DESIGN FOR NONASSEMBLY: CURRENT STATUS AND FUTURE DIRECTIONS

Sangjin Jung[1], Rianne E. Laureijs[2], Christophe Combemale[2], and Kate S. Whitefoot[3*]

[1]Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213
[2]Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213
[3]Department of Mechanical Engineering; Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213

ABSTRACT

Nonassembled products, which are produced from a raw material and post-processed to a final form without any assembly steps, form a large and potentially growing share of the manufacturing sector. However, the design for manufacturing literature has largely focused on assembled products, and does not necessarily apply to nonassembled products. In this paper, we review the literature on design for nonassembly (DFNA) and the broader literature on design for manufacturing that has design guidelines and metrics applicable to nonassembled products, including both monolithic single-part products and nonassembly mechanisms. Our review focuses on guidelines that apply across multiple manufacturing processes. We identify guidelines and metrics that seek to reduce costs as well as provide differentiated products across a product family. We cluster the guidelines using latent semantic analysis and find that existing DFNA guidelines fall into four main categories pertaining to: (1) manufacturing process, (2) material, (3) tolerance, and (4) geometry. We also identify existing product family metrics that can be modified for nonassembled products to measure some aspects of these categories. Finally, we discuss possible future research directions to more accurately characterize the relationships between design variables and manufacturing costs, including investigating factors related to the complexity of operations at particular process steps and across process steps.

1. INTRODUCTION

Nonassembled (NA) products makeup a substantial share of the manufacturing sector and have the potential to grow considerably in the future. NA products are produced from a raw material and post-processed to a final form without any assembly steps [1, 2]. We estimate NA products to account for approximately 50% of U.S. manufacturing as measured by value of shipments [3] (detailed information is provided in Appendix A). Examples of specific NA products include: products made of raw materials such as fabricated metal products (e.g., fasteners, brackets, fixtures, beams, wire, springs), glass products, wear parts, and other durable goods; monolithic plastic goods; ceramics; food and beverages; as well as chemicals and pharmaceuticals [3]. Moreover, advances in materials and production processes—such as additive manufacturing (AM), large die castings, and parts consolidation—have enabled more products to be manufactured with reduced or no assembly [4-7]. Therefore, one might expect nonassembled manufacturing to increase in the future.

While there is a long history of developing design for manufacturing (DFM) guidelines [5, 8-14], much of it is focused on assembled products, and does not necessarily apply to NA products. For example, multiple DFM studies have recommended using symmetry to reduce errors and time of assembly, such as designing a part to be symmetric around the axis of insertion so that it cannot be assembled incorrectly [13, 15, 16]. However, different design elements of NA products may be important to reducing the costs of manufacturing steps. For example, for a molded, forged, or additively manufactured part, asymmetry may not affect costs, but whether or not the design has overhangs can significantly affect costs and ease of manufacturing [17].

NA products also pose unique challenges in product differentiation. Assembled products often achieve differentiation by incorporating modular components with common interfaces, which can be swapped out to change various product attributes while maintaining the same assembly step. In contrast, achieving differentiation in NA products requires changing inherent attributes of the entire product, such as material, geometry, tolerance, size, and treatment [18]. Unlike assembled products, achieving this differentiation of attributes in NA products necessarily requires a process change, which may require additional labor, machines, and/or tooling [18].

This paper reviews the literature on design for nonassembly (DFNA) and the broader literature on DFM that has design guidelines that can apply to this domain. In this review, we examine cost-related guidelines—including recent literature on design guidelines for nonassembly mechanisms—as well as guidelines and metrics related to product differentiation and product variety. We then synthesize the identified DFNA guidelines into four main categories using latent semantic analysis and hierarchical clustering.

We find a major gap in the literature dealing with design guidelines for nonassembly: while general guidelines for assembly are widespread [13-15] and offer helpful general insights to a wide range of cases, nonassembly presents unique challenges that have thus far been addressed only in narrow product or process-specific contexts, for example steel pouring [4] or metalorganic chemical vapor deposition [19]. In reviewing the broader DFM literature, we see that many DFM guidelines focus on reduction of parts, design of part interfaces for assembly, and design for assembly steps that are not applicable to NA products. In this paper, we seek to draw out some of the general design principles underlying the presently disunified literature and to begin developing a nonassembly equivalent to the broad design guidelines that have benefited assembled products.

We find that existing design guidelines that apply to NA products focus on product size and shape, material, tolerances, and post-processing steps to reduce costs and increase variety. We also identify some existing product family metrics that can be modified to fit NA products. In addition, we discuss the limitation of the DFNA guidelines and directions for future work associated with developing a set of guidelines and metrics for capturing the relationships between design variables and production complexity and cost.

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[*]Corresponding Author: Kate S. Whitefoot

2. DESCRIPTION OF DFNA

NA production takes raw materials as inputs, and transforms them into a product (whether intermediate or final) through fabrication and post-processing steps that do not include assembly [1, 2]. For the purpose of this paper, we adopt the Merriam-Webster definition of "assemble" as "to fit together the parts of" [20]. NA products can either be sold as a standalone product (e.g. cutlery, glassware, plastics, pharmaceuticals) or sold to a customer who uses it as a subcomponent of another assembled product (e.g. fasteners, auto body components, building infrastructure including beams and joists, and other monolithic sub-components). For example, a formed plastic cup holder produced by company A that sells the product to automotive company B that assembles it into a vehicle for final sale would fit this classification (Figure 1). Examples of NA products include fabricated monolithic metal parts such as hand tools, cutlery, fasteners, brackets, fixtures, beams, wire, springs, automotive and machinery components, and other such products; plastic injection molded products; glass products; ceramics; chemical and pharmaceutical products; additive manufactured products; processed food and beverage production; and other products that do not require assembly. Common processes applied to NA products include forging, stamping, pressing, grinding, sintering, extrusion, molding, and other processes that form raw materials into shapes, remove or add material, and treat the material to change its properties [18].

While many NA products are monolithic parts, in special cases, some multi-component parts may fit the definition of NA products described above. One case is when a component is embedded into the part during fabrication (e.g., composite fibers, embedded sensors [21-23]). A second case is nonassembly mechanisms, in which distinct components are fabricated together [7, 24, 25]. In both of these cases, the components are built into the product during the fabrication process in contrast with assembled products, in which multiple discrete components are fabricated separately and fit together.

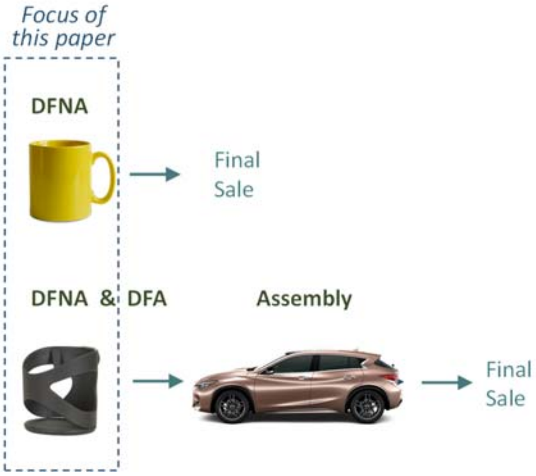

Figure 1. DFNA applies to both products that are sold as final goods, and products that are sold as intermediate goods and later assembled into final goods. We review guidelines that are relevant to both of these cases. Images from [26-28].

The concept of DFNA is the practice of designing a product for fabrication and post-processing that seeks to minimize costs and optimize product attributes (including the variety of those attributes in a product family) to maximize profits within the constraints of existing production technology [1, 18]. DFNA will naturally draw on principles in the broader DFM literature, although some of these principles may apply differently to NA products, and result in distinct DFNA design guidelines. We use Figure 2 to illustrate the relationship between design for assembly (DFA) and DFNA. As the figure shows, there is a region of design guidelines that apply to both NA and assembled products (e.g., using low-cost materials that meet functional requirements, minimizing tooling changeover, design for low-labor-cost operations). We review these strategies in this paper, as well any guidelines that apply uniquely to DFNA.

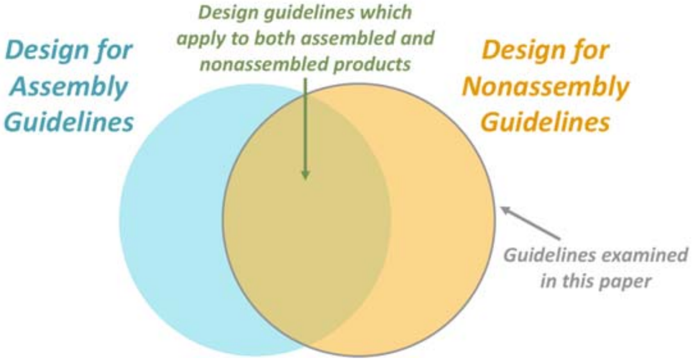

Figure 2. There is overlap between DFA and DFNA design guidelines.

3. SCOPE OF LITERATURE REVIEW

In this paper, we review design guidelines for NA products as well as DFM guidelines and metrics that can apply to NA products. In this review, we focus on guidelines that apply across multiple manufacturing processes. There are many articles that focus on design guidelines for a single manufacturing process (e.g., injection molding or additive manufacturing), which are highly specific to machine capabilities for the specific process. For example, Bralla [4], Boothroyd et al. [5], and DRM Associates [29] provide very detailed guidelines associated with specific manufacturing processes (e.g., sheet metal, casting, injection molding, stamping). Anderson [6] also introduce specific design guidelines for castings and molded parts, plastics, and sheet metal. Meisel et al. [30] suggests some specific design guidelines for metal-based AM, and Booth et al. [31] provide design guidelines and a worksheet for AM assessing complexity, functionality, material removal, unsupported features, stress concentration, tolerances, and geometric exactness. We exclude these process-specific guidelines from our review in order to synthesize more general guidelines for DFNA.

There is a significant body of literature that discusses both the benefits and tradeoffs associated with designing a product or system to be manufactured without assembly (e.g., using parts consolidation) as opposed to assembled from multiple components [32-34]. We do not review this literature here, but instead focus on guidelines for design for manufacturing after the decision to produce a non-assembled product has been made.

There is currently only a small body of literature focused on general design guidelines and methods that are specific to NA products [1, 2, 18]. However, a subset of existing DFM guidelines are applicable to NA products as well as assembled products. Our approach to collecting and synthesizing a body of literature relevant to DFNA was to review not only NA-specific guidelines, but also the broader DFM literature, identifying guidelines that are applicable to NA products.

This review consisted of three stages: literature collection, identification of NA-relevant guidelines, and synthesis. For the literature collection, we searched for articles in English on Scopus and Web of Science that have "design for manufacturing" or "design for manufacture" in their title and "guidelines," "rules", "design principles", "design for manufacture", or "design for manufacturing" in the abstract or title. This search resulted in over 200 papers published between 1978-2019. The majority of these articles are published by authors in the United States or Europe, although articles published by authors in Asia, South America, and Australia were also represented. We then reviewed the design guidelines in these papers and reduced them to the most relevant set based on two criteria: (1) the guidelines are relevant to NA products, and (2) the guidelines are general and broadly applicable. Based on the first criteria, guidelines were eliminated if they solely focused on conditions requiring multiple components assembled together. Specifically, they were eliminated if they focus on: (1) part count reduction, (2) design of interfaces for assembly, and (3) design for assembly steps. Based on the second criteria, guidelines were eliminated if they only applied to one specific NA manufacturing method—such as injection molding or additive manufacturing—but did not apply across any other manufacturing methods. The remaining set of guidelines are reviewed in this paper. Finally, we synthesized the identified guidelines using latent semantic analysis and hierarchical clustering analysis to group them according to the similarity of the guidelines and keywords used in them.

4. COST-BASED GUIDELINES FOR DFNA

4.1 General DFNA Guidelines

Many research articles and books have introduced general and specific DFM guidelines [4-6, 13-15, 29, 35, 36]. The main purpose of many DFM and DFA guidelines is to modify a design to carry out the same functions while reducing production costs [37]. The guidelines that we identify as applicable to DFNA and summarize in this section can be readily associated with minimizing production costs. For example, design for low-cost labor operations, reduce weight to reduce costs, and design for general purpose tooling (because that will reduce tooling costs). The complete list of the specific DFNA-relevant guidelines are included in Appendix B.

Stoll [15] suggests ten DFM principles, two of which are applicable to DFNA: (1) design parts for ease of fabrication and (2) minimize handling. In addition, Kirkland [12] introduces several kinds of general guidelines for DFM, some of which can be applied to NA products (e.g., optimize raw material selection and process selection). However, the remaining design guidelines (e.g., develop a modular design, avoid separate fasteners, and minimize assembly directions) are only able to be applied to the design of assembled products. Adachi et al. [38] also suggests general design guidelines for DFM, some of which are applicable to NA products that are associated with the production process and facility (e.g., synchronize with development of production facilities, minimize impacts on production processes).

Bralla [4] published the Design for Manufacturability Handbook, which introduces a wide range of general DFM principles that apply to multiple manufacturing processes and suggests numerous design considerations and guidelines for different types of parts and products. Unlike the prior research on DFM in the literature, these DFM guidelines can be generally employed to the design of both assembled and NA products. These DFM guidelines are primarily focused on design simplification, dimensioning, cost, and manufacturing processes.

Boothroyd [14], Edwards [16], Swift and Booker [39], van Vliet and van Luttervelt [40], and Luo et al. [41] have suggested more extensive and detailed DFM guidelines associated with material, cost, manufacturing process, standardization, tolerance, drafting, geometry, and size, many of which are applicable to DFNA. These guidelines have been applied to different types of products in firms [14, 16, 39-41]. For example, a heater core cover fabricated using injection molding by a U.S. automotive manufacturer was redesigned following the guideline "aim at uniform wall thickness" [14, 42]. By changing the geometry to achieve uniform wall thicknesses, the consequent cycle-time was reduced in the injection molding process and both tooling and processing costs were lowered [14, 42]. In addition, the number of cavities was reduced, and the production rate of heater core covers increased. As a result, the total manufacturing cost of the heater covers was reduced by 33% [14, 42]. The general DFNA guidelines suggested by Edwards [16], Swift and Booker [39], van Vliet and van Luttervelt [40], and Luo et al. [41] are described in Appendix B.

Similar to previous studies on DFM guidelines, Anderson [6] introduces nine kinds of high-level design guidelines for DFM, five of which are applicable to DFNA: (1) adhere to specific process design guidelines, (2) design for fixturing, (3) minimize tooling complexity by concurrently designing tooling, (4) specify optimal tolerances for a robust design, and (5) specify quality parts from reliable sources. Anderson [6] also suggests general design guidelines for fabricated parts as follows, and they can be employed to conduct DFNA that applies across multiple manufacturing processes:

- Choose the optimal processing.
- Design for quick, secure, and consistent work holding.
- Use stock dimensions whenever possible.
- Optimize dimensions and raw material stock choices.
- Design machined parts to be made in one setup.
- Minimize the number of cutting tools for machined parts.
- Avoid arbitrary decisions that require special tools and thus slow processing and add cost unnecessarily.
- Choose materials to minimize total cost with respect to post-processing.
- Concurrently design and utilize versatile fixtures.
- Understand work-holding principles.
- Understand tolerance step functions.
- Specify the widest tolerances consistent with function, quality, reliability, safety, and so forth.
- Be careful about too many operations in one part.
- Concurrently engineer the part and processes.
- Do not over-specify surface finishes.
- Reference each dimension to the best datum.

Compared to the previous studies, they contain different types of guidelines associated with manufacturing process, work-holding, material, dimension, cost, tolerance, and surface finish, but some of these guidelines are very similar to the guidelines in the other studies (e.g., choose materials to minimize total cost).

As shown in Appendix B, many similar or identical guidelines are identified in the literature.

4.2 Design for Nonassembly Mechanisms

Enabled by additive manufacturing (AM), nonassembly mechanisms are produced by fabricating multiple components with joints between them without requiring any assembly steps [7, 21, 24, 25]. While the current literature exclusively focuses on guidelines for nonassembly mechanisms that are produced through AM, they could in theory be manufactured through several other means (e.g., forming with post-processing material removal). Thus, we include this literature in our review, focusing on the guidelines that could apply not only to AM but other processes as well.

The design of NA mechanisms poses unique design challenges for joints, and thus several studies have noted important considerations for joint design and its feasibility (i.e., the product will not function if the guidelines are not followed) [7, 24, 25, 43]:

- Fabricated joints must have sufficient clearance to avoid fusing or catching.
- Fabricated joints cannot have such great clearance that they fail mechanically to connect.
- Minimize friction in the joint and other strain.
- Minimize the tolerance of each joint to improve the position accuracy.

One advantage of NA mechanisms is their wide range of geometric possibilities outside the limitations of assembly. For example, built-in elements that are internal to the nonassembly but would be impossible to insert into the product because of its geometry can be created during fabrication. However, the geometric design of NA mechanisms also raises additional guidelines associated with mechanism performance and manufacturing cost [7]:

- Pursue geometries that minimize support structures.
- Pursue geometries whose support structures are easily removable.
- Minimize interfaces for material deposition or shaping that could lead to trapping or deterioration of material and undermine mechanism performance.

With respect to the general design of multi-articulated NA products, Cuellar et al. [44] suggest ten guidelines that fall into three broad types:

- General: integration of parts functionality and facilitating supports and interfaces in production.
- Play: minimizing lost motion.
- Stress: distributing and managing applied load.

5. PRODUCT DIFFERENTIATION-BASED DFNA

The guidelines discussed above are motivated by reducing the costs of producing individual products. In addition to minimizing costs, many firms also seek to increase their market share and profits by providing differentiated products [45, 46]. Product family design, defined by Jiao et al. (2007) as "a conceptual structure and overall logical organization of generating a family of products by providing a generic umbrella to capture and utilize commonality", provides a strategy for reducing costs while increasing product differentiation [47]. In assembled products, this differentiation can be achieved through the interchangeability of unique components or modules via shared interfaces [45-48]. Interchangeability, however, does not serve to reduce costs for NA products because they either have no sub-modules or components, or—such as in the case of nonassembly mechanisms—subcomponents are fabricated together simultaneously. Therefore, different strategies are required to minimize costs of a differentiated NA product family [18]. We review product family design strategies for NA product families, and metrics that may be applied to NA product portfolios to reduce costs while preserving differentiation. We then focus on characterizing NA product attributes that may impact NA product families.

5.1 Product Family Design Strategies

While most product family literature focuses on sharing common components [49-54], which will not necessarily serve to reduce costs for NA product families, there are some existing product family guidelines that can apply to NA products. First, both Robertson and Ulrich as well as Meyer and Dalal have noted that products that can share common production assets, processes, and systems can help facilitate production flexibility [1, 55]. In the context of a product family, differentiated NA products can be developed based on platforming a set of common elements (e.g., materials) while creating variants using other elements (e.g., treatments). For instance, the manufacturing process of integral films requires coatings of fifteen different fluid layers such as acid polymer layer, image receiving layer, and blue, green, and red sensitive emulsions, and the family of integral film products share raw materials for each layer and multiple steps within their entire production process [1].

In addition, multiple authors propose scale-based strategies for creating product families [56-58], which may also be applied to NA products. Scale-based strategies define parameters of the product design (e.g., key dimensions) which can be scaled up or down in magnitude to achieve multiple product variants within a family [58]. Simpson [57] defines a scale-based product family as one which is based on stretching or shrinking along a dimension to accommodate product variety within product platforms. Simpson et al. [56] also suggest a metric for developing scale-based product platforms, the Product Platform Concept Exploration Method (PPCEM), which takes in market factors, design parameters, and scaling variables and develops a scale-based product platform output.

Our review yielded only two studies that propose strategies specifically for NA product family design. Meyer and Dalal focus on engineers' evaluation of shared process and technologies across NA products, finding platforms where there is sharing and reuse [1]. Furthermore, they suggest that the best way to measure product platforms for NA products is through platform efficiency, a measure which they propose as being primarily based on manufacturing, tooling, and engineering costs of various product generations [1]. Moving beyond shared components and resources entirely, Laureijs et al. [18] seek to define the building blocks of commonality specifically for NA products, and propose a theory of NA product family design that focuses on common design variables across NA products. These common NA design variables are: material, geometry, tolerance, size, and post-processing treatment steps (e.g., material coatings, or heat treatment). One example is a product family based on common product geometry and size but with varying materials and coatings. Diversity in these variables may affect the flexibility of the line, thus impacting total manufacturing costs from producing a product portfolio on the line [18]. Figure 3 recreates the proposed theory of how variety in each of these design variables impacts manufacturing operations that affect costs.

	You may affect the process in the following ways:							
As you Increase Variety In:	**Equipment Price/Quantity**	**Batch Size**	**Fixtures /Tooling**	**Cycle Time**	**Yield**	**Scrap**	**Material Price**	**Load/Unload /Setup**
Size	⬆	⬆/⬇	⬆	⬆	⬇			⬆
Geometry		⬆/⬇	⬆	⬆	⬇			⬆
Material	⬆	⬇	⬆	⬆	⬇	⬆	⬆/⬇	⬆
Treatment	⬆		⬆		⬇			⬆
Tolerance	⬆	⬇	⬆		⬇			⬆

Figure 3. As proposed by Laureijs et al. [18], when variety increases in each of the proposed NA product attributes, various parameters of the production process are affected in a way that can influence costs.

5.2 Product Family Metrics for DFNA

Several metrics have been created to allow engineers to evaluate the variety and commonality within a product family in order to reduce costs while maintaining differentiation [1, 49-53, 59-64]. Most of these metrics focus on the commonality of components in assembled products [49-53, 59-64]. For example, the Percent Commonality Index quantifies the percentage of shared components, connections between components, and assembly stations across a product family [61].

Lager [2] suggests a conceptual platform-based design framework which integrates product platform, process platform, and raw material platform for NA product families, and the framework can help identify the commonality related to design requirements, functionalities, production processes, and raw materials. The conceptual framework does not provide detailed design methods or metrics to evaluate the characteristics of NA product families such as platform efficiency and commonality.

One article measured platform efficiencies in a case of NA products [1], which focuses on product R&D, manufacturing, and tooling costs across product generations. The metric used is calculated as:

$$E_p = \frac{(C+M+R)_p}{\sum_{g=first\ generation}^{latest\ generation}(C+M+R)_g} \tag{1}$$

where p is the index of a single derivative product; g is the generation of the product line; C is the product engineering costs attributable to architecture and platform development, or derivative product development based on these platforms within a product family; M is the manufacturing engineering costs; and R is the retooling and related capital costs for manufacturing equipment. A smaller value of E_p means higher platform efficiency. E_p only considers costs to capture the degree of platform efficiency within NA product families. The metric does not map costs to specific design variables (e.g., choices of tolerances that increase yield losses, machine set-up, or calibration time) to inform design decisions.

Despite the lack of design-relevant metrics for NA product families, some of the existing metrics for assembled products can be used or adapted to evaluate the degree of product variety or commonality in NA product families. Metrics such as the Non-Commonality Index (NCI) [62] and the Product Family Penalty Function (PFPF) [63] have been developed to evaluate the dispersion of a product family's design variables for scale-based product families. These can be applied to NA product families to capture commonality or dispersion of non-categorical design attributes such as size, tolerance, and certain geometric measures. In theory, these metrics could be extended to binary indicator variables of other attributes such as material or treatment type.

Two other existing product-family metrics were identified that could be modified for use with NA products. The first is the Product Line Commonality Index (PCI) developed by Kota et al. [53]. This metric considers the size, shape, material, and manufacturing processes for each product. PCI also evaluates the commonality on assembly and fastening schemes, but this commonality factor can be removed for use in DFNA. PCI was originally utilized to evaluate the commonality of multiple numbers of parts in a product family, but can be adjusted to measure the commonality across NA products as follows:

$$\mathrm{PCI_{NA}} = \frac{f_1 \times f_2 \times f_3 - \frac{1}{n^3}}{1 - \frac{1}{n^3}} \times 100 \tag{2}$$

where n is the number of NA products in the product family; f_1 is the size and shape factor; f_2 is the materials factor; and f_3 is the manufacturing processes factor. For example, if the value of PCI is close to 100, it means that the NA product family has high commonality in terms of size and shape, materials, and manufacturing processes. In addition, it can be possible to add different types of commonality factors (e.g., tolerances) in design and fabrication processes for NA products. The second is the Comprehensive Metric for Commonality (CMC) developed by Thevenot and Simpson [49], which considers size, shape, material, assembly and fastening schemes, manufacturing process, and total cost within a product family. The greater value of CMC represents higher commonality (e.g., when a product family has more common size, shape, material, assembly schemes, and manufacturing process, and when the total costs for each product are lower). Like PCI, this commonality metric can be adjusted to capture the degree of commonality for NA product families by dropping the commonality factor on assembly and fastening schemes.

The existing product family metrics in the literature have not been developed for NA products, so there are limitations when applying them to NA products. Existing metrics may not be able to capture the key differentiating characteristics across an NA product family such as the degrees of commonality and differentiation of multiple manufacturing processes such as heat treatments. Additionally, distance measures of the dispersion of product attributes across the family may not necessarily map well to the costs of variety. For example, depending on the manufacturing process, the number of distinct different attribute values (e.g., three options of length) of a product may matter more for costs than the distance between these values (e.g., 10, 15, 20 cm, or 14, 15, 16 cm). We discuss these issues in the discussion of future directions of research in Section 7.

6. CLUSTERING OF DFNA GUIDELINES

In this section, we analyze the NA relevant guidelines reviewed above using latent semantic analysis and agglomerative hierarchical clustering to determine emergent themes of the guidelines.

6.1 Methods

Latent Semantic Analysis

Latent semantic analysis (LSA) is often used to quantify the degree of similarity between documents and the keywords used in them [65-67]. In this work, we employ LSA to capture the degree of similarity between the identified guidelines and keywords. Following [65], we define the term-document matrix, $\mathbf{X}_{(n_t \times n_d)}$ where n_t is the number of terms and n_d is the number of documents. The singular value decomposition (SVD) provides the decomposed matrices of $\mathbf{X}$ as shown in Eq. (3):

$$\mathbf{X} \approx \widehat{\mathbf{X}} = \mathbf{TSD}' \tag{3}$$

where $\mathbf{T}$ is the matrix of left singular vectors (i.e., the matrix of eigenvectors of $\mathbf{XX}'$); $\mathbf{D}$ is the matrix of right singular vectors (i.e., the matrix of eigenvectors of $\mathbf{X}'\mathbf{X}$); and $\mathbf{S}$ is the diagonal matrix of singular values.

In this work, we evaluate the cosine similarity between (1) two keywords, (2) two guidelines, and (3) a keyword and a guideline. The cosine similarity has been widely used to measure the similarity between terms and documents in the literature [65, 66, 68, 69]. We follow this procedure applied to guidelines rather than documents. The cosine similarity, γ_{ij} is represented using a dot product and magnitudes of the vectors, $\mathbf{A}$ and $\mathbf{B}$ as seen in Eq. (4). To evaluate the similarity between two keywords, $\mathbf{A}$ and $\mathbf{B}$ are the i^{th} and j^{th} row vectors of the matrix $\mathbf{TS}$. In addition, the cosine similarity γ_{ij} between two guidelines or a keyword and a guideline can be evaluated.

$$\gamma_{ij} = \frac{\mathbf{A} \cdot \mathbf{B}}{\|\mathbf{A}\|\|\mathbf{B}\|} = \frac{\sum_{i=1}^{k} A_i B_i}{\sqrt{\sum_{i=1}^{k} A_i^2}\sqrt{\sum_{i=1}^{k} B_i^2}} \tag{4}$$

Many existing studies have employed two-dimensional plots (i.e., when the rank k of the matrix $\widehat{\mathbf{X}}$ is 2) to analyze semantic similarities between terms and documents [65, 66, 69, 70]. However, if the rank of the original matrix $\mathbf{X}$ is very high (e.g., there exist many terms and documents), the accuracy of similarities obtained using two-dimensional singular vectors would be very low [65]. Therefore, we need to use the matrix $\widehat{\mathbf{X}}$ with the higher rank and analytically compute cosine similarities of all pairs of keywords and guidelines. In this work, we define the similarity matrix $\mathbf{R}$ which contains cosine similarities of all pairs of 83 keywords and 93 guidelines (i.e., the size of the matrix is 176 x 176). The cosine-similarity matrix is utilized to identify and cluster similar keywords and guidelines using a hierarchical cluster analysis [71-75].

Hierarchical Clustering

Agglomerative hierarchical clustering (AHC) [76-78] is a clustering method that sequentially clusters elements based on their similarities (or dissimilarities). In AHCs, the dissimilarity measure between two clusters is utilized to determine which clusters are merged [78]. In this work, the unweighted pair group method with arithmetic mean (UPGMA) [79] is employed because it has the advantage of being less affected by outliers in determining clusters. The measure is represented as follows:

$$\delta(x, y) = 1 - \gamma(x, y) \tag{5}$$

$$(C_i, C_j) = \frac{1}{|C_i| \cdot |C_j|} \sum_{x \in C_i} \sum_{y \in C_j} \delta(x, y) \tag{6}$$

where $\gamma(x, y)$ is the cosine similarity between pairs of objects x in the cluster C_i, and y in the cluster C_j, computed using Eq. (4); $\delta(x, y)$ is the dissimilarity between pairs of objects x in C_i, and y in C_j; $\delta(C_i, C_j)$ is the dissimilarity between cluster C_i and C_j; and $|C_i|$ is the cardinality of C_i (i.e., the number of elements of C_i). The similarity matrix contains cosine similarities of all pairs of keywords and guidelines, so x (or y) in Eq. (5) and (6) can be a keyword or a guideline. Thus, similar keywords and guidelines can be clustered together.

6.2 Guideline Clusters

In hierarchical clustering methods, the size and number of clusters are decided using the location of a cut-off line in the dendrogram. The optimal number of clusters are usually determined based on a clustering index such as the dissimilarity between clusters [80, 81]. In our case, the dissimilarity between clusters steadily increases when reducing the number of clusters, with no asymptote. So, instead, we investigate changes in the occurrence of the cluster's representative keywords (i.e., the keyword with the highest frequency in the cluster's guidelines) in the cluster and in other clusters. When the number of clusters is between 1-5, the guidelines in each cluster do not contain the representative keyword of a different cluster. This indicates that the clusters have mutually exclusive representative keywords. In addition, when the number of clusters increases from 1-4, the rate of keyword frequency (i.e., representative keyword frequency in the cluster per guideline) grows, but it does not grow when increasing the number of clusters from 4-5. Consequently, we chose four clusters as the preferred number of clusters. All clustering results including the keywords, guidelines, and clusters generated using different numbers of clusters are shown in Appendix C.

In the case of four clusters, the representative keyword of the first cluster is "manufacturing process", with additional keywords closely related to process steps such as "work-holding", "orientation", "tooling", "machining", and "inspection". The second cluster is mainly related to "material" guidelines. These guidelines pertain to material selection, material cost, material changeover, material properties, stock dimensions, and common materials. Meanwhile, the third cluster includes the keywords and guidelines associated with "tolerance", and the fourth is related to "geometry" such as geometric simplification, size, gradual changes of sections, drafting, and dimensioning.

Based on the characteristics of each cluster, we synthesize DFNA guidelines as follows. We first find similar or duplicated guidelines (e.g., G8: simplify the design, and G22: ensure maximum simplicity in overall design, as shown in Appendix C), and the duplicate guidelines are removed. We then standardize all the guidelines into imperative sentences based on a grammatical formulation for the articulation of design principles suggested by Fu et al. [82]. This work focuses on the synthesis of existing guidelines, so we do not suggest new extended guidelines. In addition to listing the resulting guideline clustered into their representative categories, we also include the applicable references in Table 1 to point readers to where they can read more detailed statements and examples for each guideline.

Table 1. Summary of design guidelines for nonassembly

	Guidelines
Manufacturing Process	• Choose the low-cost process that meets functional requirements. [16] • Design for low-labor-cost operations. [4] • Minimize the number of required processes. [6, 40] • Use standard manufacturing processes. [14, 16, 29, 38, 39, 41, 83] • Concurrently design the part and processes. [6] • Synchronize with development of production facilities. [14, 38] • Minimize handling and re-orientations. [4, 29, 39, 41, 83] • Design for quick, secure, and consistent work-holding. [6] • Use versatile fixtures. [6] • Design parts for easy tooling and jigging. [39, 83] • Minimize tooling changeovers. [6, 16, 39, 40, 83] • Use standard tools. [4, 16] • Design the part to be easily inspectable. [29, 39, 41, 83] • Design robustness into products to compensate for uncertainty in manufacturing, testing, and use. [29, 41] • Design product variants to make use of common production assets. [1, 55] • Use common process steps. [49, 53]
Material	• Choose low-cost materials that meet functional requirements. [6, 16] • Minimize material changeovers. [16] • Minimize the material waste. [40] • Choose materials for suitability and availability. [16] • Choose materials for a combination of properties. [16] • Optimize dimensions and choices of raw material stock. [6] • Choose the material according to the allowable stress. [44] • Use common materials. [49, 53]
Tolerance	• Specify the widest tolerances minimizing production costs and consistent with function, quality, reliability, and safety. [6, 16, 29, 39-41, 83] • Do not over-specify surface finishes. [6, 40] • Choose optimal tolerances of each joint to improve the position accuracy. [7, 21, 24, 25, 43] • Minimize friction in the joint and other strain. [7, 21, 24, 25, 43] • Choose optimal clearances to avoid mechanical and production failures. [7, 21, 24, 25, 43]
Geometry	• Simplify the geometry. [4, 16, 38] [14] • Design the geometry to exclude stress concentrations. [44] • Ensure changes of sections are gradual. [16] • Conform to drafting standards. [39, 40, 83] • Dimensions should be made from the best datum. [4, 6] • Use common geometry and size. [49, 53] • Make use of scale-based strategies to create differentiation within a product family. [62, 63]

7. DISCUSSION

The design guidelines for DFNA that are synthesized in our review are primarily focused on simplifying the design, reducing the complexity of manufacturing processes, and minimizing total cost, subject to functional requirements. It is notable, however, that the categories of these guidelines are similar to those identified in Laureijs et al. [18], which focused on differentiating features of monolithic NA products in the same family. This implies that the same design variables—relating to the geometry, material, tolerances, and processing of the product—that drive variety of NA products also drive production costs. We also recognize that similar concepts can be applied to create product families of nonassembly mechanisms that serve to increase variety while reducing production costs. For example, a product line of non-assembly mechanisms produced through AM can reduce costs by taking advantage of common material usage, common equipment for printing and finishing operations, and standardization of particular geometric features that allow them to use common fixtures for finishing operations.

Some of the guidelines identified in Table 1 serve to reduce costs without necessarily affecting variety (e.g., design the parts for easy tooling and jigging), while others create an inherent tradeoff between reducing costs and losing differentiation (e.g., commonize materials). Choosing these design variables to increase differentiation can increase market share [47], but also can increase production costs [84], For example, in NA products, the variety of different materials or geometries in a product line results in increased changeovers between different products at a single step (e.g., changing tooling, or cleaning the equipment to avoid material contamination) and possibly increased processes required [18]. So, design factors related to product variety should be optimized to balance market share increases with costs.

The guidelines reviewed were selected to represent higher-level recommendations that apply across multiple manufacturing processes. Although the majority of the existing literature on design guidelines was developed with traditional manufacturing methods in mind, many of the identified guidelines remain relevant to emerging mass-production methods such as additive manufacturing (including associated finishing processes). There is, of course, a tradeoff between giving high-level guidelines that are widely applicable, with giving the specificity needed to apply the guidelines in practice for a given application. Nonassembly mechanisms, in particular, represent a unique and evolving instance of NA design that may require unique design consideration. While these systems can avoid post-fabrication assembly steps, they may require support structures and/or interfaces that increase the costs of fabrication and necessitate their own post-fabrication steps (e.g. for material removal or shaping). Multi-articulated system design must also include management of tolerances both to avoid mechanical failures from excessive play or blockage due to low clearance and to prevent production failure from material fusing under insufficient clearance.

Revisiting Figure 2, we express where the identified guidelines fit into our proposed relationships between DFA and DFNA. As we would expect given that most of the design guideline literature was developed in the context of assembled products, the guidelines fall into the overlapping region of both DFA and DFNA. We also find that the guidelines apply to both intermediary and standalone products. Future research may further develop guidelines that are unique to DFNA that do not apply to assembled products.

7.1 Directions for Future Research

In our review of DFNA guidelines and metrics, we found that a promising area for future improvement is the development of metrics that more accurately represent the relationships between design variables and production costs. Existing metrics do not account for some important design considerations that influence costs of NA products, including choices of tolerances that increase yield losses, machine set-up, or calibration time. In addition, current metrics rely on heuristics of product variety, such as the number of different geometries used in a product family. This metric can accurately capture certain circumstances (e.g., with molds or dies) where any change in geometry would increase costs due to additional tooling. However, in other cases, a change in geometry may have very little impact on costs so long as the dimensions used for fixturing remain the same.

Relatedly, scale-based product family strategies may in some cases create product differentiation while minimizing cost increases (e.g., by preserving commonality of manufacturing operations unaffected by the length of the scale dimension). However, scaling a dimension that would require changes in fixturing or tooling could dramatically increase costs. As such, the choice of which design variables to scale should consider the influence of those variables on fixturing and tooling.

Another challenge in developing more realistic metrics to guide DFNA is that production costs depend not only on the costs associated with product geometries, material, and tolerances, but also on the complexity of manufacturing operations that are necessary to produce the product. The existing literature on DFM recommends reducing the complexity of product designs and production processes to reduce costs and the potential for production and product failure. Complexity is described within the literature as being proportional to the expected number of person-weeks required to complete tasks [85]. Implied by this definition is the fact that, as design complexity increases, the rate of consumption of resources increases.

From our review of the literature [86-88], we propose as a premise for further work that complexity may be a function of the number and variety of interfaces between part, equipment and tooling and operator, mapping to uncertainty in achieving the functional specifications of the design [89, 90]. Considerations of complexity comprise two elements: the complexity of an individual product at a single process step, and the complexity of an individual product across multiple process steps. Within any single process step, complexity should consider the number of tools or fixtures, the number of changeovers thereof and the number of reorientations of the part itself. Each of these elements affect the time required to conduct a production step, and the number of operators (human or machine) acting on the part in each step. Process-level complexity should consider the number of unique processes required, the interaction between operators at various steps (e.g. the handoff of a part from one operator to another), and the number of repetitions of process steps. Future literature building toward a formal definition and measurement of complexity could extend the metrics offered here to quantity and measure complexity, perhaps mapping it formally to design guidelines and metrics.

A further challenge in advancing DFNA (and DFM more broadly) is that there exist many tradeoffs between processes and product attributes. Guidelines and metrics that encourage the reduction of post-processing operations, for example, may require tighter tolerances in earlier process steps, which could offset the hoped-for cost reductions or even increase costs. It is difficult to know *a priori* which set of competing guidelines will lead to cost reductions or cost increases. Further efforts to quantify these tradeoffs and characterize common trends between design variables and production costs or complexity across a range of product domains could give engineers useful insights into DFM.

Finally, a limitation of the DFNA literature is the application- or process-specific nature of many guidelines (e.g. for additive manufacturing). In many design processes, the specific production operations are not chosen until later stages when product material, and geometry have been specified. Developing more comprehensive design guidelines for NA products that apply across a range of manufacturing operations could avoid additional design iterations in later steps of the design process that lead to increased development costs and time delays.

With an expanded understanding of the relationship between NA product attributes, and production costs, as well as a set of metrics to assess complexity costs of NA products and product families, designers can establish NA product and product-family design strategies for the next generation.

8. CONCLUSION

We review the DFM literature for guidelines applicable to nonassembled products. We find that DFNA guidelines fall into four broad categories: manufacturing process, material; tolerance; and geometry. Many existing DFNA design guidelines are also pertinent to assembled products, such as resource sharing through product family design, although future guidelines could be created that are unique to nonassembled products. Our review leads us to note the importance of design metrics focused on the attributes of nonassembled products—such as material type, geometry, tolerances, and finishes—as these attributes have a strong relationship to both production costs and product differentiation. We note also the lack of design guidelines and metrics that capture the interacting relationships between design variables and manufacturing factors that increase cost (such as complexity), and the often process-specific nature of some nonassembly design guidelines. Further work is needed to develop design guidelines and metrics that take into account the relationships between nonassembled product attributes and costs that apply in more general classes of production operations, so they can guide decisions in earlier stages of the design process.

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APPENDIX A

The estimate of NA shipments is estimated by the authors from Nicholson and Noonan [3], and is the sum of the value of shipments in the following industries: primary and fabricated metals, semiconductors, other electronic components, petroleum and coal, chemical and pharmaceutical, and food and beverage. These values are seen in Table A1.

Table A1. Estimate of NA shipments

Major Nonassembly Segments:	Value of Shipments ($B)	% of Total US Mfg. Shipments
Food and Beverage	881	15.19%
Petroleum and Coal	851	14.67%
Chemical and Pharmaceutical	795	13.70%
Fabricated Metal	345	5.95%
Primary Metal	279	4.82%
Semiconductors	72	1.24%
Other Electronic Components	11	0.19%
Total	3,234	55.75%

APPENDIX B

Adachi et al. [38] and Boothroyd [14]

- G1: Fit with specification of production facilities.
- G2: Synchronize with development of production facilities.
- G3: Reflect feedback information from production processes quickly.
- G4: Minimize impacts on production processes.
- G5: Optimize the trade-off between function and cost.
- G6: Simplify the structure.
- G7: Be standardized.

Bralla [4]

- G8: Simplify the design.
- G9: Design for low-labor-cost operations whenever possible. For example, a punchpress pierced hole can be made more quickly than a hole can be drilled. Drilling, in turn, is quicker than boring. Tumble deburring requires less labor than hand deburring.
- G10: Avoid generalized statements on drawings that may be difficult for manufacturing personnel to interpret. Examples are "Polish this surface….Corners must be square," "Tool marks are not permitted," and "Assemblies must exhibit good workmanship." Notes must be more specific than these.
- G11: Dimensions should be made not from points in space but from specific surfaces or points on the part itself if at all possible. This facilitates fixture and gauge making and helps avoid tooling, gauge, and measurement errors.
- G12: Dimensions should all be from one datum line rather than from a variety of points.
- G13: Once functional requirements have been fulfilled, the lighter the part, the lower its cost is apt to be. Designers should strive for minimum weight consistent with strength and stiffness requirements. Along with a reduction in materials costs, there usually will be a reduction in labor and tooling costs when less material is used.
- G14: Whenever possible, design to use general-purpose tooling rather than special tooling. The well-equipped shop often has a large collection of standard tooling that is usable for a variety of parts. Except for the highest levels of production, where the labor and materials savings of special tooling enable their costs to be amortized, designers should become familiar with the general-purpose and standard tooling that is available and make use of it.
- G15: Design a part so that as many manufacturing operations as possible can be performed without repositioning it. This reduces handling and the number of operations but, equally important, promotes accuracy, since the needed precision can be built into the tooling and equipment.

Edwards [16]

- G16: Minimize production steps.
- G17: Avoid slow processes and design for high speed continuous processes.
- G18: Eliminate expensive operations not really needed to achieve function.
- G19: Simplify design details.
- G20: Eliminate the need for expensive machining of components to excessively close tolerances.
- G21: Select materials for suitability as well as lowest cost and availability.
- G22: Ensure maximum simplicity in overall design.
- G23: Use the widest possible tolerances and finishes on components.
- G24: The designer must make every effort to specify the lowest grade of material that will meet his needs.
- G25: The best way to achieve true reliability is by simplicity.
- G26: Design to fit the manufacturing processes and reduce costs.
- G27: Choose materials for a combination of properties.
- G28: It is not desirable to design structures with abrupt changes in section.
- G29: Design the component so that the number and duration of machining operations required are minimized.
- G30: Select materials that, consistent with minimum cost and with other requirements, machines most readily.
- G31: Design the component so that it can be machined with a minimum number of tools and with standard tools.
- G32: Ensure changes of section are gradual.
- G33: Aim at uniform wall thickness and cross-sections and at gradual changes of cross-section.
- G34: Avoid excessively small tolerances.
- G35: Use standards and codes wherever possible.
- G36: For economic reasons, the attempt should always be made to fulfill several functions with a single function carrier.
- G37: Put a price on every tolerance and finish.
- G38: Select materials that will lead themselves to low cost production as well as design requirements.

Swift and Booker [39] and Ferrer et al. [83]

- G39: Identify critical characteristics (tolerances, surface finishes).
- G40: Identify factors that influence the manufacture of critical characteristics.
- G41: Estimate manufacturing costs.
- G42: Minimize component cost.
- G43: Establish maximum tolerances for each characteristic.
- G44: Determine process capability of characteristics early.
- G45: Avoid tight tolerances.
- G46: Design the part to be easily inspectable.
- G47: Minimize number of machined surfaces.
- G48: Minimize number of re-orientations during manufacture.
- G49: Use standard manufacturing processes where possible.
- G50: Avoid secondary processes.
- G51: Design parts for easy tooling/jigging using standard systems.
- G52: Utilize special characteristics of processes.
- G53: Use good detail design for manufacture and conform to drafting standards.

van Vliet and van Luttervelt [40]

- G54: Minimize the number of required manufacturing processes.
- G55: Minimize the material waste.
- G56: Verify if the machine processing range is suitable to realize the required part dimensions.

- G57: Minimize the number of required tools.
- G58: Apply international standards for dimensioning.
- G59: Choose the least-tight tolerance value possible.
- G60: Make as much as possible use of the surface roughness of the stock material.

Luo et al. [41] and DRM Associates [29]

- G61: Design verifiability into the product and its components to provide a natural test or inspection of the item.
- G62: Avoid tight tolerances beyond the natural capability of the manufacturing.
- G63: Design "robustness" into products to compensate for uncertainty in the product's manufacturing, testing and use.
- G64: Design for part orientation and handling to minimize non-value-added manual effort and to facilitate automation.
- G65: Utilize common materials to facilitate design activities and to minimize the amount of inventory in the system.
- G66: Standardize handling operations.

Anderson [6]

- G67: Choose the optimal processing.
- G68: Design for quick, secure, and consistent work holding.
- G69: Use stock dimensions whenever possible.
- G70: Optimize dimensions and raw material stock choices.
- G71: Design machined parts to be made in one setup.
- G72: Minimize the number of cutting tools for machined parts.
- G73: Avoid arbitrary decisions that require special tools and thus slow processing and add cost unnecessarily.
- G74: Choose materials to minimize total cost with respect to post-processing.
- G75: Concurrently design and utilize versatile fixtures.
- G76: Understand work-holding principles.
- G77: Understand tolerance step functions.
- G78: Specify the widest tolerances consistent with function, quality, reliability, safety, and so forth.
- G79: Be careful about too many operations in one part.
- G80: Concurrently engineer the part and processes.
- G81: Do not over-specify surface finishes.
- G82: Reference each dimension to the best datum.

De Laurentis et al. [21], Yang et al. [24], Chen and Zhezheng [43], Calì et al. [25], and Cuellar et al. [7]

- G83: Fabricated joints must have sufficient clearance to avoid fusing or catching.
- G84: Fabricated joints cannot have such great clearance that they fail mechanically to connect.
- G85: Minimize friction in the joint and other strain.
- G86: Minimize the tolerance of each joint to improve the position accuracy.

Cuellar et al. [44]

- G87: Design the geometry to exclude stress concentrations.
- G88: Choose the material according to the allowable stress.

Kota et al. [53] and Thevenot and Simpson [49]

- G89: Use common geometry and size.
- G90: Use common materials.
- G91: Use common process steps.

Meyer and Dalal [1] and Robertson and Ulrich [55]

- G92: Design product variants to make use of common production assets.

Simpson et al. [62] and Messac et al. [63]

- G93: Make use of scale-based strategies to create differentiation within a product family.

APPENDIX C

The total number of elements including keywords and guidelines is 176, so the hierarchical clustering is possible to provide various clustering results from 1 to 176 clusters depending on the location of a cut-off line in the dendrogram. Table C1 shows the clustering results from 1 to 16 clusters. For example, Clusters 16C.1 and 16C.2 are merged as Cluster 15C.1 in the 15-clusters result, and Cluster 14C.5 contains Clusters 15C.5 and 15C.6 as seen in Table C1.

Table C2 shows more detailed results including clustered keywords and guidelines in Cases 1, 2, and 3 (i.e., 4 clusters, 8 clusters, and 16 clusters, respectively). In Table C2, each cluster contains similar keywords and guidelines, and the keywords within each cluster are sorted in descending order (i.e., from the highest term-frequency to the lowest term-frequency). In Cluster 16C.1, "manufacturing process" is the most frequent keyword. Interestingly, the keywords and guidelines included in Clusters 16C.1-16C.5 have higher similarities each other, so the clusters are merged into a larger cluster in Case 1 or 2. "orientation," "handling," "work-holding," "tooling", and "inspection" included in Clusters 16C.2-16C.5 are highly associated with "manufacturing process" in Cluster 16C.1. When the number of clusters is set to 4 as seen in Case 1, the keywords and guidelines in Cluster 4C.1 are closely related to manufacturing process steps such as "work-holding", "orientation", "tooling", "machining", and "inspection".

Cluster 4C.2 includes Clusters 16C.6, 16C.7 and 16C.8, which mainly contain material-related guidelines. The keyword, "material" is included in Cluster 16C.8, but the other guidelines in Clusters 16C.6 and 16C.7 also have "material" (e.g., G21 in Cluster 16C.6: Select materials for suitability as well as lowest cost and availability). Although "cost" has the highest frequency in Cluster 16C.6, this cluster also includes material-related guidelines such as G21, G30, G38, and G74. In addition, this result shows that "material" and "cost" are closely related in the DFNA guidelines, so the material-related clusters are merged into Cluster 4C.2 in Case 1. Meanwhile, Cluster 4C.3 includes the keywords and guidelines associated with tolerance, and Cluster 4C.4 is related to geometry and size.

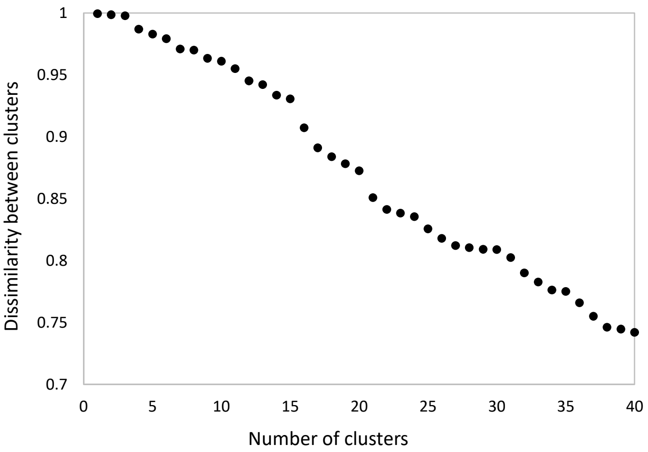

Figure C1. Dissimilarity between clusters with respect to the number of clusters.

Table C1. Hierarchical clustering results for 1-16 clusters

<table>
<tr><td>1 Cluster</td><td colspan="16">1C.1</td></tr>
<tr><td>2 Clusters</td><td colspan="11">2C.1</td><td colspan="5">2C.2</td></tr>
<tr><td>3 Clusters</td><td colspan="8">3C.1</td><td colspan="3">3C.2</td><td colspan="5">3C.3</td></tr>
<tr><td>4 Clusters</td><td colspan="5">4C.1</td><td colspan="3">4C.2</td><td colspan="3">4C.3</td><td colspan="5">4C.4</td></tr>
<tr><td>5 Clusters</td><td colspan="5">5C.1</td><td colspan="3">5C.2</td><td colspan="3">5C.3</td><td colspan="4">5C.4</td><td>5C.5</td></tr>
<tr><td>6 Clusters</td><td colspan="5">6C.1</td><td colspan="3">6C.2</td><td colspan="3">6C.3</td><td colspan="3">6C.4</td><td>6C.5</td><td>6C.6</td></tr>
<tr><td>7 Clusters</td><td colspan="4">7C.1</td><td>7C.2</td><td colspan="3">7C.3</td><td colspan="3">7C.4</td><td colspan="3">7C.5</td><td>7C.6</td><td>7C.7</td></tr>
<tr><td>8 Clusters</td><td colspan="3">8C.1</td><td>8C.2</td><td>8C.3</td><td colspan="3">8C.4</td><td colspan="3">8C.5</td><td colspan="3">8C.6</td><td>8C.7</td><td>8C.8</td></tr>
<tr><td>9 Clusters</td><td colspan="3">9C.1</td><td>9C.2</td><td>9C.3</td><td colspan="3">9C.4</td><td colspan="2">9C.5</td><td>9C.6</td><td colspan="3">9C.7</td><td>9C.8</td><td>9C.9</td></tr>
<tr><td>10 Clusters</td><td colspan="2">10C.1</td><td>10C.2</td><td>10C.3</td><td>10C.4</td><td colspan="3">10C.5</td><td colspan="2">10C.6</td><td>10C.7</td><td colspan="3">10C.8</td><td>10C.9</td><td>10C.10</td></tr>
<tr><td>11 Clusters</td><td colspan="2">11C.1</td><td>11C.2</td><td>11C.3</td><td>11C.4</td><td colspan="3">11C.5</td><td colspan="2">11C.6</td><td>11C.7</td><td colspan="2">11C.8</td><td>11C.9</td><td>11C.10</td><td>11C.11</td></tr>
<tr><td>12 Clusters</td><td colspan="2">12C.1</td><td>12C.2</td><td>12C.3</td><td>12C.4</td><td colspan="2">12C.5</td><td>12C.6</td><td colspan="2">12C.7</td><td>12C.8</td><td colspan="2">12C.9</td><td>12C.10</td><td>12C.11</td><td>12C.12</td></tr>
<tr><td>13 Clusters</td><td colspan="2">13C.1</td><td>13C.2</td><td>13C.3</td><td>13C.4</td><td colspan="2">13C.5</td><td>13C.6</td><td colspan="2">13C.7</td><td>13C.8</td><td>13C.9</td><td>13C.10</td><td>13C.11</td><td>13C.12</td><td>13C.13</td></tr>
<tr><td>14 Clusters</td><td colspan="2">14C.1</td><td>14C.2</td><td>14C.3</td><td>14C.4</td><td colspan="2">14C.5</td><td>14C.6</td><td>14C.7</td><td>14C.8</td><td>14C.9</td><td>14C.10</td><td>14C.11</td><td>14C.12</td><td>14C.13</td><td>14C.14</td></tr>
<tr><td>15 Clusters</td><td colspan="2">15C.1</td><td>15C.2</td><td>15C.3</td><td>15C.4</td><td>15C.5</td><td>15C.6</td><td>15C.7</td><td>15C.8</td><td>15C.9</td><td>15C.10</td><td>15C.11</td><td>15C.12</td><td>15C.13</td><td>15C.14</td><td>15C.15</td></tr>
<tr><td>16 Clusters*</td><td>16C.1</td><td>16C.2</td><td>16C.3</td><td>16C.4</td><td>16C.5</td><td>16C.6</td><td>16C.7</td><td>16C.8</td><td>16C.9</td><td>16C.10</td><td>16C.11</td><td>16C.12</td><td>16C.13</td><td>16C.14</td><td>16C.15</td><td>16C.16</td></tr>
</table>

* The keywords and guidelines included in each cluster from 16C.1 to 16C.16 are provided in Table C2.

Table C2. Hierarchical clustering result for three cases (4 clusters, 8 clusters, and 16 clusters)

Case 1: 4 Clusters	Case 2: 8 Clusters	Case 3: 16 Clusters		
		Cluster	Terms (descending order)	Guidelines
4C.1	8C.1	16C.1	manufacturing process standardization manufacturing cost facility feedback information labor cost repositioning code process capability	G1: Fit with specification of production facilities. G2: Synchronize with development of production facilities. G3: Reflect feedback information from production processes quickly. G4: Minimize impacts on production processes. G7: Be standardized. G9: Design for low-labor-cost operations whenever possible. G15: Design a part so that as many manufacturing operations as possible can be performed without repositioning it. G16: Minimize production steps. G17: Avoid slow processes and design for high speed continuous processes. G18: Eliminate expensive operations not really needed to achieve function. G26: Design to fit the manufacturing processes and reduce costs. G35: Use standards and codes wherever possible. G40: Identify factors that influence the manufacture of critical characteristics. G41: Estimate manufacturing costs. G44: Determine process capability of characteristics early. G49: Use standard manufacturing processes where possible. G50: Avoid secondary processes. G52: Utilize special characteristics of processes. G54: Minimize the number of required manufacturing processes. G66: Standardize handling operations. G67: Choose the optimal processing. G73: Avoid arbitrary decisions that require special tools and thus slow processing and add cost unnecessarily. G79: Be careful about too many operations in one part. G91: Use common process steps. G92: Design product variants to make use of common production assets.
		16C.2	orientation handling non-value-added activity automation	G48: Minimize number of re-orientations during manufacture. G64: Design for part orientation and handling to minimize non-value-added manual effort and to facilitate automation.
		16C.3	work-holding concurrent engineering speed-up safety consistency	G68: Design for quick, secure, and consistent work holding. G75: Concurrently design and utilize versatile fixtures. G76: Understand work-holding principles. G80: Concurrently engineer the part and processes.

	8C.2	16C.4	tooling machining cutting jigging duration setup	G14: Whenever possible, design to use general-purpose tooling rather than special tooling. G29: Design the component so that the number and duration of machining operations required are minimized. G31: Design the component so that it can be machined with a minimum number of tools and with standard tools. G47: Minimize number of machined surfaces. G51: Design parts for easy tooling/jigging using standard systems. G57: Minimize the number of required tools. G71: Design machined parts to be made in one setup. G72: Minimize the number of cutting tools for machined parts.
	8C.3	16C.5	inspection test verifiability robustness uncertainty	G46: Design the part to be easily inspectable. G61: Design verifiability into the product and its components to provide a natural test or inspection of the item. G63: Design "robustness" into products to compensate for uncertainty in the product's manufacturing, testing and use.
4C.2	8C.4	16C.6	cost requirement lightweight suitability availability machine post-processing	G13: Once functional requirements have been fulfilled, the lighter the part, the lower its cost is apt to be. G21: Select materials for suitability as well as lowest cost and availability. G30: Select materials that, consistent with minimum cost and with other requirements, machines most readily. G38: Select materials that will lead themselves to low cost production as well as design requirements. G42: Minimize component cost. G74: Choose materials to minimize total cost with respect to post-processing.
		16C.7	function trade-off economy function carrier	G5: Optimize the trade-off between function and cost. G36: For economic reasons, the attempt should always be made to fulfill several functions with a single function carrier.
		16C.8	material stock stock dimension commonality material grade property material waste surface roughness allowable stress	G24: The designer must make every effort to specify the lowest grade of material that will meet his needs. G27: Choose materials for a combination of properties. G55: Minimize the material waste. G60: Make as much as possible use of the surface roughness of the stock material. G65: Utilize common materials to facilitate design activities and to minimize the amount of inventory in the system. G69: Use stock dimensions whenever possible. G70: Optimize dimensions and raw material stock choices. G88: Choose the material according to the allowable stress. G90: Use common materials.
4C.3	8C.5	16C.9	tolerance surface finish machining cost price step function	G20: Eliminate the need for expensive machining of components to excessively close tolerances. G23: Use the widest possible tolerances and finishes on components. G34: Avoid excessively small tolerances. G37: Put a price on every tolerance and finish. G39: Identify critical characteristics (tolerances, surface finishes). G43: Establish maximum tolerances for each characteristic. G45: Avoid tight tolerances. G59: Choose the least-tight tolerance value possible. G62: Avoid tight tolerances beyond the natural capability of the manufacturing. G77: Understand tolerance step functions. G81: Do not over-specify surface finishes.
		16C.10	reliability simplification quality	G25: The best way to achieve true reliability is by simplicity. G78: Specify the widest tolerances consistent with function, quality, reliability, safety, and so forth.
		16C.11	joint clearance catching fusing mechanical failure friction strain	G83: Fabricated joints must have sufficient clearance to avoid fusing or catching. G84: Fabricated joints cannot have such great clearance that they fail mechanically to connect. G85: Minimize friction in the joint and other strain. G86: Minimize the tolerance of each joint to improve the position accuracy.

4C.4	8C.6	16C.12	drafting standards drafting manufacturing personnel	G10: Avoid generalized statements on drawings that may be difficult for manufacturing personnel to interpret. G53: Use good detail design for manufacture and conform to drafting standards. G58: Apply international standards for dimensioning.
		16C.13	dimension point datum surface	G11: Dimensions should be made not from points in space but from specific surfaces or points on the part itself if at all possible. G12: Dimensions should all be from one datum line rather than from a variety of points. G82: Reference each dimension to the best datum.
		16C.14	design simplification geometry detailed design stress concentration	G6: Simplify the structure. G8: Simplify the design. G19: Simplify design details. G22: Insure maximum simplicity in overall design. G87: Design the geometry to exclude stress concentrations.
	8C.7	16C.15	gradual change section cross-section wall thickness	G28: It is not desirable to design structures with abrupt changes in section. G32: Ensure changes of section are gradual. G33: Aim at uniform wall thickness and cross-sections and at gradual changes of cross-section.
	8C.8	16C.16	size machine-processing-range differentiation product family	G56: Verify if the machine processing range is suitable to realize the required part dimensions. G89: Use common geometry and size. G93: Make use of scale-based strategies to create differentiation within a product family.