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A COMPREHENSIVE METRIC FOR EVALUATING COMPONENT COMMONALITY IN A PRODUCT FAMILY

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ABSTRACT

The competitiveness in today's market forces many companies to rethink the way they design (and redesign) products. Instead of developing one product at a time, many manufacturing companies are developing families of products to provide enough variety for the marketplace while keeping costs relatively low. Although the benefits of commonality are widely known, many companies are still not taking full advantage of it when developing new products or redesigning existing ones. One reason is the lack of appropriate methods and useful metrics to assess a product family based on commonality and diversity. Although many component-based commonality metrics have been proposed in the literature, they do not (1) help resolve the tradeoff between commonality and diversity in a product family and (2) capture enough information to be completely useful during product family design and redesign. In this paper, we propose the Comprehensive Metric for Commonality (CMC) to evaluate the design of a product family on a 0-1 scale based on the components in each product, their size, geometry, material, manufacturing process, assembly, costs, and the allowed diversity in a family. To demonstrate the usefulness of this metric for product family benchmarking and redesign, the CMC is compared to six other component-based commonality indices. A CMC-based method is also proposed and applied to a family of staplers to (1) assess the level of commonality in the product family and (2) give recommendations for redesigning the product family.

Keywords*:* commonality, diversity, product family design

1. INTRODUCTION AND MOTIVATION

Today's marketplace is highly competitive, global and volatile: customer demands are constantly changing, and they seek wider varieties of products at prices comparable to mass-produced goods. In order to meet customers' needs while keeping costs relatively low, many manufacturing companies are developing families of products [1]. By doing so, they try to share as many components, processes, and materials as possible between the different products in the family.

While commonality can offer a competitive advantage to a company [2], too much commonality (i.e., not enough diversity) within a product family can have major drawbacks, including a lack of product distinctiveness [3] and a compromise in product performance [4]. Consequently, there is an inherent tradeoff between commonality and diversity within any product family [5]. The optimal commonality is obtained by minimizing the non-value added variations across the products within a family without limiting the choices for customers in each market segment. From a more general view, the idea is to make *each product within a family distinctive in ways that customers notice and identical in ways that customers cannot see*.

Although the benefits of commonality are widely known, they are not always fully understood, and hence they are not always implemented correctly when (re)designing a product family. One of the reasons is the lack of appropriate methods and useful metrics to assess a product family based on commonality. We note that parallel research by Gershenson and his co-authors are attempting to resolve similar issues with modularity, an important factor driving much of product family design, and related metrics for assessing the modularity of product (and platform) architectures can be found in Ref. [6].

In this paper, we propose a new metric, the Comprehensive Metric for Commonality (CMC), which evaluates the design of a product family on a 0-1 scale, based on the components in each product, their size, geometry, material, manufacturing process, assembly, costs, and the allowed diversity in a family.

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In the next section, we review existing component-based commonality metrics. The CMC is introduced in Section 3 and then compared to existing metrics in Section 4. In Section 5, a method using the CMC for product family redesign is proposed and demonstrated using a family of staplers. Finally, Section 6 gives closing remarks and future research directions.

2. RELATED RESEARCH

To assess the degree of commonality within a product family, several commonality indices have been developed based on different parameters such as the number of common components, their connections, their costs, etc. An extensive comparison between many of these commonality indices and their usefulness for product family design or redesign can be found in Ref. [2]. A brief overview of several component-based commonality indices follows.

The *Degree of Commonality Index* (DCI) is the most traditional measure of component standardization [7]. It can be interpreted as the ratio between the number of common components in a product family and the total number of components. While the DCI is easy to compute, its moving boundaries make it difficult to estimate relative increases in commonality when redesigning or comparing different families of products. *The Total Constant Commonality Index* (TCCI), introduced by Wacker and Trelevan [8], is a modified version of the DCI with absolute boundaries ranging from 0 to 1 that facilitates comparisons between families (benchmarking) and between competing designs. Martin and Ishii [9,10] also introduced a commonality index similar to Collier's, namely, the *Commonality Index* (CI), along with indices for measuring *set-up costs* and the *point of product differentiation*, which correlate with many of the indirect costs of providing variety. Jiao and Tseng [11] extend Collier's DCI to create indices for component commonality and process commonality, including the *Component Part Commonality Index* $CI^{(C)}$, which takes into account production volume, quantity per operation, and component costs. Another index found in the literature is the *Product Line Commonality Index* (PCI) developed by Kota, et al. [12]. The PCI does not penalize the components that are unique given the product mix. It is based on size and shape, materials and manufacturing processes, and assembly and fastening schemes. Siddique, et al. [13] propose using separate indices for measuring *component commonality*, *connection commonality*, and *assembly commonality*, applying them to automotive underbodies, which are predominantly integral architectures. Each of these indices results in a percentage of commonality, which can be combined to determine an overall measurement of commonality by weighting each index. More recently, Alizon, et al. proposed the *Commonality Versus Diversity Index* [14], a metric that values or penalizes both commonality and diversity whether they are desired or not desired, respectively.

While these indices may help designers resolve the tradeoff between too much commonality (lack of product differentiation) and not enough commonality (higher manufacturing costs), they do not fully evaluate the impact of each component within a product family on the degree of commonality within the family. For example, the CI, TCCI, DCI and CDI only consider the list of components (or functions) of each product and compare them to see if they are common, variant and/or unique, overlooking information such as component costs, materials, etc. Similarly, the $CI^{(C)}$, does not look at material, manufacturing processes, or assembly. Another limitation of these indices is that they do not fully consider the desired variety in a product family, penalizing it most of the time (except for the CDI). In other words, these indices can only reach their "perfect" value when all the parameters are common between all the components in all the products in a product family regardless of whether these components are adding desired variety to the product family or not. Consequently, there is a need for a new metric that assesses the effect of each component on the overall level of commonality in the product family more comprehensively. The Comprehensive Metric for Commonality (CMC) presented in this paper integrates various aspects of the aforementioned indices into a single measure to capture more information for each component to assess the impact of each component on the overall level of commonality and diversity in the product family. The CMC is introduced in the next section, followed by an example application in Sections 4 and 5.

3. THE COMPREHENSIVE METRIC FOR COMMONALITY

3.1 Definition of the CMC

The Comprehensive Metric for Commonality (CMC) can be considered as an extension of the PCI [12] in order to include production volume and component costs. The required data and the details of its computation are discussed next.

Data for the CMC

The CMC is a component-based commonality metric, and the following information is needed for each component in each product in the product family being analyzed: manufacturing process, material, assembly scheme, production volume, and initial cost (e.g., cost of producing a mold for an injection plastic process). For each product, the information required is: list of components and associated information described above, number of components used in each product, estimated number or products manufactured over the lifetime of the product. Finally, a cost per unit volume is needed for the different materials that are used. To help designers choose the manufacturing process, materials, and assembly, a list of possible choices can be given to the designers (see Refs. [15,16]). The CMC may first appear to be more information-intensive than other indices; however, its formulation makes it more flexible, and if some of the previously data are not available, the index can be adapted to use whatever is available. Moreover, the index can be used at different levels of granularity: in this paper, the CMC is computed at the component level, but if the number of components becomes too large, the CMC can be computed at the module level, where each module is considered as a single entity rather than multiple components. By using modules rather than individual components, designers can identify more clearly the reuse of modules between different products in the product family.

Common, variant, and unique components

The CMC is based on a comparison of components across the different products in the family. Three types of components are identified: *common*, *variant*, and *unique*. A *common* component is the exact same component shared by some or all of the products in the family. A *variant* component has the same function between some or all the products in the family, but the design, shape and/or material differ slightly from one product to the next. A *unique* component is a component used by only one product in the family. The term *component* refers to the entities obtained after the lowest level of disassembly possible, i.e., to the point where the products cannot be divided further and still be re-assembled into a functioning product.

Differentiating components

Components can also be classified as either being *differentiating* or *non-differentiating* [12]. *Differentiating* components are ones that are external (used to differentiate the products aesthetically) or that provide unique function(s) for the product. For example, when considering a family of single-use cameras, the *Identification Label* (aesthetic differentiation, see Figure 1a) and the *APS Film* (functional differentiation, see Figure 1b) are differentiating components. On the other hand, *non-differentiating* components are not used to differentiate products, neither aesthetically nor functionally. As an example, the *Flash* is a non-differentiating component in the single-use camera family (see Figure 1c).


(a) Identification label, differentiating component (aesthetically)

(b) APS film, differentiating component (functionally)

(c) Flash, non-differentiating component

Figure 1. Example of component types

In our work, all unique components are considered to be differentiating; the common components are non-differentiating, and the variant components can be either differentiating or non-differentiating. Before computing the CMC, the first task is to define which components can be made common and/or variant based on whether or not they are differentiating or non-differentiating. This is used later in the *Redesign Strategy* and is decided internally by the company based on the products' specifications. Each company may have a very specific and different redesign strategy: while some companies may want to focus on commonality and minimize the differences between the products, others may prefer to develop specific products with high performance for small market niches at the expense of commonality. In any case, the specific redesign strategy is included in the computation of the CMC to accurately reflect how good the current design of a product family is compared to the goals in the company.

Computation

The CMC is defined as:

$$CMC = \frac{\sum_{i=1}^{P} n_i * (C_i^{\max} - C_i) * \prod_{k=1}^{4} f_{ki}}{\sum_{i=1}^{P} n_i * (C_i^{\max} - C_i^{\min}) * \prod_{k=1}^{4} f_{ki}^{\max}} \qquad (1)$$

where:

P = Total number of components.

n_i = Number of products in the product family that have component *i*.

f_{1i} = Ratio of the greatest number of products that share component *i* with identical size and shape to the number of products that have component *i* (n_i).

f_{2i} = Ratio of the greatest number of products that share component *i* with identical materials to the number of products that have component *i* (n_i).

f_{3i} = Ratio of the greatest number of products that share component *i* with identical manufacturing processes to the number of products that have component *i* (n_i).

f_{4i} = Ratio of the greatest number of products that share component *i* with identical assembly and fastening schemes to the number of products that have component *i* (n_i).

f_{1i}^{max} = Ratio of the greatest number of products that share component *i* with identical size and shape to the greatest possible products that could have shared component *i* with identical size and shape schemes.

f_{2i}^{max} = Ratio of the greatest number of products that share component *i* with identical materials to the greatest possible number of products that could have shared component *i* with identical materials.

f_{3i}^{max} = Ratio of the greatest number of products that share component *i* with identical manufacturing processes to the greatest possible number of products that could have shared component *i* with identical manufacturing processes.

f_{4i}^{max} = Ratio of the greatest number of products that share component *i* with identical assembly and fastening schemes to the greatest possible number of products that could have shared component *i* with identical assembly and fastening schemes.

C_i = Current total cost for component *i*.

$$C_i = \sum_{j=1}^{n_i} C_{ij}$$

C_{ij} = Total cost for component *i* variant *j*.

$C_{ij} = Q_{ij} * c_{ij}$

Q_{ij} = Quantity of component i variant j.

c_{ij} = unit cost for component i variant j.

C_i^{min} = minimum total cost for component i (obtained when the component is common between all the products having component i).

$C_i^{\min} = \sum_{j=1}^{n_i} C_{ij}^{\min}$ C_i^{max} = maximum total component cost (obtained when the component is variant in each of the products having component i).

$C_i^{\max} = \sum_{j=1}^{n_i} C_{ij}^{\max}$ (computed by taking the most expensive variant available and the most expensive materials).

In this paper, the following two cost estimates are used for c_{ij} as an illustrative example. The choice of the cost estimate is independent of the CMC formulation.

(1) For the components produced in-house, c_{ij} is given by:

$$c_{ij} = c_{ij}^a + \frac{c_{ij}^b}{Q_{ij}} \tag{2}$$

where:

c_{ij}^a = material and processing cost (further estimated using component volume * material and processing cost per unit volume).

c_{ij}^b = setup cost (for example, for plastic injection components, this will be the cost to produce the mold).

(2) For purchased components, an appropriate cost estimate should be considered, with decreasing costs as quantity increases due to volume discounts.

The CMC weights the components in the products based on their costs similar to the CI$^{(C)}$ [11], as well as their size and geometry, their material, their manufacturing process, and their assembly scheme, which is similar to the PCI [12]. The CMC ranges from 0 to 1. The highest value of the CMC (=1) is obtained when all the non-differentiating components are common between all the products, and they use the cheapest variant available. The lowest value of the index (=0) is obtained when all the non-differentiating components are different (size, geometry, manufacturing process, assembly, material) between all the products.

Impact of each component on the CMC

The CMC classifies the different components based on their costs C_i and the f_{ji} factors. The total cost to produce a component i ranges from C_i^{min} to C_i^{max}, with C_i^{min} being the lowest cost achievable (best commonality) and C_i^{max} being the most expensive cost possible (worst commonality).

Table 1 shows the effect of each component on the CMC based on its type (common, variant, unique, non-differentiating, differentiating), illustrated by an example from a single-use camera family. First, a non-differentiating component k that is common between all the products using it is considered "ideal", and there is no need for improvement. In Table 1, the cam is shared between the four cameras, and this is a non-differentiating element. The corresponding cost C_k is the lowest that can be achieved (called C_k^{min}), and the corresponding factors f_{jk} take the highest value, i.e., 1. Next, a variant component l that is differentiating needs to remain variant, and hence there is no need for improvement, e.g., the front identification label is made different between the four cameras in order to differentiate them. The corresponding cost C_l is the lowest that can be achieved (called C_l^{min}); the factors take the highest value, i.e., f_{jl}^{max}, but in this case they are lower than one.

Table 1. Impact of different component types on the CMC

Common, Unique or Variant?	Diffentiating or non-differentiating?	Cost		f_{ji}	f_{ji}^{max}	Component	Camera without Flash	Camera with Flash old model	Camera with Flash new model	Waterproof camera
		C_i^{min}	C_i^{max}							
Common Component *k*	Non-differentiating	⊗		$= f_{ji}^{max}$	1	Cam				
Variant Component *(l, m)*	Differentiating	⊗		$= f_{ji}^{max}$	<1	Front Identification Label				
	Non-differentiating	⊗⟷⊗		$< f_{ji}^{max}$	=1	Shutter Base				
Unique Component *n*	Differentiating	⊗		$= f_{ji}^{max}$	1	Waterproof Front Cover				

Table 2. Comparison of the commonality indices based on the information used

Commonality Indices	Components in products	Size and geometry	Materials	Manufacturing processes	Assembly schemes	Component-component connections	Component costs (fixed costs)	Component costs (linked to production volume, setup costs, etc.)	Penalize non-differentiating components only?
DCI	Yes	No	No	No	No	No	No	No	No
TCCI	Yes	No	No	No	No	No	No	No	No
CI	Yes	No	No	No	No	No	No	No	No
PCI	Yes	Yes	Yes	Yes	Yes	No	No	No	No
%C	Yes	No	No	No	Yes	Yes	No	No	No
$CI^{(C)}$	Yes	No	No	No	No	No	Yes	No	No
CMC	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes

Meanwhile, a variant component *m* that is non-differentiating between the products is not "ideal", and hence penalizes the CMC. As an example, the shutter base has two variants, but this component does not differentiate the products. The current cost C_m is higher than the minimum cost achievable C_m^{min}, and C_m can reach the highest value possible (C_m^{max}) when all the products having this component are different (size, geometry, material, manufacturing process, assembly schemes). In this case, the factors f_{jm} are lower than f_{jm}^{max}, indicating that there is room for improvement. Finally, a component *n* that is unique is considered non-differentiating and does not penalize the CMC. For example, the waterproof housing is a function specific to only one camera. The corresponding C_n takes the lowest value (C_n^{min}), while the factors f_{jn} take the highest value (f_{jn}^{max}). As such, CMC only penalizes components *that should ideally be common in a product family* such that the *desired variety* added by differentiating components is not penalized.

3.2 Relationship between the CMC and other component-based commonality indices

The different parameters considered in the CMC are shown in Table 2. The component costs are related to the production volume, the material used, the component volume, and the initial costs. The different variants in geometry, in material, and in manufacturing processes of each component are analyzed as well. While the other commonality indices are also based on this information, they do not capture all of it: the DCI, TCCI, CI and %C fails to capture the size, geometry, manufacturing processes and costs of each component; the PCI fails to capture the component costs; and the $CI^{(C)}$ does not take the size, geometry, manufacturing processes into consideration as shown in Table 2. Moreover, the CMC is the only index that penalizes *only non-differentiating components*. By doing so, the maximum value (in this case 1) can potentially be obtained when all the non-differentiating components are common, while in the other indices, the maximum value is obtained when all the components are common between all the products in the family, including the differentiating components (except for the PCI, which removes the unique components but still penalizes the remaining differentiating components). The CMC includes most of the data that are used in the six other indices; hence, we assert that it provides a more comprehensive assessment of the impact of each component on the level of commonality. A detailed comparison of the CMC to other component-based commonality metrics follows.

4. COMPARISON OF THE CMC WITH OTHER COMMONALITY INDICES

This section demonstrates computation of the CMC and compares it to six other component-based commonality indices from the literature: DCI, TCCI, PCI, %C, CI, and $CI^{(C)}$. The example provided is done at the component level; a similar study could be done at the module level to identify which module(s) can be shared between the products in the family.

4.1 Computation of the CMC

This section details the following steps for the computation of the CMC: (1) gathering the data (data input), (2) defining what can be potentially made common and/or variant between the products (redesign strategy), and (3) computing the CMC (data output).

Step 1: Data input

To demonstrate computation of the CMC, we examine a product family that consists of the three staplers shown in Table 3. No data were available for this family; hence, dissection was conducted to gather the necessary data. The dissection was performed at Bucknell University as part of a summer Research Experience for Undergraduate (REU) Program [17]. To ensure consistency in the dissection, each product within the family is dissected to the lowest possible level. The dissected products are shown in Figure 2. More details on the dissection method can be found in Ref. [18].

Table 3. The stapler family

Model	500	1000	2000
Capacity	2-15 sheets	2-20 sheets	2-60 sheets
			

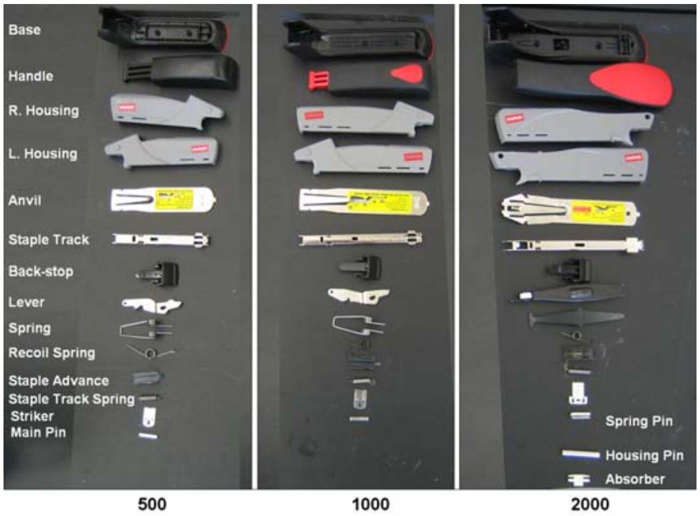


Figure 2. Components in dissected staplers

The staplers are dissected, and the data is stored as shown in Table 4. The first two columns list the name of the components and the corresponding product. In the next column, designers enter a number indicating if the component has the same size and geometry between different products. For example, if two products have the same size and geometry for a given component, then they have the same number. If they use different variants of the component with different size and geometry, then the number is different in the *Size and Geometry* column. If a product does not contain a component, then there is no number in the corresponding column. Using the same idea, designers enter a number corresponding to the material, the manufacturing process, and the assembly and fastening scheme in the next three columns (a proposed coding scheme can be found in Ref. [16]). In the last column, designers enter the quantity of components used per product. Another table containing the quantity per product is created, based on discussion with the stapler manufacturer. A production estimate of each stapler over its lifetime is entered: 2,000,000 for the 500, 3,750,000 for the 1000 and 2,500,000 for the 2000.

Table 4. Example of data entered for the stapler family

Component		Size and geometry	Material	Manufacturing process	Assembly and fastening scheme	Quantity per product
Anvil	in 500	1	41	31	23	1
	in 1000	2	41	31	23	1
	in 2000	3	41	31	23	1
Base	in 500	1	31	11	23	1
	in 1000	2	31	11	23	1
	in 2000	3	31	11	23	1
Track Back-stop	in 500	1	31	11	11	1
	in 1000	1	31	11	11	1
	in 2000	3	31	11	11	1

The third table created is for the component costs (see Table 5). The components are either manufactured in-house, or purchased, using the cost model in Section 3.1. For the components manufactured in-house, the initial costs, the volume of the component and the material cost is entered; for the purchased components, only the purchasing price is entered. The production level for each variant is determined automatically using Tables 4 and 5. The size and geometry factor affects the production level, and hence the initial cost (setup price/total production for this component); the material factor, associated with the component volume, gives an estimate of the material cost.

Step 2: Redesign strategy

The next step is to define which components can be made common and/or variant. This is done by examining the current market segmentation grid for the stapler family [19]. As shown in Figure 3, market segments are plotted horizontally in the grid while price tiers are plotted vertically; each intersection of a market segment with a price tier constitutes a market niche that is served by one or more of a company's products. Based on the given market segmentation, both the 500 and 1000 models target the same market segment, and hence a different design is not necessarily required for the two staplers. If the company still wants to have two products (with different capacities and different aesthetics), then most of the components could be made common between the 500 and the 1000, including the anvil, the base, the staple track, the left and right housing, the striker, the lever, the absorber, and the recoil spring. Currently, only 6 components are common (see Figure 2).

Table 5. Component costs table

Component	Size and Geometry												Material		
	Variant 1				Variant 2				Variant 3				Variant 1	Variant 2	Variant 3
	Volume g	Initial Cost $	Purchasing cost	Production	Volume g	Initial Cost $	Purchasing cost	Production	Volume g	Initial Cost $	Purchasing cost	Production	Price per unit volume $/g	Price per unit volume $/g	Price per unit volume $/g
Anvil	10.04		0.1400	2,000,000	12.65		0.1600	3,750,000	14.81		0.1800	2,500,000			
Base	26.90	29,700		2,000,000	30.10	29,700		3,750,000	70.20	31,020		2,500,000	0.009	0.009	0.009
Track Back-stop	3.20	6,600		5,750,000					3.60	6,600		2,500,000	0.009	0.009	0.009
Staple Track	8.19		0.1200	2,000,000	10.81		0.1700	3,750,000	15.04		0.2000	2,500,000			
Staple Track Spring	0.35			0	0.27		0.0700	5,750,000	0.42		0.0923	2,500,000			
Staple Track Advance	1.12		0.0800	5,750,000	1.00				2.00		0.1400	2,500,000			
Handle	24.40	19,800		2,000,000	46.70	19,800		3,750,000	68.00	33,000		2,500,000	0.009	0.009	0.009
Right Housing	18.60	36,300		2,000,000	23.30	36,300		3,750,000	39.00	37,620		2,500,000	0.009	0.009	0.009
Left Housing	21.10	36,300		2,000,000	24.80	36,300		3,750,000	40.10	37,620		2,500,000	0.009	0.009	0.009
Striker	0.35		0.0800	5,750,000	0.42				0.65		0.1500	2,500,000			
Recoil Spring	0.31		0.1200	2,000,000	0.38		0.1400	3,750,000	0.38		0.1800	2,500,000			
Spring	2.08		0.0800	5,750,000	2.04				5.46		0.2800	2,500,000			
Lever	4.04		0.1600	2,000,000	4.85		0.1600	3,750,000	43.10		0.5000	2,500,000			
Absorber	0.42		0.0400	5,750,000	0.42			0.04	0.27		0.0400	2,500,000			
Housing Pin	4.04		0.0600	2,500,000											
Spring Pin	0.92		0.0600	2,500,000											

Table 6. Product costs table

Component	PaperPro 500				PaperPro 1000				PaperPro 2000			
	Initial	Material	Purchase	Total	Initial	Material	Purchase	Total	Initial	Material	Purchase	Total
Anvil	0.0000	0.0000	0.1400	0.1400	0.0000	0.0000	0.1600	0.1600	0.0000	0.0000	0.1800	0.1800
Base	0.0149	0.2372	0.0000	0.2521	0.0079	0.2654	0.0000	0.2734	0.0124	0.6191	0.0000	0.6315
Track Back-stop	0.0011	0.0282	0.0000	0.0294	0.0011	0.0282	0.0000	0.0294	0.0026	0.0317	0.0000	0.0344
Staple Track	0.0000	0.0000	0.1200	0.1200	0.0000	0.0000	0.1700	0.1700	0.0000	0.0000	0.2000	0.2000
Staple Track Spring	0.0000	0.0000	0.0700	0.0700	0.0000	0.0000	0.0700	0.0700	0.0000	0.0000	0.0923	0.0923
Staple Track Advance	0.0000	0.0000	0.0800	0.0800	0.0000	0.0000	0.0800	0.0800	0.0000	0.0000	0.1400	0.1400
Handle	0.0099	0.2152	0.0000	0.2251	0.0053	0.4118	0.0000	0.4171	0.0132	0.5997	0.0000	0.6129
Right Housing	0.0182	0.1640	0.0000	0.1822	0.0097	0.2055	0.0000	0.2152	0.0150	0.3439	0.0000	0.3590
Left Housing	0.0182	0.1861	0.0000	0.2042	0.0097	0.2187	0.0000	0.2284	0.0150	0.3536	0.0000	0.3687
Striker	0.0000	0.0000	0.0800	0.0800	0.0000	0.0000	0.0800	0.0800	0.0000	0.0000	0.1500	0.1500
Recoil Spring	0.0000	0.0000	0.1200	0.1200	0.0000	0.0000	0.1400	0.1400	0.0000	0.0000	0.1800	0.1800
Spring	0.0000	0.0000	0.0800	0.0800	0.0000	0.0000	0.0800	0.0800	0.0000	0.0000	0.2800	0.2800
Lever	0.0000	0.0000	0.1600	0.1600	0.0000	0.0000	0.1600	0.1600	0.0000	0.0000	0.5000	0.5000
Absorber	0.0000	0.0000	0.0400	0.0400	0.0000	0.0000	0.0400	0.0400	0.0000	0.0000	0.0400	0.0400
Housing Pin		0.0000		0.0000		0.0000		0.0000	0.0000	0.0000	0.0600	0.0600
Spring Pin		0.0000		0.0000		0.0000		0.0000	0.0000	0.0000	0.0600	0.0600

Table 7. CMC computation table

Part	Size and geometry f1	Material f2	Process f3	Fastening f4	ni	Ci	Ci max	Ci min
Anvil	1/3	1	1	1	3.00	1,330,000	1,330,000	1,104,063
Base	1/3	1	1	1	3.00	3,107,887	3,107,887	2,972,365
Track Back-stop	2/3	1	1	1	3.00	254,827	274,654	239,408
Staple Track	1/3	1	1	1	3.00	1,377,500	1,377,500	1,060,625
Staple Track Spring	2/3	1	1	1	3.00	633,125	685,625	505,313
Staple Track Advance	2/3	1	1	1	3.00	810,000	870,000	660,000
Handle	1/3	1	1	1	3.00	3,546,424	3,546,424	3,546,424
Right Housing	1/3	1	1	1	3.00	2,068,586	2,068,586	1,876,860
Left Housing	1/3	1	1	1	3.00	2,186,534	2,186,534	2,027,877
Striker	2/3	1	1	1	3.00	835,000	895,000	835,000
Recoil Spring	1/3	1	1	1	3.00	1,215,000	1,215,000	1,010,625
Spring	2/3	1	1	1	3.00	1,160,000	1,220,000	1,160,000
Lever	1/3	1	1	1	3.00	2,170,000	2,170,000	1,997,500
Absorber	2/3	1	1	1	3.00	330,000	360,000	330,000
Housing Pin	1	1	1	1	1.00	150,000	150,000	150,000
Spring Pin	1	1	1	1	1.00	150,000	150,000	150,000

To differentiate the products, a variant handle and spring could be used. While the 2000 model needs a different architecture due to different sheet capacity, some components can still be made common between the three staplers, namely, the track back-stop, the track spring, and the staple track advance. If these potential recommendations are implemented, then the staplers are produced at the lowest cost that can be achieved, resulting in a CMC value of 1. On the other hand, if all the components are variant in each product, then the commonality is the "worst", resulting in the highest production costs, and the CMC takes a value of 0 in this case.

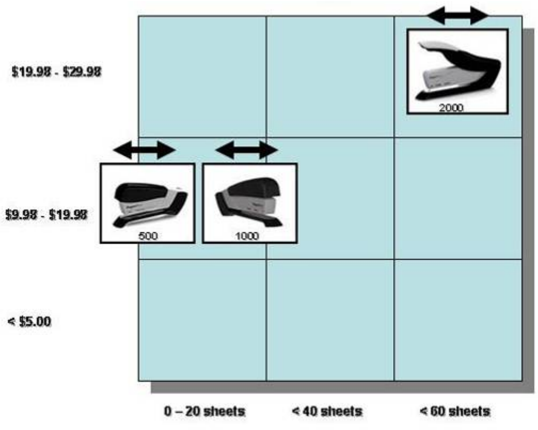


Figure 3. Market segmentation grid for the staplers

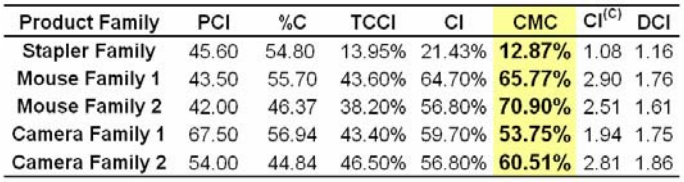
Step 3: Data output

Two tables are created automatically, based on the previous data: the product costs table (see Table 6) and the CMC table (see Table 7). While the product costs table summarizes the cost for each component in each product, the CMC table computes the different terms f_{ji} and C_i for each component, as well as the resulting CMC. The process is done automatically, limiting possible errors during computation and increasing its repeatability. For this product family, the computed CMC is 0.1287, which is rather low on the 0-1 scale. The reason is that although the company did try to share some components between the 500 and 1000 models, they did not focus on sharing the most expensive components; hence, the costs can still be significantly reduced. This is illustrated in Table 7, where the C_i is close to C_i^{max} for most components. Note that for the unique components (e.g., Housing Pin), $C_i = C_i^{max} = C_i^{min}$.

4.2 Comparative study with other component-based commonality indices

The CMC is now compared to the six component-based commonality indices previously analyzed in Ref. [2]: the DCI, TCCI, PCI, %C, CI, and CI$^{(C)}$. These indices consider commonality from a component perspective, i.e., the similarities or differences between components within a product family; they do not focus on aspects such as functionality or performance. The commonality indices are computed for the stapler family, as well as for four other product families: two families of computer mice, each containing 6 products, and two families of single-use cameras (one with 4 products, and one with 7 products). Details on the products and computation of these indices can be found in Ref. [2]. The process follows the one described in Section 4.1 for the CMC. Table 8 summarizes the results, which are analyzed following the table. Note that five indices have fixed boundaries, either between 0 and 1 (TCCI, CI, CMC), or between 0 and 100 (PCI, %C), making it easy to compare the values across product families and across commonality indices. The $CI^{(C)}$ and the DCI, both with moving boundaries, are more difficult to interpret.

Table 8. Commonality indices for five product families



Product Family	PCI	%C	TCCI	CI	CMC	$CI^{(C)}$	DCI
Stapler Family	45.60	54.80	13.95%	21.43%	**12.87%**	1.08	1.16
Mouse Family 1	43.50	55.70	43.60%	64.70%	**65.77%**	2.90	1.76
Mouse Family 2	42.00	46.37	38.20%	56.80%	**70.90%**	2.51	1.61
Camera Family 1	67.50	56.94	43.40%	59.70%	**53.75%**	1.94	1.75
Camera Family 2	54.00	44.84	46.50%	56.80%	**60.51%**	2.81	1.86

For the stapler family, the CMC (12.87%) is relatively low compared to the PCI and %C (45.60 and 54.80, respectively). The reason is that although some efforts were made to make some components common between two of the three staplers, these components are not the most expensive; hence, the costs can still be significantly reduced (e.g., have the housing, the base and the anvil common between two of the three staplers). On the other hand, the PCI and the %C are much higher, as they focus on the material, manufacturing process, assembly, and connections, which are mostly common across the three products, but these indices fail to capture the effect of component costs on the commonality. The TCCI, the CI, the $CI^{(C)}$ and the DCI are quite low as well, due to their focus only on the percentage of common/unique components in the family.

In the families of computer mice, the opposite trend is observed: the CMC has a higher value than the other indices. Two reasons can be given: (1) both manufacturers did a good job at making expensive components common, and (2) they managed to provide commonality in the non-differentiating components while keeping the differentiating components different. While the same trend is observed for the other indices, their information is incomplete, being based only on the number of common components, connections, etc. They also penalize the desired variety, hence making the ideal value of 1 (or 100) not a desired reachable commonality. Also note that the $CI^{(C)}$ is lower for family 2 than for family 1 (2.51 versus 2.90), while the opposite trend is observed for the CMC (70.90% vs. 65.77%). This is due to the fact that the $CI^{(C)}$ does not have fixed boundaries, making comparisons between two families difficult using this index.

For the single-use cameras, an interesting trend is observed: while the PCI, %C, TCCI and CI are higher for the family 1 than for the family 2, the CMC is lower (53.75% versus 60.51%). In other words, family 1 may share more common components, materials, etc., but family 2 focuses more on making the expensive components and the non-differentiating components common. This is also seen in the $CI^{(C)}$, which is higher for family 2 (2.81) than for family 1 (1.94), although a direct comparison is not possible due to its moving boundaries. In summary, the CMC gives more comprehensive results, incorporating both component costs as well as materials, manufacturing process, assembly schemes, and desired variety/commonality, as discussed in Section 3.2.

5. EXAMPLE APPLICATION OF CMC TO REDESIGN A PRODUCT FAMILY

In this section, an example of a method for product family redesign is implemented, using the CMC as the objective function to maximize. First, an overview of the method is given, followed by the results obtained for the stapler family.

5.1 Method for product family redesign

A systematic method for product family redesign using a genetic algorithm (GA) to give recommendations at the component level was introduced in Ref. [16]. The idea is to use a commonality metric to (1) assess the level of commonality in a product family, and (2) provide recommendations for its redesign to improve this metric. This method consists of four phases: (1) data input, (2) commonality assessment, (3) optimization, and (4) recommendations. In this example, the commonality assessment is done using the CMC. Phases 1 and 2 are the same as described in Section 4.1: in Phase 1, the data are gathered through product dissection, and in Phase 2, the CMC is computed, after defining what can be potentially made common and/or variant between the products. In Phase 3, a GA is used to maximize the CMC. GAs are adaptive stochastic optimization algorithms for search and optimization. Instead of working with a single solution at each iteration, a GA works with a number of solutions (collectively known as a population). GAs are based on the notion of the “survival of the fittest”, and they operate by searching for and choosing optimal solutions in much the same way that natural selection occurs [20]. The GA method of optimizing product family redesign utilizes the stochastic search nature of genetic algorithms to find combinatorial designs within the search space. GAs are well-suited for solving combinatorial problems typical in product family (re)design as evidenced by the many approaches using GAs [21]. In this paper, each attribute of a component is encoded as an integer, which is later converted into a binary representation for the GA. The algorithm maximizes the CMC, subject to the following additional constraints to facilitate the selection of components to be redesigned.

Constraint 1: the differentiating components should not be modified during redesign.

Constraint 2: the components that are unique to one product should not be modified. The unique components are defined as differentiating components to keep each product different aesthetically and functionally. Hence, it is desired not to modify unique components.

Constraint 3: if a component is already common throughout the whole family, the optimizer should not modify the component. We are only looking here at the degree of commonality within a product family. Other parameters, such as the performance of each product, are not considered yet. Hence, the components that are common through the whole are considered 'best' for the commonality and should not be modified, although the individual performances of each product may not be optimized.

Constraint 4: maximum number of components allowable to change: there is a restriction on the number of parameters to change between the original design and the redesigned family. If this constraint is not added, the optimizer will find the "best" commonality when all the components are common. By adding this constraint, designers specify a maximum number of allowable changes.

Based on these four constraints, the design variables are chosen such that only variant components are considered. Within this set of components, four attributes are considered: (1) size and geometry, (2) material, (3) manufacturing process, and (4) materials. For a given component, if an attribute is common between all the products using this component, then this attribute is not considered during optimization.

For more details on Phase 3 and 4 and the GA implementation, please refer to Ref. [16]. The GA maximizes the CMC under the previously described set of constraints. One important constraint is the maximum number of changes between the current and the optimized design (Constraint 4): with this constraint, designers specify a maximum number of changes allowable, and the GA returns the best commonality that can be achieved with a given number of changes.

5.2 Recommendations for redesigning stapler family

With the maximum number of changes set to 6 and the GA parameters: Crossover Probability = 0.6; Mutation Probability = 0.01; Population Size = 200 (see Ref. [16] for more detail and experimental parameter testing), the GA returns the following recommendations for the stapler family:

- make the *Anvil* common between the 500 and the 1000;
- make the *Track Back-Stop* common between the 3 staplers;
- make the *Staple Track* common between the 500 and the 1000;
- make the *Staple Track Advance* common between the 3 staplers;
- make the *Left Housing* common between the 500 and the 1000;
- make the *Right Housing* common between the 500 and the 1000.

The feasibility of this solution is ensured by the fact that only feasible changes are allowed during the optimization phase—the constraints entered take into account the feasibility of the solutions. For example, designers do not want to share the *Anvil* between the three staplers; hence, by adding constraints, the anvil can only be shared by the 500 and 1000. In a more generic case, these constraints may be relaxed, but the feasibility of the solutions will not be guaranteed. By implementing the six recommendations previously described, the CMC increases from 12.87% to 70.72%; the costs are also significantly reduced (from -1.90% to -8.38%, see Table 9.

Table 9. Product costs for the staplers family.

Model	500	1000	2000
Original costs	\$2.05	\$2.46	\$4.32
Optimized costs	\$1.97	\$2.26	\$4.24
Difference	-4.06%	-8.38%	-1.90%

While the CMC value is increased by almost 4.5 times, the corresponding cost savings are much smaller. The reason is that the CMC does not only integrate component costs but also similarity factors. In this case, the similarity factors (f_{ji}) are significantly improved, but the corresponding costs savings do not follow the same trend. For example, by making the *Left Housing* common between two of the three staplers (the 500 and the 1000), the similarity factors (f_{ji}) jump from 1/3 to 2/3 (an increase of 100%), while the corresponding decrease in cost is smaller (-2.10% for the 500 and -12.45% for the 1000).

In this example, the scale of the problem is rather limited (fewer than 15 components per product and only three products); the use of optimization for such a simple family is not necessary; however, the same method and metric can be applied on much larger families with more complex products, which could help designers quickly identify the components that influence the commonality the most.

The same method was also applied to five of six indices previously computed, namely, the DCI, the TCCI, the PCI, the CI and the $CI^{(C)}$. The same constraints were used, as well as the maximum number of changes (6). Four of these indices weight the components equally; hence, when maximizing their value using the GA, thousands of solutions are returned, with the same maximum value, and it is difficult to identify on which components to focus. The maximum values returned for each of these four indices are shown in Table 10. For comparison, we analyze the recommendations returned by the algorithm when using the $CI^{(C)}$ instead of the CMC.

Table 10. Comparison of five indices before and after improvement of the stapler family.

	Initial Value	Optimized Value	Difference
CMC	12.87%	70.72%	+449.49%
DCI	1.16	1.38	+18.53%
TCCI	13.95%	27.91%	+100.05%
PCI	45.6	60.44	+32.54%
CI	21.43%	42.86%	+99.99%

The GA returns the following recommendations for the stapler family when using $CI^{(C)}$ instead of CMC:

- make the *Anvil* common between the 500 and the 1000;
- make the *Base* common between the 500 and the 1000;
- make the *Staple Track* common between the 500 and the 1000;

- make the *Handle* common between the 500 and the 1000;
- make the *Left Housing* common between the 500 and the 1000;
- make the *Right Housing* common between the 500 and the 1000.

By implementing these six recommendations, the $CI^{(C)}$ increases by 1.85%, from 1.08 to 1.10. This relatively low increase is due to the way the index is formulated: first, the $CI^{(C)}$ does not have fixed boundaries, making comparisons difficult; second, the original design in not taken into account when computing it. Hence, even if the costs can be dramatically reduced compared to the original design, the $CI^{(C)}$ does not take this difference into account but rather looks at the final cost of each component. Compared to the recommendations obtained with the CMC, only four of six are identical. These two indices, focusing both on costs, tend to put more emphasis on the expensive components. The differences are due to the fact that the CMC includes more data in the analysis and may consider less expensive components that are significantly different in shape, materials, etc.

6. CLOSING REMARKS

Although many component-based commonality metrics have been proposed in the literature, most do not capture enough information to be very useful during product family (re)design and benchmarking. The Comprehensive Metric for Commonality (CMC) proposed in this paper assesses the commonality of a product family more thoroughly based on the components in each product, their size, geometry, material, manufacturing process, assembly and costs, and the desired variety/commonality in a product family. The CMC has some limitations however: it does not take into account component performance. Another limitation is the availability of data: while this index assesses the commonality in a product family more comprehensively, the data needed also increases and may not always be available, and some estimates may be required. Future work suggests studying the sensitivity of the CMC based on uncertainties in the input data. Finally, the CMC focuses on mechanical products and their physical components; future work suggests extending the CMC to assess the effect of software cost on the design as well.

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