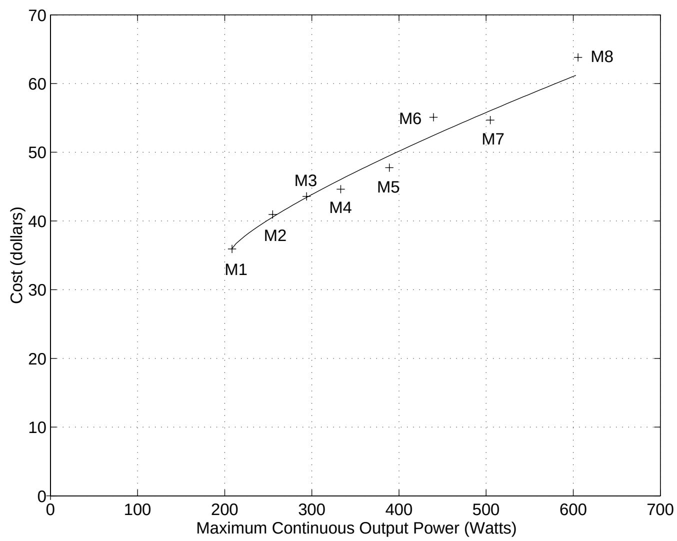


Figure 6. Cost versus Maximum Continuous Power for the BDCPM Motors

The '+' marks in the figure are the data points $(C_i, P_{d_i}^*)$ for the eight motors where the subscript i refers to the motor number. By fitting a curve through the data points the CER for the continuous power output is obtained as

$$C_{est}(P_d) = 35.92 + 0.217(P_d - 208)^{0.7957} \quad (10)$$

with the coefficient of regression $R = 0.92$. Thus, given a specified operating point (T_d, ω_d), or equivalently the continuous power output P_d, the cost of the motor may be estimated using Eq. (10).

6.1.3 Comparison of Cost Estimates for Specified Operating Points.

Table (4) compares the cost estimates obtained from the optimization formulation C_{tot}^* to the function-costing estimates C_{est} for a set of operating points. The operating points have been chosen so that the corresponding continuous output power values uniformly span the available maximum continuous power output values that the BDCPM motor family provide. The costs obtained are observed to be similar. Thus, function-costing may be used to obtain a cost estimate given a specified torque at a specified speed and the requirement that this operating point corresponds to the maximum continuous power operating point.

Table 4. Comparison of Cost Estimates for Operating Point Specifications

(T_d, ω_d)	C_{tot}^*	L_{type}	P_d	C_{est}	I	$L_{type} \cong I$
(0.35,650)	36.12	X	227	38.22	M1	X
(0.6,500)	42.86	X	300	43.84	M3	X
(0.8,450)	46.75	Z	360	47.73	M4,M5	Z,Y
(0.7,600)	50.30	Y	420	51.31	M5,M6	Y
(1.1,400)	53.12	Y	440	52.46	M6	Y
(1.0,500)	56.54	Z	500	55.78	M7	Z
(1.2,450)	57.20	Z	540	57.92	M7	Z
(1.45,400)	62.75	Z	580	60.00	M8	Z

Table (4) also identifies the standard motor I that is closest to realizing the specified torque at a specified speed (or a specified continuous output power) using

$$I = \arg\{\min_{i=1}^{8}(|C_i - C_{est}(P_d)|\} \quad (11)$$

For instance, if $P_d = 580$ W, $C_{est}(P_d) = \$60.00$, and the 'closest' motor is identified as 'M8' from $I = \arg\{\min_{i=1}^{8}(|\{35.93, 40.94, 43.58, 44.63, 47.76, 55.1, 54.68, 63.8\} - 60.00|\}$. The lamination type L_{type} corresponding to this motor is compared to the L_{type} obtained from the optimization formulation. We observe that the the L_{type} obtained from the optimization formulation is a subset of the L_{type} of the closest motor. This suggests that the lamination type is the critical factor in determining the cost of a motor for a specified operating point.

Thus, given a specified operating point that needs to be realized at maximum efficiency, the standard motor that is closest in cost to the custom-design may be identified using function-costing (based on the continuous output power), and the lamination type of this motor may be used as the lamination type of the custom-design, thereby simplifying its optimization formulation.

We now solve a customization scenario where, in addition to a specified operating point, there is a constraint on the available power supply.

6.2 Specified Operating Point and Power Supply Constraint

This example illustrates how function-costing and feature- abstraction (from a standard base design) may be used to simplify the optimization formulation of customization with multiple requirements.

In the examples discussed so far, the maximum supply voltage available $V_d = 80$ volts and the required voltage (regulated by a variable power supply drive) is always less than this, so that the power supply constraint described in Eq. (5) is inactive. We now consider a customization situation where the operating point $(T_d, \omega_d) = (1.5, 395)$ and the power supply available is a battery supplying a voltage $V_d = 32$ volts. None of the standard motors can operate at $V_d = 32$ volts and realize the specified operating point—customization is necessitated. We have $P_d = T_d \times \omega_d = 592.5$ Watts so that an approximate cost of the custom-design is estimated as $C_{est}(P_d = 600) = \$60.80$ using Eq. (10). The standard motor closest in cost to this estimate of the customized motor is M8 and the lamination type L_{type} corresponding to this motor is Z. The simplified problem is obtained as

$$
\begin{array}{ll}
\text{Minimize} & C_{tot}(n_l, A_{wire}, N, M_{ph}) \\
\text{w. r. to} & \{n_l, A_{wire}, N, M_{ph}, a\} \\
\text{subject to} & \\
\end{array}
$$

$$
\begin{aligned}
& h_1 : \omega^*_{cont} = \frac{-3T_h}{8D} + \frac{\sqrt{9T_h^2 + \frac{1088D}{R_{th}}}}{8D} \\
& h_2 : T^*_{cont} = k_t\left\{\frac{\frac{168}{R_{th}} - D{\omega^*_{cont}}^2 - T_h\omega^*_{cont}}{R}\right\}^{0.5} \\
& h_3 : D = 1.77 \times 10^{-6} n_l \quad h_4 : T_h = 3.27 \times 10^{-4} n_l \\
& h_5 : R_{th} = \frac{1}{171.67 A_{cas}} \\
& h_6 : A_{cas} = 2\pi\{2.3 \times 10^{-3} + 4.8 \times 10^{-2}(5.8 \times 10^{-4} n_l + 0.095)\} \\
& h_7 : k_t = C_{tor}\frac{11.31 N n_l}{10^{-5} a} \; ; h_8 : C_{tor} = \{\tfrac{2}{3}, \tfrac{1}{3}\} \cong M_{ph} = \{Y, \Delta\} \\
& h_9 : 1.26 \times 10^{-5} \frac{T_{req} K C_{res} L_{wire}}{C_{tor} A_{wire} N n_l} + C_{tor}\frac{11.31 \times 10^{-5} N n_l}{a}\omega_d = 32 \\
& h_{10} : L_{wire} = 24N[5.8 \times 10^{-4} n_l + 0.0721] \\
& h_{11} : K = \{4, 2\} \cong a = \{1, 2\} \\
& h_{12} : C_{res} = \{2, \tfrac{2}{3}\} \cong M_{ph} = \{Y, \Delta\} \\
& h_{13} : T_d + D\omega_d + T_h - T^*_{cont} \approx 0 \quad h_{14} : \omega_d - \omega^*_{cont} \approx 0 \\
& g_1 : A_{wire} N \leq 260 \times 10^{-7}
\end{aligned} \tag{12}
$$

Constraint h_9 models the power supply constraint. The other constraints have been obtained from the constraints of Eq. (9) after substituting $L_{type} = Z$. Using the genetic algorithm with the fitness function taken as $F = C_{tot} + 100h_9^2 + h_{14}^2 + 500h_{13}^2 + 100g_1^2$, we get the optimal cost of the customized motor ${C_{tot}}^* = \$61.53$. The optimal values of the design variables are obtained as $\{n_l^*, {A_{wire}}^*, N^*, {M_{ph}}^*, a^*\} = \{132, 17, 16, Y, 2\}$.

The customized motor realizes the specified torque of 1.5 N-m at the specified speed of 395 rad./sec with a supply voltage of 32 Volts. The constraint g_1 is active at the optimum. The design solution is similar to the standard M8 design except for variables A_{wire} and N. Also the product $A_{wire} \times N$ is the same for the standard and custom designs. The standard design is infeasible because it violates the power supply constraint and the customized design 'fixes' this with a winding change. Our solution for the customized design is consistent with an industry practice of changing the windings (while keeping $A_{wire}N$ constant) to accommodate non-standard supply voltages.

7 INSIGHTS OBTAINED AND DISCUSSION

The primary contribution of this paper is the development of a new method of mass customization, namely the customization around standard products or catalog-based customization. The method addresses the customization requirements of a class of products that are complex in configuration, multi-functional and structurally similar. We have formulated catalog-based customization as an optimization problem consistent with the manufacturer's desire of to minimize the cost of redesigning existing standard components to meet customer specifications.

We identified the generational structure as the preferred structure for the cost analysis in developing the objective function of this optimization problem. The cost-estimation methods that the generational structure uses to calculate its component costs are weight-based, similarity principles and regression analyses. The material cost components of the components are estimated by the weight-based estimation methods. The production costs associated with the assembly of the primitives are estimated by using similarity principles. The exponents of the power law suggested by the similarity principle may be accurately estimated by applying regression analyses to the production cost data of the existing standard catalog products. The product cost function may thus be developed and the resulting optimization problem (or customization model) solved using genetic algorithms.

Another cost structure that we have identified as useful to customization is the function-based structure which depends on product functionality. The cost/performance data for the standard products in a catalog allow us to obtain a cost-performance relation (also called function-costing) using the regression method of cost estimation. Besides obtaining a rough idea of the cost of customization, function-costing may be used to simplify the optimization formulation of catalog-based customization. Given multiple and conflicting design specifications, if we can identify a primary specification, an estimate of the cost of the customized design may be obtained using function-costing. The standard product that is closest in cost to the estimate obtained can then be used as the standard design upon which to base the customization. By comparing features of the standard base design obtained by function-costing with the features obtained by solving the optimization formulation of customization (for the specified primary performance measure), the features that have the maximum impact on determining product cost may be identified. These features may be abstracted into and used to simplify customization scenarios with multiple specifications (including the primary performance measure). Of course, the validity of function-costing needs to be first established and this is accomplished by comparing cost-estimates obtained by function-costing and from the optimization formulation.

From the perspective of the design of fractional horse-power brushless permanent magnet motors, this paper makes the following contributions. We have provided evidence supporting the function-costing hypothesis for fractional horse-power BDCPM motors with the primary function of providing a continuous operating torque at a specified speed. We have developed equations that capture the cost/performance relation for these motors. The equations developed are global and may be used to search different catalogs for potential candidates for customization. We have also shown that domain-specific knowledge about BD-CPM motor design can be abstracted by comparing the features of the closest motor (in the cost sense) identified by function-costing to the features obtained from the optimization formulations for the primary performance requirements. The common features obtained from this comparison are essentially the (manufacturer-specific) principle cost-drivers for the primary performance requirements. For the manufacturer considered in this study, we observed that the lamination type is the principal cost-driver for the requirement of continuous operating torque at a specified speed—similar insights may be obtained by applying catalog-based customization to other manufacturers of BD-CPM motors.

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