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Creating Commonality Indices to Gain an Understanding of the Product Family for Mass Customization

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Research Article

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Abstract

The basic issue with creating a product family is that a business must maximize both internal complexity and external variety, even though the logic of doing so as a way to achieve economy of scale and production standardization has been widely acknowledged in both industry and academia. In light of this perspective, this study acknowledges the need to create commonality metrics in order to comprehend the product family. The paper's objective is to provide design and process engineers an understanding of product family design and manufacturability. The component part commonality and the process commonality are the two sources of similarity that are identified in this study. Product volume, quantity per operation, and component part price/cost are all taken into consideration while formulating the component part commonality, which is based on the idea of calculating the average applications per component part. Process flexibility, lot size, and schedule sequencing are all included in the process commonality index as a single analytical metric. In response to modifications in their parameters, the impact of these two commonality indices on product family design is investigated. The management ramifications are so deduced. The viability of assessing the product family by connecting commonality indicators to the system's performance is examined in order to aid comprehension of the product family. To determine the association between commonality indices and performance metrics, regression analysis is recommended. An outline for further study is included in the paper's conclusion.

Keywords: Product design and performance, engineering design, mass customization, product family, and design evaluation.

Introduction

Mass customisation is an emerging paradigm that seeks to maintain near mass production efficiency while meeting the demands of individual customers [Pine II, 1993]. Customization highlights the distinctions and individuality of items. A significant issue of part proliferation—an increase in the number of different part types that a business needs manufacture or acquire in order to supply a range of goods—will arise from this desire for more diversity and more new products [Child et al., 1991]. The ensuing design variance may result in needless design work as well as significant production and manufacturing support function inefficiencies, including buying, inventory management, and product costing [Vakharia et al., 1996]. Instead of attempting to employ as many current parts as feasible, designers are likely to create new parts every time a new product is proposed unless standardization efforts have been institutionalized. The product family appears as a logical method to enable more effective and economical product creation because of the commonality (similarity) across product lines or among particular tailored items [Meyer et al., 1997]. Tseng and Jiao [1996] suggested using product family architecture (PFA) as a means of enabling mass customisation. In essence, a PFA seeks to present a generic architecture that captures and makes use of commonality, within which every new product instantiates and extends in order to anchor future designs to a common product line structure. This allows a class of products to significantly vary their designs in response to various customization requirements.

The basic issue with creating a product family is that a business must evaluate the degree of variety at which customers will still find its offerings appealing and the level of complexity that will keep the company's costs low [Child et al., 1991], i.e., optimizing internal complexity and external variety. This is true even though the rationale of the product family as a means of achieving the

economy of scale and standardization of production has been well recognized in both industry and academia [Ishii et al., 1995]. The complexity of both product design and production planning and control is reflected in the quantity and variety of component parts and the accompanying procedures. The degree to which design, production, planning, and control systems may be challenging may thus be determined by measuring internal complexity. More precisely, a commonality assessment is the most effective way to address the standardization and complexity problem that underlies the product family [Roque, 1977; Collier, 1978; Wacker and Treleven, 1986]. Additionally, the commonality measurement offers a lever to describe the distinction between individual product design and product family design. In light of this perspective, this study acknowledges the need to create commonality metrics in order to comprehend the product family. The paper's objective is to provide design and process engineers an understanding of product family design and manufacturability. This study expands on earlier research on complexity indices of offering diversity [Ishii, 1995; Martin and Ishii, 1996; 1997] and commonality indices [Collier, 1981; Wacker and Treleven, 1986; Treleven and Wacker, 1987].

With a focus on commonality indices, relevant work on commonality is addressed in the next section. In order to comprehend the product family, Section 3 addresses the sources of similarity. The measurements of two sources of commonality—component part commonality and process commonality—are also provided. Section 4 looks at how the two commonality indices affect product family design when their parameters are changed. The management ramifications are so deduced. The viability of assessing the product family by connecting commonality indexes to the system's performance is covered in Section 5. To determine the association between commonality indices and performance metrics, regression analysis is recommended. The report ends with an idea for further research after discussing the creation of commonality indexes.

Background Review

A typical definition of commonality is the ratio of a system's common (or unique) components to its overall number of components [Thomas, 1992]. The degree to which similar components (architectures, parts, or subsystems) may be used across a product line is referred to as commonality. A substantial amount of research is dedicated to different elements of commonality, such as commonality metrics, identification of common parts, and operational implications on production.

Many people have seen the practical advantages of commonality. These include lowering planned loads through larger lot sizes [Collier, 1982; Guerrero, 1985], lowering inventory levels by lowering safety stock requirements [Collier, 1982; Baker, 1985; Eynan and Rosenblatt, 1996], lowering planning complexity by lowering the number of items to be planned [Collier, 1981; 1982; Vakharia, 1996], and lowering system development costs by reducing redesign efforts [Hopson et al., 1989]. Additionally, the costs of commonality have been examined. As commonality increases, the product line becomes less flexible [Collier, 1980], and loading variability (workload imbalance) increases [Vakharia et al., 1996; Tsubone et al., 1994]. The application of commonality in tightly constrained systems would be limited by the disutility that results from failing to provide each segment of customers with an item that meets their exact requirements. This would lead to lost sales and, consequently, the degradation of a system's functional parameters [Thomas, 1992].

The commonality problem's solution has drawn a lot of interest. Several nonlinear programming approaches constitute the foundation of early solution methodologies [Passy, 1970; Shaftel, 1971]. Heuristics were later used to identify common things [Rutenberg and Shaftel, 1971]. For commonality analysis, Dogramaci [1979] created an intuitive heuristic clustering technique. Orlicky [1975] provided techniques for determining the level of the product structure where modules are recognized as the proper place to choose the MPS (master production schedule) units. Several scholars have used commonality indices to address commonality measurement as the core problem of commonality. Roque [1977] proposed potential resource savings via a reduction in complexity and characterized the degree of component standardization as the mean number of

applications per component. Collier [1978; 1981] developed a cardinal measurement of the degree of commonality index (DCI) for component part commonality and demonstrated the correlation between the DCI and setup and holding costs using statistical techniques. Wacker and Treleven [1986] proposed differentiating between within-product and cross-product commonality using TCCI (total constant commonality index), a modified form of DCI that is a relative measure ranging from 0 to 1. Three process commonality indices in terms of setup time, sequencing flexibility, and expediting flexibility were produced by Treleven and Wacker [1987] after they investigated the origins of process commonality. Although DCI and TCCI seem to have a lot of potential, prior studies have only examined the production planning component, without taking into account the impact on product design. According to this perspective, Tsubone et al. [1994] distinguished between process and component part commonality and combined the two forms of commonality when evaluating manufacturing performance. Nevertheless, their commonality metrics are only appropriate for a two-level product model, which is not very useful in real-world scenarios.

Ishii et al. [1995] highlighted the significance and viability of creating complexity indices for assessing the costs of offering variation in the context of mass customisation. They recommended utilizing the commonality index, postponement index, and setup index to comprehend the costs of product proliferation [Martin and Ishii, 1996; 1997]. These indices provide a deeper understanding of the true meaning of product variation, particularly from a design viewpoint, which has up to now mostly been expressed qualitatively, despite their imprecise articulation of quantitative data.

Commonality Measurement for Product Family

When designing for mass customisation, product family assessment is crucial [Tseng and Jiao, 1996]. The commonality measure must take manufacturing and design considerations into account. Tsubone et al. [1994] noted that for systematic examinations of the product family, two distinct sources of similarity—the component part commonality and the process commonality—must be clarified. Additionally, Treleven and Wacker [1987] promoted separating component part similarity from process commonality. In contrast to component part commonality, high process commonality does not need a high degree of component similarity since a single process might generate a variety of components. Furthermore, one might argue that a high degree of similarity across domestically generated component parts would need a high degree of commonality among the associated processes. The opposite is not always the case, either, as in the case of those parts that were obtained from outside sources. Additionally, comparable (or even identical) processes may be shared by unique (different) things. This section introduces two metrics, the component part commonality index and the process commonality index, denoted as CI (C) and CI (P), respectively, to describe two sources of commonality included in the product family.

Product structure model for representing product family

In this research, a bill-of-material (BOM)-like product structure is employed to represent the product family. McKay et al. [1996] and Erens et al. [1994] have demonstrated that the BOM-based product structure excels in modeling the product family. The set of three product structures depicted by Collier [1981] is used here as examples to illustrate the applicability of such a hierarchical product structure model to represent the product family (Figure 1). In Figure 1, the product structure model is also explained using a simplified family (NFS40) of power suppliers as examples. The notions are described as follows.

Figure 1 The product structure model for representing product family

Each node in the hierarchical structure represents a distinct component part in the product family, noted as d_j ($j = 1,2,...,d$, where d denotes the total number of distinct component parts in a product family). These distinct component parts can be applied across the member products of the family with some repetition. There are three types of meaning for a d_j according to its level in the product tree. Each highest-level node represents an end-item, i.e., a member product in the family. The lowest nodes comprise the purchased parts for the family which are externally ordered. All the intermediate nodes represent internally made parts that involve either manufacturing or assembly operations.

The parent-child relationships indicate different operations. A one-to-one relationship represents the manufacturing process(es), where the parent node is made from the child node, e.g., $d_8 \rightarrow d_{11}$ in Figure 1. A one-to-many relationship indicates assembly operation(s), where the parent node is a subassembly and consists of child nodes, e.g., $d_9 \rightarrow (d_{11}, d_{12})$ in Figure 1. The annotation beside each node represents the number of units required for its higher node by one parent-child operation, noted as q. For example, in Figure 1, one unit of part d_4 is made from two units of part d_{10} in product 1 and one unit of d_6 is assembled from two units of d_8 and one unit of d_9 in product 3.

The principal characteristics of real product structures, such as multiple end items, multiple component parts, multiple parents, and common component parts at the same level and at different levels, can be modeled by the hierarchical structures in Figure 1. Generally, the representation is applicable to a single end item, a product family, to the firm's entire product line, or to any level of the product structure [Collier, 1981]. For example, in case of more than one product family, the same representation can be applied, where distinct component parts may be used beyond one family.

Component part commonality index – $CI^{(C)}$

The Collier's [1978; 1981] degree of commonality index (DCI) is well known for measuring component part commonality. The mindset underpinning component part commonality is to count the mean number of applications (repetitions) per component [Roque, 1977]. In the analysis of whether or not a product family is adequately designed, measuring component part commonality depends on more dimensions than only repetition, such as the cost or price of each component part, the volume of the final product, and the quantity per operation. Wacker and Treleven [1986] took these concerns into account in their development of the variable total constant commonality index. Instead of pursuing a relative measurement of component part commonality, this paper extends their study to include internally made parts and applies these factors to Collier's DCI. The formulation of $CI^{(C)}$ is described next.

The price or cost of each component part affects $CI^{(C)}$ in the way that sharing a high-priced component part exerts a positive effect on $CI^{(C)}$. Taking this price/cost factor into account, Collier's DCI can be elaborated as the following:

$$\square\square P_j \square\square_j \square$$

Where $CI_{(1)}^{(C)}$ □ the initial component part commonality index for a product family,
d – the total number of distinct component parts used in all the product structures of a product family,
j – the index of each distinct component part d_j, $\square j \square 1,2,...,d$,
P_j – the price of each type of purchased parts or the estimated cost of each internally made component part,
m– the total number of end products in a product family,
i – the index of each member product of a product family, $\square i \square 1,2,...,m$,
$\square_{ij}$ – the number of immediate parents for each distinct component part d_j over all the product levels of product i of the family,

$\sum_{i\square 1}^{m} \square_{ij}$ – the total number of applications (repetitions) of a distinct component part d_j across all the member products in the family,

$\alpha_{(1)}$ – the maximal degree of commonality, $\alpha_{(1)} \square \square \sum_{j\square 1}^{d} \max_{i\square 1}^{m} \square_{ij} \square 1$.
The boundaries of the $CI^{(C)}$ are 1 and α , where a value of 1 represents no commonality and a value of $\alpha_{(1)}$ represents the highest possible commonality. The calculation of $CI^{(C)}$ is according to the BOM-like representation of a product family. As an aside, the costs of internally made parts are not straightforward to obtain. In our research, a pragmatic approach to cost estimation is developed [Jiao and Tseng, 1999], which is based on the standard time estimation.
Another dimension that $CI^{(C)}$ should take into account is the quantity of component parts for each operation (parent-child relationship) which has been specified in the BOM-like product structures. Let Q_{ij} denote the quantity of distinct component part d_j required by the product i, then the $CI_{(1)}^{(C)}$ of Eq. (1) can be further refined as follows:

$$CI^{(C)} \square \frac{\sum_{j\square 1}^{d} \square \sum_{i\square 1}^{m} \square P_j \square \square_{ij} \square Q_{ij} \square}{\sum_{j\square 1}^{d} \square \sum_{i\square 1}^{m} \square P_j \square Q_{ij} \square} \square 1 \square CI^{(C)} \square \alpha \quad (2)$$

(2) d m (2) (2)

where $\alpha_{(2)}$ is the maximal degree of commonality, $\alpha_{(2)} = \sum_{j=1}^{d} \sum_{i=1}^{m} \delta_{ij} - 1$.

Since multiple end products are involved with $CI^{(C)}$ for a product family, end product volume must also be considered. Let V_i denote the volume of end product i in the family. Then we can rewrite Eq. (2) as following:

$$CI_{(C)} = \frac{\sum_{j=1}^{d} P_j \left(\sum_{i=1}^{m} V_i Q_{ij} \right)}{\sum_{j=1}^{d} P_j \left(\sum_{i=1}^{m} V_i Q_{ij} \right)} \left(1 - CI^{(C)} \right) + \alpha \quad (3)$$

where $\alpha = \sum_{j=1}^{d} \sum_{i=1}^{m} \delta_{ij} - 1$, representing the largest possible value of $CI^{(C)}$.

The quantity of distinct component parts d_j applied to one particular product i can be calculated by multiplying quantity per operation q through the levels of the product tree, i.e.,

$$\square \quad \square h \square 1,2,...,n_h$$

$$n_h \square n_k$$

$$Q_{ij} \square\square\square\square q_{hk} \square \quad \square k \square 0,1,2,...,n \text{ , for each item } d_j \text{ in product } i \text{ (4)}$$

$$h\square 1 \square k \square 0 \quad \square \quad k$$

where h represents one particular path from the item d_j to the end item node through the levels of the product tree for a particular end product in the family (the path includes node d_j and excludes the end item node and is identified in the same way as
finding immediate parent nodes for d_j in a product i), n_h denotes the total number of such paths for d_j within product i, n_k denotes the total number of parent nodes on
path h, k is the index of the nodes on path h, where $k \square 1,2,...,n_k$ represents parent
nodes and k 0 represents the node d_j itself, and q_{hk} represents the quantity per operation (either manufacturing or assembly) of node k required by its immediate parent node along path h. For instance, in Figure 1, for item d_{12} (j 12) of product 1
(P1), there are two paths ($n_h \square 2$) from d_{12} to end item P1, which can be represented by the nodes along the path, i.e.,
$h \square \{d_{12} \square d_{10} \square d_4 \square d_1, d_{12} \square d_9 \square d_6 \square d_1\}$
and
$\{k \mid k \square 0,1,2,3\} \square \{\{d_{12}, d_{10}, d_4, d_1\},\{d_{12}, d_9, d_6, d_1\}\}$.
Therefore, the quantity of d_{12} used in P1 can be calculated according to Eq. (4):
$Q_{1,12} \square 3\square 2\square 4\square 1\square 1\square 1\square 1\square 1\square 25$. Table 1 illustrates the calculation of $CI^{(C)}$ for the
product family shown in Figure 1, where the volumes of three end products are assumed as 100, 80, and 50, respectively.
Combining Eq. (3) and Eq. (4), we have the final formulation of component part commonality for a product family as following:

$$d \quad \square \quad m \qquad m \quad \square \quad n_h \quad \square\square\square \quad \square \quad n_k$$

$$\square\square P_j \square\square_{ij} \square\square V_i \square\square\square q_{hk} \square\square\square$$

$$CI^{(C)} \square \frac{j\square 1 \quad \square \quad i\square 1 \; h\square 1 \quad \square}{i\square 1 \quad \square \quad \square k \quad \square} \quad 1\square CI^{(C)} \square \alpha \text{ (5)}$$

$$\square 0 \quad \square$$

$$d \quad \square \quad m \quad \square \qquad n_h \quad \square\square\square$$

$$\square n_k$$

Table 1 The $CI^{(C)}$ calculation sheet for product structures in Figure 1

Process commonality index – $CI^{(P)}$

The process commonality, $CI^{(P)}$, of a product family is characterized by the mean utilization of manufacturing capabilities for producing all the internally made parts and end products in the family. Therefore, the initial formulation of $CI^{(P)}$ can be defined by modifying the process flexibility measure of Tsubone et al. [1994] as follows:

$$CI^{(P)} = \frac{\sum_{p=1}^{n_p} \sum_{j=1}^{n_d} \lambda_{pj}}{n_p} - 1 \quad \text{if } CI^{(P)} < \beta \quad (6)$$

(1) *n* (1) (1)
p

where n_p = total number of processes needed for producing a product family,
p = the index of a particular process, either be a fabrication or assembly operation, $p = 1, 2, ..., n_p$,
n_d = total number of internally made items in a product family, including all the end products and internally made component parts (refer to the product structure model in Figure 1),
j = the index of an internally made item, either of a final product or internally made component part, excluding purchased parts, $j = 1, 2, ..., n_d$,
λ_{pj} = a 0-1 variable, indicating that part item j can either be produced at process p or not, that is, if part item j can be made or assembled at process p, then $\lambda_{pj} = 1$, otherwise $\lambda_{pj} = 0$,
$\beta_{(1)}$ = the maximal degree of commonality, $\beta_{(1)} = n_d - 1$.
The introduction of λ_{pj} encompasses the situation that one process could produce more than one distinct part item and similar component parts could share one process, which is a major difference between the process commonality and the component part
commonality. The derivation of λ_{pj} depends on the process planning of a product family,
which basically determines process-part assignments according to the product structures of the family as well as existing process facilities. Table 2 gives an example

of process capabilities for the product family in Figure 1, where there are three processes ($n_p = 3$) available for producing 13 internally made parts (3 end products and 13 internally made component parts since d_{11} and d_{12} are purchased component parts). For the power supply example, these processes represent three actual assembly lines

with different configurations. In this example $CI^{(P)}_{(1)} = (7+7+9)/3 = 7.67$, which

indicates a kind of process commonality measure in terms of process flexibility for a given product family.

Table 2 An example of process capabilities for the product family in Figure 1

The value of the above flexibility-based process commonality index ranges from 1 to n_d, where a larger value indicates a higher process commonality (capability/flexibility).

When all the part items need unique processes, $CI^{(P)}_{(1)}$ equals 1, meaning there is no

sharing of common process(es). On the other hand, if all the part items utilize one

identical process, then $CI^{(P)}_{(1)} = n_d$, representing the highest process commonality possible.

While process flexibility represents an important dimension of process commonality measurements, lot sizing is another area in which process commonality has been recognized as having an impact on scheduling. In determining the appropriate economic lot size, the setup time (cost) required is a key factor since lower setup times result in smaller economic lot sizes. Therefore, the appropriate measure of this lot sizing component of process commonality should consider the mean of the setup times for all possible setups at a particular process [Treleven and Wacker, 1987]. Moreover, the importance of the setup times is directly related to the part volume. The setup times for the high volume parts can be crucial and should be more heavily weighted than other setup times [Treleven and Wacker, 1987]. Furthermore, whether production is in large lots or single units, management should schedule the production so that the total of setup times is minimized. The setup times used in calculating process commonality should be those that reflect this minimum total set time sequence. Taking these concerns into account, the $CI^{(P)}$ of Eq. (6) can be elaborated as follows:

□ nd pd pd □ n* n*
□ □λ □SET** □D* □
np □j pj pj j |1 □CI(P) □β (7)
CI(P) □ □ j* □1 j* □1
1

(2) □□ n □ (2) (2)
n*
——————————
□ □□D* SET** □ □
p□1 □ p pd □
□ j pj □
j* □1

*
where n_p, p, n_d, j, and λ_{pj} have the same meanings as those in Eq. (6), n is the
total number of part items produced by process p when production is scheduled in the

n_p
sequence that minimizes the total setup times ($\square n_d$), SET^*_{pj} denotes the setup
$\square n^*$

p□1

time of part item j^* ($\square j^* \square 1,2,...,n^*_{pd}$) on process p according to the sequence of the
minimum total setup time, $\beta(2)$ is the maximal degree of commonality ($\beta(2) \square n_d \square 1$),
and D represents the demand (volume) of part item j^* and is derived from the product structures of the family:
m for part item $j^* \square 1,2,...,n^*$. (8)
$D_j^* \square \square V_i Q_{ij}^*$
i□1

pd

Treleven and Wacker [1987] pointed out an important dimension of process flexibility, the sequencing flexibility, referring to the differences in the penalties (setup times) for changing between any two operations. This flexibility would be the highest if the setup times required for all operations in a process were identical. Consequently, there would be no penalty (difference in setup time) for choosing any particular sequence of shop orders over any other sequence. Therefore, other things being identical, the scheduler would be indifferent to the sequence of the jobs to be processed. In other words, having setup times that are sequence independent allows the scheduler greater freedom in determining the order in which the jobs are to be scheduled. Ideally, from a sequencing standpoint, all setup times would be equal and

sequence independent so that they would not be a constraint in the sequencing decision. Since this would be true regardless of the magnitude of the setup times, the setup time variance is the appropriate measure of this sequencing component of process commonality [Treleven and Wacker, 1987]. In this research, we characterize this sequencing flexibility using the coefficient of variation (i.e., standard deviation to mean ratio, σ_m) of setup times.

Therefore, incorporating the consideration of setup time variance, the ${}_{(3)}CI^{(P)}$ of Eq. (7)
can be further refined as the following:

$$CI^{(P)} = \sum_{p=1}^{n_p} \left[\frac{\sum_{j=1}^{n_d} \lambda_{pj} \sum_{j^*=1}^{n_{pd}^*} SET_{pj^*}^* \sum_{j^*=1}^{n_{pd}^*} D_{j^*}}{n_p \sum_{j^*=1}^{n_{pd}^*} \left(D_{j^*} SET_{pj^*}^* \right)} \left(1 - \frac{n_{pd}}{\sum_{j=1}^{n_{pd}} SET_{pj}} \sqrt{\frac{\sum_{j=1}^{n_{pd}} \left(SET_{pj} - \overline{SET_p} \right)^2}{n_{pd} - 1}} \right) \right]$$

$1 \leq CI^{(P)} \leq \beta$ (9)

where $\beta = n_d \geq 1$, representing the largest possible value of $CI^{(P)}$, SET_{pj} represents the setup time needed for a job (part item) j at process p if this job could be processed at the process ($\lambda_{pj} = 1$), $\overline{SET_p}$ denotes the average setup times of the set of jobs that can be produced at process p, and n_{pd} is the total number of part items required by a product family to be produced by process p. Different from n_{pd}^* for a specific scheduling sequence, n_{pd} is defined for all candidate jobs that can be produced by process p regardless of scheduling sequences. Moreover, $\sigma_m \geq 1$ is assumed to reflect real production situations.

To determine all the possible jobs that can be processed by a process p, simply let $j = j_k \mid \lambda_{pk} = 1, k = 1,2,\ldots,n_d$. Therefore, we have:

for each process $p = 1, \ldots, n_p$. (10)

$$\overline{SET_p} = \frac{\sum_{j=1}^{n_{pd}} \left(\lambda_{pj} SET_{pj} \right)}{\sum_{j=1}^{n_{pd}} \lambda_{pj}}$$

Substituting Eqs. (8) and (10) into Eq. (9) yields the final formulation of the process commonality index as the following:

$$CI^{(P)} = \sum_{p=1}^{n_p} \left[\frac{\sum_{j=1}^{n_d} \lambda_{pj} \sum_{j^*=1}^{n_{pd}^*} SET_{pj^*}^* \sum_{j^*=1}^{n_{pd}^*} D_{j^*}}{n_p \sum_{j^*=1}^{n_{pd}^*} \left(D_{j^*} SET_{pj^*}^* \right)} \left(1 - \frac{n_{pd}}{\sum_{j=1}^{n_{pd}} SET_{pj}} \sqrt{\frac{1}{n_{pd} - 1} \sum_{j=1}^{n_{pd}} \left(SET_{pj} - \frac{\sum_{j=1}^{n_{pd}} \left(\lambda_{pj} SET_{pj} \right)}{\sum_{j=1}^{n_{pd}} \lambda_{pj}} \right)^2} \right) \right]$$

$1 \leq CI^{(P)} \leq \beta$. (11)

Table 3 illustrates the calculation of $CI^{(P)}$ for the product family shown in Figure 1. In order to calculate the process commonality, which part items can be produced by which processes and their respective setup times must be known. The part-process assignments are derived from process planning according to the product structures in Figure 1. The estimated setup times of part items at particular processes are obtained based on the standard time estimation [Jiao and Tseng, 1999]. The process specifications include two types of setup times. One is for all possible assignments of part-process (denoted as "general" in Table 3). The other type contains only those setup times corresponding to the sequence of minimum total set time (denoted as "special" in Table 3). In this example, there exists high process commonality ($CI^{(P)}$ $\square 28.134$) since only 3 processes accommodate all 13 part items, demonstrating a high utilization of process capabilities.

Table 3 The $CI^{(P)}$ calculation sheet for the product family in Figure 1

Analysis and Managerial Implication

Essentially, the component part commonality index $CI^{(C)}$ represents the degree to which common part costs have been distributed across all products in a product family. This can be examined via parameter analysis which is described next.
Figure 2 demonstrates the changes of $CI^{(C)}$ with respect to the cost of a component part. It reveals that the impact of part cost on product family commonality is correlated with the utilization of the part. That is, the commonality is more sensitive to the cost of a common part (d_{12} with $\square_{12}$ $\square 6$) than a less common part (d_{10} with $\square_{10}$ $\square 3$). While large cost of a common part (d_{12} with $\square_{12}$ $\square 6$) contributes to the overall commonality,
large cost of an uncommon part (d_7 with $\square_7$ $\square 1$) or a less common part (d_{10} with
$\square_{10}$ $\square 3$) has negative effect on the family commonality. This suggests to managers that the part standardization program should focus more on expensive parts rather than on inexpensive ones, meanwhile product family design should avoid using those uncommon parts with high price/cost.

Figure 2 Changes of component part commonality index with respect to part cost

Figure 3 shows the response curve of component part commonality with respect to changes of quantity per operation (QpO). The increase of QpO of a common part (d_{12} with $\square_{12}$ $\square 6$) exerts a positive effect on overall commonality, whereas increased usage of an uncommon part (d_7 with $\square_7$ $\square 1$) or a less common part (d_{10} with $\square_{10}$ $\square 3$) impairs the index. This is coincident with the mindset of using common parts wherever possible and as many as possible.

Figure 3 Changes of component part commonality index with respect to quantity per operation

Combining Figures 2 and 3, it is concluded that when price or quantity per operation for a particular component part dominates the product family, in terms of cost and usage, the index falls to reflect loss in commonality if the part has low repetition in product structures; on the contrary, increased usage and cost of common parts with high repetition contribute to the family commonality. That is, as common (uncommon) cost and usage increase, the commonality index increases (decreases). Such a dichotomy of utilization of common component parts in contribution to overall commonality of the product family manifests decision tradeoffs inherent in the product family design.

The component part index can be applied to either a product family or a single product. Using Eq. (5) for each end product in the family in Figure 1 yields a commonality index at a single product level, i.e., $CI^{(C)}_1 \square 1.75$, $CI^{(C)}_2 \square 4.66$, and $CI^{(C)}_3 \square 4.72$. Such a single product commonality index conforms to the within-product commonality index as defined by Wacker and Treleven [1986]. Figure 4 shows the index's change in response to the volume change of a particular product (within-product commonality). The results reveal that as the volume of any end item increases, the family commonality index moves in the direction of the within-product commonality index for the end item that has the increased volume. In other words, increase in end item volume of those items that have high within-product commonality contributes to the overall component part commonality. From a managerial perspective, a volume increase in a high within-product commonality should increase the overall commonality of a product family.

Figure 4 Changes of component part commonality index with respect to product volume

To examine the formulation of the process commonality index, sensitivity analysis is used to test the response of the index with respect to changes in parameter value. Table 4 presents various process specifications and the responses of the index, where scenario A is used as a base line.

The measure of process commonality index, $CI^{(P)}$, indicates that as setup times increase in aggregate (SET_p), the value of $CI^{(P)}$ decreases (A, F and D), since with aggregated setup times increasing from 4 to 4.67 and to 8, the $CI^{(P)}$ value decreases from 9 to 7.89 and to 7.53 with almost the same setup time variations (0, 0.124 and 0.125). Thus, the index moves in the proper direction when aggregated setup times change.

The impact of setup time on process commonality can be further examined by changing the setup time of a particular job and holding all other parameter values the same for a particular situation (A). As shown in Figure 5, the process commonality tends to diminish when a particular setup time increases and dominates all other jobs. The work center A, in which all setups require the same amount of time, has no process imposed constraints on the sequencing of its jobs. Therefore, the standard deviation to mean ratio (σ / m) reflects this with a value of zero. However, even though the aggregated setup times are equal for work centers A and B (SET_p 4), the work center B has a higher variability in setup times (0.25 ~~0)~~ and, presumably, more difficulty in job sequencing with a relatively small value of $CI^{(P)}$ (6.75 9).

The impact of demand on process commonality can be demonstrated by work centers D and E. While large setup times are weighted by large demand in E, resulting in a low index value, the heavy demand weighting is on small setup times in D and yielding a relatively high value of $CI^{(P)}$.

Therefore, the results of this sensitivity analysis show that the process commonality index appropriately reflects the relative process commonality in a variety of situations.

Table 4 Process specifications used in sensitivity analysis and the responses of process commonality index

Figure 5 The impact of setup time on process commonality

The managerial implications of the process commonality index can be manifested at both strategic and operational levels. At the strategic level, the process commonality index could be used to evaluate the impact of product family designs on existing process capabilities, and vice versa. If, for instance, a customized product were under planning, information about how well the processes required for production of this product fit with the current set of processes would be extremely useful. Taking this type of information into account would facilitate a systematic approach to maintaining the economy of scale. An organization can use the process commonality index as one criterion for the value analysis of its product planning and strategy. In addition, the process commonality index could be used at the tactical level as an important lever with which to assist process reengineering by streamlining the utilization of process capabilities. For example, the index could be used to evaluate the impact of different groupings on process commonality. This would be especially appropriate for organizations that tend to have many alternate routings. This type of information would also be useful in grouping items into families for cellular manufacturing. Additionally, greater process commonality, if coupled with reduced setup times (as it often would be), would make small lot production possible, thus catering an enabler of mass customization.

In summary, all of two commonality indices seem to respond adequately to changes in parameters to give an adequate overall picture of product family commonality and its sources. These measurements give a better indication of component part standardization and process flexibility and their sources, thus providing useful assistance in understanding and evaluating product family design.

Discussion

The importance of developing product families has been well recognized in design for mass customization [Tseng and Jiao, 1996]. The effects of alternate product structures on the production system's performance must be understood and evaluated in product family design. The development of commonality indices enables analytical measurements of describing product family characteristics, thus presenting a prerequisite to understanding the relationships between product family structures and the system's performance. This section discusses how to evaluate product family design and performance based upon the two commonality indices developed.

A lot of researchers investigated the operating impacts of commonality involving total cost, safety stock levels, workload variability, and delivery performance, etc. They demonstrated various methods to evaluate the system's performance based on some forms of commonality measurements, regarding the development of manufacturing performance criteria and measurements, simulation experimental design, and statistical analysis [Tsubone et al., 1994; Vakharia et al., 1996; Guerrero, 1985].

The elegant work of Collier [1981; 1982] used the analysis-of-variance technique to show the relationship between the DCI and setup and holding costs and further applied regression analysis to finding a linear equation describing the effect of commonality on safety stock. This illustrated the feasibility of regressing commonality measurements on the system's performance. Here we suggest following Collier's method to develop the relationships between our commonality indices and the system's performance. The general polynomial function for regression analysis can be expressed as:

$$\psi r \quad \square \varphi \cdot r \qquad r2$$

$$\square A_{r1}\,(CI^{(C)}\ \square CI.^{(C)})\ \square A \qquad \overline{(CI^{(C)}\ \square CI.^{(C)})^2}\ \square A_{r3}(CI^{(C)}\ \square CI.^{(C)})^3 \tag{12}$$

$$\square B_{r1}(CI^{(P)} \square CI.^{(P)} \square B\ (CI^{(P)} \square_{r2} CI.^{(P)})^2 \square B\ (CI^{(P)} \square_{r3} CI.^{(P)})^3$$

where ψ_r defines the performance measurement for the r-th criterion variable, A_{rs} and
B_{rs} are regression coefficients, s represents tests for linear (s 1), quadratic (s 2),
and cubic (s 3) trends, respectively, $CI^{(C)}$ and $CI^{(P)}$ are numerical values of commonality indices. In Eq. (9), $\varphi_{.r}$ is defined as the mean value of performance levels

$\overline{\quad}$ $\overline{\quad}$

in experimental design, while $CI.^{(C)}$ and $CI.^{(P)}$ are the average over all degrees of commonality levels in experimental design.
In this regression analysis, several criterion variables are used to reflect the multi-criteria nature of the system's performance. They could be total cost, throughput, on-time delivery, safety stock levels, etc., depending on particular operating characteristics [Treleven and Wacker, 1987]. In addition, a trend analysis [Collier, 1981] across different levels of commonality indices for each performance criterion can provide the regression coefficients necessary to develop equations that can be used to estimate the change in any performance measure for any level of the degree of commonality. Since the trend analysis considers the deviation of each observation, the analysis-of-variance technique [Lindman, 1974] is used to reveal its statistical significance.

Moreover, the statistical package SAS [Kalt, 1991] can be used to perform the effect analysis of variance, the trend analysis, and selected planned orthogonal contrasts.
Whatever approach taken, the commonality indices provide analytical measurements to characterize product structures. They are possibly directly related to the evaluation of the system's performance, thereby helping managers better understand product families.

Summary

The product family has been proved to be an instrument for mass customization. Commonality is the most important lever with which to characterize and discern product family design from individual product development. The analytical measure of commonality is necessary to understand and evaluate the product family. The clarification of the component part commonality and the process commonality helps to understand different sources and consequences underlying the product family. The development of the component part commonality index and the process commonality index facilitates the assessment of the product family from both design and manufacturing perspectives.
This research extends Collier's DCI to include more important dimensions of component part commonality such as product volume, quantity per operation, and the costs of component parts. This work is different from Wacker and Treleven's TCCI in that the formulation of the component part commonality index is designed to be incorporated with the process commonality index. Instead of ignoring different origins and components of commonality like Ishii et al.'s complexity indices, this work clearly clarifies various facets of commonality underpinning the product family. The formulation of the process commonality index facilitates the composition of different ingredients of process commonality such as process flexibility, lot sizing, and scheduling sequencing, and is more comprehensive than the postponement

index's ignoring the sequencing feasibility [Martin and Ishii, 1996; 1997]. Moreover, the linkage between the system's performance and commonality indices is possible through regression analysis. This would benefit the understanding and evaluation of product family design.

As witnessed in the research, commonality measure is the fundamental issue and carries important managerial implications in product family design for mass customization. However, this study is just a beginning upon which further research can be built. Future work takes on two aspects, validating the indices and elaborating the relationships between the indices and the system's performance. This work can be best approached by working with industry partners and using commercial examples.

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