Proceedings of DETC'03
ASME 2003 Design Engineering Technical Conferences and Design Theory and Methodology
Chicago, Illinois, September 2-6, 2003

DETC2003/DTM-48661

A CLASSIFICATION METHOD TO COMPARE MODULAR PRODUCT CONCEPTS

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ABSTRACT

In recent years the design of modular products has become the focus of significant research in the area of design theory and methodology. This focus is the result of the increased awareness of the power of modularity to achieve certain product objectives. To add to this surge in modular product research, this paper focuses on developing design tools for use in industrial settings where modular products are being designed. In developing these tools the many definitions and methods for classifying modular products are consolidated and refined. Drawing from this consolidated research a new scheme for classifying modularity types, the Modularity Type Space (MTS), is developed. This classification scheme not only succinctly defines the types of modularity, but shows the relationships between them. Metrics and tools are also presented that are to be used for the purposes of classifying modular products on the MTS.

INTRODUCTION

The motivation behind this research is to help design teams more easily design modular products. To accomplish this better tools are needed that specifically address the unique nature of modular products. To date, most of the design tools for modular products have focused on how to group product sub-functions into modules. This process is sometimes referred to as chunking[1]. However, few tools have been developed that can aid designers in comparing modular products. Such tools could be used to compare competing modular product designs for the purposes of concept screening and final concept selection.

Researchers have proposed many methods for capturing a product's architecture, such as by taxonomy [2], target cost and required functionality [3] and many others as summarized by Kusiak [4], but only a few appear to be widely accepted and cited. In addition, many of these methods are disjointed, redundant, and or unrelated to one another. In this document, existing classification methods will be pooled, relationships between classifications will be shown, and a new classification method will be developed. It is the goal of this research to provide designers with a tool that can be used for comparing competing modular product design concepts for the purposes of concept screening and final concept selection. This new classification method will include metrics and rules to objectively and consistently classify similar modular products for the purposes of comparison.

Therefore, the objective of this paper is to develop a new method for classifying modular products for the purposes of concept screening and final concept selection by:

1. Consolidating and standardizing classification methods and terminology for modularity types.
2. Creating metrics that provide a means by which similar modular products can be simultaneously and objectively classified within the above mentioned consolidated framework.

This paper begins with a brief background on existing research on this topic. Afterwards, this paper outlines the development of the new classification scheme, explains the key concepts of the new scheme, and defines the new classifications for modularity types contained in the new scheme. Following this, metrics and rules are presented for classifying products within the new scheme, and an example of how to use the new scheme is presented. This paper ends with a discussion of conclusions and future work.

BACKGROUND

Before discussing the new classification scheme developed in this paper, it is necessary to first discuss the existing research that was used to develop it. The first sub-section below will discuss the degrees of modularity. The second sub-section will discuss types of modularity. And the third sub-section will discuss existing modularity metrics. The last sub-section will briefly discuss some existing methods for evaluating modular products.

DEGREES OF MODULARITY

A car might be modular to the engineers that built it, but appear entirely integrated to the end user. As stated by Mattson [5] "product modularity exists at three fundamental phases which are design phase modularity, manufacturing phase modularity and consumer phase modularity. At each of these phases, modularity is a primary tool used to achieve customer needs or product strategies." The definitions of these three terms were revised by Strong [16] to make them more easily applicable to all modular products. The revised definitions for each of these three terms are:

Design Phase Modularity: A product is modular at the design phase if the product function is defined through the addition, subtraction or substitution of design modules

Manufacturing Phase Modularity: A product is modular at the manufacturing phase if the product function is determined, by a manufacturing process or assembly step, through the addition, subtraction or substitution of previously designed modules.

Consumer Phase Modularity: A product is modular at the consumer phase if a consumer, through the addition, subtraction or substitution of previously designed modules, can modify the product function.

The findings of Mattson are supported by Otto and Wood [6], and similar conclusions to those of Mattson can be drawn from the work of Ulrich and Eppinger [1] on the motives for product development.

TYPES OF MODULARITY

Modules use interfaces to interact with other modules. Ulrich and Eppinger [1] define three types of modularity based on the type of interface a modular system uses. A graphical representation of each can be seen in Figure 1, and their definitions are:

Slot-modular Architecture: Each of the interfaces between modules in a slot-modular architecture is of a different type from the others, so that the various modules in the product cannot be interchanged. An example of such a system is a car radio in an automobile. It performs one function and its interface is different from that of any other interface in the vehicle.

Bus-modular Architecture: In bus-modular architecture, there is a common bus to which the other modules connect via the same type of interface. The various modules are therefore interchangeable. Examples of such a system are track lighting, desktop computers, and shelving systems.

Sectional-modular Architecture: In sectional-modular architecture, all interfaces are of the same type but there is no single element to which all the other modules attach. The assembly is built up by connecting chunks directly to each other via identical interfaces. Examples of such a system are piping systems, sectional sofas and office partitions.

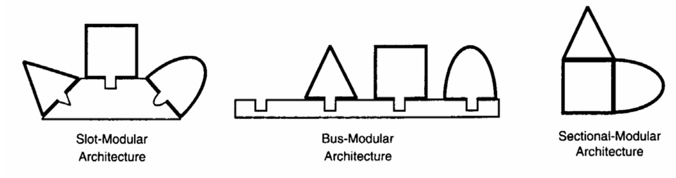


Figure 1 Types of Modularity

Otto and Wood [6] support the classifications of modularity listed above. In addition to these three types of modularity, Otto and Wood define one additional type of modularity:

Mix-modular Architecture: In mix-modular architecture, several standard components are combined together through webs of modules rather than a simple chain as in sectional-modular architecture. Modules must be equipped with at least two complimentary interfaces to create a new device. An example of such a system is the Tinkertoy. The Tinkertoy's components can be combined to form an almost limitless number of new toys.

It is interesting to note that there are similarities between the definition of mixed-modular architecture and sectional-modular architecture. The primary difference between the two is that sectional-modular architecture uses a standard interface and mixed-modular architecture does not. It must have at least two types of interfaces (i.e. slot and bus, slot and sectional, etc.).

Stake [7] also classifies modularity into three different types. These types are defined as:

Component-Sharing Modularity: where the slots are the same on a family of base products allowing the sharing of modules between products.

Component-Swapping Modularity: where the slots are designed to allow the interchanging of different components on the same base product.

Cut-to-Fit Modularity: where the slots are designed so that only a specific module fits into any given slot on the base product.

Again, it is important to note that Stake's definitions of component-swapping modularity and cut-to-fit modularity are the same as Ulrich and Eppinger's definitions of bus-modular architecture and slot-modular architecture respectively.

MODULARITY METRICS

While there has been significant work on classifying modularity based on qualitative observations, there exists relatively little work on quantifying modularity. In Mattson's [5] work on modular consumer-products he presents Equation (1) and Equation (2) that can be used to objectively quantify modularity. The first is a measure of the degree of modularity, M:

$$M = \frac{N_{modules}}{N_{functions}} \quad (1)$$

The second is a measure of interface reuse, I:

$$I = 1 - \frac{N_{interfacetypes}}{N_{interfaces}} = 1 - \frac{N_{it}}{N_i} \quad (2)$$

Both metrics are bounded by 0 and 1. A product with a modularity metric of 1 is said to be the most modular while a value of 0 is considered to be the most integral. According to Mattson, a product with an interface metric that approaches 1 would have a single common interface used on all modules. A product with an interface metric of 0 would not reuse a single interface in the entire product. Every interface would be unique.

EVALUATING MODULARITY

When a design team is faced with the process of screening competing modular product concepts for the purpose of final concept selection, it is important to select the right method, tools, and criterion. Design teams currently have few tools to choose from to aid them in this process. None of these existing tools address the unique characteristics of modular products. Some of these tools are benchmarking [8], the utility based approach [9], and the customer needs approach [10], [11]. Some other methods that are currently being explored for use with modular products are the conjoint method [12], [13], [14], and the design objective tree [5].

DEVELOPING A MODULARITY TYPE SPACE

Building on the degrees and types of modularity, as well as the metrics discussed above, the Modularity Type Space (MTS) was developed as a way to consolidate the previous work on modularity types and move towards a method to classify competing modular concepts. This section will discuss how the MTS was developed by beginning with a discussion of the phases of modularity and concluding with a discussion on modularity types.

PHASES OF MODULARITY

Although this paper will focus on the consumer phase of modularity, it is important to note that a product's classification might vary depending on the phase of modularity at which the product is being considered. For example, the primary function of a module at the manufacturing phase might be to provide a common assembly platform while that same module might have a different primary function at the other two phases. Therefore, when discussing a modular product it is important to always take into consideration the phase of modularity.

MODULARITY TYPES

Having explained how a product's classification might vary depending on the phase of modularity it is now possible to examine types of modularity. Definitions for types of modularity from Ulrich and Eppinger, Otto and Wood, and Stake were provided earlier. With some redundancy, each of these sets of definitions defines a type of modularity using two distinguishing factors.

1. If a base module is used or if the modules attach directly to other modules (for clarification on the definition of a base module see Definition 5).
2. If the interface employed allows modules to attach only in specific locations, or if the module's locations can be swapped.

For example, Ulrich and Eppinger's definition of a slot-modular architecture states that a product is using this architecture if it has a base unit, and the interfaces on that base unit are configured in such a way that modules will only fit into a designated slot (does not allow the swapping of modules). Drawing from these two criteria for defining the different types of modularity, Table 1 shows the relationship between these existing definitions.

Table 1: Modularity Type Criterion

	Base	Baseless
Unique Interface(s)	Slot-Modular (Ulrich & Eppinger) Cut-to-fit (Stake)	Mixed-Modular (Otto & Wood)
Standard Interface(s)	Bus-Modular (Ulrich & Eppinger) Component Swapping (Stake)	Sectional Modular (Ulrich & Eppinger)

Looking at Table 1, it can be seen that the criterion on the vertical axis deals specifically with interface type (standard vs. unique), and the criterion on the horizontal axis deals specifically with the architecture (base vs. baseless). The definitions developed to describe the interface types are:

> **Definition 1:** *Standard Interface:* An interface that allows any module to be attached to any interface on the product in question.
>
> **Definition 2:** *Unique Interface:* An interface that requires modules to be attached to a specific interface on the product in question.

The definitions developed to describe the architecture types are:

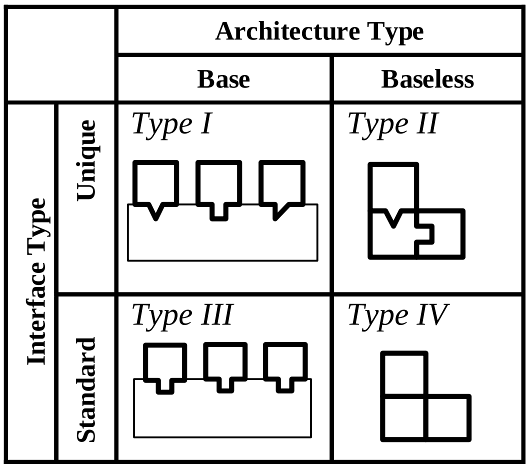
> **Definition 3:** *Base Architecture:* An architecture that utilizes a base unit.
>
> **Definition 4:** *Baseless Architecture:* An architecture that does not use a base unit.

Using these new definitions and categories of criteria, Table 1 evolves into the Modularity Type Matrix (Table 2). Contained in the Modularity Type Matrix (MTM) are four types of modularity that will be discussed and defined later in this paper. By adding a third dimension to the MTM, the MTM expands into the MTS. This third dimension is discussed in the following section.

DEGREE OF MODULARITY

The MTM provides a solid framework for discussing the four types of modularity. However, one of the things it does not address is the question of a product's ability to reconfigure. In

Table 2: Modularity Type Matrix (MTM)



other words, how flexible is a modular product? Is every product sub function its own module? If so, every sub function can be replaced independent of all other sub-functions, and every module can be repositioned independent of all other sub-functions. Or, are all sub-functions divided between two modules limiting the number of configurations and the ability to replace sub-functions? This is a question of product sub function density within product modules. A product with low sub function density would have a high degree of modularity. In a sense, this kind of product would be more modular than a product with a high sub function density.

This question of the degree to which a product is modular adds a third dimension to the MTM. Therefore, the MTM is renamed the Modularity Type Space (MTS) and can be seen in Figure 2.

In order to use the MTS effectively as a means for classifying modular products, a solid understanding and definition for the term base unit is required. This is the topic of the following section.

DEFINING THE TERM BASE UNIT

To define the term base unit the three examples shown in Figure 3 were considered. Figure 3a shows a slightly altered picture of the representation of Type II modularity in Table 2. The difference between these two pictures is that module B1 no longer plugs into C1. Instead, both modules A1 and C1 plug into B1 making its architecture more closely resemble that of Type I modularity. Would this simple change in interface arrangement constitute a change in the definition of component B1?

Figure 3b shows an altered picture of Type III modularity that is contained in Table 2. In this case, the base unit is shown to be interchangeable. Does the fact that the base unit is replaceable change this product's classification from a base to a baseless architecture?

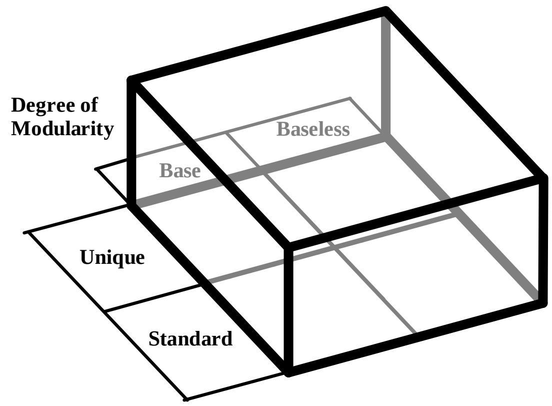
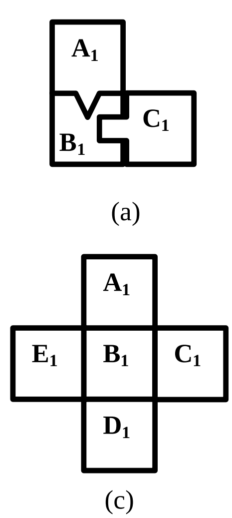


Figure 2 Modularity Type Space

Figure 3c shows the picture contained in the Type IV quadrant of the modularity type matrix except now there are four modules that are attached to module B1. Does the fact that B1 now acts as a hub for the product constitute a change in its classification?

There are no good answers to any of the three questions above. Because these questions have no clear answers, the term base unit is better defined leaving these questions aside. All of the questions above deal with the physical appearance of the components in question. Not one of the three questions above deal with the function of the components in question. Therefore, the term base unit is more easily defined based on the function of the components in question rather than the physical appearance. The definition of the term base unit is therefore:

> **Definition 5:** *Base Unit*: A base unit is a module that allows the majority of the other product module(s) that are attached directly to it to carry out their primary function(s). A base unit may require a certain configuration of basic modules in order to function such as a power module, information module, material supply, etc.



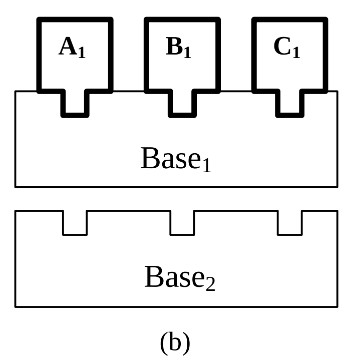


Figure 3 Variations on Module Configurations Presented in the Modularity Type Matrix

Figure 4 Two Module Blender

To illustrate Definition 5 consider the following example. The blender shown in Figure 4 is composed of two modules. Module one houses the motor, transformer, and controls. Module two is the container that sits on top of module one and contains the blades of the blender. The question is, does this modular product use a base or baseless architecture? To answer this question the function of each of the two modules must be defined. Module one's primary functions are to transform electrical energy into mechanical motion, provide a means for controlling that motion, and to provide a support structure for module two. Module two's function is to stir, blend, and or mix the material contained in module two.

In order to determine if this product uses a base or baseless architecture these modules' functions must now be considered in the context of Definition 5.

Blender Module One:

1. Transform Energy - independent of module two
2. Control - independent of module two
3. Provide Support - independent of module two

Blender Module Two:

1. Stir, Blend, and or Mix - dependent on module one
2. Contain Material - independent of module one

Without module one there is no motion created that module two can use to stir, mix and or blend anything contained in module two. Even though module two can contain material without module one, module two cannot carry-out its primary function of stirring, blending, and or mixing without module one. Module one can carry out all functions without module two. Therefore, the blender shown in Figure 4 would be classified as having a base architecture with module one being the base.

It is important to note that this blender requires no minimum configuration to operate, but some products do. Consider a portable blender that has three modules. Modules one and two are the same as in the two module example, and module three is a battery module that plugs into the bottom of module one. Module one is now dependent on module three to be able to carry out one of its primary functions of transforming energy, and module three is not dependent on any module to carry out its primary function of supplying power. Should module three be classified as the base unit? The answer is no. Module one remains the base unit, while module three is classified as a module that the base unit requires for minimum configuration.

Having fully defined the MTS, the following section will define each of the four types of modularity contained therein.

MODULARITY TYPES

There are four types of modularity contained in the MTS. They are each defined as:

Type I Modularity

Type I modularity as expressed in Table 2 is defined as:

> **Definition 6:** *Type I*: A product is classifiable as type one modular when there is a base unit and the interfaces are designed so that modules only fit into their unique interface.

Figure 5 is a picture of common interfaces that can be found on a laptop computer. It is no doubt that from the macro level depicted in Figure 5 that the laptop computer (with its needed minimum configuration modules of a battery and or power cord) functions as a base unit for all other peripherals attached to it. Figure 5 shows 12 different examples of unique interfaces through which modules (computer peripherals) can be attached to the base unit. It is important to note that even though this interface array is composed of 12 unique interfaces, there are 14 interfaces present. This means that there is some reuse of the unique interfaces. For example, there are two USB ports and two 1/8" microphone/speaker jacks. Both of these groups of reused unique interfaces should be considered groupings of standard interfaces. Even though this product is a good example of Type I modularity, because of its slight reuse of interfaces,

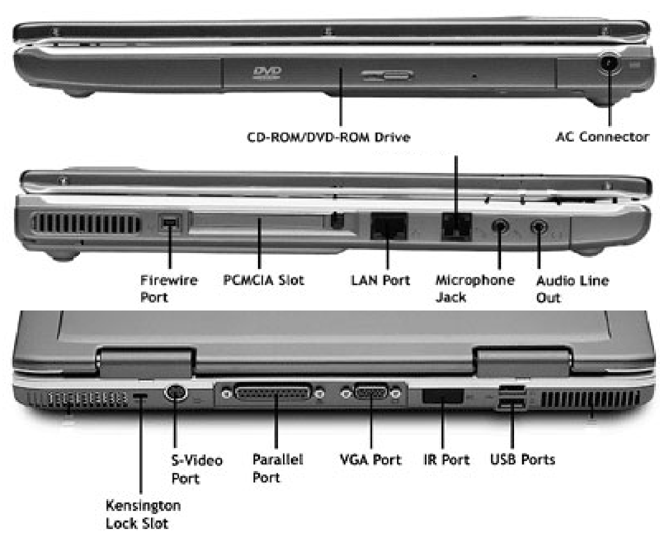


Figure 5 Type I Modularity “Laptop Computer Interfaces” Right View, Left View, and Back View

this product is not an example of Type I modularity at the extreme. This concept of varying levels of classification will be addressed later

Type II Modularity

Type II modularity as expressed in Table 2 is defined as:

Definition 7: *Type II*: A product is classifiable as type two modular when there is no base unit and the interfaces are designed so that modules can only be attached to other specific modules through a unique interface.

Figure 6 contains drawings that represent some modules that might be used together to photograph an object. Each of these modules uses a unique interface to attach to the others. None of these modules is dependent upon the other to carry out its primary function making this a baseless architecture. For example, the primary function of the flash is to provide a bright flash of light. While it is true that the flash can be attached to the camera and timed so that the light is delivered in time with the taking of a photograph, the flash can provide a bright flash of light without the camera. A flash carries its own power supply and can be triggered without a camera (if so desired). A tripod functions as a steady support with or without any of the rest of the equipment depicted in Figure 6. The lens will focus light and bring images closer with or without the camera. And even the film, albeit unsatisfactorily, will capture light when it is exposed with or without the camera. Because each module is functional independent of all others, and they use unique interfaces to attach to one another, the system depicted in Figure 6 is a good example of Type II modularity.

It is also important to mention that many people might consider the camera to be a base unit making this an example of Type I modularity. While it is true that the camera sends out a control signal to the flash, controls the exposure of the focused light on the film, and acts as a central hub to which everything attaches, all the modules do maintain their functional independence. However, this example does put forth an interesting question. Is it possible that a product can be baseless in some respects and use a base in others? For example, perhaps the photography equipment is baseless with respect to module function but uses a base with respect to product control and product structure. Whatever the answer to this question, the photography equipment is one example of Type II modularity as defined by Definition 5 and Definition 7. However, it is also obvious that the definition of a base unit (Definition 5) needs further development.

Type III Modularity

Type III modularity as expressed in Table 2 is defined as:

Definition 8: *Type III*: A product is classifiable as type three modular when it uses a base unit where the interfaces are designed so that any module will fit into any given interface.

Figure 7 is a picture of a track lighting system that would be used to illuminate the room in a home. Modules 1-3 fit together to form the base unit. These three modules make up the minimum required configuration. Module 3 comes in many different shapes and module 2 comes in many different lengths so that the desired shape of the base unit can be formed. Once the base unit is configured, varying numbers of module 4 can be attached to it. Although module 4 comes in varying shapes, sizes, and styles, each one connects to the base unit through a standard interface. The top of Figure 7 shows three module 4's of the same type attached to the base unit (modules 1 and 3 are not visible).

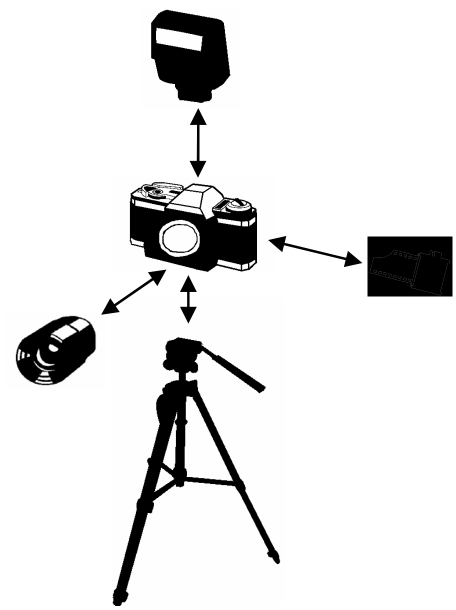


Figure 6 Type II Modularity “Photography Equipment”

Type IV Modularity

Type IV modularity as expressed in Table 2 is defined as:

Definition 9: *Type IV*: A product is classifiable as type four modular when it does not use a base unit and the interfaces are designed so that any module will attach to any other module. Examples of such a system are sectional walling, scaffolding, stackable compliant constant force springs, stackable storage systems, and plumbing systems.

Figure 8 shows two types of stackable containers. Figure 8a shows four plastic bins in two stacked configurations. The taller of the two configurations allows objects to be stored in the bins. The shorter of the two configurations allows for compact storage when the bins are not being used to store other goods. In either case, each module (bin) interfaces with every other module through a standard interface. There is no base unit to which the bins attach. Figure 8b shows plastic bins of various sizes that are also stackable. Despite the fact that these bins are of different sizes, each module (bin) can interface with every other module through a standard interface. Again, there is no base unit to which these bins attach.

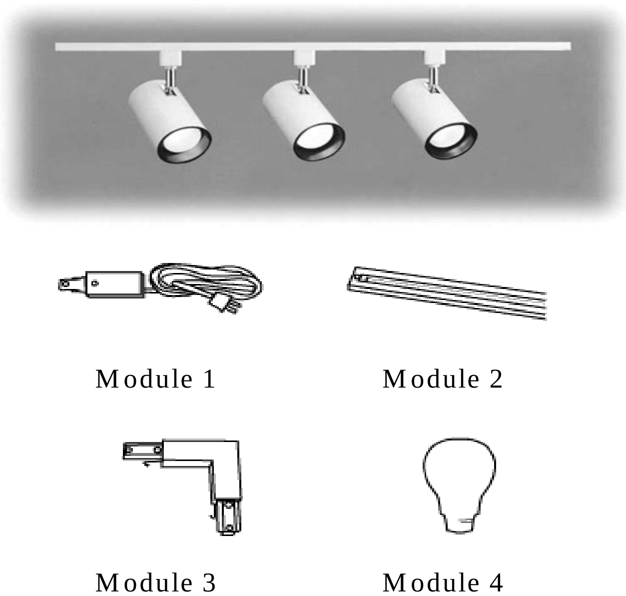


Figure 7 Type III Modularity “Track Lighting”

CLASSIFYING MODULAR PRODUCT CONCEPTS USING THE MTS

This section explains how to plot the location of a product on the MTS. It is split into three sub-sections each addressing one of the three axes of the MTS. Following these three sections will be a summary section.

INTERFACE AXIS

The interface axis is located on the left side of the MTS (Table 2). When attempting to place a product on this axis it is important to remember that the MTS does not address all product characteristics. For example, one end of the interface axis is labeled standard to represent the use of standard interfaces. The term standard interface, in the context of the MTS, only addresses the product itself. In other words, the term standard interface does not attempt to address the question of whether or not a product uses industry standard interfaces. It only addresses the question of whether or not all the interfaces used on the product in question are the same (standard). For more clarification on this point see Definition 1 and Definition 2.

The only question the interface axis of the MTS addresses is the question of interface reuse. At one extreme every interface on a product would be the same. This situation corresponds to the end of the interface axis labeled standard (Table 3) and is defined in the following manner:

$$N_{interfacetypes} \equiv 1 \tag{3}$$

$$N_{it} \equiv 1 \tag{4}$$

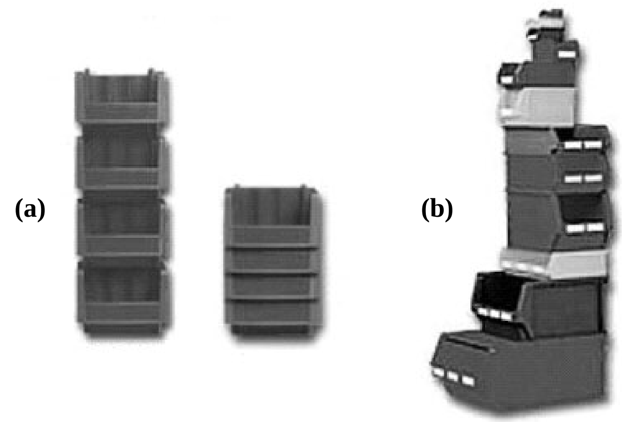


Figure 8 Type IV Modularity “Stackable Storage”

At the other extreme, every interface on a product would be different. This situation corresponds to the end of the interface axis labeled unique (Table 3) and is defined in the following manner:

$$N_{interfacetypes} \equiv N_{interfaces} \tag{5}$$

$$N_{it} \equiv N_i \tag{6}$$

Products that contained a mixture of standard and unique interfaces would be located somewhere in-between the two extremes.

Equation (3) through Equation (6) were developed based on the following criteria:

- A metric that uses the two variables number of interfaces (N_i) and the number of interface types (N_{it}).
- A metric that accurately reflects a product design's reuse of interfaces relative to competing designs.

Drawing from these needs, the following metric is based on Equation (2) through Equation (6).

$$I = \frac{N_{it} - 1}{N_i - 1} \tag{7}$$

Where,

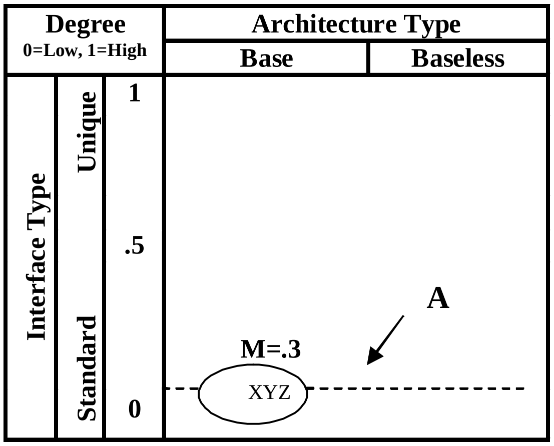
$$N_i \geq 2 \tag{8}$$

$$1 \leq N_{it} \leq N_i \tag{9}$$

In order for there to be any discussion about interface reuse, a product must have at least two interfaces. For this reason the number of interfaces is restricted to an integer of greater than or equal to two. Also, the number of interface types is restricted to a value between 1 and N_i to reflect the fact that the number of interface types can never exceed the number of interfaces, and there will always be at least one interface type.

Equation (7) gives what is called the Interface Score (I) and is called the interface metric. This score will always be between 0 and 1. An Interface Score of 0 corresponds to a product that uses

Table 3: MTS with Product Plot



only one type of interface (standard interface where $N_{it} = 1$). An Interface Score of 1 corresponds to a product where every interface is different (unique interface where $N_{it} = N_i$). A score that falls in-between 0 and 1 corresponds to a product that uses some mixture of both standard and unique interfaces. For example, a product with *I = 0.1* would plot somewhere along the line labeled “A” in Table 3. More illustrations of the use of the interface metric are provided by Strong [16].

ARCHITECTURE AXIS

The architecture axis is located at the top of the MTS Table 2. Placing a product on this axis is a binary decision.

The steps for deciding if a product uses a base or baseless architecture are:

1. Define the product, or parts of a product, of interest.
2. Identify all modules and list each module’s primary function(s).
3. Check for functional dependency between modules (Blender Example).
   a. In products with a large number of modules the five indicators of a base unit listed previously.
4. Label all modules as either functionally independent or dependent and the modules to which they have dependencies.
   a. Be sure to check all modules for functional independency
5. If any of the modules satisfy Definition 5 then the base unit has been identified and the product can be classified as using a base architecture. If none of the modules satisfy Definition 5 then there is no base unit and the product can be classified as using a baseless architecture.

There won't always be a clearly identifiable base unit as in the blender example. Some products might have more than one functionally independent module, or small clusters of functionally dependent modules that are independent of all others. In theses cases the design team must make a judgment call. This need for a judgment call is an example of why the MTS is not well suited for classifying and comparing dissimilar products. When comparing similar products on the MTS, such as competing product designs in a concept screening scenario, the design team can make consistent judgment calls for all design concepts. This level of consistency would be difficult when comparing dissimilar products.

A product that with *I = 0.1* and that was classifiable as a base architecture would plot in the location of product XYZ in Table 3. More illustrations of how to classify products along the architecture axis are provided by Strong [16].

DEGREE OF MODULARITY AXIS

The degree of modularity axis is located perpendicular to the plane created by the architecture and interface axes of the MTS and is oriented out of the page as shown in Figure 2.

To plot a product on the degree of modularity axis the modularity metric was developed. It was developed based on the following criteria:

- A metric that gives a value of 0 at one extreme and a value of 1 at the other extreme.
- A metric that takes into account the chunking of product sub-functions (function density per module)

Drawing from these needs, the following metric, based on Equation (1) was developed:

$$M = \frac{N_{modules} - 2}{N_{subfunctions} - 2} = \frac{N_m - 2}{N_{sf} - 2} \tag{10}$$

Where,

$$N_{sf} \geq 2 \tag{11}$$

$$2 \leq N_m \leq N_{sf} \tag{12}$$

In order for a modular product to exist there must be some division of product sub-functions between at least two modules. In order to have a division of product sub-functions there must be at least two sub-functions present. For this reason the number of product sub-functions is restricted to an integer of greater than or equal to two. Also, the number of modules is restricted to a value between 2 and N_{sf} to reflect the fact that the maximum number of modules can never exceed the number of sub-functions, and that there will always be at least two modules. In the case of a product with redundant modules, all redundant modules should be counted, and all subfunctions within each module should also be counted. For example, if a product has three identical modules that each contained two product subfunction N_m would equal 3 and N_{sf} would equal 6.

Equation (10) gives what is called the Modularity Score (M). This score will always be between 0 and 1. A modularity score of 0 corresponds to a product that uses only two modules. In other words, this product will have the highest concentration of product sub-functions in its modules and would exhibit a low degree of flexibility. This end of the degree of modularity axis is located at the intersection of the three axes (Figure 2). A modularity score of 1 corresponds to a product that has one module for every function. In other words, this product will have the lowest concentration of product sub-functions in its modules and would exhibit a high degree of flexibility. This end of the degree of modularity axis is located at the point furthest from the intersection of the three axes along the degree of modularity axis (Figure 2).

It is important to note that the modularity axis does not attempt to show product concept superiority. In other words, a product with M=1 is not necessarily better than a product with M=0. The only conclusion that can be drawn from the modularity scores is how modular a product is. Weather or not a product concept with high modularity is better than a concept with low modularity would depend upon the overall objectives for the product.

Rather than attempting to represent this product's location in a three dimensional figure like Figure 2, which can be hard to read, it was chosen to represent the location of a product in the MTS in the manner shown in Table 3. By adding the Modularity Score to the plotted position of the product on the MTM, the MTS can be clearly represented without the need for a confusing three dimensional plot. For example, a product with $I = 0.1$, that was classifiable as a base architecture, and an $M = 0.3$ would plot as shown in Table 3. More illustrations of how to classify products on the MTS are provided by Strong [16].

With a full understanding of all four types of modularity, the MTS and its accompanying metrics and rules, the following section will describe how to plot a group of competing modular product designs for the purposes of final concept selection.

VACUUM CLEANER EXAMPLE

This section shows how to plot a set of five competing modular products. The product in question is a household vacuum cleaner. A design team was given the task of developing a new modular vacuum cleaner. They generated the five concepts shown in Figure 10 through Figure 13.

The design team first calculates the Modularity Scores. Table 4 contains the data used to calculate theses scores and the calculated scores.

Next the design team calculates the Interface Scores Table 5. contains the data used to calculate the Interface Score and the calculated scores.

Finally the design team classifies each concept as base or baseless. For example, the Stick was classified as a concept that used a baseless architecture. This decision was based on the following:

1. Every module can carry out its primary function without the need for any other module (except for module 4 - see next bullet point)

2.Although module 4 is the module from which the electrical power originates, module 4 does not exclusively distribute that power. Every module shares the task of distributing the electricity. This product was classified as using a baseless architecture because this function of electricity distribution is not exclusive to any module.

The Tower was classified as a concept that used a baseless architecture. This decision was based on the following:

1. Almost every module can carry out its primary function without the need for any other module.
   a. Every module is dependent upon the electricity that originates in module 2 (see point #2).
   b. Although module 4 is dependent upon module 3 to prepare the extraction medium, and module 8 is also dependent upon module 3 for the mechanical motion of its beater bar, there exists no single module or configuration of modules that all other modules are dependent on.
2. Although module 2 is the module from which the electrical power originates, module 2 does not exclusively distribute that power. Every module shares the task of distributing the electricity. This product was classified as using a baseless architecture because this function of electricity distribution is not exclusive to any module

The Dragger was classified as a concept that used a baseless architecture. This decision was based on the following:

1. Almost every module can carry out its primary function without the need for any other module.
   a. Every module is dependent upon the electricity that originates in module 1 (see point #2).
   b. Although module 3 is dependent upon module 2 to prepare the extraction medium, their exists no single.

Table 4: Modularity Score Calculations

Concept	Number of Modules (N_m)	Number of Sub-functions (N_{sf})	Modularity Score (M)
The Stick	4	25	0.16
The Tower	8	25	0.32
The Dragger	8	25	0.32
The Pistol	6	25	0.24
The Wand	4	25	0.24

Table 5: Interface Score Calculations

Concept	Number of Interfaces (N_i)	Number of Interface Types(N_{it})	Interface Score (I)
The Stick	3	1	0
The Tower	7	7	1
The Dragger	7	7	1
The Pistol	5	5	1
The Wand	5	3	0.5

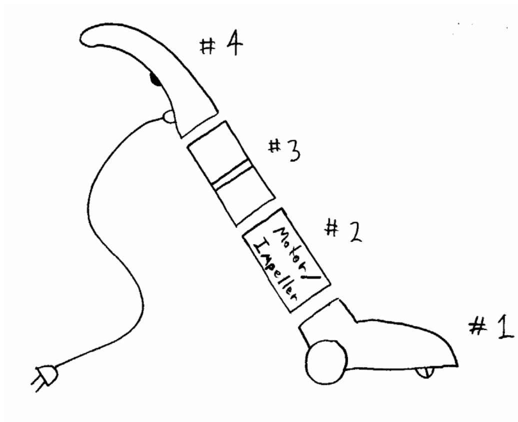


Figure 9 The Stick

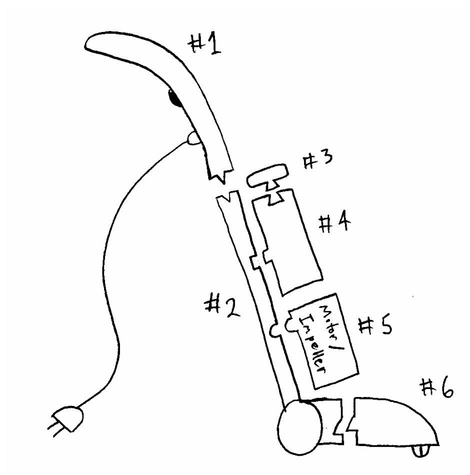


Figure 12 The Pistol

c. module or configuration of modules that all other modules are dependent on.

2. Although module 1 is the module from which the electrical power originates, module 1 does not exclusively distribute that power. Every module shares the task of distributing the electricity. This product was classified as using a baseless architecture because this function of electricity distribution is not exclusive to any module.

The Pistol was classified as a concept that used a base architecture. This decision was based on the following:

1. Modules 1 and 2 join to form the base unit that exclusively distributes the electrical power that almost all other modules are dependent upon to carry out their primary functions.

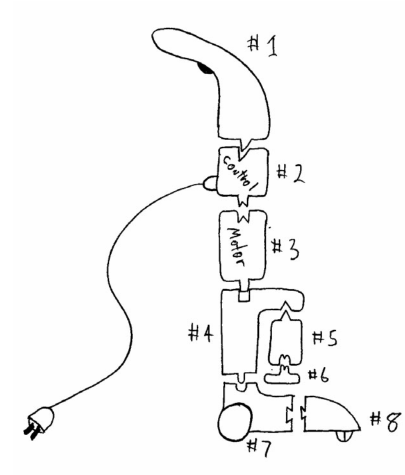


Figure 10 The Tower

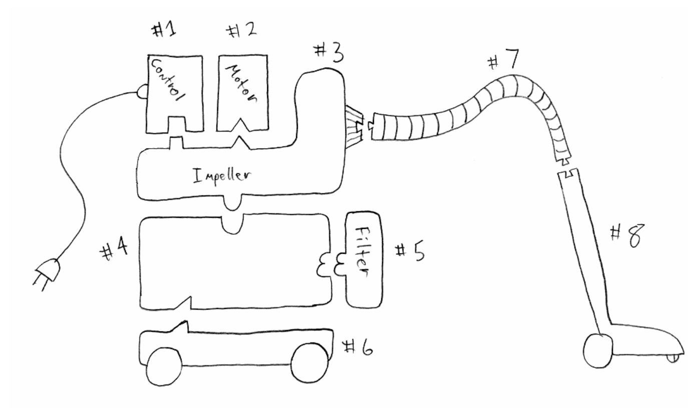


Figure 11 The Dragger

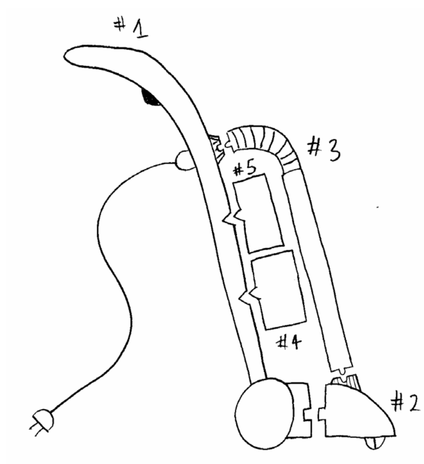
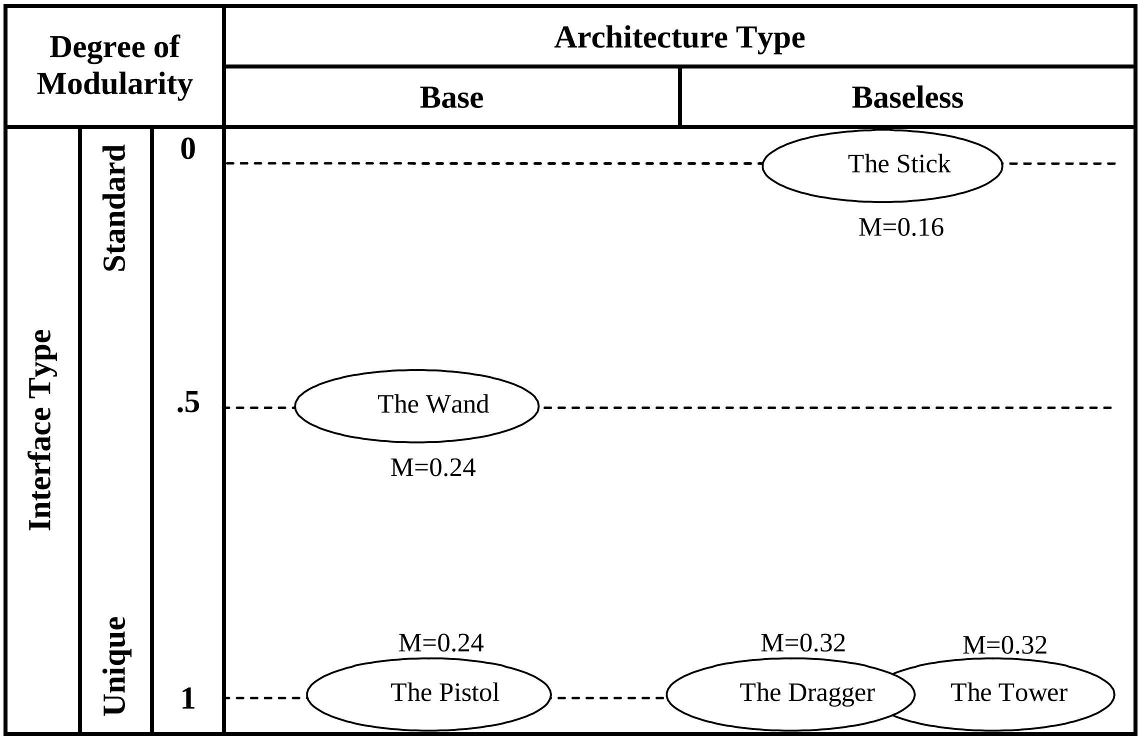


Figure 13 The Wand

Table 6: MTS with Vacuum Plots



2. Modules 1 and 2 also exclusively manage and distribute the extraction medium that the vacuum system needs to function.

The Wand was classified as a concept that used a base architecture. This decision was based on the following:

1. Module 1 is the base unit that exclusively distributes the electrical power that almost all other modules are dependent upon to carry out their primary functions.
2. Module 1, in conjunction with module 3, also exclusively manages and distributes the extraction medium that the vacuum system needs to function.

Based on the information contained in this section, the five vacuum cleaner concepts were then plotted on the MTS (Table 6).

APPLICATIONS

Having developed this new method for classifying modular products, the question of usefulness still remains. The authors of this paper see two useful applications for the MTS and its related definitions. First, the MTS can be used during the concept generation step of design to force new ideas to the drawing board. For example, if after a few brain-storming sessions the generated concepts are plotted on the MTS and it is observed that the majority of concepts fall in only a few of the octants of the MTS, the design team can identify the vacant octants and concentrate their concept generation efforts on those octants of the MTS.

Second, the MTS can be used as a means for evaluating and screening product concepts based on the overall strategic objective of the product. By matching the strategic objectives of the product to the axes of the MTS that can be used to describe a concepts ability to achieve those objectives, competing modular product designs can be compared and screened based on their individual ability to achieve the overall product objectives [16].

CONCLUSIONS

The schemes, metrics, and tools developed in this document are both valuable and useful to the designers of modular products. They provide designers with a systematic and repeatable method for classifying similar modular product design concepts. The following is a list of conclusions that can be drawn from the research contained in this document.

1. The MTS more accurately defines modularity types, and shows how one type of modularity relates to the next, than did previous definitions and classification methods.
2. The metrics and definitions included in this document are for the purposes of plotting product concepts on the MTS are both functional and useful.
3. The MTS can be used to generate a broad scope of product concept during concept generation.
4. The MTS can help designers to select a final product concept based on strategic objectives.

5. The MTS does not fully characterize modular products and therefore should not be used as the only screening and selection criteria.
6. Additional tools are needed to manage the balance of strategic, performance, and other objectives for the purposes of screening and selecting a final concept.

The authors also acknowledge that the value of this research can be increased with future research. For example, by linking strategic product objectives to each of the three axes of the MTS as described in the applications section of this paper, the MTS becomes a powerful tool for screening the ability of different product concepts to achieve those objectives[16].

Other areas of additional research that would add to the value of the MTS include further development of the term base unit, and the possibility of varying a modular product's classification as base or baseless depending on different levels of architecture (i.e., structural level, control level, material level, power level, etc.). Also, the development of generalized strategic strengths and weaknesses for each of the octants of the MTS at all three phases of modularity, and the development of generalized categories for all modular products (i.e., mechanical, electronic, self-configuring[19]) would add to the value of this research.

ACKNOWLEDGMENTS

This work was furthered by the support of Brigham Young University and its facilities. The authors acknowledge the work of Megan McAllister in the preparing and formatting of the paper.

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