A Product Dissection-Based Methodology to Benchmark Product Family Design Alternatives

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Today's companies are pressured to develop platform-based product families to increase variety, while keeping production costs low. Determining why a platform works, and alternatively why it does not, is an important step in the successful implementation of product families and product platforms in any industry. Internal and competitive benchmarking is essential to obtain knowledge of how successful product families are implemented, thus avoiding potential pitfalls of a poor product platform design strategy. While the two fields of product family design and benchmarking have been growing rapidly lately, we have found few tools that combine the two for product family benchmarking. To address this emerging need, we introduce the product family benchmarking method ($PF^{benchmark}$) to assess product family design alternatives (PFDAs) based on commonality/variety tradeoff and cost analysis. The proposed method is based on product family dissection, and utilizes the Comprehensive Metric for Commonality developed in previous work to assess the level of commonality and variety in each PFDA, as well as the corresponding manufacturing cost. The method compares not only (1) existing PFDAs but also (2) the potential cost savings and commonality/variety improvement after redesign using two plots—the commonality/variety plot and the cost plot—enabling more effective comparisons across PFDAs. An example of benchmarking of two families of valves is presented to demonstrate the proposed method. [DOI: 10.1115/1.3086789]

Keywords: product family, benchmarking, commonality and variety

1 Introduction

Companies are increasingly being challenged to develop a wider variety of products and offer them at nearly the same price as mass-produced goods. To this end, many companies have implemented platform-based product families, allowing cost-effective development of a sufficient variety of products to meet customers' diverse demands. Determining why a platform works, and alternatively why it does not, is an important step in the successful implementation of product families and product platforms in any industry [1]. Moreover, companies investigating competitors' approaches or examining their own product lines for potential improvement can benefit from platform development. This knowledge of successful product family design and implementation can be leveraged to help create new or redesigned product families, thus avoiding potential pitfalls of a poor product platform design strategy.

Product benchmarking provides a rich source of ideas for both product and process design [2,3]. Benchmarking is "a systematic way to identify, understand, and creatively evolve superior, products, services, designs, equipment, processes, and practices to improve [an] organization's real performance" [4]. Competitive benchmarking is a common practice in the automotive industry. For example, General Motors' Vehicle Assessment and Benchmarking Activity Center dissects and analyzes nearly 40 of its competitors' vehicles each year using a "teardown" process that takes about 6 weeks to complete [5]. Hoffman [5] quotes auto industry analyst Lindsay Brooke who emphasizes the importance of competitive teardowns, "as much as you think you know, nothing beats picking up the parts, feeling them, weighing them, and knowing the processes that made them." DaimlerChrysler disassembles competitors' products within their Competitive Teardown Operations Department, and Ford has competitive intelligence teams in their Automotive Strategy and Corporate Strategy Offices [6]. Automobile manufactures are joined by suppliers, such as Lear, Johnson Controls, TRW, and Motorola, which conduct competitive intelligence activities with teardown rooms, competitor product databases, and part performance analyses [7–10]. Many companies also use internal benchmarking to improve their own product lines. For instance, Whirlpool Corporation holds an annual Supplier Innovation Challenge during which suppliers have the opportunity to disassemble Whirlpool products [11]. The goal of the competition is to identify ways to reduce costs, to improve quality, and to identify innovative ideas. In 1999, Ticona Corporation, one of Whirlpool's plastic suppliers, spent 2 days evaluating a high-volume washer and electric dryer. Selecting 12 of Ticona's 30 recommendations to investigate further, Whirlpool Corp. identified an aggregate potential savings of $7 million [11]. Tools that can support product benchmarking include functional flow diagrams [12], quality function deployment [13–15], house of quality [16], and value analysis [17]. In general, benchmarking involves the following steps: identify the criteria to benchmark, identify the competing products, conduct information search (journals, magazines, the Internet, libraries, patent office, etc.), gather additional information through product dissection, and finally, analyze data and compare products.

The growing interest in benchmarking is also observed in the literature, on which extensive reviews can be found [18–24]. Dattakumar and Jagadeesh [25] reviewed the recent publications on benchmarking. Out of 382 publications analyzed, 170 publications

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belong to general aspects or fundamentals of benchmarking, 164 papers discuss specific applications/case studies in benchmarking, 27 publications present innovations/extensions/new approaches in benchmarking, and finally, 21 publications fall under the category of benchmarking applicable to the education sector. However, none of these approaches tackle the issue of product family benchmarking, focusing entirely on individual product benchmarking.

A key step in the benchmarking activity is a comparative understanding of the cost structures that different competitors face [26]. While product family assessment metrics, such as commonality indices [27], and methods, such as those in Refs. [28–32], exist, we have found no approaches that explicitly address the issue of product family benchmarking. One reason is the complexity of the process, where sets of products need to be compared against one another rather than individual products. Likewise, determining which products are in which family can be a difficult task [1]; however, at a time when companies are increasingly being pressured to develop product families, there is a clear need for tools to help them benchmark the product families developed, both internally and competitively. Hence, we propose the product family benchmarking method ($PF^{benchmark}$) to assess product family design alternatives (PFDAs) using commonality/variety tradeoff and cost analysis. The remainder of the paper is organized as follows. In Sec. 2, the proposed method is explained, followed by an example application in Sec. 3. Section 4 gives closing remarks and discusses future work.

2 Product Family Benchmarking

The product family benchmarking method ($PF^{benchmark}$) helps assess different product family design alternatives based on their cost and their balance of commonality and variety. The proposed method focuses primarily on mechanical products. It uses a commonality index, namely, the comprehensive metric for commonality (CMC) [33] to assess the design of each product family alternative; however, alternative commonality indices such as the product line commonality index [34] could be used instead based on the user's focus (component commonality, product performance, etc.). In any case, the commonality assessment is often obtained through product family dissection and teardown. The design alternatives that are compared can be either competing product families (competitive benchmarking) or possible design solutions (internal benchmarking).

2.1 The Comprehensive Metric for Commonality. The CMC [33] is a component-based metric that assesses the balance of commonality and variety in a product family based on size and geometry, manufacturing process, material, assembly/fastening scheme, production volume, and initial cost (e.g., cost of producing a mold for an injection plastic process). The CMC is defined as:

$$\mathrm{CMC} = \frac{\sum_{i=1}^{N} n_i * (C_i^{\max} - C_i) * \prod_{x=1}^{4} f_{xi}}{\sum_{i=1}^{N} n_i * (C_i^{\max} - C_i^{\min}) * \prod_{x=1}^{4} f_{xi}^{\max}} \quad (1)$$

where N is the total number of components, and n_i is the number of products in the product family that have component i. $\{f_{1i}, f_{2i}, f_{3i}, f_{4i}\}$ is the ratio of the greatest number of products that share component i with identical {size and shape (f_{1i}), materials (f_{2i}), manufacturing processes (f_{3i}), and assembly and fastening schemes (f_{4i})} to the number of products that have component i (n_i). $\{f_{1i}^{\max}, f_{2i}^{\max}, f_{3i}^{\max}, f_{4i}^{\max}\}$ is the ratio of the greatest number of products that could have shared component i with identical {size and shape ($f_{1i}^{\max}$), materials ($f_{2i}^{\max}$), manufacturing processes ($f_{3i}^{\max}$), and assembly and fastening schemes ($f_{4i}^{\max}$)} to the number of products that have component i (n_i). C_i is the current total cost for component $i = \sum_{j=1}^{n_i} C_{ij}$. C_{ij} is the total cost for component i variant $j = Q_{ij} c_{ij}$. Q_{ij} is the quantity of component i variant $j = Q_{ij} c_{ij}$. c_{ij} is the unit cost for component i variant j. $C_i^{\min}$ minimum total cost for component $i = \sum_{j=1}^{n_i} C_{ij}^{\min}$. $C_i^{\max}$ is the maximum total cost for component $i = \sum_{j=1}^{n_i} C_{ij}^{\max}$, which is computed by taking the most expensive variant available and the most expensive materials.

$C_i^{\min}$ is obtained when the "perfect" balance of commonality and variety is obtained for component i, i.e., when all the nondifferentiating instances of component i are common across the products, while the differentiating instances of component i are maintained variant (note that the definition of perfect is based on the information utilized in the CMC and does not include other parameters such as individual product performance, for instance). Due to its multiplicative form, the CMC can be modified to include more detailed information if it is available [33]). $C_i^{\max}$ is obtained when the "worst" balance of commonality and variety is present for component i, i.e., when all the instances are different between all the products in the family, each instance being produced without any commonality. To obtain the "ideal" commonality/variety tradeoff, expert opinions are needed (see Ref. [35] for more information, or Sec. 3.3 for an illustrative example). The choice of the cost estimate is independent of the CMC formulation. For this paper, a cost model based on material cost, mass, tooling cost, and production volume is used (see Ref. [33] for more details and examples).

The CMC weights the components in the products based on their costs, as well as size and geometry, material, manufacturing process, and assembly/fastening process. The CMC ranges from 0 to 1. CMC equals 1 when all the nondifferentiating components are common between all the products in the family, and they use the cheapest variant available (a nondifferentiating component is not used to differentiate a product, neither aesthetically nor functionally), and CMC is equal to 0 when all the nondifferentiating components are different (size, geometry, manufacturing process, assembly, and material) between all the products.

2.2 The Product Family Benchmarking Method. The proposed product family benchmarking method ($PF^{benchmark}$) is detailed in Fig. 1. Its primary objective is to benchmark a set of product family design alternatives (referred to as $PFDA_k$) using commonality/variety and cost assessments. For each $PFDA_k$, the assessment is done on the current design, as well as on the potentially improved design (using the CMC and a genetic algorithm (GA) based method, as described in Ref. [36]). The $PF^{benchmark}$ consists of four steps that are conducted on each $PFDA_k$: (1) data collection, (2) commonality/variety assessment and improvement, (3) cost estimates, and (4) benchmarking plots. Details on each step follow.

In Step 1 (data collection), the necessary data to compute the CMC_k for each $PFDA_k$ is collected. For each component, the following information is needed: manufacturing process, material, assembly/fastening scheme, production volume, and initial cost (e.g., cost of producing a mold for an injection plastic process). To help designers specify the manufacturing process, material, and assembly/fastening scheme, a list of possible choices can be given to the designers [37,38]. If the number of components is large, the data collection can become very time consuming; in this case, this information can be provided for each subassembly or module instead, depending on the desired level of analysis. This level of analysis must be consistent across the PFDAs. While this approach may give a less thorough assessment of the product families, it is less computationally intensive and may be more applicable in the case of complex products. In addition to the aforementioned component data, the following information is required for each product: list of components and associated information described above, component quantity in each product, and estimated number or products manufactured over its lifetime (this information may be readily available through a bill of materials

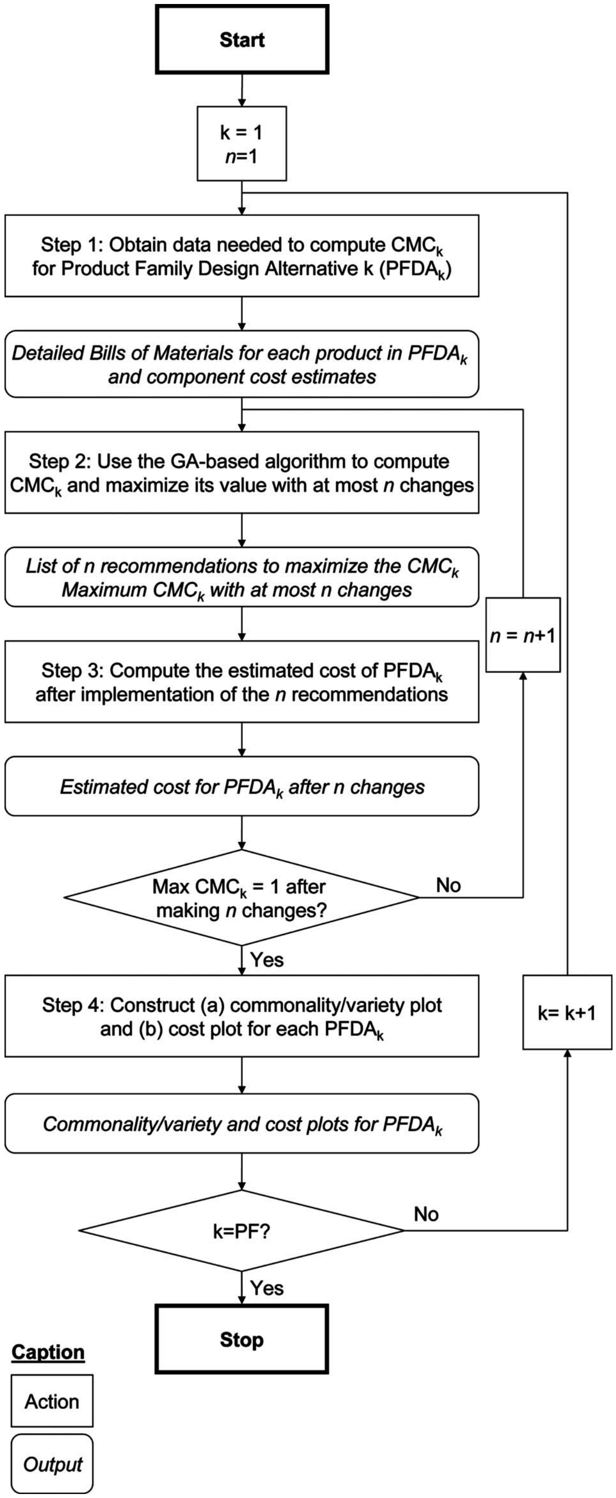


Fig. 1 Product family benchmarking method ($PF^{benchmark}$)

(BOM)). Finally, a cost per unit volume is needed for the different materials that are used. To obtain the information needed for the commonality/variety assessment, the data may not be readily available, especially when looking at competing product families. Hence, product teardown may be necessary to obtain the information (see for instance Ref. [38] that proposes guidelines for product family dissection).

In Step 2 (commonality/variety assessment and improvement), the CMC_k is computed after defining what can potentially be made common and/or variant between the products in each $PFDA_k$ (redesign strategy). A genetic algorithm-based method developed in Ref. [36] is then used to maximize the CMC_k for each $PFDA_k$ by recommending specific components to redesign. Each attribute of a component is encoded as an integer, which is later converted into a binary representation for the genetic algorithm. The GA maximizes the CMC_k by varying the size and geometry, material, manufacturing process, and assembly attributes associated with each variant component. Common attributes of the variant components are not allowed to change, and common and unique components are constrained to remain unchanged. We restrict the GA from changing parameters associated with common components, since doing so would decrease the commonality in the family, worsening the value of CMC_k, and we restrict the GA from changing attributes associated with unique components since they differentiate each product aesthetically and functionally. Finally, we limit the maximum number of changes that the GA can make between the original design and the redesigned family (referred to as n in Fig. 1). For each $PFDA_k$, the maximum CMC_k achievable for a given n is recorded. Limiting the number of changes has the added benefit of identifying redesign recommendations that have the biggest impact on improving commonality first. For more details on the GA implementation and its parameter settings, we refer the reader to Ref. [36].

In Step 3 (cost estimates), an estimate of the cost of $PFDA_k$ is computed. The purpose in this paper is not to develop the cost estimates; for this paper, cost estimates based on material cost, mass, tooling cost, and production volume are used as an illustrative example. The choice of the cost estimate is independent of the proposed method. It may be difficult, if not impossible, to obtain exact production costs, especially for competing product families (external benchmarking); however, dedicated software can help obtain good cost estimates (e.g., Design for Manufacturing and Assembly cost reduction tools[1]). In this study, the cost estimates are computed for the original design of each $PFDA_k$, as well as for each improved $PFDA_k$ after implementing the recommendations formulated in Step 2. For each $PFDA_k$, the minimum cost achievable C_i for a given n is recorded. The CMC value will reach 1 after a certain number of changes. If n is very large, then other stopping criteria can be used, such as the difference between CMC_k and CMC_{k-1} for instance.

In Step 4 (benchmarking plots), the minimum estimated cost to manufacture each $PFDA_k$, as well as the maximum CMC_k achievable for a given n are recorded and plotted. Steps 1–3 are repeated until the CMC value achieves its highest value of 1. The benchmarking plots are described in Sec. 2.2.

2.3 $PF^{benchmark}$ Benchmarking Plots. The $PF^{benchmark}$ returns two outputs for each $PFDA_k$: (1) the commonality/variety plot (see Fig. 2) and (2) the cost plot (see Fig. 3). The commonality/variety plot illustrates how "well" the PFDA respects the balance of desired commonality and variety (see Fig. 2). The higher the CMC, the closer the family is to the ideal desired commonality and variety (based on the parameters considered in the CMC). It is important to note that the CMC is a relative measure computed for each product family (i.e., the CMC for a given PFDA will reach the value of 1 when the ideal balance of commonality, and variety is achieved for this PFDA). For the specific case of internal benchmarking of product families, we may have the same "strategy" and the CMC may be an "absolute" measure across the different PFDAs (this is the case in the illustrative example in this study). However, in general, each PFDA will have its own "target" CMC, as each family will have different architectures (for instance, when comparing two families of competing single-use cameras, each product family will have a different architecture, and the CMC will be a relative measure to each family). What is important when comparing CMC is to analyze (1) how good the

[1] http://www.dfma.com, accessed on February 25th, 2009.

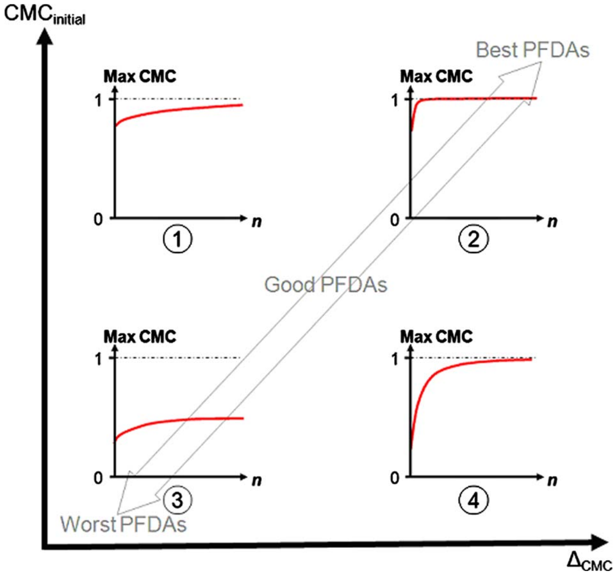


Fig. 2 Four types of commonality/variety plots

design of each PFDA is, and (2) how easy it is to improve the design. Toward this end, we have identified four cases based on the initial commonality/variety assessment ($CMC_{initial}$), as well as the initial slope (Δ_{CMC}), as shown in Fig. 3: ① high $CMC_{initial}$ and low Δ_{CMC}, ② high $CMC_{initial}$ and high Δ_{CMC} (2), ③ low $CMC_{initial}$ and low Δ_{CMC}, and ④ low $CMC_{initial}$ and high Δ_{CMC}. The four plots possess the same general shape: they end at a value of 1, which is the highest CMC achievable, and the slope decreases as the number of changes increases. This is due to the fact that the GA first recommends improving the components that have the most influence on the CMC value.

$CMC_{initial}$ shows how "good" the design of the current PFDA is, while Δ_{CMC} shows the potential for improvement. Ideally, a design alternative would have a high $CMC_{initial}$ and a high Δ_{CMC}, meaning that the design already has a good balance between commonality and variety, and it can be easily redesigned to increase it even more (Case ②). On the other end of the spectrum, a design with low $CMC_{initial}$ and low Δ_{CMC} will not be appealing (Case ③). Cases ① and ④ are in between, as they either already achieve a good balance of commonality and variety (Case ①), or they can reach it with few changes on the design (Case ④).

While this plot can give insight into how good the design of a product family is and how easy it is to redesign, the highest CMC value achievable, 1, is case-specific. Hence, a PFDA can be inexpensive to produce, but with a very low $CMC_{initial}$ and a very low Δ_{CMC}, while another PFDA can have a very high $CMC_{initial}$ and very high Δ_{CMC}, but be extremely expensive to produce. Hence, this plot needs to be combined with the cost plot for a more thorough analysis.

The cost plot aims at estimating the total cost of producing a $PFDA_k$ (sum of the total cost for producing each product in the $PFDA_k$), not only for a current design, but also for a potentially improved design (see Fig. 3). The plot monotonically decreases, but the slope does not strictly increase as n increases (unlike in the commonality/variety plot, where the slope strictly decreases as n increases). The reason is that the GA tries to not only minimize cost but also to maximize the CMC; hence, the recommendations returned by the algorithm do not necessarily yield the cheapest design for a given n—they yield the highest CMC for a given n. However, after a certain threshold ($n_{threshold}$), corresponding to a CMC of 1, the cost reaches the value C_{min} and cannot be further decreased without affecting the balance of commonality and variety. This plot is very useful to estimate not only the current cost of a $PFDA_k$, but also the potential cost saving for a given number of changes, as demonstrated next.

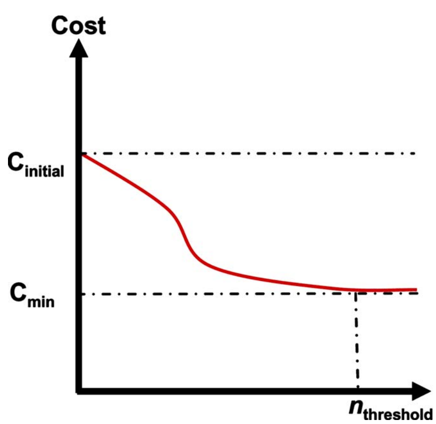


Fig. 3 Cost plot example

3 Example: Benchmarking Two Families of Valves

3.1 Introduction to the Valve Families. To demonstrate the $PF^{benchmark}$, consider the two families of flow control valves shown in Table 1. Specifically, each family contains three types of valves (piston check, stop, and stop check) in two sizes (1 in. and 2 in.), creating two product family design alternatives: $PFDA_1$ and $PFDA_2$. A particularity of these two PFDAs is that despite providing similar functionality, their design and manufacturing processes differ greatly. These differences are due to the way these two

Table 1 Valve product families analyzed

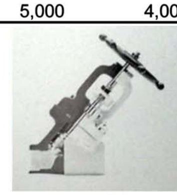
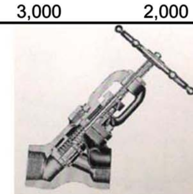
Valve Type	Piston Check Valve		Stop Valve		Stop Check Valve	
Size	1"	2"	1"	2"	1"	2"
Production Volume	5,000	4,000	5,000	4,000	3,000	2,000
$PFDA_1$						
$PFDA_2$						

Table 2 Data for $PFDA_1$

Component	Piston check 1 in		Piston check 2 in.		Stop 1 in.		Stop 1 in.		Stop check 1 in.		Stop check 2 in.	
	Variant	Cost	Variant	Cost	Variant	Cost	Variant	Cost	Variant	Cost	Variant	Cost
Body forging	1	12.20	2	38.06	1	12.20	2	38.06			2	38.06
Bonnet forging					1	10.87	2	25.20	1	10.87	1	25.20
Bushing yoke					1	3.27	2	12.34	3	3.27	3	12.34
Cover	1	7.43	2	23.96								
Cable					1	0.08					2	0.09
Disk	1	17.33	2	25.20	3	31.58	4	26.20	1	17.33	1	25.20
Eyebolt					1	3.46	2	5.88	1	3.46	1	5.88
Gland					1	2.63	2	3.94	1	2.63	1	3.94
Gskt spl wnd	1	2.59	2	3.05	1	2.59	2	3.05	3	3.20	3	3.05
Handwheel					1	0.95	2	2.63	1	0.95	1	2.63
Nameplate	1	0.25	2	0.01	3	0.08						
Nut disk					1	4.88	2	6.29				
Nut hex					1	0.02	2	0.13	1	0.02	1	0.13
Nut self locking					1	0.10	2	0.03	1	0.10	1	0.03
Packing					1	0.71	2	1.08	3	0.53	3	6.54
Packing					1	1.06	2	4.36	3	0.71	3	1.08
Pin knurled (*B*)					1	1.00	2	1.26	1	1.00	1	1.26
Protector	1	0.07	2	0.16	1	0.07	2	0.16	1	0.07	1	0.16
Ring junk					1	0.89	2	1.18			2	1.18
Screw flg hex hd	1	1.93	2	2.60	1	1.93	2	2.60	1	1.93	1	2.60
Sleeve (crimp)					1	0.08					1	0.08
Spring	1	1.02	2	1.23					1	1.02	1	1.23
Stellite #21M												
Tubular	1	6.27	2	6.17	1	6.27	2	6.17			2	6.17
Stem					1	7.79	2	14.91	3	37.30	3	79.07
Washer									1	0.01		
Component cost		49.08		100.45		92.51		155.47		84.38		215.92
Labor cost		5.91		13.62		30.90		35.52		25.57		35.52
Burden cost		24.06		55.43		125.74		144.53		104.06		144.53
Total cost		79.06		169.50		249.15		335.52		214.02		395.97

PFDAs were designed: $PFDA_1$ was developed without taking commonality into consideration, while $PFDA_2$, a more recently developed family, was designed with the idea of a product platform and component sharing in mind. Moreover, although these two PFDAs offer similar functions, they are still both in production. The reason is that they are not competing directly, as the market is very specific, and consumers want to replace defective valves with the exact same models: if the consumers bought valves from $PFDA_1$ in the past, they do not want to switch to the ones in $PFDA_2$, and vice versa. This example shows only two different design alternatives for ease of understanding; the same method can be applied to more design alternatives as needed.

3.2 Step 1: Data Collection. Data collection took place on-site at the valve manufacturer. For each of the twelve products analyzed, a bill of materials was obtained, containing the component name, description, and costs. The additional information required to compute the CMC was collected by hand. The data is then entered into a spreadsheet (see Tables 2 and 3 for $PFDA_1$ and $PFDA_2$, respectively). For a given component, in both families, the manufacturing process, the material, and the assembly scheme are identical; the size and geometry is the only factor that varies. Hence, in both tables, only the "size and geometry" factor is represented, along with the cost of each component. This example does not disclose the actual costs; hence, the cost estimates employed are for illustrative purposes only. The on-site data collection took about 3 days, with an engineer from the company involved half of the time.

3.3 Step 2: Commonality/Variety Assessment and Improvement. In Step 2, three subtasks are performed. The first subtask is to define which components could potentially be made common and/or variant. After discussion with the engineers at the manufacturing company, the size difference between the 1 in. and 2 in. valves were determined to be too different to make most parts common between these two sizes; however, for a given size, components can be made common across valve types. As a result, only four components can potentially be made common between all the products in the family: packing 1, packing 2, handwheel, and nameplate. Aesthetic differentiation is not critical here; hence, the external components need not be different aesthetically. For this specific example, designers were asked to identify components that could potentially be shared across products without compromising product performance.

The next subtask is to compute the CMC. Using the data in Tables 2 and 3, CMC_1 and CMC_2 are computed automatically for $PFDA_1$ (see Table 4) and $PFDA_2$ (see Table 5), respectively. The values are shown for the current design; similar assessment is also done after redesign of each $PFDA_k$. The process is done automatically, limiting possible errors during computation and increasing its repeatability. CMC_1 is 0.5624, much lower than the value in the $PFDA_2$ ($CMC_2=0.8067$). This result was as expected, as $PFDA_2$ has been designed with more emphasis on component sharing.

The final subtask is to utilize the GA proposed in Ref. [36] to maximize the CMC value based on the constraints mentioned in Sec. 2.2. One constraint, the maximum number of changes n, is varied, starting at 1, and is increased until the algorithm can find a solution where CMC is equal to 1 (perfect balance of commonality and variety). For each value of n, the algorithm returns a list of possible changes to maximize the CMC. This enables the designer to focus not only on the most expensive components, but also on the ones that are needed to achieve a good balance between commonality and variety in each PFDA. An example of recommendations for the improvement of $PFDA_1$ can be found in Table 6 for $n=5$.

The recommendations in Table 6 concern the disk casting,

Table 3 Data for PFDA$_2$

Component	Piston check 1 in.		Piston check 2 in.		Stop 1 in.		Stop 2 in.		Stop check 1 in.		Stop check 2 in.	
	Variant	Cost	Variant	Cost	Variant	Cost	Variant	Cost	Variant	Cost	Variant	Cost
Adapter							1	1.39			1	1.39
Body forging	1	11.39	2	42.95	1	11.39	2	42.95	1	11.39	2	42.95
Bushing yoke					1	3.06	2	8.10	1	3.06	2	8.10
Cable	1	0.03	1	0.03	2	0.05	3	0.08	2	0.05	3	0.08
Collar locking					1	0.50	2	8.57	1	0.50	3	2.77
Disk casting	1	10.56	2	37.62	1	10.56	3	38.42	1	10.56	2	37.62
Eyelet	1	0.13	1	0.13								
Gland					1	3.80	2	9.43	1	3.80	2	9.43
Gland bolt					1	2.72	2	5.17	1	2.72	2	5.17
Handle impactor							1	3.26			1	3.26
Handwheel					1	1.73			1	1.73		
Nut hex					1	0.01	1	0.01	1	0.01	1	0.01
Nut hex 2					1	0.01	2	0.02	1	0.01	2	0.02
Nut self locking					1	0.02	2	0.06	1	0.02	2	0.06
Packing 1					1	0.87	2	1.02	3	0.38	2	1.02
Packing 2					1	0.38	2	2.20	3	0.87	2	2.20
Plug steel					1	0.10	2	0.14	3	0.10	2	0.14
Protector	1	0.04	2	0.11	1	0.04	2	0.11	1	0.04	2	0.11
Ring seal	1	0.75	2	1.35	1	0.75	2	1.35	1	0.75	2	1.35
RND-1	1	1.45	2	3.77	3	1.63	4	1.28	5	2.34	6	6.29
RND-2					1	2.34	2	6.29				
Screw hex	1	0.01	1	0.01	2	0.10	3	0.03	4	0.10	5	0.05
Screw SQ HD					1	0.17	2	0.44	1	0.17	2	0.44
Sleeve	1	0.06	1	0.06	1	0.06	1	0.06	1	0.06	1	0.06
Spring	1	0.60	2	1.14								
Stellite #21M												
Tubular	1	3.08	2	3.76	1	3.08	2	3.76	1	3.08	2	3.76
Stem					1	8.87	2	21.78	3	58.91	4	112.79
Washer					1	0.04	2	0.26	1	0.04	2	0.26
Yoke forging					1	5.85	2	20.14	1	5.85	2	20.14
Component cost		28.08		90.92		58.13		176.30		106.53		259.46
Labor cost		38.77		43.28		27.55		58.61		21.64		43.28
Burden cost		157.76		176.11		128.56		238.48		88.05		176.11
Total cost		224.62		310.31		214.24		473.39		216.22		478.84

packing 1, and packing 2. The GA recommends using only two variants of the disk casting, one for the 1 in. diameter products (stop 1 in., stop check 1 in., and piston check 1 in.) and one for the 2 in. diameter products (stop 2 in., stop check 2 in., and piston check 2 in.), as already implemented in PFDA$_2$. The GA also recommends reducing the number of variants for packing 1 and packing 2, as observed in PFDA$_2$. By implementing these recommendations, CMC$_1$ is improved by 65%, from 0.5624 to 0.9295. The algorithm is run for PFDA$_1$ (from $n=1$ to $n=15$) and for PFDA$_2$ (from $n=1$ to $n=20$), and the results are summarized in Table 7.

3.4 Step 3: Cost Estimates. In Step 3, the cost of producing each PFDA is estimated, not only for the current design, but also for the redesign that would implement the improvements proposed in Step 2, for the different values of n. Results can be found in the rightmost columns of Table 7. Each cost corresponds to the total cost to produce each family with the production volumes given in Table 1. Looking at the initial cost estimates, PFDA$_2$ is less expensive to manufacture than PFDA$_1$; however, if the PFDAs are redesigned to increase the CMC value, then PFDA$_1$ can be produced cheaper than PFDA$_2$ for most of the n values. The results are discussed next.

3.5 Step 4: Benchmarking Plots. In the last step, the commonality/variety plot (Fig. 4) and the cost plot (Fig. 5) are constructed for PFDA$_1$ and PFDA$_2$. If we first analyze the commonality/variety plot, the shape of the graphs is very different for the two alternatives: for PFDA$_1$, the slope is steep at the beginning and drops remarkably after five changes; on the other hand, in PFDA$_2$, the slope does not indicate a decrease as the number of changes increases. Recalling Fig. 2, PFDA$_1$ and PFDA$_2$ represent Cases ④ and ①, respectively. Another main difference is the initial value, which is lower for the PFDA$_1$ than for PFDA$_2$. The explanation is that in PFDA$_2$, the components that are critical for commonality are already shared between the products, unlike in PFDA$_1$. Hence, while the initial CMC is lower for PFDA$_1$, the potential for improvement is greater than for PFDA$_2$ by focusing on components that strongly affect commonality. The slope is hence directly related to the potential commonality improvement in the family. Another remark is that, although there was a common agreement from the designers on the fact that PFDA$_2$ was a better design based on its increased commonality (confirmed with a higher initial CMC$_2$ value), the graph shows that the ease of redesign (represented by Δ_{CMC}) in PFDA$_1$ is higher than in PFDA$_2$: with more than five changes, CMC$_1$ is higher than CMC$_2$. Moreover, the minimum number of changes to achieve perfect commonality is higher for PFDA$_2$ than for PFDA$_1$ (20 versus 15). This can be explained by the fact that although PFDA$_1$ was designed with an emphasis on making critical components common (high initial CMC$_1$), designers might have overlooked other components that could have been easily made common (although they have less influence on the overall commonality), such as the screw hex, which has five variants when one would have been enough for all six.

Figure 5 shows the estimated cost versus n in the Cost Plot. The

Table 4 CMC computation table for $PFDA_1$

Component	Size and geometry (f_1)	Material (f_2)	Process (f_3)	Fastening (f_4)	n_i	C_i	$C_{i\,max}$	$C_{i\,min}$
Body forging	3/5	1	1	1	5	502,600	692,822	502,600
Bonnet forging	1/2	1	1	1	4	238,160	299,383	238,160
Bushing yoke	1/2	1	1	1	4	100,160	134,770	100,160
Cover	1/2	1	1	1	2	132,990	132,990	132,990
Cable	1	1	1	1	2	546	572	491
Disk	1/3	1	1	1	6	552,520	631,139	370,519
Eyebolt	1/2	1	1	1	4	62,960	75,167	62,960
Gland	1/2	1	1	1	4	44,640	52,130	44,640
Gskt spl wnd	2/3	1	1	1	6	65,589	76,637	63,729
Handwheel	1/2	1	1	1	4	23,310	30,109	9261
Nameplate	1/3	1	1	1	3	1690	1690	70
Nut disk	1/2	1	1	1	2	49,566	49,566	49,566
Nut hex	1/2	1	1	1	4	932	1311	932
Nut self locking	1/2	1	1	1	4	1002	1233	1002
Packing 1	1/4	1	1	1	4	22,545	22,545	3308
Packing 2	1/4	1	1	1	4	27,042	27,042	4498
Pin knurled (*B*)	1/2	1	1	1	4	15,560	17,594	15,560
Protector	1/2	1	1	1	6	2498	3611	2498
Ring junk	2/3	1	1	1	3	11,516	11,986	11,516
Screw flg hex hd	1/2	1	1	1	6	51,156	63,521	51,156
Sleeve (crimp)	1	1	1	1	2	588	630	588
Spring	1/2	1	1	1	4	15,540	17,427	15,540
Stellite #21M tubular	3/5	1	1	1	5	112,054	125,239	112,054
Stem	1/4	1	1	1	4	368,608	368,608	368,608
Washer	1	1	1	1	1	30	30	30
							CMC	0.5624

initial cost is lower for $PFDA_2$ than for $PFDA_1$. This is also reflected by looking at the initial CMC_2, which is higher than the initial CMC_1. If only two changes are made on the designs, then the potential costs are lower for $PFDA_1$ than for $PFDA_2$. Hence, by looking not only at the current cost, but also the potential cost saving by improving commonality, designers can get a better assessment of the designs and their potential for improvement, helping the decision process.

Table 5 CMC computation table for $PFDA_2$

Component	Size and geometry (f_1)	Material (f_2)	Process (f_3)	Fastening (f_4)	n_i	C_i	$C_{i\,max}$	$C_{i\,min}$
Adapter	1	1	1	1	2	8316	8593	8316
Body forging	1/2	1	1	1	5	577,533	867,232	577,533
Bushing yoke	1/2	1	1	1	4	73,051	90,953	73,051
Cable	1/3	1	1	1	6	1107	1459	385
Collar locking	1/2	1	1	1	4	43,819	62,197	18,982
Disk casting	1/2	1	1	1	6	516,674	754,422	516,674
Eyelet	1	1	1	1	2	1129	1191	1129
Gland	1/2	1	1	1	4	86,948	107,167	86,948
Gland bolt	1/2	1	1	1	4	52,776	62,184	52,776
Handle impactor	1	1	1	1	2	19,543	20,194	19,543
Handwheel	1	1	1	1	2	13,860	14,510	13,860
Nut hex	1	1	1	1	4	194	210	194
Nut hex 2	1/2	1	1	1	4	234	263	234
Nut self locking	1/2	1	1	1	4	540	687	540
Packing 1	1/2	1	1	1	4	11,595	11,799	3818
Packing 2	1/2	1	1	1	4	17,721	18,162	4082
Plug steel	1/2	1	1	1	4	1605	1788	1605
Protector	1/2	1	1	1	6	1649	2,275	1649
Ring seal	1/2	1	1	1	6	23,225	29,641	23,225
RND-1	1/6	1	1	1	6	55,216	55,216	15,477
RND-2	1/2	1	1	1	2	36,857	36,857	18,968
Screw hex	1/3	1	1	1	6	1168	1377	207
Screw SQ HD	1/2	1	1	1	4	3944	4901	3944
Sleeve	1	1	1	1	6	1275	6065	1275
Spring	1/2	1	1	1	2	7526	7526	7526
Stellite #21M tubular	1/2	1	1	1	6	77,652	88,459	77,652
Stem	1/4	1	1	1	4	533,762	533,762	533,762
Washer	1/2	1	1	1	4	2381	3040	2381
Yoke forging	1/2	1	1	1	4	207,926	260,520	207,926
							CMC	0.8067

Table 6 Recommendations for $n=5$

Component	From product	Factor	Recommendation
Disk casting	Stop 1 in.	f_1	Variant $3 \rightarrow 1$
Disk casting	Stop 2 in.	f_1	Variant $4 \rightarrow 1$
Packing 1	Stop check 1 in.	f_1	Variant $3 \rightarrow 1$
Packing 1	Stop check 2 in.	f_1	Variant $4 \rightarrow 1$
Packing 2	Stop check 1 in.	f_1	Variant $3 \rightarrow 1$

4 Closing Remarks

Increasing competition is forcing companies to redefine many of their product development practices, including developing product families and benchmarking competitors' product lines, as well as their own. Toward this end, we propose the product family benchmarking method ($PF^{benchmark}$) to assess product family design alternatives using commonality/variety tradeoff and cost analysis obtained through product family dissection and teardown. By comparing existing PFDAs and the potential cost savings and commonality/variety improvement after redesign, the $PF^{benchmark}$ can help designers select a PFDA (internal benchmarking) or assess their PFDAs more thoroughly against the competition. Future work includes looking at more detailed commonality assessment (including a more detailed cost estimates, as well as a more parameters, such as individual product performance) to refine the proposed method further. Another research direction is to look at the feasibility of the redesign recommendations returned by the GA, as well as the scalability of the method for more complex product families (a preliminary study on the scalability can be found in Ref. [35].). Finally, the method can be extended to provide recommendations not only on how to reuse components across products, but also on how to combine and merge components if possible.

Table 7 Impact of n on maximum CMC and cost

n	Max CMC_1	Max CMC_2	$Cost_1$	$Cost_2$
0	0.562	0.807	2,477,387	2,379,227
1	0.669	0.829	2,388,213	2,376,528
2	0.765	0.849	2,332,143	2,364,512
3	0.855	0.867	2,324,808	2,361,275
4	0.899	0.885	2,307,793	2,354,905
5	0.930	0.900	2,307,447	2,342,403
6	0.947	0.914	2,305,560	2,309,546
7	0.957	0.927	2,303,151	2,304,554
8	0.966	0.939	2,302,746	2,286,664
9	0.972	0.950	2,284,473	2,279,454
10	0.978	0.959	2,275,705	2,277,517
11	0.983	0.968	2,268,303	2,273,025
12	0.987	0.976	2,268,212	2,271,856
13	0.992	0.983	2,267,914	2,272,295
14	0.996	0.989	2,266,987	2,270,883
15	1.000	0.994	2,266,987	2,270,445
16	1.000	0.995	2,266,987	2,270,358
17	1.000	0.997	2,266,987	2,270,017
18	1.000	0.998	2,266,987	2,269,862
19	1.000	0.999	2,266,987	2,269,612
20	1.000	1.000	2,266,987	2,269,295

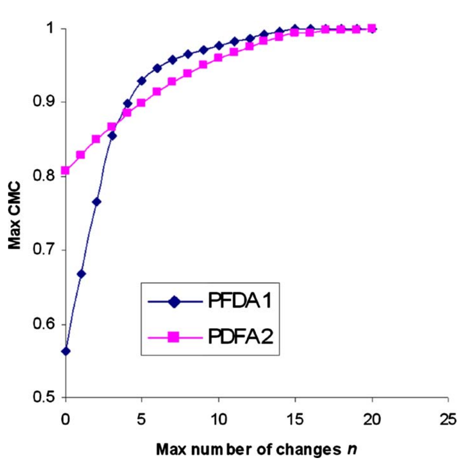


Fig. 4 Max CMC versus n

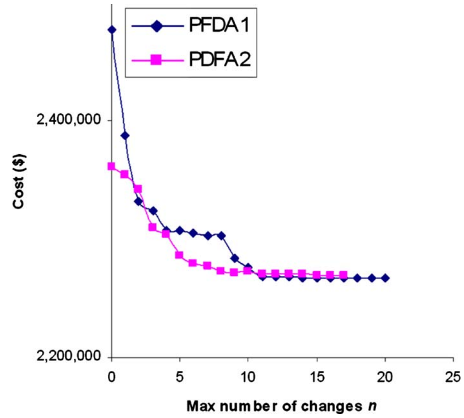


Fig. 5 Cost versus n

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References

[1] Steva, E. D., Rice, E. N., Marion, T. J., Simpson, T. W., and Stone, R. B., 2006, "Two Methodologies for Identifying a Product Platform Within an Existing Set of Products," ASME Paper No. DETC2006-99234.

[2] Ulrich, K. T., and Eppinger, S. D., 2004, *Product Design and Development*, 3rd ed., McGraw-Hill/Irwin, New York, NY.

[3] Ding, Y., Ceglarek, D., and Shi, J., 2002, "Design Evaluation of Multi-Station Assembly Processes by Using State Space Approach," ASME J. Mech. Des., **124**(3), pp. 408–418.

[4] Harrington, H. J., 1996, *The Complete Benchmarking Implementation Guide: Total Benchmarking Management*, McGraw-Hill, New York.

[5] Hoffman, C., 2006, "The Teardown Artists," Wired, **14**(2), pp. 136–140.

[6] Mian, M., 2001, "Modularity, Platforms, and Customization in the Automotive Industry," MS thesis, Department of Industrial and Manufacturing Engineering, The Pennsylvania State University, University Park, PA.

[7] Upham, S. D., 2000, "Automotive Competitive Intelligence 101: A Beginner's Guide," Automotive Manufacturing & Production, **112**(8), pp. 34.

[8] Conover, G., and Day, S., 2002, "Mining Your Competition," Automotive Industries, **182**(3), pp. 32–33.

[9] Mahmoud, H., Kabamba, P., Ulsoy, A. G., and Brusher, G., 2005, "Target Management in Complex System Design Using System Norms," ASME J. Mech. Des., **127**(4), pp. 536–544.

[10] Steva, L., 2006, "Methods for Product Dissection and Product Family Analysis," MS thesis, Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA.

[11] Sheridan, D., Graman, B., Beck, K., and Harbert, J., 2001, "Improving From the Inside Out," Appliance Manufacturer, **49**(1), pp. 82–84.

[12] Stone, R. B., and Wood, L. W., 2000, "Development of a Functional Basis for Design," ASME J. Mech. Des., **122**(4), pp. 359–370.

[13] Clausing, D., 1994, *Quality Function Deployment*, MIT Press, Cambridge, MA.

[14] Kreng, V. B., and Lee, T.-P., 2004, "QFD-Based Modular Product Design With Linear Integer Programming—A Case Study," J. Eng. Des., **15**(3), pp. 261–284.

[15] Takai, S., and Ishii, K., 2006, "Integrating Target Costing Into Perception-Based Concept Evaluation of Complex and Large-Scale Systems Using Simultaneously Decomposed QFD," ASME J. Mech. Des., **128**(6), pp. 1186–1195.

[16] Hauser, J., and Clausing, D., 1998, "The House of Quality," Harvard Bus. Rev., **66**(3), pp. 63–73.

[17] Miles, L. D., 1972, *Techniques of Value Analysis and Engineering*, 2nd ed., McGraw-Hill, New York.
[18] Jackson, A. E., Safford, R. R., and Swart, W. W., 1994, "Roadmap to Current Benchmarking Literature," J. Manage. Eng., **10**, pp. 60–67.
[19] Zairi, M., and Youssef, M. A., 1995, "A Review of Key Publications on Benchmarking: Part I," Benchmarking for Quality Management & Technology, **2**(1), pp. 65–72.
[20] Zairi, M., and Youssef, M. A., 1996, "Benchmarking for Quality Management and Technology," Benchmarking for Quality Management and Technology, **3**(1), pp. 45–49.
[21] Vig, S. N., 1995, "Benchmarking: A Select Bibliography," Productivity, **36**(3), pp. 521–524.
[22] Czuchry, A. J., Yasin, M. M., and Darsch, J. J., 1998, "A Review of Benchmarking Literature," International Journal of Public Sector Management, **11**(2/3), pp. 91–115.
[23] Dorsch, J. J., and Yasin, M. M., 1998, "A Framework for Benchmarking in the Public Sector: Literature Review and Directions for Future Research," International Journal of Public Sector Management, **11**(2/3), pp. 91–115.
[24] Yasin, M. M., 2002, "Theory and Practice of Benchmarking: Then and Now," Benchmarking: An International Journal, **9**(3), pp. 217–243.
[25] Dattakumar, R., and Jagadeesh, R., 2003, "A Review of Literature on Benchmarking," Benchmarking: An International Journal, **10**(3), pp. 176–209.
[26] Otto, K., and Wood, K. L., 2001, *Product Design-Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Upper Saddle River, NJ.
[27] Thevenot, H. J., and Simpson, T. W., 2005, "Commonality Indices for Assessing Product Families," *Product Platform and Product Family Design: Methods and Applications*, T. W. Simpson, Z. Siddique, and J. Jiao, eds., Springer, New York, pp. 107–129.
[28] Dai, Z., and Scott, M. J., 2006, "Effective Product Family Design Using Preference Aggregation," ASME J. Mech. Des., **128**(4), pp. 659–667.
[29] Messac, A., Martinez, M. P., and Simpson, T. W., 2002, "Introduction of a Product Family Penalty Function Using Physical Programming," ASME J. Mech. Des., **124**(2), pp. 164–172.
[30] Hernandez, G., Allen, J. K., Simpson, T. W., Bascaran, E., Avila, L. F., and Salinas, F., 2001, "Robust Design of Families of Products With Production Modeling and Evaluation," ASME J. Mech. Des., **123**(2), pp. 183–190.
[31] Fellini, R., Kokkolaras, M., Papalambros, P. Y., and Perez-Duarte, A., 2005, "Platform Selection Under Performance Bounds in Optimal Design of Product Families," ASME J. Mech. Des., **127**(4), pp. 524–535.
[32] Thevenot, H. J., Steva, E. D., Okudan, G. E., and Simpson, T. W., 2007, "A Multiattribute Utility Theory-Based Method for Product Line Selection," ASME J. Mech. Des., **129**(11), pp. 1179–1184.
[33] Thevenot, H. J., and Simpson, T. W., 2007, "A Comprehensive Metric for Evaluating Commonality in a Product Family," J. Eng. Des., **18**(6), pp. 577–598.
[34] Kota, S., Sethuraman, K., and Miller, R., 2000, "A Metric for Evaluating Design Commonality in Product Families," ASME J. Mech. Des., **122**(4), pp. 403–410.
[35] Thevenot, H. J., 2006, "A Method For Product Family Redesign Based on Component Commonality Analysis," Ph.D. thesis, Department of Industrial and Manufacturing Engineering, The Pennsylvania State University, University Park, PA.
[36] Thevenot, H. J., Nanda, J., and Simpson, T. W., 2005, "A Methodology to Support Product Family Redesign Using Genetic Algorithm and Commonality Indices," ASME Paper No. DETC2005-DAC84927.
[37] Swift, K. G., and Booker, J. D., 1997, *Process Selection From Design to Manufacture*, Arnold, London, UK.
[38] Thevenot, H. J., and Simpson, T. W., 2007, "Guidelines to Minimize Variation When Estimating Product Line Commonality Through Product Family Dissection," Des. Stud., **28**(2), pp. 175–194.