Proceedings of DETC 2006
2006 ASME Design Engineering Technical Conferences
Philadelphia, PA, USA, September 10–13, 2006

DETC2006-99289

TOWARDS A SUITE OF PROBLEMS FOR COMPARISON OF PRODUCT PLATFORM DESIGN METHODS: A PROPOSED CLASSIFICATION

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ABSTRACT

This paper presents the status of an ongoing project to develop a comprehensive suite of test problems suitable for comparing methods for scale-based product platform design. Despite a growing body of work in the area, there is no adequate set of testbed example problems for product platform design and benchmarking. A lack of consensus as to exactly what scale-based platform design entails has also hampered comparison of methods. In order to make a comprehensive test suite, we first need to define what different capabilities of platform design methods should be tested. To further this end, a classification scheme for example problems for scale-based platform design is presented. This simple taxonomy classifies example problems on the basis of two criteria: selection of platform architecture and incorporation of market demand.

A brief review of examples from the literature shows that the existing examples are useful to test only a few of the capabilities of platform design methods. A new extension of an existing example, the design of a family of universal electric motors, is presented to test capabilities not covered by the existing set. This extended example is the first in our suite of examples.

Keywords: product family, platform design, taxonomy, scale-based design

1 INTRODUCTION

Product platform design has received considerable attention lately as a strategy for achieving product variety while keeping costs low. The development of formal methods for product platform design has been a subject of considerable interest in the research community. References [1–10] are representative but by no means exhaustive.

While there are some generally accepted definitions in product platform design, such as the distinction between modular- and scale-based platforms [11], different methodologies often address different variants of the product platform design problem. Even within the relatively simple and structured subset of scale-based product platforms, there is still not complete agreement on what exactly comprises product platform design.

This variety in product platform design problems is echoed in the variety of test problems exercised in the literature. With the notable exception of the electric motor example first modified for product platform use by Simpson [1], there are no test problems in general use by researchers on product platform methods, and even the electric motor example does not consider all aspects of scale-based platform design, as will be shown later. In most cases, the examples found in the literature are intended to illustrate a proposed product platform approach, and each example fits the particular characteristics of that method. Unfortunately, due to the variety of approaches with different final objectives, many times it is not easy to see how to apply any other method than that proposed in the same paper to a test problem. This makes the task of comparing different methods difficult if not impossible.

There is a pressing need for a reliable testbed for product platform design and optimization, a useful set of test examples to facilitate comparison of different product platform design meth-

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ods. A testbed serves not only as a means of comparing different methods, but also as a means of clarifying the objectives of product family design in general. As a first step, this paper concentrates on the relatively tractable case of scale-based product platforms, and proposes a taxonomy for test problems for scale-based product platform design.

2 SCALE- AND MODULE-BASED PRODUCT PLATFORM DESIGN

Simpson [11] first drew the distinction between *module-based* product platform approaches, in which product variety is achieved by adding and subtracting different modules, and *scale-based* approaches, in which all product variants have the same parametric description and variety is achieved by scaling one or more parameters. Cost savings in module-based design are derived from the sharing of modules among product variants, whereas cost savings in scale-based design are derived from the sharing of variable values. Scale-based product platform design generally lends itself more easily to computational simulation, since all product variants are described by exactly the same variables and use the same computational approximation of performance. A comprehensive testbed of examples would cover both module- and scale-based approaches. The research presented here is concerned with scale-based design, as a first step, since the common parametric description of all products in scale-based design simplifies the statement of scale-based problems as optimization problems.

A general scale-based platform design problem may be stated: "given a parametric description of a product, select design variable values for a number of different product variants to optimize some measure of performance over some range of requirements while minimizing cost (or optimizing some other measure of commonality)." This statement is accurate but incomplete. It covers the basic features of scale-based design:

1. a common parametric description of the product, including the design variables that define an individual product, the performance variables that measure the objectives, and a functional relationship between the two (which might be analytic equations, numerical simulation, statistical or experimental methods, or a black box). This is distinct from module-based design, where such a common description cannot be assumed.
2. the set (or range) of requirements that the family of products must fulfill, and acceptable constraints on the performance of individual products in the product family.
3. the fundamental idea that product platform design is used to derive some benefit from having some variable values held common over more than one product.

It is not specific, however, on some points that distinguish existing methods in the literature, such as:

4. how to aggregate multiple performance objectives, if there is no single overall objective measure.
5. how to compare the relative importance of cost savings and performance enhancement.
6. how many platforms are permitted to develop the entire family. (Here, a product *family* is a set of related products; in particular, they are all described by the same variables. A product *platform* is a division of the given set of variables into platform variables and non-platform variables.)
7. how much freedom there is to determine which variables will be platform variables, and how they will be shared.
8. the coupling among platform variables. For example, the description of a family of ten products may include two variables x and y, where x shares the same value x_1 for products 1 to 5 and the value x_2 for products 6 to 10, and y takes different values $y_1, \ldots, y_5$ for products 1 to 5. In determining values of y for products 6 to 10, there are two different scenarios:
   (a) x and y are coupled (*e.g.*, are part of the same manufacturing process). In this case, there is a commonality incentive to give y common value (or values) for products 6 to 10, but there is no incentive to use any of the values $y_1, \ldots, y_5$. (In this case, we would not expect five different values of y for the first five products, as there is incentive to make those common as well.)
   (b) x and y are not coupled (*e.g.*, are manufactured independently). In this case, the commonality incentive is to set y equal to any one of $y_1, \ldots, y_5$ for products 6 to 10, but no incentive for them to be common with each other.
9. other factors, such as uncertainty, market demand, marketing cost, *etc.*, which may have influence on the final outcome.

If different methods make different assumptions about these points, the results will, in general, not be comparable. This motivates the development here of a taxonomy of example problems for scale-based product platform design. By creating an explicit set of categories, product platform design methods can be compared within the categories that they cover. Most methods will not cover all categories. One advantage of an explicit taxonomy is that it makes it obvious when a supposed comparison of methods is actually treating two different problems.

3 TAXONOMY OF THE PROBLEM

One of the main objectives in this paper is to give a sensible classification of the examples that have been proposed in the literature to illustrate the application of different methods to the design of product platforms. As noted, this task is motivated by the lack of an adequate set of test problems suitable to identify the strengths and weaknesses of the different approaches to product family design (a need that has been pointed out previously by Simpson [12]). A first step is to identify which methodological features can be tested using the examples currently available. This then leads to the identification of other features that might be interesting to test but for which there are no suitable examples.

In order to classify the examples in the literature, the general structure of a test problem is first described in Section 3.1. The characteristics of the methods that would be desirable for examples to be able to test are discussed in Section 3.2. The classification of the examples in Section 3.3 is done according to the potential capability of the examples to test those characteristics.

3.1 A General Structure of Examples

A product platform test example generally contains the following characteristics:

1. A set of input variables that describe each product.
2. A set of output variables, some of which will be evaluated as measurements of the product performance. Individual objectives will be given in terms of those output variables.
3. A set of constraints on the values of both input and output variables.
4. A relationship between the input and the output variables, which may be specified in a number of possible ways:
   (a) Analytical equations that explicitly relate input and output variables.
   (b) Computational simulations, such as finite element models.
   (c) Black box problems for which the designer does not have the physical equations to map the relation between the input and output variables.

   When explicit equations are not given, one possible approach is the use of design of experiments (DOE) [13] to develop a response surface [14] and then use these equations as an approximation to the relationship between variables.
5. At least two competing objectives. In platform design, there are generally two main objectives to take into account:
   (a) Performance: how the products behave in terms of the characteristics of interest. Performance may be a single feature, or it may be a multi-objective function if we are interested in more than one aspect of the product behavior. In the latter case, the different goals have to be combined to form an aggregate objective function. It is assumed that the performance of a family of products will never be improved by greater commonality, since the way to maximize their performance is by designing each product individually.
   (b) Cost: the manufacturing cost per unit should decrease when increasing commonality. It is typically assumed that product platform design reduces costs by promoting commonality, and that a penalty in individual performance will be paid for this commonality.
6. The problem may have a market demand model associated with it.

3.2 Examples vs. Methods Characteristics

Let us draw a clear distinction between what an example *can* be used for and what it *has been* used for so far. As discussed below, some of the examples in the literature are potentially richer than the methods to which they are applied.

For example, many methods, such as the Product Platform Concept Exploration Method (PPCEM) [15, 16], do not include the selection of the platform variables. Nevertheless, the example that is used in that method, the design of ten universal motors, has the potential (with enhancements, as will be discussed) to test methods that include a mathematical procedure to select the variables that will be part of the platform [17, 18]. It is also used to select which family of products will share the same value for a certain platform variable [9, 19].

The classification of examples from the literature is based upon the potential uses of those examples for test purposes, without regard to any limitations of the methods that they are used to test. The criteria used to sort the examples are the design method capacities that could be tested with the currently existing examples and other desirable method features that could be tested in the future. These characteristics are grouped in two major areas covering three different cases. Examples may cover more than one case in each area.

3.3 Classification Criteria

There is no single standard in product platform design for how to measure the effectiveness of a proposed methodology. The existence of a trade-off between commonality and performance is assumed, with the goal of platform design being to strike the best balance. Still, most methods, and their respective examples, do not include a quantitative way to balance these two objectives. Product platform test examples are classified here using two categories:

A Selection of the platform architecture.
B Incorporation of market demand.

These two criteria suffice to classify all scale-based example problems. Each criterion is now discussed in detail.

3.3.1 Classification Criterion A: Selection of the Platform Architecture

It is generally assumed in the platform literature that increased commonality decreases costs, but this is rarely modeled explicitly. It is also common to note that cost *should* be modeled [12]. **We argue here that cost**

is actually just another kind of performance, and that the fundamental distinction in product platforms is not between "cost" and "performance" but is whether some performance attribute is dependent on the level of sharing. Let us further clarify that we are interested in the cost savings that can be achieved by one platform configuration over another. Therefore, in general we do not attempt to model the full cost, but only that portion of cost that is potentially affected by the platform configuration. Seen in this light, there are two possible situations.

The first possibility is that the performance metrics do not depend on the architecture of the platform (*i.e.*, on the commonality), but only on the values of the variables of each member product. For example, the mass of an electric motor [15] does not depend on whether it shares variables with other variants. If this is the case for all performance metrics, the example cannot effectively compare methods that select the platform architecture.

The second possibility is that performance metrics explicitly depend on how many and which variables will be shared and to what extent they will be shared, in addition to the values taken by the design variables. For example, an explicit cost model will typically, but not necessarily, meet this criterion. The cost model in [4] provides an example of a cost model that does *not* depend on commonality.

For test examples that do include the conceptual task of selecting a platform or platforms, there are three stages to platform definition:

1. Selection of the platform variables, *i.e.*, which of the design variables will be part of the platform (or platforms).
2. Once the platform variables have been selected, determination of whether each shares one value for the entire family of products or different values for different groups of products.
3. In the case that the platform variables may take more than one value, determination of whether the groups of products that share the same values must be identical for all platform variables. (In other words, it must be determined whether the platform variables are correlated.)

The purpose of sharing the same value for some of the design variables across a certain number of products is the savings that may arise. If no reward is given for commonality, then there is no point in designing a product platform, given the complexity it involves. Without quantification, the comparison of the performance achieved by different methods that select different platform architectures is meaningless. This kind of (meaningless) comparison can, however, be found in the literature. It is to be expected that performances resulting from cases where platform variables take more than one value are better than those where the platform variables are forced to share the same value across the entire family, and it is also to be expected that the savings will be greater in the latter case. Unless we quantify the benefit of the sharing there is no common ground on which to compare the different architectures. Thus, if the benefits of sharing are not quantified, there is only one case worth considering, and that is an example where both the platform variables and the extent of the platforms are given.

Among examples that include the performance dependence on commonality, we distinguish those in which the design variables are coupled from those in which the design variables are not coupled. In the coupled case, if one of the variables shares the same value across a certain subset of products, the other platform variables must also take a single value for the same subset of products. Otherwise, we would have as many platforms as combinations of the different values for the platform variables. For an example of coupled platform variables, consider a part with two separate dimensions, say length and width of a stamped piece of metal. It is costly to create a new tool for stamping; thus, each tool defines a platform extent for all the dimensions of importance.

It is possible for some of the design variables to be coupled and others to be decoupled, but since the objective here is to classify the example in terms of the features of the methodologies they can test, the distinction will be drawn between those for which all of the design variables are coupled and those that possess at least one decoupled variable eligible to be a platform variable.

In summary, the different cases of platform architecture selection, depending on the existence of performance dependence on commonality, are as follows:

A1 The platform variables and their extent are given.
A2 All the design variables are coupled.
A3 At least one pair of design variables is decoupled.

3.3.2 Classification Criterion B: Incorporation of Market Demand

The universal electric motor example makes a radical, if typical, simplification concerning the impact of product variety. It dictates ten fixed torque targets for ten different member products, with no model of demand for each member product. It seems reasonable to assume that product differentiation increases revenue, while commonality decreases cost. A more realistic model would take into account the willingness of the market to purchase particular products, and indeed would allow the platform designer to define the particular set of products. For a defined set of products, the optimal settings of platform and non-platform variables will depend on the volume of sales of each product. These will in turn depend on both product performance and generalized market demand information. It may be desirable, for instance, to set the value of a platform variable to favor the performance of a product with sales that are sensitive to product performance, or that have higher volume.

The second classification of examples is based on the handling of market demand. This demand can be included in a test example in two basic ways. The first is by an explicit model that would be given as part of the problem statement (assumed, perhaps, to have been previously estimated by a marketing department). The second is by a survey model, in which a product platform method could include the possibility of survey queries. For a test example, this would most likely entail having a software program to deliver a requested number of surveys with an associated simulated cost. This is called an agent-based demand model. The second option has the advantage that accuracy of demand information entails greater expense.

This paper does not discuss the factors that have an impact on the demand for a particular manufacturer or product. Nevertheless, for the case of an agent-based survey model some insights from Piana [20], who describes consumer decision rules for an agent-based model, will be briefly included. The decision process is described in four stages, in which the consumer has to decide: to buy or not to buy, which one to buy, how many units to buy, and how often to buy. The first three decisions depend mainly on the price and overall quality of the product. The fourth one is more complicated since the customers have to be classified as either heavy or light consumers, or some intermediate position. One interesting advantage of using an agent-based demand model is that the manufacturer need not define *a priori* a strategy on price, but may set prices reactively, according to the customers' behavior.

The classification of examples following their handling of marketing demand uses three categories:

- **B1** The example does not include any demand information. It is simply not taken into account.
- **B2** Explicit model: There is a specific demand function as part of the data for the problem.
- **B3** Survey feedback: A demand model is assumed but is not given to the designer, who instead has the possibility of making a survey, which will have an associated cost depending on the number of people surveyed. This will be done with software, using an underlying model with some non-deterministic component. This implies uncertainty in the real demand.

In general, product platform design methods and test problems have glossed over the aspect of market demand. It is interesting to note that when a demand model is available (**B2** or **B3**), then another distinction may be drawn about the platform architecture, and that is whether the number of variants is given or is to be determined by the method. The existence of a market demand model admits the possibility that the requirements that define the individual variants within the family of products should be selected by the method rather than given in advance. We have chosen not to further subdivide the category at this time, but future development may require a refinement of the taxonomy.

This taxonomy with its three categories can be represented using a 3 × 3 grid, shown in Table 1. This will be discussed in greater detail in the next section.

Table 1. Classification of Examples by Reference

	No demand info **(B1)**	Explicit model **(B2)**	Survey feedback **(B3)**
Platform is given **(A1)**	[15] [2,21] [22] [6] [23]	[4] [19] [5]	
PV's correlated **(A2)**			
PV's uncorrelated **(A3)**		NEW	

4 EXAMPLES FROM THE LITERATURE

Two examples from the literature are discussed here. Many more are presented in a companion paper [25]. However, the wider set of examples presented in [25] does not cover any more of the grid defined by the taxonomy. The full set is presented in Table 2, although only examples 1 and 2 are discussed here. It can be seen that the existing examples cover only the **A1-B1** and **A1-B2** categories.

4.1 Universal Electric Motor Family

The example that is most widely used to test the application of different methods for the design of a family of products based on a common platform was originally proposed in [15]. The motivation of this example was to recreate a case similar to the real world situation that Black & Decker faced in the 1970's. According to Lehnerd [26], Black & Decker had been manufacturing different motors for each of their 122 basic tools, involving hundreds of variations. After the application of a new safety regulation they redesigned a family of universal motors for their power tools. These motors varied in the stack length and in the amount of copper wire wrapped within the motor. This new approach in the design of the motors yielded an annual saving of \$1.82M due to the decrease of material and tools cost and other savings related with the standardization involved.

In the test example described here, the specific objective is to: *"design a family of ten (10) universal electric motors that satisfies a variety of torque and power requirements by scaling a common motor platform around the stack length of the motor"* [15].

Following [15], the design variables (or inputs) and their ranges of interest for each motor are listed in Table 3. The constraints on the five responses (or outputs) of interest, and one additional constraint to ensure geometric feasibility, are shown in Table 4. The equations that relate the design variables with the response are described in [15].

Table 2. An Index of Product Platform Examples

Ex. No.	Example	# in family	Reference	Architecture selection	Market demand
1	Universal electric motors	10	Simpson *et al.* [15]	**A1**	**B1**
2a 2b	Absorption chillers Absorption chillers	8 12	Hernandez *et al.* [4] Seepersad *et al.* [24]	**A1**	**B2**
3	General aviation aircraft	3	Simpson *et al.* [2] D'Souza & Simpson [21]	**A1**	**B1**
4	Automobile vehicle frames	2	Fellini *et al.* [22]	**A1**	**B1**
5	Commercial aircraft	4	Fujita & Yoshida [5]	**A1**	**B2**
6	Flow control valves	16	Farrell & Simpson [6]	**A1**	**B1**
7	Oil filters	5	Ortega *et al.* [23]	**A1**	**B1**

Table 3. Universal Electric Motors Design Variables and Ranges

Variable	Description	Range
N_c	Number of wire turns on the armature	100 – 1500 turns
N_s	Number of wire turns on each pole on the field	1 – 500 turns
A_{wa}	Cross-sectional area of the wire on the armature	0.01 – 1.0 mm^2
A_{wf}	Cross-sectional area of the wire on the field	0.01 – 1.0 mm^2
r	Radius of the motor	0.01 – 0.10 m
t	Thickness of the stator	0.005 – 0.1 m
I	Current drawn by the motor	0.1 – 6.0 Amp
L	Stack length	0.057 – 5.18 cm

The way this example is described above indicates that the platform is given, *i.e.*, we know *a priori* which variables will be part of the platform (all of them apart from the stack length) and which one will be the scale factor (the stack length). On the other hand, this same example has been used by other researchers [17, 18, 27] to test methods which include the selection of the platform variables. Other methods [19] that include the possibility of having more than one value for each platform variable across the family have also used this example. Since there is no calculated performance that depends on commonality, there can be no comparison of different platforms, and the example is classified as **A1**. Since the example does not include any market demand model, this example belongs to category **B1**.

4.2 Absorber-Evaporator Module for Absorption Chillers Family

This example, which appears in [4], considers the design of the absorber-evaporator module for a family of absorption chillers that offer the following refrigeration capacities: 600, 700, 800, 900, 1000, 1100, 1200 and 1300 tons. In order to reduce inventory it is desired to design the family of modules with different cooling capacities using only one tube type in each part of the module and the same length tube in both parts. The benefits of sharing are not quantified. In this example, the designer does not have the option of choosing a different set of variables to form the platform, since the benefits of different levels of commonality are not defined.

Table 4. Constraints for the Universal Electric Motors

Variable	Constraints
Magnetizing intensity, H	$H \leq 5000$ Amp-turns/m
Power, P	$P = 300W$
Torque, T	$T = \{0.05, 0.1, 0.125, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5\}$ Nm
Efficiency, η	$\eta \geq 0.15$
Mass, M	$M \leq 2.0$ kg
(Feasible geometry)	$r > t$

Market demand is assumed to be 80 units distributed as shown in Figure 1. As noted above, allocating demand by fixed percentages without regard for performance or price is unrealistic. However, this simple market model does affect the design of the platform, and the problem is classified as case **B2**.

The absorber-evaporator module combines two of the four components in the absorption-refrigeration cycle. A simplified production system as shown in Figure 2 is considered, where SA1, SA2 and SA3 represent three sub-assembly stations. Those

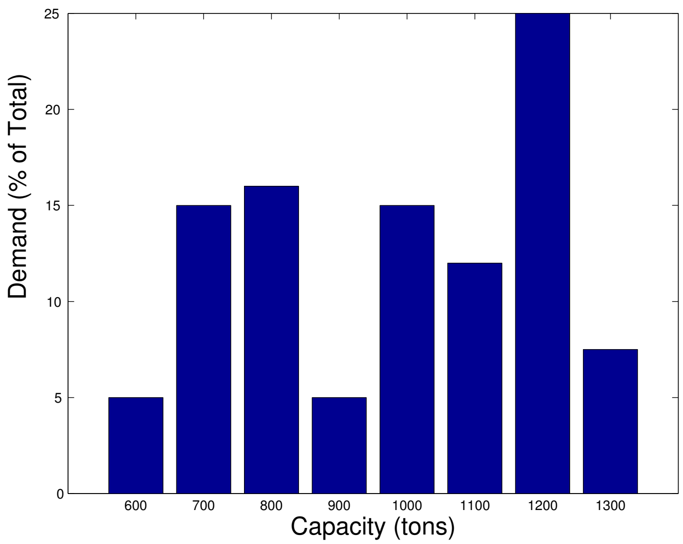

Figure 1. Expected Demand Distribution for Absorption Chillers

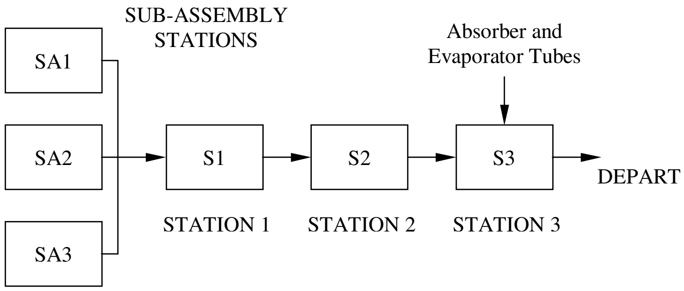

Figure 2. Production Line of the Absorber-Evaporator Module

Table 5. Standard Operating Conditions for the Absorption Chiller

Property	**Value**
Entering temperature of chilled water	54 °F
Exit temperature of chilled water	44 °F
Flow rate of chilled water	2.4 GPM/ton
Refrigerant fluid	Fresh Water
Saturation temperature of refrigerant	41 °F
Flow rate of water in the absorber	4.5 GPM/ton
Entering (absorber) water temperature	85 °F
Solution fluid	LiBr
Entering solution concentration	62%
Entering solution temperature	110 °F
Entering solution flow rate	222.5 lb / (hr ton)
Fouling factor for tube walls	0.00025 hr · ft^2·°F/BTU
Fouling factor for shell walls	0.00025 hr · ft^2·°F/BTU

Table 6. Absorber-Evaporator: Design Variables and Performances

Name	**Category**	**Range**
Tube length	platform variable	17.0 -24.0 ft
Evaporator tube type	platform variable	E1, E2
Absorber tube type	platform variable	A1, A2,A3
No. of evaporator tubes	scale factor	440 - 900
No. of absorber tubes	scale factor	440 - 900
Cost	performance	($)
Average cycle time	performance	(hr)

sub-assemblies would be assembled in station S1, in which there are three servers. In station S2 there are two servers and in station S3 there are three servers. There would be two working shifts, operating only during weekdays.

The reasons given to use a product platform approach instead of designing the modules for each capacity requirement individually are as follows:

1. The higher the variety, the more difficult it is to protect the line against disruption by means of safety stock.
2. The mentioned disruptions would cause waiting times in the assembly line that have an unfavorable impact on the price and lead times.

Unfortunately, the example does not provide any quantifiable way to take into account these savings achieved by using a common platform when designing the module for the family of absorption chillers, as will be explained.

The absorber-evaporator module is conceived to work in the operating conditions shown in Table 5. The design variables that define an absorber-evaporator module are: tube length (L), evaporator tube type ($E1$ or $E2$), absorber tube type ($A1$, $A2$ or $A3$), number of tubes of the evaporator (N_e) and number of tubes of the absorber (N_a). The first three variables will be platform variables and the other two will be scale factors. This is given as part of the example (case **A1**). The objectives are to minimize manufacturing cost and lead times (see Table 6).

The original relationships between design variables and performance parameters are not given as part of the example. Instead, a response surface is calculated through the Robust Concept Exploration Method [28]. The equations are provided in [4]. The total cycle time is calculated based on the equations of the response surface for the mean processing times of each station. The final expression of the cycle time is in terms of the values of the design variables of each module.

Also, due to the simplified cost model used, the total cost is the sum of the material cost, the labor cost, and the burden cost that ultimately is a function of the individual design variables. Therefore, as previously stated, cost and cycle time are not dependent on the level of commonality and the example is classified as **A1**.

Table 7. Wire Unit Costs for Different Lengths and Cross-sections

Total Length [m]	**Unit Cost [\$/m]**	A_{wa} **[mm^2] 0.2**	A_{wa} **[mm^2] 0.4**	A_{wa} **[mm^2] 0.6**	A_{wa} **[mm^2] 0.8**	A_{wa} **[mm^2] 1.0**
10000	$C_1(A_{wa})$	0.475	0.525	0.575	0.625	0.675
68000	$C_2(A_{wa})$	0.356	0.394	0.431	0.469	0.506
300000	$C_3(A_{wa})$	0.238	0.263	0.288	0.313	0.338
500000	$C_3(A_{wa})$	0.238	0.263	0.288	0.313	0.338

4.3 Classification Chart and Conclusions

The seven examples listed in Table 2 may also be presented in a graphical classification chart as shown in Table 1. A quick look at the classification chart reveals some key points about the current situation of the research on product platform design:

1. None of the examples reviewed presents an explicit way to quantify the benefits of sharing the same value for a certain variable across a subset of the family products. Without a measure of the benefits derived from sharing, any kind of comparison between different platforms is meaningless. All examples are classified as **A1**. The final objectives for those examples do not depend on the level of commonality but only on the values of the individual products.

   One method characteristic that cannot be tested with the examples available in the literature is the ability to select the most beneficial set of platform variables and the extent they are to be shared. This selection is essential in order to design an optimal product platform, which is why this paper stresses the importance of examples that include an explicit dependence of the goals on the variables being shared.
2. Most of the examples do not include market demand considerations (case **B1**). There are two that include a market demand model (case **B2**) and even in these cases, the market model is simplistic, with fixed demand independent of the price or quality of the products being manufactured for future selling. It would be more realistic to model the demand as a function of the final price of the product and of the quality perceived by customers.

It is suggested here that the set of test examples should be expanded first by including an explicit dependence on the platform architecture so that different platforms can be compared and second by offering a more realistic accounting of market demand, either through an explicit model including all pertinent information or through agent-based survey software. The first step is presented in the next section, and is indicated in Table 1 by the example labeled as “NEW”; the second step is left for future work.

5 EXTENDED UNIVERSAL ELECTRIC MOTOR PLATFORM DESIGN EXAMPLE

We here extend the electric motor example to include some of the features provided by no other example reviewed in the literature. Based on the taxonomy provided in Section 3, the desirable features a test example should include are the following:

1. The objective of the platform should depend on the level of commonality, *i.e.*, which and how many design variables are made common across the family.
2. The designer should be able to choose different sets of variables to be part of the platform. In other words, the platforms should not be given *a priori*.
3. The design variables should be decoupled. This will give the opportunity of testing those methods that are capable of choosing different subsets of products for sharing a value for each platform variable.
4. The market demand should be considered either through a explicit model or a survey feedback simulation.

When the characteristics of the universal electric motors example [15] were explained in Section 4.1, the lack of any relation between the objective function and the level of commonality in the family of products was pointed out. For that reason, the only way to compare two different methods using that example is by fixing the product platform architecture and comparing only the loss of product performance. By adding a specific cost dependency, the example can be used to compare different platforms. In addition, a uniform market demand distribution across the family will be assumed.

It is not our objective here to create an accurate cost model; that is a topic of current research in platform design [29], and cost models for the same product may vary from company to company. This simplified model illustrates how a realistic cost model may be included in the example with a direct relationship with the final objectives.

As explained in greater detail in [15], the motor consists of two main parts: the armature (rotor) and the field (stator). Both parts have wire wrapped around them longitudinally and the field outer structure is a hollow cylinder. These are the elements that we can modify by choosing different values of the design variables, which are (from Table 3):

N_c	Number of wire turns on the armature
N_s	Number of wire turns on each pole on the field
A_{wa}	Cross-sectional area of the wire on the armature
A_{wf}	Cross-sectional area of the wire on the field
r	Radius of the motor
t	Thickness of the stator
I	Current drawn by the motor
L	Stack length [m]

In order to mathematically express the impact of sharing certain variables for a number of products, the following assumptions are made:

1. The wire is bought from a certain manufacturer with whom a one-year contract is established in order to obtain the necessary wire to satisfy the market demand for that year.
2. The market demand is uniform across the family and equal to 200 units of each motor. This is a simplifying assumption where the demand becomes just a multiplying factor to calculate the total cost. A more comprehensive model could be included where the demand function is dependent upon price and/or quality.
3. The price per unit length of wire decreases when the total length of wire with the same cross section ordered for that year increases.
4. The wire used for the armature and field are of different kinds and therefore, no benefits result from having the same cross section for wires that will be used for different parts. This assumption is made so that the example illustrates the benefit of sharing the same value for a single variable across different products in the family. Without this assumption, some benefits could be achieved by sharing the cross section values for the wire in the armature and the field without distinction. That would not include any significant mathematical complexity, but it has been avoided for a clearer exposition of the concepts involved in product platform design.

A realistic way to show the wire unit price as a function of the total ordered length would be a discontinuous function, constant in different intervals. Since we are not concerned about the precision of this example but rather the conceptual innovation this approach involves, the unit cost function will be approximated to a continuous function through a cubic Hermite polynomial, interpolated through the points shown in Table 7.

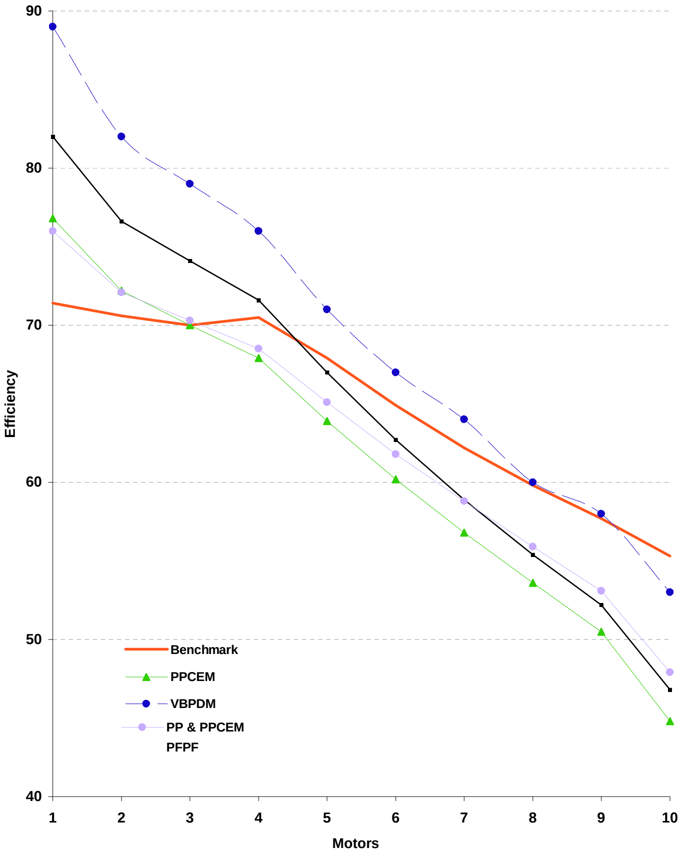

Figure 3. Comparison of the Efficiency of the Families of Motors Developed by Four Methods

The assigned costs C_1, C_2 and C_3 in Table 7 depend on the cross-section of the wire. The following equations express this relationship:

$$C_1 = 0.25A_{wa} + 0.425 \quad (1)$$

$$C_2 = \frac{3}{4}C_1 \quad (2)$$

$$C_3 = \frac{1}{2}C_1 \quad (3)$$

The final cost of the necessary wire to satisfy the demand of motors for a year will be the sum of the products of the unit cost for each cross-section area multiplied by the total length of wire with that cross-section.

An additional cost that depends on the level of commonality is the manufacturing cost of the field. The hollow cylinder that forms the main piece of the field is assumed to be cast. Part of the manufacturing cost of the set of cylinder would depend on the number of different castings to be made. There will be as many different casting patterns as there are combinations of outer field ratio r and thickness t. These two variables are coupled, and no savings will result from sharing the value of one among two or

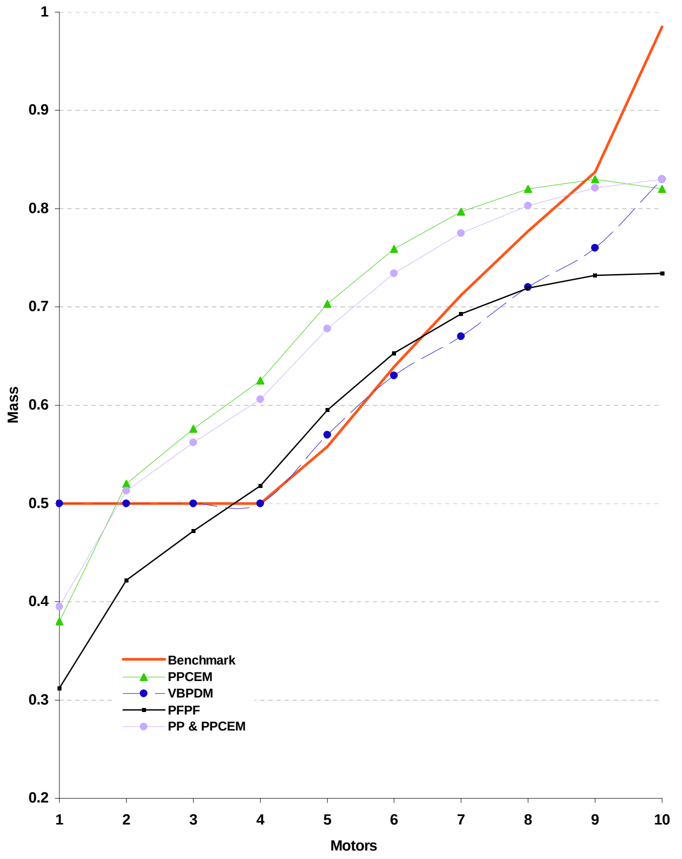

Figure 4. Comparison of the Masses of the Families of Motors Developed by Four Methods

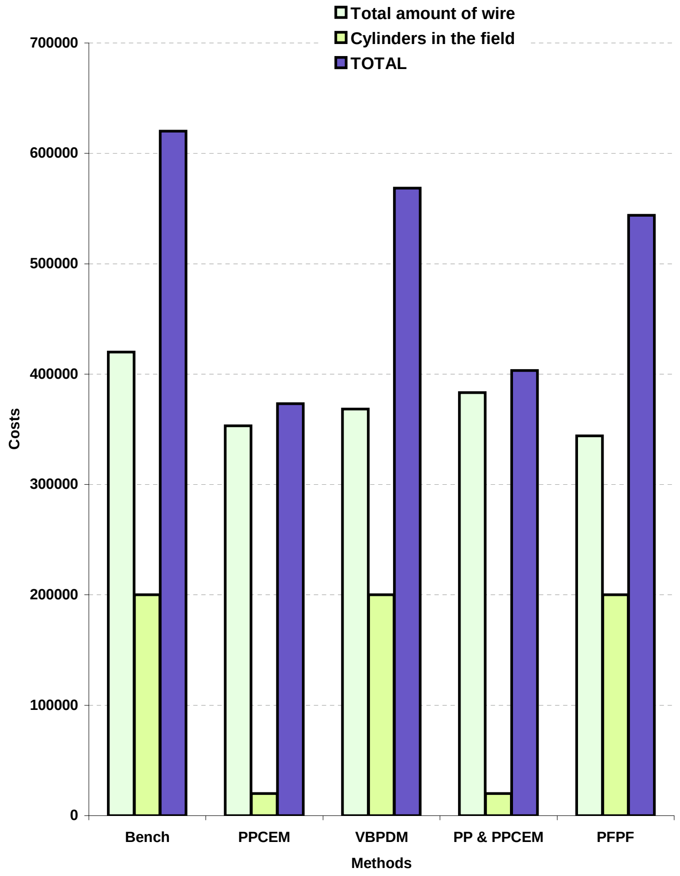

Figure 5. Comparison of the Cost of the Families of Motors Developed by Four Methods

more products if the other variable is not also shared by the same products.

Given the above assumptions, and assuming similar costs for each casting regardless of its dimensions, the impact of the level of sharing on this part of the cost is expressed in Eq. 4:

$$C_{\text{cast}} = 20000 N_{\text{cast}} \tag{4}$$

where N_{cast} is the number of different cylinders to be manufactured. Eq. (4) expresses and quantifies the benefits to be derived from commonality.

5.1 Comparisons of Existing Methods

The extended universal electric motor example is used to compare published results from four different methods: the Product Platform Concept Exploration Method (PPCEM) [15], the Variation-Based Platform Design Method (VBPDM) [17], the Product Family Penalty Function (PFPF) method [27], and the PPCEM with physical programming (PP) [30]. In Figures 3 and 4, the performances (efficiencies and masses, respectively) obtained by the four different methods are compared graphically to each other and to a benchmark family of products. The benchmark family was presented in [15] and optimizes the ten motors individually without platform constraints. The ten motors are shown on the horizontal axis in increasing order of torque. Each performance is known only at the ten points that represent the ten individual motors, and the continuous graph interpolating those points is drawn to make the figure more legible. Based on these results the four methods would be ranked from best to worst in the following order: VBPDM, PFPF, PP & PPCEM and in the last position PPCEM.

However, any such comparison is meaningless unless the methods use the same platform. That is the case of the comparison between PPCEM by itself and the PP & PPCEM. We can conclude that the PP & PPCEM performs better than the original PPCEM on this example. In order to make such a statement more general, it would be necessary to test both methods with other examples.

The apparent superiority of the VBPDM and PP & PPCEM

Table 8. Cost Associated with the Level of Commonality for the Family of Universal Electric Motors Designed Through the PP & PFPF

	VBPDM motors		
	η	M	Cost
PPCEM	-6.74%	8.89%	-39.80%
VBPDM	1.23%	-3.74%	-8.31%
PP & PPCEM	2.53%	-1.84%	34.96%
PFPF	-7.05%	-5.11%	-12.28%

methods can be attributed to their use of different platforms: VBPDM uses a greater number of scale factors, and the radius is a scale factor in both cases. The improved performance comes with increased cost, however. Figure 5 shows a plot of the costs of each method calculated using the new extended example shown here. We see that these two methods have higher costs. A summary of the results achieved by each method on both performance and cost is shown in Table 8. Those results indicate that there is no one method that outperforms another on both performances and cost.

6 CONCLUSIONS

A taxonomy for scale-based product platform design examples is an initial step towards creating a suite of testbed problems to compare product platform design methods. Examples are classified here on the basis of whether the measured performance depends on the level of commonality, how the example admits the selection of a platform architecture, and how the problem incorporates market demand. A review shows that existing examples cover only a very small portion of the space defined by this classification. An extension of the most-exercised problem, the design of a family of universal electric motors, is presented here. This new example includes a cost model with explicit dependence on how variables are shared among member products, covering categories in the classification scheme not covered by any existing methods. The extended example is tested using various methods from the literature, with the result that the methods that produced the best performance also incurred the greatest cost. We invite researchers to utilize these test problems freely to benchmark their own approaches to product family design and optimization.

ACKNOWLEDGMENTS

Support for this work came from the National Science Foundation under Grant Nos. IIS-0325402 and IIS-0325415. Any opinions, findings, and conclusions or recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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