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MODULARITY IN PRODUCT DESIGN FOR MANUFACTURABILITY

John K. Gershenson, Assistant Professor
G. Jagannath Prasad, Graduate Research Associate
Department of Mechanical Engineering
The University of Alabama

ABSTRACT
This paper discusses the relationship between modular products and manufacturing. The relationship is based on an expanded definition of modularity which incorporates the potential of modularity based not only on end uses of a product but also on the manufacturing processes. By incorporating this expanded definition of modularity, called *manufacturing modularity*, into product development, a more robust product modularity can be achieved.

Modularization, due to the functional independence it creates, has been called the goal of good design. Industry has made an effort to modularize products to be flexible to the needs of end users and marketing. This effort has led to the creation of product families. Occasionally, modules are created with some aspects of production in mind. However, this modularization is done without fully understanding the implications of the design. Although often yielding highly functional products, once the entire manufacturing process is accounted for, this unstructured modularization often leads to costly redesigns or expensive products. In addition, the unstructured modularization makes the process difficult to repeat if it is successful and difficult to avoid if it is unsuccessful. Modularity requires maintaining independence between components and processes in different modules, encouraging similarity in all components and processes in a module, and maintaining interchangeability between modules. Modularity with respect to manufacturing necessitates understanding the various manufacturing processes undergone by each attribute of each component.

This paper presents a basic methodology for creating manufacturing modules. These modules decrease manufacturing costs, decrease lead time, and strengthen product families. A design methodology is developed which prevents a cascade of product design changes due to changes in manufacturing processes and supports agility in the face of changes in manufacturing processes. The methodology and its elements are highlighted in the redesign of an electric coffee maker.

1. INTRODUCTION
Life-cycle engineering is a methodology of incorporating a product's life time values at the early stages of product design (Barkan, 1988). These values include functionality, business concerns, manufacturing, assembly, service,

product retirement, and any other requirement put on the product from concept to grave. Boothroyd and Dewhurst (1985) and others (Sturges, 1992; Miyakawa, 1990) have shown that Design for Assembly (DFA) can lead to significant savings during production. One aspect of assembly cost is minimizing the number of components in the product. Modular products tend to have fewer components for assembly. By increasing pre-assembly and using common interfaces, modularity decreases the cost of assembly. Modules are usually dictated by the supplier sub-assemblies and are not necessarily the best possible choice for lowest cost. Design for Manufacturability (DFM) improves product design to decrease production costs. No matter the manufacturing process, there are several process-specific design rules or algorithms as well as several universal best practices in DFM. These universal best practices include reduction in tooling costs and set up time. Increasing commonalities within components and sub-systems, a key part of modular design, leads to fewer tooling sets and few changes in set up. In addition, modularity increases the number of components using a particular process or set up, thereby yielding a positive economy of scale. Modularity is a strong, but unexplored, thread though life-cycle engineering and manufacturing in particular.

In developing a methodology for modular manufacturing design, there are three main questions to be tackled: "What is meant by manufacturing modularity?"; "How can manufacturing modularity be applied to product design?"; and "Are the benefits of manufacturing modularity worth the effort?". Previous research has answered some parts of these questions while raising additional questions.

1.1 Previous research into modularity

Most of the research into the theory behind modularity originates from Suh's (1990) independence axiom, which states that, "[i]n good design the independence of functional requirements is maintained." Therefore, if possible, each function that a product performs should be independent of all other functions the product performs. This axiom, coupled with a push toward understanding the relationship between the form of a product and its functions, has led to a search for a connection between physical independence and functional independence.

In one of the first works to discuss modular design theory, Ulrich and Tung (1991) define modularity in terms of two characteristics of product design: "1) Similarity between the physical and functional architecture of the design and 2) Minimization of incidental interactions between physical components." In an extension of this work, Ulrich (1995) states that a modular product or sub-assembly has "a one-to-one mapping from functional elements in the function structure to the physical components of the product." As in Suh's work, this definition only accounts for the functional aspects of a product, ignoring all other life-cycle characteristics.

Ishii, *et al.*'s (1995) work on design for product variety attempts to capture the broadest customer preference while minimizing the life-cycle cost of providing those preferences. The key to their work is late point product identification, designing products that are similar enough that they can be differentiated as late in the production process as possible. In their work, Ishii, *et al.* use "modular" to mean minimizing the number of functions per component.

Ad hoc modular design has been used for many years to create products with interchangeable functions. Some examples of functional modularity include sectional sofas, power drills with multiple functionality, kitchen mixers, stereos, vehicle roof racks, and computers. These products offer greatly increased flexibility in meeting end user requirements through function grouping and standard interfaces. Should the end users want a new attachment in the years to come, the attachment can be designed with a similar interface that will fit the end users' current product. However, the nature in which these products are designed has led to these products being more costly than similar, non-modular products.

In the realm of manufacturing, the concept of Group Technology (GT) has been employed to develop modular manufacturing systems. GT is a relatively old concept and an important precursor to the development of automated manufacturing cells. In GT, different types of conventional machines are grouped together to form production cells based upon the grouping of manufacturing features in the product. The logic behind the formation of production cells is to create a production line environment for an individual component or sub-assembly of a product. Doing so requires that there exist a family of parts whose manufacturing parameters are similar enough to permit group processing with minimal process changes. GT production cells reduce the work in progress and increase the operating efficiency of the production line by saving handling time and reducing transfer machinery. GT production cells reduce the chaos that persists in most manufacturing plants by increasing visibility of the product schedule status and allowing for access to the manufactured components. The design and implementation of a cellular manufacturing system is often considered as the basis of the factory of the future and as a prerequisite to the implementation of just-in-time manufacturing and synchronous manufacturing. The grouping of manufacturing features in products has not progressed as rapidly.

Modular manufacturing systems greatly reduce the time it takes to design and deploy an automated assembly or machining system. The manufacturing floor space can be greatly reduced because one work cell can be reconfigured to cater to diversified task requirements without the use of several different machine tools. Mini-workshops and desktop manufacturing become possible. Most important of all, converting a manufacturing line from one product to another can be very fast and easy to keep up with the rapid changing market.

In summary, work exists which defines functional modularity and applies it to product design. Modularity also has been widely implemented in the design of manufacturing systems. Modularity has not, however, been applied to design and manufacturing concurrently. Two aspects missing in the current works include a definition for modularity that takes into account aspects of a product other than its function, particularly manufacturing and a methodology for developing modular products. This paper supplies working definitions of modularity and manufacturing modularity, gives a design methodology to incorporate manufacturing modularity, and shows a short example of the definitions and methodology in use.

1.2 Benefits of modularity

Ulrich and Tung's (1991) work details the costs and benefits of modular products. The benefits of product modularity they discuss include 1) component economies of scale due to the use of components across product families, 2) ease of product updating due to functional modules, 3) increased product variety from a smaller set of components, and 4) decreased order lead-time due to fewer components. The costs of modularity they discuss include 1) lack of performance optimization due to lack of function sharing and larger size, 2) increased unit variable costs due to the lack of component optimization (although Ulrich and Tung don't discuss the decreased unit cost over a product family), and 3) excessive product similarity due to similar components (although this is only a problem if end user requirements are ignored).

Modularity allows the designer to control the degree to which changes in manufacturing processes affect the product design. By promoting interchangeability, modularity also gives designers more flexibility, with decreased cycle time, to meet these changing processes. The flexibility that modularity offers is increasingly important as uncertainty in manufacturing requirements increase. This flexibility allows some design decisions to be delayed because they have a lower impact on the total product. Controlling the impact of changes and being flexible to respond to changes are the benefits of product agility. An agile product can more readily adapt to a late influx of manufacturing technology or a late change in manufacturing strategy. While different than agile manufacturing, agile products only increase the benefits of agile manufacturing. Agile manufacturing can utilize production and assembly systems to serve the needs of the different component versions of agile, or modular, products.

Modularity arises from the division of a product into independent components. This independence increases the use of standardized components and allows designers to more easily create a wide variety of products using a much smaller set of components. Product variety is created by having several different versions of each component in the final product. The physical and functional interfaces between the components are the same. The result is that any combination of components can be assembled into the different versions of the same product, or even a different product, with minor modifications.

2. APPROACH

There are three key definitions which enable product design for manufacturing modularity. *Product modularity* is the foundation of this work. *Characteristic modularity*, an instance of product modularity, and *manufacturing modularity*, a specific case of characteristic modularity, are the functional definitions supporting the design methodology. The definitions of product and characteristic modularity are discussed briefly below but more detail can be found in Gershenson and Prasad (1997).

2.1 Product modularity

Components or sub-assemblies (heretofore referred to as components) which are, or are intended to be, relatively modular in nature are called *modules*. Modules contain a high number of components which have minimal dependencies upon and similarities to other components in the product not in the module but which have a high degree of dependency upon and similarity to other components in the module. These dependencies and similarities include those which arise from the relationships between the components' attributes and those which arise from the relationships between the components during the various phenomena the components undergo in their life-cycle (Figure 1).

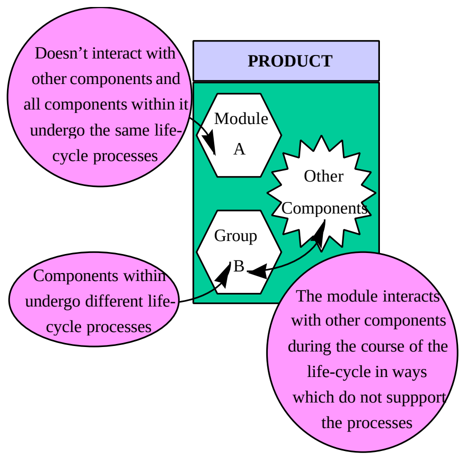

Figure 1: *Representation of a product with modular (Module A) and non-modular (Group B and Other Components) sub-systems.*

Therefore, in a module, each component is independent of all components not contained in the same module (independence). In addition, each component in a module must be processed in the same manner during each phase of it life-cycle (similarity) to reduce interdependencies between modules. This definition parallels Suh's (1990) form-function independence definitions used in previous modularity research but considers the application of modularity to other concerns in addition to end user functions. The form-function relationship has therefore been replaced with a form-process relationship. While complete modularity may be unrealistic except in the most trivial cases, a product which exhibits a higher degree of modularity is more likely to incur a lower total life-cycle cost especially when the entire product family is examined.

2.2 Manufacturing modularity

In previous work, *characteristic modularity* is defined as modularity applied to an individual life-cycle characteristics (Gershenson and Prasad, 1997). Characteristic modules contain a high number of components which have minimal dependencies upon and similarities to other components in the product with regard to a particular phase of the life-cycle. Examples of characteristic modularities are shown in Figure 2. Characteristic modularity may be more useful than total product modularity for a product, especially if there are one or two characteristics which dominate the requirements and costs of a product. Developing products which are modular in terms of characteristics besides the primary drivers could result in excessive modularity and/or decreased value.

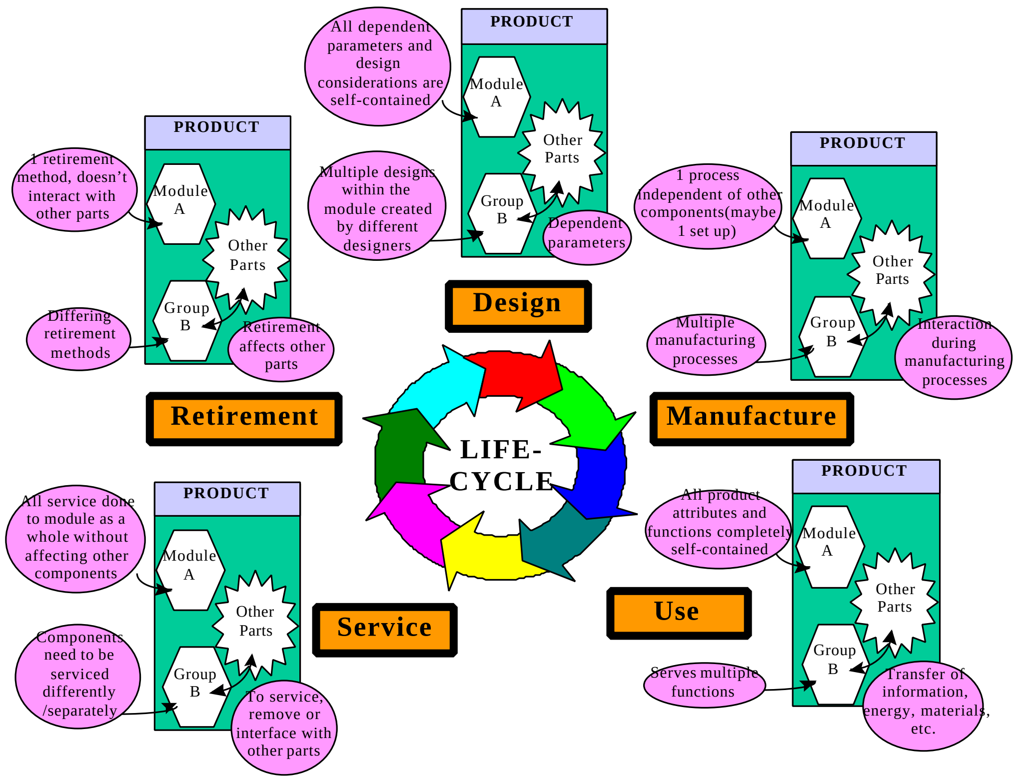

Figure 2: Views of a product as it goes through some of the major life-cycle processes. Once again, Module A is modular while Group B and Other Parts are non-modular.

Manufacturing modularity, a particular characteristic modularity, is the development of product modules with minimal dependencies upon other components in the product with regard to manufacturing processes. In addition, the components within the module have maximal similarities to each other and minimal similarities to external components with regard to their manufacturing processes. Such modularity can arise from, for example, a module which comprises all of the components in a product that are injection molded.

An important consideration when defining the manufacturing modularity of a product is the chosen level of abstraction of the manufacturing process itself. The manufacturing of a product is made up of many tasks. These tasks are, in turn, made up of sub-tasks. A product may be modular (independent and similar) when examined from the standpoint of the overall manufacturing processes (*e.g.*, injection molding versus forging) but at some task level, the structure may not be very modular with respect to the manufacturing process (*e.g.*, similarity of fixturing components within a module). Therefore, when defining the relative manufacturing modularity of a product, one must do so with respect to the tasks and sub-tasks of the manufacturing process. This is parallel to considering the level of abstraction of the product.

Lastly, it is important that each manufacturing modularity takes into account manufacturing's effect on each product attribute. When looking for dependencies and interactions between modules and components, each attribute of the product, modules, and components must be considered. As an example, consider the housing of an electric coffee maker which is one modular assembly composed of many components. All of the components of the housing are made of the same plastic, are manufactured to similar tolerance specifications, possess the same surface condition, and undergo the same manufacturing process. Product attributes include: geometry, features, tolerances, surface condition, materials, and facilities (Gershenson, 1995).

3. DESIGN METHODOLOGY FOR *MANUFACTURING MODULARITIES*

It is important to view manufacturing modularity from the standpoint of creating more modular products. This is quite different from designing products with interchangeable or reconfigurable parts. It is also quite different from maintaining form/function independence. Modular design techniques are the crux of this research. It is the goal of modular design to group all attributes with like processes into a single module and decouple them from all other attributes and processes. Creating modular products involves making sure that, at each level of abstraction, the product's attributes are as independent from one another as possible for each level of abstraction of the manufacturing tasks. If a dependency does occur, it should occur within a module. In addition, within a module, every manufacturing process should be similar for every attribute.

Part of the goal of modular design for manufacturing involves a one-to-one form/process relationship (independence). This includes maintaining both form/form and process/process independence as well as the relationship between the two. Another aspect of modular products is the similarity of how the module and its components are manufactured (similarity) (Gershenson, 1996-2). Similarity is another perspective on the independence between form and process. For each part of the form (module), the entire module must undergo the same manufacturing processes. The last aspect of modular design is minimizing the different types of interfaces (interchangeability). This is more easily done and common in industry today.

To increase independence and similarity, a product must be designed with the following facets of modularity in mind: attribute independence, attribute similarity, process independence, and process similarity. The more independent, and unique the components and their manufacturing processes are, the more modular the product is. Attribute similarity is excluded because it is not necessary for modular products as long as attribute independence is preserved. As an example, many different modules can have black components and still remain modular, however, if the components must all match in color then there is a dependency that reduces modularity.

Following are definitions and examples of the three facets of modular product design:

1) *Attribute Independence*: Component attributes have fewer dependencies on attributes of components outside of the module, called external attributes. If there are dependencies, there should be fewer of them and they should be dependent to a lesser degree. Attribute independence yields form independence which enables modularity. Attribute independence allows for the redesign of a module with minimized effects on the rest of the product. This makes a product more agile in meeting changing requirements. A simplistic example of attribute dependence decreasing agility would be a large cast aluminum component which rests on a plastic box. If the cast component now needed to be of a heavy iron, the plastic box would need to change in material and/or a rib pattern would be needed on the inside. Therefore, both modules would need redesign for a change that should have only affected one module.

2) *Process Independence*: Each manufacturing process of each module has fewer dependencies on the processes of external components. This requires that the manufacturing processes (including all tasks) that a module undergoes are independent of the processes undergone by external components and modules. Once again, any dependencies that do exist are minimized in number and criticality. *E.g.*, two cast parts which are pressed together while still hot to strengthen the connection. If the process of one part changes so that there is a different cooling time, the process of the other component must change so that they can be pressed together at the same time. Processes independence allows for the redesign of a module in isolation in the manufacturing process of a product should change.

3) *Process Similarity*: Group components and sub-assemblies which undergo the same manufacturing processes into the same module where possible. This minimizes the number of external components which undergo the same processes and creates a strong differentiation between modules. *E.g.*, reinforced plastic components for a motorcycle such as rear forks, rear swing arm, wheel and discs can be chopped fibers, woven fabric, continuous lengths of fiber, or a slightly twisted fiber. To obtain a good bonding between the reinforcing fiber and the polymer matrix, it is necessary to coat the reinforcement with the polymer. The components all undergo this specialized process. If they were therefore grouped in a single module, all of the components which underwent

this process could be made at a single location and have a singular reaction to any changes in the manufacturing process. Process uniqueness also conserves redesign energy by insuring that changes to individual life-cycle phenomena only affect one module of the product. This, coupled with the other three facets prevents the cascade of design changes caused by small changes in a product's manufacturing processes.

While designing only for manufacturing modularity and ignoring the rest of the product life-cycle is not optimal, manufacturing modularity is important. For design, manufacturing is currently one of the most influential parts of the life-cycle and because it has the largest body of knowledge. Both of these factors facilitate developing a sound methodology. In addition, understanding manufacturing modularity is, in itself, a useful end. Products which are modular in terms of manufacturing have decreased set up costs and decreased change time, better utilize production resources, and decrease scheduling complexity.

3.1 Example Application

In this brief example of an electric coffee maker, we can illustrate relative manufacturing modularity and how to increase manufacturing modularity through design. The body of the coffee maker (Figure 3) is a very good example of a production module. A production module is one in which the components have been grouped primarily because of a similarity and dependence in their manufacturing and assembly processes. Production modules are designed independently of their function, but in the case of this coffee maker, the design incorporates both production and functional characteristics of modularity.

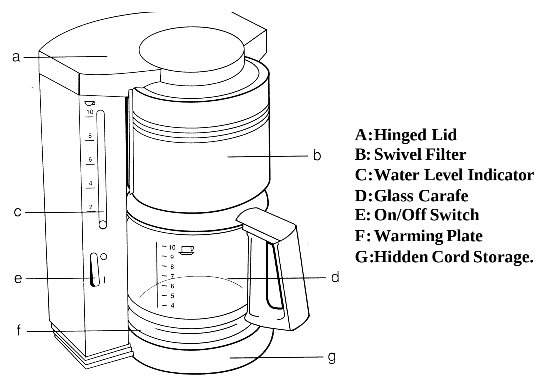

Figure 3: *An assembly diagram for the electric coffee maker.*

The coffee maker's components are described in the component tree of Figure 4. A component tree details the levels of abstraction of a product. Although relationships between components are missing on this tree, one can still see the general partitioning of components. To explain the manufacturing process of the coffee maker, a manufacturing graph is shown in Figure 5. A manufacturing graph illustrates the tasks necessary to produce a product. The graph contains the top level processes and the tasks that make them up. Once again, one can see if the processes are partitioned even without showing the dependencies.

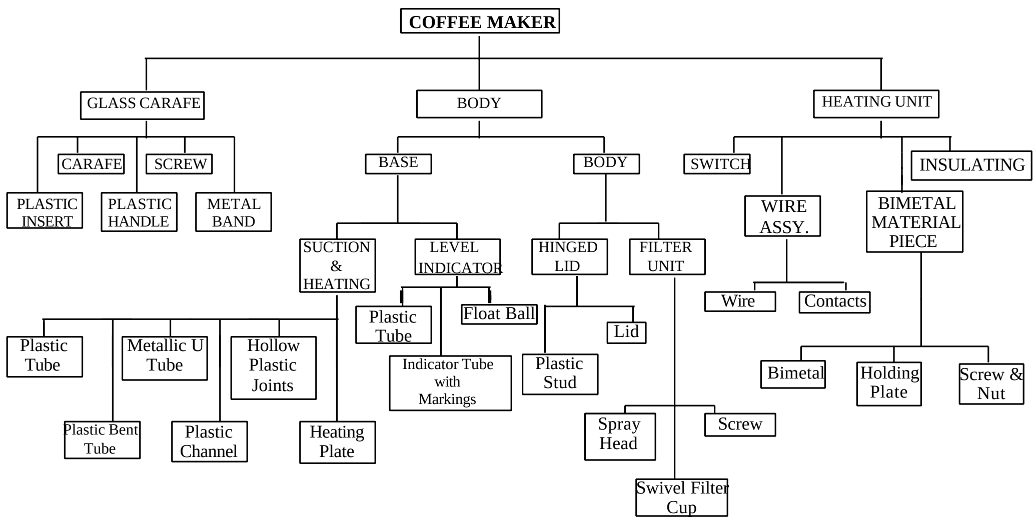

Figure 4: *A component tree diagram for an electric coffee maker.*

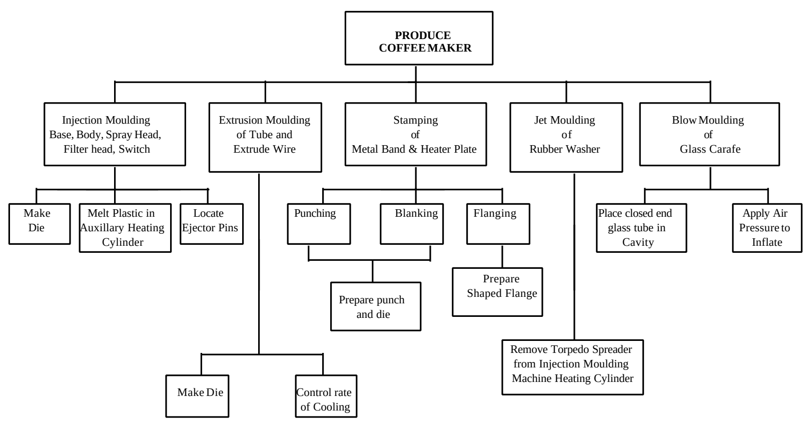

Figure 5: *A manufacturing graph showing the top level manufacturing tasks for an electric coffee maker.*

By comparing the form partitioning shown in the component tree with the process partitioning shown in the manufacturing graph, one can see the manufacturing dependencies and similarities between modules of the coffee maker. All of the parts of the coffee maker's body undergo the same manufacturing processes (namely injection molding) and can be produced together leading to shorter delivery times, increased productivity and reduced overheads. This similarity demonstrates the benefits of manufacturing modularity. This modularity does not exist with other assemblies such as the glass carafe. The components of the glass carafe are assembled after its components undergo different manufacturing processes such as injection molding, stamping, blow molding and metal finishing. The glass carafe is a poor example of modular design in that it does not satisfy process independence and similarity.

The glass carafe can be made more modular by eliminating the plastic insert, metal band, and screw. In addition, the handle of the carafe can be provided with a hook so that it can easily fix on to the groove on the carafe and it can be assembled to the carafe with a strong bonding agent. These design changes will make the glass carafe more modular than its previous design with respect to production. The glass carafe module in the new design will have improved process similarity. Because, with the elimination of the metal parts (the band and the screw), more of the module's parts will be of a similar material and a number of component-specific manufacturing process will be eliminated. The result is an assembly with reduced parts, which is less complicated and cheaper to manufacture and assemble. Also, the new design of the carafe is more modular without compromising on the aesthetics of the product.

4. CONCLUSIONS

The benefits of modular design for manufacturing center around extending the elements of flexibility and economies of scale that modular products have used to greatly increase the end user value. "[I]ncorporating flexibility, modularity, and adaptability into design to provide additional freedom to adjust and adapt to change" (Shah, 1996). The benefits of manufacturing modularity include: "streamlined suppliers, reduced inventory, fewer works in process, [and] faster process time..." (Ishii, 1995), as well as component economies of scale, ease of product update, increased product variety from a smaller set of components, and decreased order lead-time (Ulrich, 1991).

This paper has proposed a definition of manufacturing modularity which accounts for one of the many different phenomena in the product life-cycle. Defining the key elements of manufacturing modularity (independence, similarity, and interchangeability) set the premise for the development of a design methodology to create modular products. This methodology enables the benefits of manufacturing modularity. The key elements of manufacturing modularity are manifested in the three facets of the design methodology (attribute independence, process independence, and process similarity). These facets were illustrated in the electric coffee maker example.

This practical method of developing more modular products can be used in conjunction with a structured design process to decrease the life-cycle costs of a product. The three facets of the design methodology can be considered singularly or as a group. Implementing the methodology early in the design process will allow for a more complete investigation of component, configuration, and manufacturing process options.

While the development and application of a modular design for manufacturing methodology is quite useful on its own, there are three suggested extensions to this work: 1) a manufacturing modularity measure must be developed to aid the designer in moving towards more modular products; 2) a method of balancing the many different characteristic modularities should be developed to aid the designer in making modularity decisions; and 3) the point of diminishing returns for increased manufacturing modularity should be explored so that the designer knows where to stop increasing relative modularity.

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