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TOOLS AND METRICS FOR EVALUATING MODULAR  
PRODUCT CONCEPTS BASED ON  
STRATEGIC OBJECTIVES

By:

Matthew Bailey Strong

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Mechanical Engineering

Brigham Young University

April 2003

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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Matthew Bailey Strong

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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As chair of the candidates graduate committee, I have read the thesis of Matthew Bailey Strong in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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## ABSTRACT

# TOOLS AND METRICS FOR EVALUATING MODULAR PRODUCT CONCEPTS BASED ON STRATEGIC OBJECTIVES

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The design of modular products has recently become the focus of significant research in the area of design theory and methodology. This focus is the result of increased awareness of the potential power of modularity to achieve certain product objectives. However, there continues to be a gap between the results of academic research and industrial application. The refinement, consolidation, and extension of this academic research would help design teams who are charged with developing modular products to use these academic findings in real world, industrial applications.

The research presented in this document focuses on developing design tools, based on past and present academic research, for use in industrial settings where the design of a modular product is the goal. In this document the many definitions and methods for classifying modular products are consolidated and refined. Through this

refinement and consolidation a new scheme for classifying modularity types, the Modularity Type Space (MTS), is developed that not only succinctly defines the types of modularity, but shows the relationships between them. Metrics and heuristics are also presented that are helpful in identifying the type of modularity a product uses in its architecture. The MTS is presented as a tool to help design teams screen modular product designs for the purposes of concept selection based on the strategic goals that the product must achieve. Several examples, as well as a case study, are presented in this document to show how to use the tools contained herein and to illustrate their usefulness.

With the modular product design tools developed in this document, design teams will be able to more quickly and cost-effectively design modular products that meet their desired strategic objectives.

## ACKNOWLEDGEMENTS

I would like to thank my beautiful wife Stacey for the loving patience and understanding she showed me throughout the process of writing this thesis, and to my daughter Bailey Michelle Strong, for motivating me to finish. I give thanks to my parents who always encouraged me to be creative and pursue my dreams. I would like to also give thanks to Spencer Magleby for guiding me through this process and helping me to see the big picture. And lastly, I would like to thank the faculty and staff of both the Mechanical Engineering and Master of Business Administration Departments at Brigham Young University who are involved in the Interdisciplinary Product Development (IPD) program. It was that program that provided me with the knowledge and confidence to write this thesis.



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# 1.0 INTRODUCTION

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There is a saying in entrepreneurial circles that claims the best way to achieve market success is to identify any particular pain a consumer experiences and then discover a way to eliminate that pain. If you can significantly ease the pain of any individual by providing a new service or product without introducing any new pain into the equation, you will win the support of that person in the form of a financial reward. For example, the difficulty of on-the-go communication was, and continues to be, reduced with the introduction of wireless electronic devices.

Among other reasons, designers have begun to design modular products in order to produce products with better problem/solution fit. Because of the advantages that can be gained by designing a modular product, such as mass customization at reduced production costs, as well as a whole host of other strategic and functional benefits, the concept of product modularity has been receiving a lot of attention. To help designers better understand modular products and how to design them, much attention is currently being focused on developing design approaches and tools specifically for modular products.

## 1.1 THE MODULAR PRODUCT CONCEPT

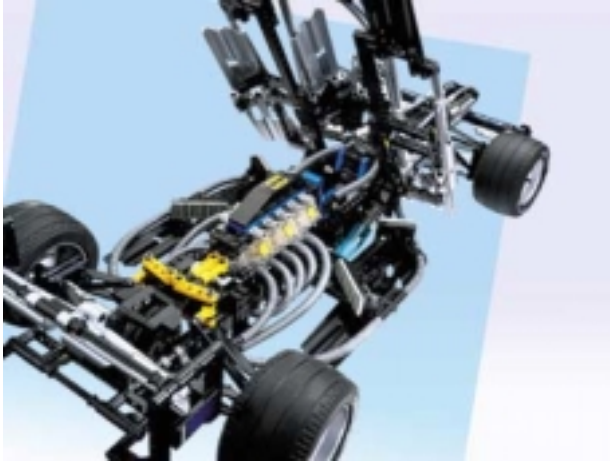
The concept of modularity is often misunderstood or looked at too narrowly. For example, in an article written by Melissa A. Schilling (2000) for the Academy of Management Review, she states that at its most abstract level modularity “refers simply to the degree to which a system’s components can be separated and recombined. Systems are said to have a high degree of modularity when their components can be disaggregated and recombined into new configurations – possibly substituting various new components into the configuration – with little loss of functionality.” While this definition is valid it does not consider modularity at its most abstract level. Something does not have to be reconfigurable in order to be classified as modular. In this thesis, a product will be classified as modular if it meets the definition in the following paragraph.

A term that helps describe product modularity is chunk. A chunk is a major physical building block into which physical elements of a product are organized. The verb chunking refers to the process of grouping product sub-functions into modules. Ulrich and Eppinger (2000) define a modular product as one having the following two properties:

- Chunks implement one or a few functional elements in their entirety,
- The interactions between chunks are well defined and are generally fundamental to the primary functions of the product.

The concept of product modularity will be better understood by comparing two products that were designed to perform the same basic function. Figure 1.1 shows a picture of a toy car constructed using Legos. Figure 1.2 shows a picture of a conventional toy car. While the design goals of the Lego car and conventional toy car





**Figure 1.1**  
Modular Design – Lego Car



**Figure 1.2**  
Integrated Design – Conventional Toy Car

were not the same, both of these products fulfill the same basic design goal of physically realizing a toy car. It is because of the differing design goals that the conventional toy car was designed using an integrated architecture, and the Lego car was designed using a modular architecture. The Lego car is a good example of a highly modular product according to the definition stated above. Every chunk in the car contains a very limited number of functional elements in their entirety and the interactions between chunks are well defined and fundamental to the primary function of the product. In fact, the parts can be put together in many different configurations. This ability to reconfigure is one of the benefits of a modular product. On the other hand, there are fewer chunks in the conventional design. In fact, the major functional units of the conventional design are all integrated into the overall design and cannot be removed and reconfigured as they can in the Lego design. The conventional design is an integrated product.

This example illustrates the benefit of reconfigurable components that can be gained by designing a product to be modular.

## 1.2 CHALLENGES IN MODULAR PRODUCT DESIGN

There are many advantages and disadvantages to using product modularity (discussed in detail in Chapter 2). Modular products provide unique strategic advantages when compared with non-modular products. Because of these unique advantages, different tools and metrics are required to be able to effectively manage modular product designs from those that are currently used for non-modular products. As such, there currently exists a high demand for tools, strategies and metrics that can help designers to effectively harness the power of modular design. Design teams that are currently attempting to use modularity in their product designs face challenges such as:

- Quantifying and classifying modularity,
- Deciding how to group functional components into chunks to most efficiently meet strategic objectives,
- Objectively evaluating competing modular designs,
- And, deciding whether to use modularity at the design, manufacturing, and/or consumer levels.

The Autococker paintball gun shown in Figure 1.3, illustrates the power of a product that has been designed so that its chunks satisfy the strategic objective of consumer upgradeability and customization.

Paintball enthusiasts want to be recognized as individuals. One way of differentiating themselves from other players is to customize their gun to not only outperform other guns, but to have a unique appearance. Paintball guns that offer this ability to the market are warmly received. One such gun is the Autococker. Despite the fact that the Autococker is one of the oldest semi-automatic paintball guns on the market it simply refuses to go away (The Splatter Times, 2001). Because the Autococker was built using a modular architecture that makes it easy to upgrade, service, and customize,



**Figure 1.3**  
Autococker Paintball Gun

consumers continue to purchase it knowing that they are buying a product that can grow with their skill, and that can be customized to reflect their individuality. It is precisely the ability to be upgraded and customized that have increased the useful life of the Autococker (The Splatter Times, 2001). These abilities are a direct result of the Autococker's modular architecture.

Even though many of the benefits for using modular product architecture are strategic in nature (such as lengthened product life due to upgradeability), and not performance based (such as increased reliability), there is little research being done in regard to measuring a modular product's ability to achieve strategic objectives. Currently published research findings focus on the functional decomposition of products and how to group product sub-functions into the most efficient chunks based on function, maintenance, replacement of consumables and other design criterion of this nature (Pahl

1996). Design research has not yet turned its focus to evaluating modular product design concepts based on their ability to achieve strategic (not performance) design criteria. As such, designers have been left without guidance or established methods for choosing the best design concept from a list of competing modular design concepts based on strategic objectives.

### **1.3 THESIS OBJECTIVE**

There are many methods for effectively grouping functions into chunks, each one providing designers with multiple solutions. Thus, designers are often faced with the task of deciding between two or more competing modular design concepts with limited tools to assist them in the selection process. Because the methods used for grouping modules into chunks are based on the functionality and performance of a product, they almost always yield designs that are functionally sound. Therefore, a decision of which design concept to choose based only on the overall function or performance of a product would not take into account important differences between competing concepts. In order to choose the best design, competing modular design concepts should be evaluated and compared based on the strategic objectives of the product in addition to their performance objectives.

The objective of this research is three fold. They are:

1. To consolidate and standardize modularity classification methods and terminology.
2. To create metrics useful for classifying modular products.
3. To develop the metrics and classifications schemes spoken of previously into tools that capable of evaluating a modular products ability to achieve strategic objectives.

This document will limit its discussion of strategic objectives to those that affect modularity at the consumer level (levels of modularity will be discussed in detail in Chapter 2). By providing these tools, engineers and designers will be able to use these metrics to objectively evaluate and compare competing modular product designs.

## **1.4 THESIS OUTLINE**

To provide the reader with insight into the information contained in this thesis, a global view of the thesis is provided on a chapter-by-chapter basis in the following paragraphs.

Chapter 2 contains information about research that has already been performed or that is being performed in the areas of product modularity. The purpose of this chapter is to provide readers with a knowledge of existing product modularity research, show where additional research could be done, and provide a context within the metrics developed in this thesis will fit.

Chapter 3 contains the research method used in achieving the objectives of this thesis. The purpose of this chapter is to define the research approach, research scope and desired characteristics of the tools to be developed.

Chapter 4 discusses current classification schemes for modular products, and presents a new scheme for classifying modular products. This scheme will become the basis for the metrics and heuristics developed in the Chapters 5 and 6. The purpose of this chapter is to show how the tools developed in this document relate to past research, and to show the relationships that exist between different types of modular products.

Chapter 5 provides metrics and heuristics that can be used to classify modular products into the scheme developed in Chapter 4. The object of this chapter is provide the tools necessary and show how to classify a set of modular product concepts into the scheme developed in Chapter 4.

Chapter 6 discusses in detail how to discuss and compare the strategic strengths and weaknesses of a set of modular product concepts for the purposes of screening competing design concepts. The purpose of this chapter is to show designers how to use the tools developed in Chapters 4 and 5 to make design decisions.

Chapter 7 contains case studies that will illustrate the principles and guidelines developed in this thesis. The purpose of this chapter is to provide the reader with a practical example of how to use the metrics contained in this thesis and to provide evidence that these tools are of value.

Chapter 8 is the thesis summary and contains the conclusions of this research. Contained therein will be a discussion of areas for future research that builds upon the research contained in this thesis.

A list of the references used in writing this document, as well as an appendix containing information pertaining to the case study can be found at the end of this document.

## **2.0 LITERATURE REVIEW**

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Even though there still remains a large amount of research left to do in the field of modularity, researchers have made progress towards better understanding some of the principles of modular design. The purpose of this chapter is to summarize previous research that has been done by others in the field of product modularity that relates to this thesis. To provide the context within which an intelligent discussion of modularity can be held, this literature summary will begin by discussing current methods of classifying modularity, including a discussion of existing modularity metrics, followed by a discussion of the benefits and costs of product modularity. These two sections will be followed by a discussion of the most popular methods for grouping functions into modules and a discussion of some of the methods currently in use for evaluating modular product designs. This literature summary will end with a list of conclusions about the state of modular product research.

### **2.1 CLASSIFICATIONS OF MODULARITY**

Products can be modular on many different levels. For example, to a consumer a car is not a modular product. However, a mechanic might claim that to some degree a car is a modular product because many of its components can simply be unbolted, removed,

and replaced. And again, the designer might also claim that a car is modular because of the way it was designed. One group of engineers worked on the transmission while another worked on the engine, etc. In the end, all these design modules were assembled and the car was built.

In order to better define modularity and eliminate the confusion illustrated by the above paragraph, researchers have created different ways of classifying modularity. The purpose of this section is to present these methods and associated nomenclature, and metrics to establish a basis from which this thesis can discuss modularity.

### **2.1.1 Levels of Modularity**

As was discussed before, a car might be modular to the engineers that built it, but be entirely integrated to the end user. Mattson (2001) discusses this very issue in chapter four of his Masters Thesis entitled “Principles for the Design and Development of Modular Consumer-Products.” He states “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.” Mattson defines each of these three levels of modularity in the following ways:

**Design Phase Modularity:** A product is modular at the design phase if the product function is defined through the combination of various modules, and at least one module has been previously designed.

**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 similar findings by Otto and Wood (2001). Conclusions similar to those of Mattson can be drawn from the work of Ulrich and Eppinger (2000) on the motives for product development. These findings are further supported by the work of Sand et al (2001).

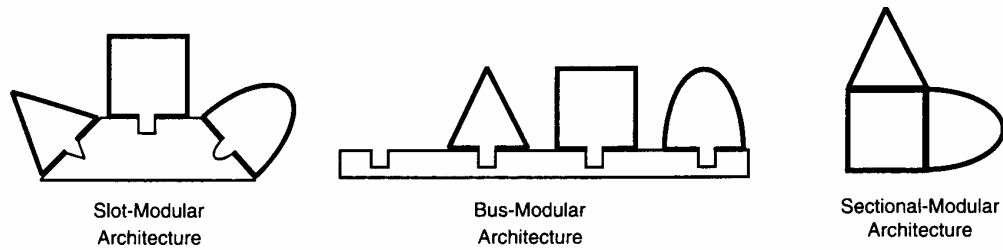
### 2.1.2 Types of Modularity

As was stated in the definition of a modular product in Chapter 1, modules use interfaces to interact with other modules. Ulrich and Eppinger (2000) define three types of modularity based on the type of interface a module uses. A graphical representation of each can be seen in figure 2.1, 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 2.1**  
Types of Modularity

Otto and Wood (2001) 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 devices (in the form of toys).

It is important 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 (2001) 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.

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.

### 2.1.3 Types of Modules

In addition to classifying components by their interface type, components can also be classified by module type. Pahl and Beitz (1996) have a method for classifying modular products based on two different categories of module types – functional and production modules. The following lists of module types were adapted from their work.

**Function Modules:** Designed to implement technical functions independently or in combination with others.

**Production Modules:** Designed independent of their function and are based on production considerations alone.

Pahl and Beitz continue to classify types of modules by breaking down functional modules based on the five types of functions a module might serve.

**Basic Functions:** are functions that are fundamental to a system and are not variable in principle. They can fulfill an overall function simply or in combination with other functions. Basic modules are “essential.”

**Auxiliary Functions:** are implemented by locating or joining auxiliary modules that are kept in step with the basic modules and are usually of the “essential” type.

**Special Functions:** are complimentary and task-specific sub-functions that need not appear in overall function variants. They are implemented by special modules of the “possible” type.

**Adaptive Functions:** are necessary for adaptation to other systems and to marginal conditions. Adaptive functions can be of the “essential” or “possible” types.

**Consumer-specific Functions:** not provided for in the modular system and will recur time and again in the most careful development. Such systems are implemented by non-modules.

Otto and Wood (2001) developed the following four categories for use in further classifying types of modules:

**OEM Modules:** groups of components or functions that are grouped together simply because a supplier can provide them at less expense than they could be developed and manufactured in-house.

**Assembly Modules:** components or groups of components that solve related functions but are bundled to increase assembly ease.

**Sizable Modules:** components that are exactly the same except for their physical scale.

**Conceptual Modules:** components that solve the same functions but have different physical embodiments. This type of module can apply a change in manufacturing without causing significant changes to the remainder of the product.

There are many reasons for using modularity in the design of a product. Some of these reasons are useful for discussing modularity. It is important to note that while these classifications are useful to discuss modularity they are not classifications of module types. These are motives, strategic objectives, for using modular design. Ulrich and Eppinger (2000) specify seven categories which can be used to categorize modules based on the motives for developing any given module. These categories are:

**Upgrade:** to enable a product to evolve with technology.

**Add-ons:** to facilitate user added components.

**Adaptation:** to facilitate the use of a product in various environments.

**Wear:** to enable the replacement of worn components.

**Consumption:** to extend the life of a base product beyond that of its consumable components.

**Flexibility in use:** to allow the user multiple configurations of use.

**Reuse:** to allow a firm to reuse parts of a design in subsequent products.

### 2.1.4 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 work on modular consumer-products (2001) he presents two Equations (2.1 and 2.2) that can be used to objectively quantify modularity.

$$M = \frac{N_{\text{modules}}}{N_{\text{functions}}} = \frac{N_m}{N_f} \quad (2.1)$$

$$I = 1 - \frac{N_{\text{interface\_types}}}{N_{\text{interfaces}}} = 1 - \frac{N_{it}}{N_i} \quad (2.2)$$

Equation (2.1) defines what Mattson calls the modularity metric, and Equation (2.2) defines the interface metric. 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.

## 2.2 THE BENEFITS AND COSTS OF MODULARITY

In the world of product design, whenever something is gained through a design decision, something else is given up. In other words, nothing is for free. Whenever a designer makes a decision he or she must carefully weigh the benefits and the costs of that decision. In a sense, design is the art of managing these tradeoffs to obtain the best overall design. The decision to design a modular product is no exception to this rule. While it is true that there is much to be gained from using a modular architecture, there are also some costs involved.

This section will consist of a discussion of the benefits of modularity, followed by a discussion of the costs, followed by a brief observation drawn from the discussions on benefits and costs.

### 2.2.1 The Benefits of Modularity

There are many benefits for choosing to use a modular product architecture. Loughborough University, in their “Holonc Product Design Workbook” (Marshall, 1997), states that modular design is for any company that is seeking:

- Flexible or agile manufacturing
- A rationalized introduction of new technology
- An efficient means of deploying customer requirements
- A structured approach for dealing with complexity.

Because researchers discuss these benefits to some degree in their own writings, there is quite a bit of redundancy between publications that list the benefits of modular design. To avoid those same redundancies in this thesis each successive authors list will omit anything that has been listed previously.

In their book “Design Rules: The Power of Modularity,” Baldwin and Clark

(2000) list the following items as benefits of product modularity:

- Modularity increases the range of manageable complexity
- Modularity allows different parts of a large design to be worked on concurrently
- Modularity accommodates uncertainty during design – if knowledge yields a better solution at some point in time into development, the new solution can be incorporated into a module with little or no need for change in the rest of the design

The benefits of product modularity as outlined by Phal and Beitz (1996) in their book “Engineering Design: A Systematic Approach” are split into two categories. The categories and corresponding benefits are listed below:

**Benefits to the manufacturer:**

- Ready documentation is available for project planning and design
- Additional design effort is needed for unforeseeable orders only
- Combinations with non-modules are possible
- Overall scheduling is simplified and delivery dates may be improved
- Computer-aided execution of orders is greatly facilitated
- Calculations are simplified
- Modules can be manufactured for stock with consequent savings
- Appropriate subdivision of assemblies ensures favorable assembly conditions
- Modular product technology can be applied at successive stages of product development, for example, in product planning, in the preparation of drawing and parts lists, in the purchase of raw materials and semi-finished materials in the production of parts, in assembly work, and also in marketing

**Benefits to the user:**

- Short delivery times
- Better exchange possibilities and easier maintenance
- Better spare parts service
- Possible changes of functions and extensions of the range
- Almost total elimination of failures thanks to well-developed products

The benefits of modularity outlined by Ulrich and Tung (1991) in “Fundamentals of Product Modularity” are:

- Improved component economies of scale
- Improved product variety
- Improved order lead-time
- Improved design and product focus
- Ease of product diagnosis, maintenance, repair, and disposal
- Ease of component verification and testing
- Ease of managing differential consumption
- Ease of product change
- Facilitates decoupling of tasks
- Facilitates production, installation and use

### 2.2.2 The Costs of Modularity

The benefits of modularity are always achieved at some cost. The following is a summary of the costs associated with modularity. Again, any redundancies in these lists are omitted.

The costs of modularity as outlined by Phal and Beitz (1996) in their book “Engineering Design: A Systematic Approach” are again split into two categories. The categories and corresponding costs are listed below:

#### **Costs to the manufacturer:**

- Adaptations to special customer’s wishes are not as easily made as they are with individual designs (loss of flexibility and market orientation)
- The stock of drawings may be inadequate
- Changes can only be considered at long intervals because original development costs are high
- Technical features and overall shape are more strongly influenced by the design of modules than they would be by individual designs
- Production costs are increased, for example because of the need for accurate locating surfaces
- Increased assembly effort and care are required
- Rare combinations needed to impellent unusual designs may prove costly
- Since the user’s as well as the producer’s interests have to be taken into consideration, the determination of an optimal modular system may prove very difficult



### **Costs to the user:**

- Special wishes cannot be met easily
- Quality might be less satisfactory than they would be with integrated designs
- Weight and size of product will be larger than a comparable integrated design

The costs of modularity outlined by Ulrich and Tung (1991) in “Fundamentals of Product Modularity” are:

- Increased likelihood of static product architecture
- Compromised performance optimization
- Ease of reverse engineering for competitors
- Increased unit variable costs
- Excess in product similarity

### **2.2.3 Discussion on the Benefits and Costs of Modularity**

It is important to note that not all of the listed benefits and costs apply in all situations. For example, take the first cost listed in by Phal and Beitz. This cost claims that special customer wishes are more expensive for a modular product than for an integrated product. While this may be true for a product that must be redesigned in order to incorporate a special request, the opposite might be true for a product that was designed to be modular at the consumer level. These contradictions and the need for classifying the costs and benefits of modularity will be discussed in Chapter 3 of this thesis.

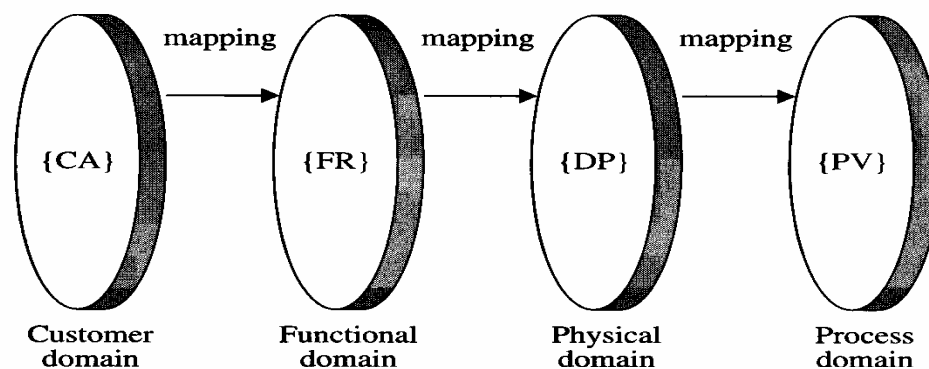
## **2.3 METHODS FOR CREATING “CHUNKING” MODULES**

One of the key steps in the design of modular products is to identify the sub-functions of a product, which sub-functions depend on other sub-functions, and how each

sub-function interacts with one another. Once a design team achieves this fundamental knowledge, it then becomes possible to group the sub-functions into modules and proceed with design. Researchers have proposed many methods for capturing a product's architecture, such as by taxonomy (Koopman, 1995), or by target cost and required functionality (Takai and Ishii, 2001) and many others as summarized by Kusiak (1995), but only a few appear to be widely accepted and cited. This section will focus on the most widely accepted methods. Three of the most cited methods of accomplishing this are Nam Pyo Suh's Axiomatic Design Method (Suh, 2001), the method of Functional Structures (Otto, 2001), and the Design Structure Matrix (DSM) (Steward, 1981; Eppinger, 1991; Pimmler, 1994; Ulrich, 2000). These methods will be discussed in the following sections.

### 2.3.1 The Axiomatic Approach

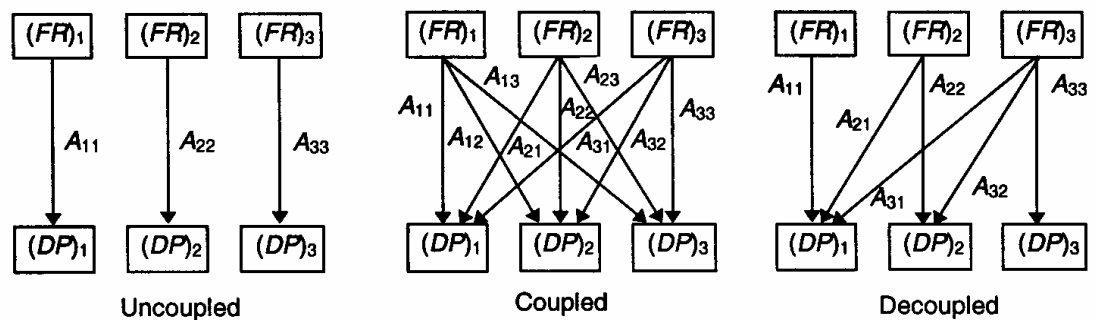
The overall goal of axiomatic design is to provide designers with a theoretical foundation for design based on logical and rational thought processes. This theoretical foundation acts as a road map that guides a designer through the four domains of the



**Figure 2.2**  
Four Domains of the Design World  
(Suh, 2001)

design world (figure 2.2). Axiomatic design relies on customer attributes (CA), functional requirements (FR), design parameters (DP), and process variables (PV) (Suh, 2001). CA's are related to FR's most commonly by using Quality Function Deployment (QFD). FRs are defined as the minimum non-unique set of independent requirements that completely characterize the design objectives for a specific need. DPs represent the physical entities by which the corresponding FR will be realized. PVs are the processes by which the DPs will be made (Magrab, 1997).

One of the benefits that the structure of the axiomatic design process gives the designer is a map that outlines all FR's, all DP's and the dependencies that exist between them. The process of making this map, or a completed map intended for revision, can then be used as a guide in developing uncoupled and decoupled designs. Uncoupled designs are ones in which functional requirements are mapped directly to a corresponding design parameter (figure 2.3). In other words, no two functional requirements are linked to each other through shared DPs. This makes actual design simple and straightforward, because design decisions can be made independently (Magrab, 1997).



**Figure 2.3**  
Types of Designs  
(Magrab, 1997)

Decoupled designs are designs in which there exists a hierarchy (chain) of design decisions created by interdependencies between functional requirements. These interdependencies are caused by shared design parameters. As can be seen in figure 2.3, with a decoupled design,  $FR_1$  can be changed without affecting any DP other than number 1, but a change in  $FR_2$  will affect  $FR_1$  because of the shared design parameter  $DP_1$ . Axiomatic design makes this situation manageable by providing designers with a map that explains how one decision affects another. While a decoupled design is more difficult to manage than an uncoupled design, it is manageable. Even though design decision cannot be made independently of each other as they could be in an uncoupled design, every design decision chain has an easily definable starting point and a distinct ending point (Magrab, 1997).

In a coupled design (see figure 2.3), all functional requirements are linked through interlocking dependencies of design parameters. With a coupled design there exist never ending loops of dependencies that require iteration during the design process in order to achieve any level of optimization (Suh, 2001). As a result, uncoupled and decoupled designs are preferred to coupled designs (Magrab, 1997).

During the process of axiomatic design, designers must begin by first asking themselves what it is that the product must achieve at its highest level. This is labeled FR and is called the functional statement. Designers should next ask what the product must do in order to accomplish this primary objective. In the case of three supporting FRs needed to accomplish the driving FR, they would be labeled  $FR_1$ ,  $FR_2$ , and  $FR_3$ . Next designers must conceptualize three DPs that will satisfy these three FRs, taking into consideration any design constraints (CA's). Once the DPs have been decided upon,

designers can ask what functional requirements are needed to support any of the FRs one level above. This process is continued until there are no more FRs needed to accomplish any FR on any level of the design. These lowest level FRs are known as design leaves. Because FRs represent a product at its lowest level of decomposition, they are said to drive design.

With each iteration of FRs, corresponding DPs are developed before moving on to the next level. Suh (2001) refers to this as “zigzagging.” Because the selection of DPs will affect the system interdependencies, a designer must define a level of FRs, “zig” to the physical domain and define corresponding DPs, then “zag” back to the functional domain for the next level of decomposition. Suh points out that in order to keep from limiting design possibilities, it is important that both FRs and DPs are written in such a way that they don’t drive the solution. In other words, they are written in the most general language possible.

All FRs and DPs are then expressed as matrices. The interdependencies are then expressed by equating the FRs to the DPs multiplied by what is called the design matrix size  $n \times n$ , where  $n$  is the number of rows in both the FR column matrix and the DP column matrix (Magrab, 1997). Examples of such matrices for an uncoupled design are shown in Equations (2.3 – 2.6).

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (2.3)$$

$$\begin{bmatrix} FR_{31} \\ FR_{32} \end{bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{bmatrix} DP_{31} \\ DP_{32} \end{bmatrix} \quad (2.4)$$

$$\begin{bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \end{bmatrix} = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \end{bmatrix} \quad (2.5)$$

$$\begin{bmatrix} FR_{211} \\ FR_{212} \end{bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{bmatrix} DP_{211} \\ DP_{212} \end{bmatrix} \quad (2.6)$$

The design equations that would be derived from Equation (2.3) are:

$$\begin{aligned} FR_1 &= (x_{11})DP_1 \\ FR_2 &= (x_{22})DP_2 \\ FR_3 &= (x_{33})DP_3 \end{aligned}$$

Equation (2.3) and corresponding design equations for the more complex situation of a coupled design can be seen in Equation (2.7):

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} x & x & x \\ x & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (2.7)$$

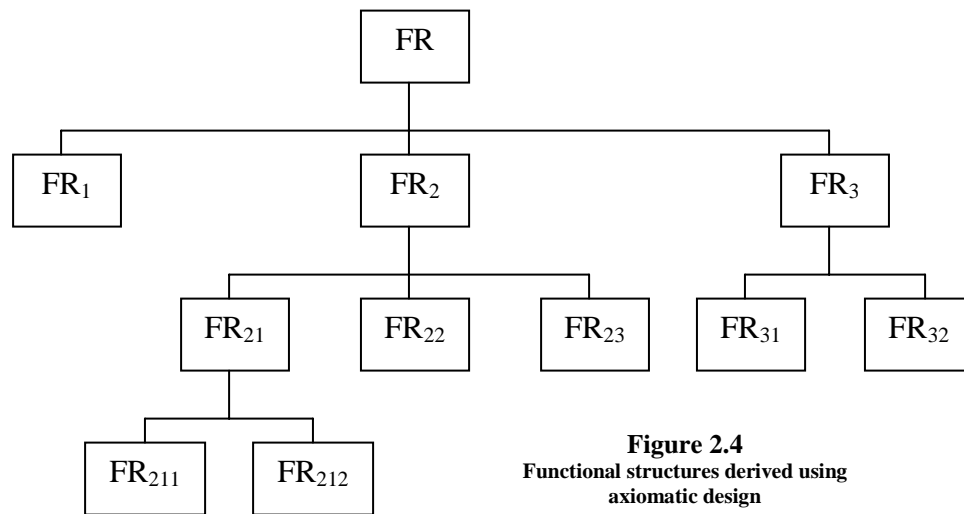
and the following:

$$\begin{aligned} FR_1 &= (x_{11})DP_1 + (x_{12})DP_2 + (x_{13})DP_3 \\ FR_2 &= (x_{21})DP_1 + (x_{22})DP_2 \\ FR_3 &= (x_{33})DP_3 \end{aligned}$$

Figure 2.4 is a graphical representation of the functional requirements shown above. The graphical representation for the design parameters would look the same as figure 2.4, with DP's replacing their corresponding FR's.

The design matrices and design equations, as well as their graphical representations, allow designers to see how a product's sub-functions interact with each other. By understanding these interactions expressed by the axiomatic design method, designers can effectively group a product's sub-functions into valid chunks (Magrab,

1997). For example, because all FR's and DP's in an uncoupled product are independent, designers are free to group product sub-functions in any manner they see fit. Because each FR/DP pair is independent of all others, the idea that some sub-function combinations (or modules) might create complex dependencies upon a large number of other modules is mute. However, in the cases of a decoupled or coupled design, designers must take into account the interactions between all FR's and DP's. In these cases designers would not be free to group sub-functions in any manner they see fit. Sub-functions groupings would be partially restricted by the dependencies that exist between FR's and DP's. There currently exists no systematic method or well defined heuristic for doing this using the axiomatic approach.

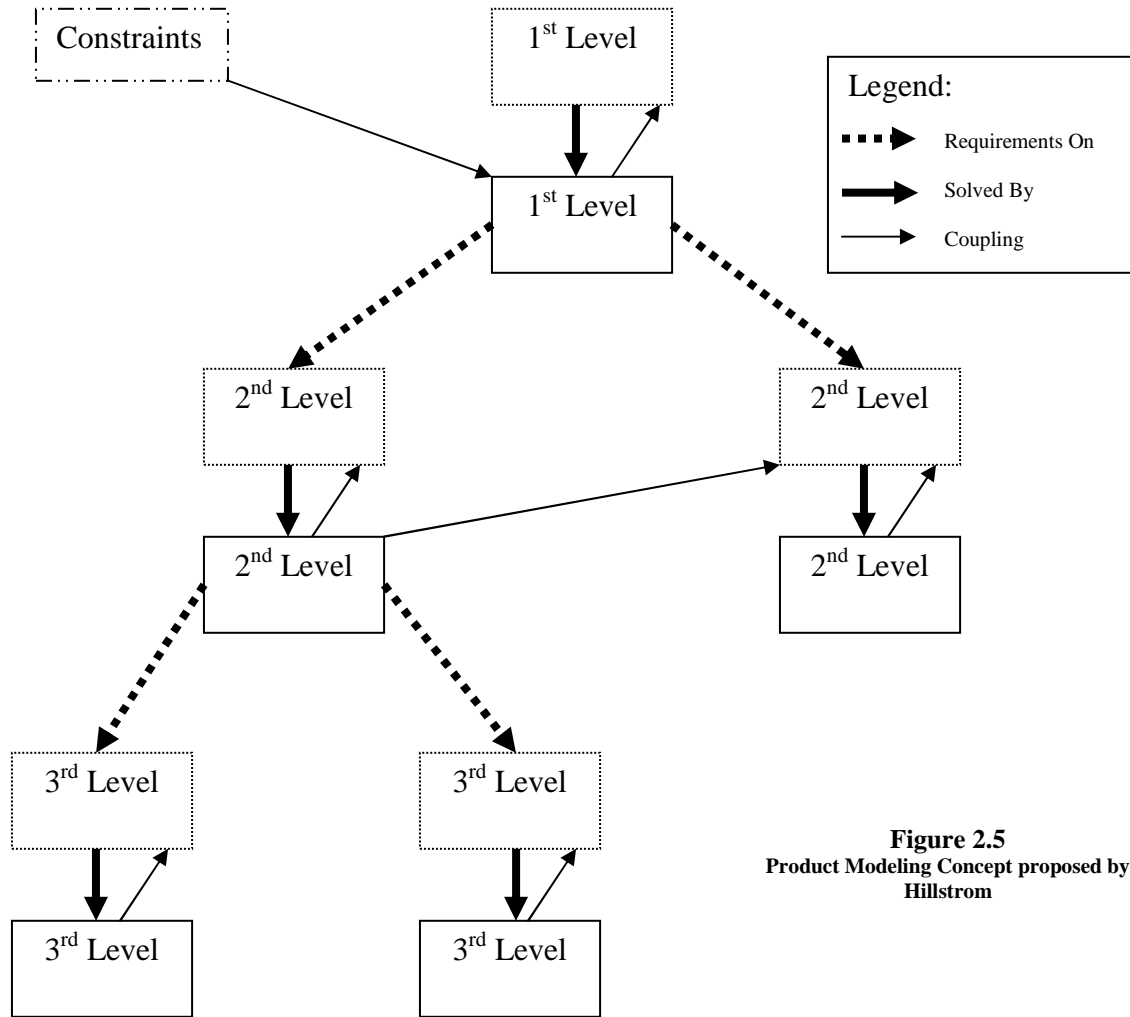


**Figure 2.4**  
Functional structures derived using  
axiomatic design

### 2.3.1.1 Related Axiomatic Design Topics

Many authors have built upon Suh's work in axiomatic design. Hillstrom (1994) explores the use of axiomatic design to analyze the interfaces of modular products.

Hillstrom's method builds on the functional and physical hierarchies developed in axiomatic design to evaluate the interfaces between mating modules in a modular product.



**Figure 2.5**  
Product Modeling Concept proposed by Hillstrom

In his work, Hillstrom proposes a product-modeling tool that integrates FR hierarchy, DP hierarchy, and the design equations of axiomatic design into one representation. Figure 2.5 is an example of this product-modeling tool. Hillstrom proposes that by identifying the “design leaves” in his product model that are directly related to an interface, a designer can perform a series of “what-if” tests in order to



systematically identify the best interfaces. A ‘what-if’ test is performed bottom-up, starting with the design leaves that are interface related. A designer then alters the DP and follows the couplings of such a decision up the product model. Hillstrom illustrates this process in his paper by discussing the example of a motor/gearbox interface.

According to Hillstrom, the best interfaces will positively influence (as defined by product objectives) module functions, and influence a relatively small number of DP’s.

### 2.3.2 Functional Structure Diagrams

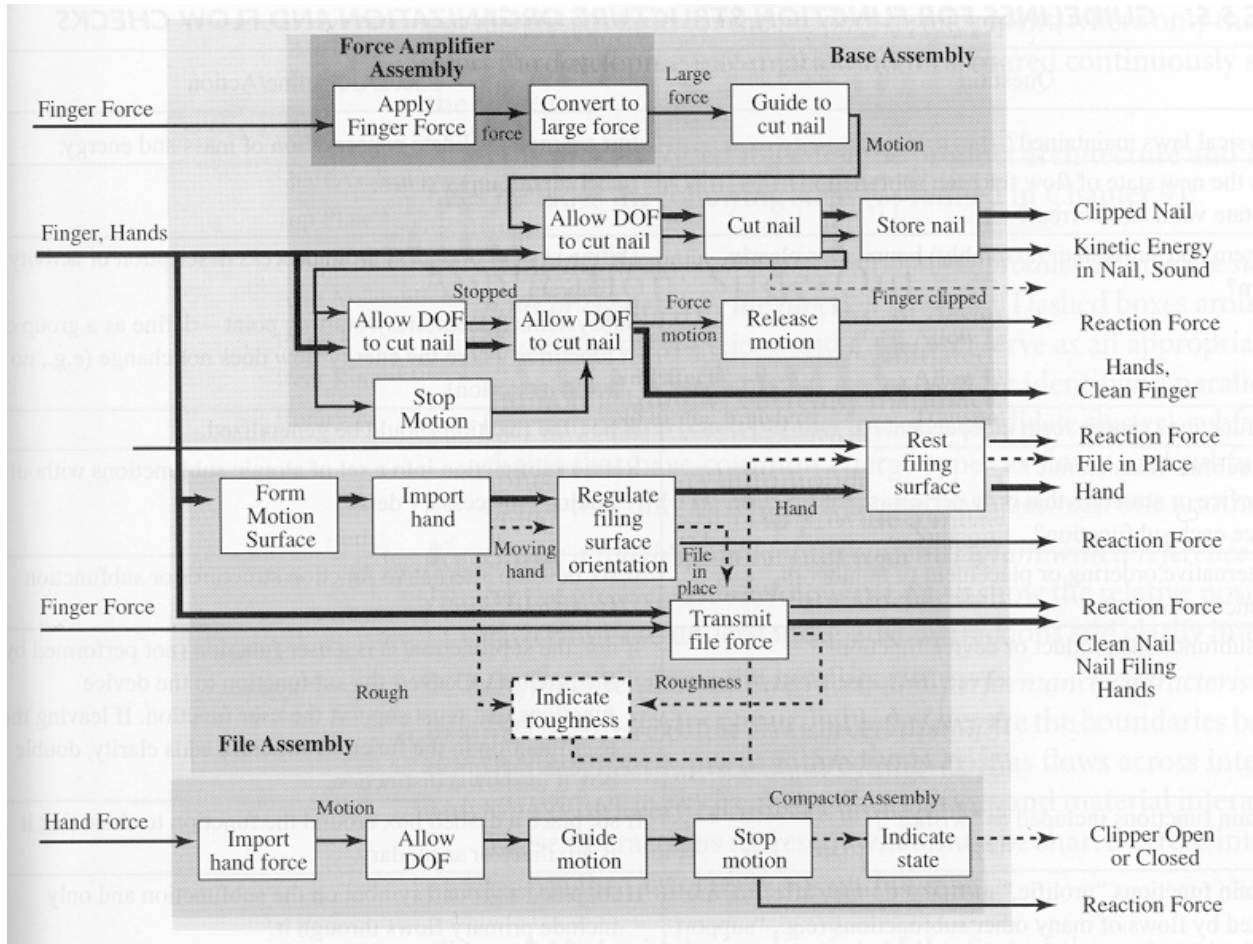
Another popular method for providing designers with a theoretical foundation from which to base design decisions is the functional structures method. A functional structure diagram, as seen in figure 2.6, is based on the idea that there are only three basic ways in which product functions interact – through energy flow, material flow, and information flow (Otto and Wood, 2001). The basic structure of a functional structure diagram can be seen in figure 2.7. A functional structure diagram is created by completing each of the following six phases (Otto and Wood, 2001) as shown in figure 2.8. Phase six is the step when functions are grouped into modules.

Stone (Stone et al., 1998) presents three heuristics for grouping functions into various modules. These three rules are all based on the path of energy, material, and information flow through the functional structure of the product.

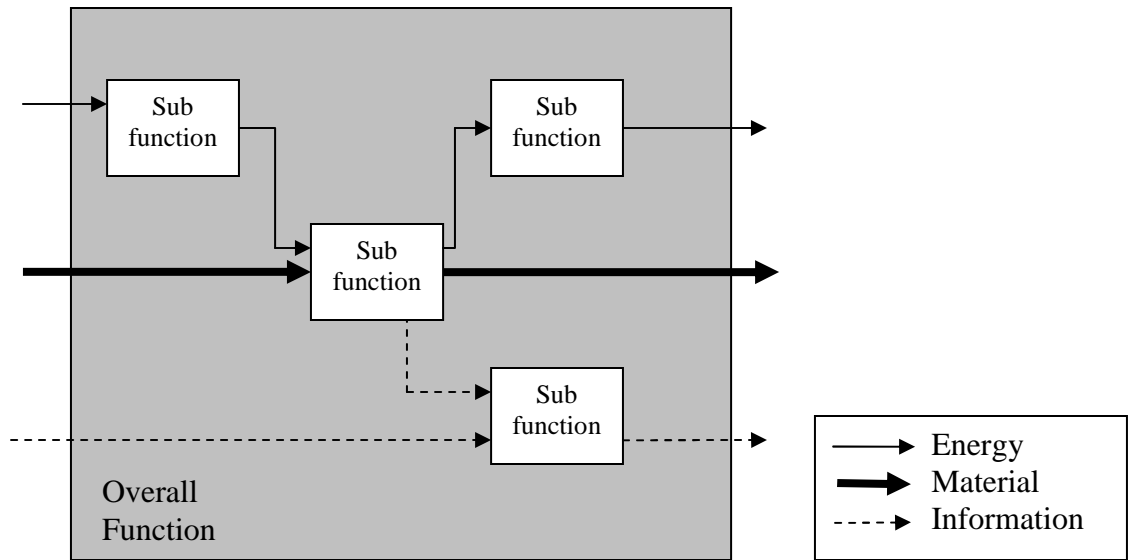
**Dominant Flow:** Examination of a flow until it is transformed or exits the system. A transformation or exit marks the end of a module.

**Branching Flow:** Examination of flows that branch into or converge from parallel function chains – convergence or divergence marks the limits of a module.

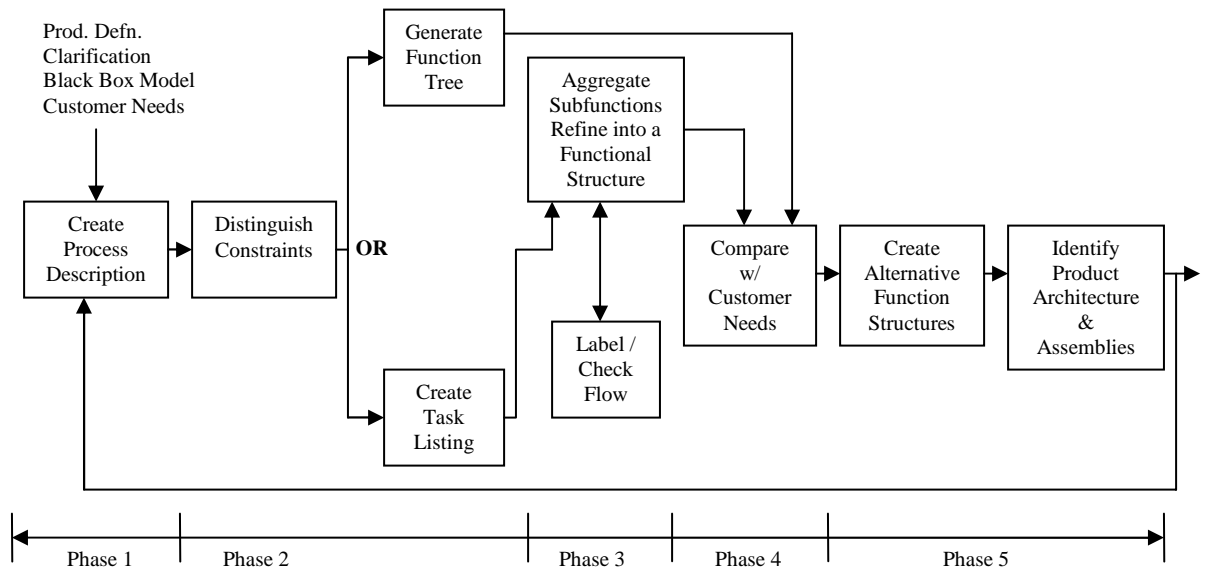
**Conversion / Transmission Flow:** Examination of flows that are converted from one type to another – most of the time the conversion is enclosed in a separate module such as an electric motor, which converts electrical current into rotational motion.



**Figure 2.6**  
Functional Structures diagram for a pair  
of fingernail clippers  
(Otto and Wood, 2001)



**Figure 2.7**  
Basics of a Functional Structures Diagram



**Figure 2.8**  
Six Phases of Functional Structure Development

In addition to these three heuristics developed by Stone, Otto, in both his work with Wood (Otto and Wood, 2001) and Zamirowski (Otto, 1999), developed two additional rules that can be used to help group functions into modules.

**Shared Functions:** Functional groups that share similar flow and functions, and appear multiple times in a comprehensive portfolio should be grouped into a single module and then used again and again.

**Variant Functions:** Unique functions to a single product should be grouped into a module.

When following these five heuristics for grouping functions into modules, it is also important to remember that different components fail at different rates. As such, designers try to group the sub-functions so that products that have similar failure rates are easily replaced and or repaired (Dahmus, 2001).

### 2.3.3 Design Structure Matrix

The Design Structure Matrix was first introduced by Steward in 1981, but was further developed by Eppinger in 1991, 1994 and 2000 (Steward, 1981; Eppinger, 1991; Pimmler, 1994; Ulrich, 2000). The design structure matrix is created by listing design components in both the first row and the first column of a matrix whose dimensions are  $n \times n$ , where  $n$  is the number of design components. A map that shows all component interactions is then created by asking, with respect to each component, “If this component were changed for any reason, what other components might have to change as well (Baldwin, 2000)?” An “x” in the DSM represents an interaction between design components. A DSM can be used to show the interactions of either the components of a product (Figure 2.9) or the steps of a process (Figure 2.10).

Because the DSM shows the interactions between product components and steps of the process it can be used as a means of effectively dividing design tasks among team members. As such it is also an effective tool for dividing functions into modules (Stewart, 1981).

	A	B	C	D	E	F	G
Handle Bar	A	X		X	X	X	
Neck	B	X	X				
Fork	C		X				
Shifters	D	X					
Hand Grips	E	X					
Hand Break	F	X					
Seat	G						

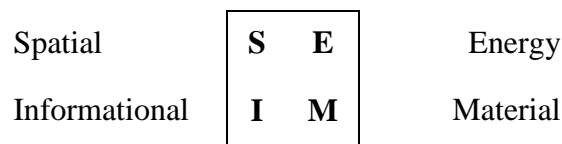
**Figure 2.9**  
Partial DSM for a Bicycle

	A	B	C	D	E	F	G
Receive Specifications	A						
Concept Generation	B	X					
Design Beta	C	X	X				
Produce Beta	D			X			
Design Testing Process	E	X	X	X			
Test Beta	F			X	X	X	
Design Production Model	G	X	X	X			X

**Figure 2.10**  
Partial DSM for a Design Process

Eppinger extended the DSM to include multiple dependencies based on four different types of interactions. To use this method a designer must consider the dependencies of components based on spatial, informational, materials and energy relationships. These four types of dependencies are considered for every possible

component combination, just like the standard DSM, and each is given a score of -2, -1, 0, 1, or 2 based on the strength of the interaction. These scores are then placed their respective cells of the DSM according to the legend shown in figure 2.11. This method allows designers to represent negative relationships (not possible to do using the standard DSM method). For example, a heating unit and a cooling unit might need to be placed at least three feet from one another – this would correspond to a negative spatial interaction. Therefore, these units should be placed in separate modules but given to the same team so that this spatial interaction is considered in the design.



**Figure 2.11**  
Legend for Eppinger’s Alternate DSM  
Method

Again, because this extended version of the DSM provides even greater depth into how product sub-functions interact, it can be used to guide designers in how to group functions into chunks.

## 2.4 EVALUATING MODULARITY

Regardless of the method used for developing competing modular designs, the step that must follow the completion of the design is an objective comparison of each design to all the rest. By objectively comparing designs to one another, the most effective design can be selected based on the comparison criterion. While there has been

a significant amount of research done on classifying modularity, understanding the benefits and the costs of modularity, and how to group functions into effective modules, very little research has been done on how to evaluate modular designs.

One of the greatest challenges a designer faces is to ensure that he or she selects the design that best meets customer requirements. Because this is such an important part of the product development process, researchers have developed tools to aid designers in this step. For example, designers will often choose a benchmark product with which to compare their designs. The process of finding a benchmark product can be helped by using the tools provided by McAdams (McAdams, 1999) for quantifying product similarity. Or perhaps, designers might like to take a utility based approach for design selection as proposed by Fernandez (Fernandez et al, 2001). Other research has been performed to help designers meet the maximum possible customer needs with a minimum number of products. Tools for accomplishing such goals have been contributed by Olewnik (Olewnik et al, 2001) and Claesson (Claesson et al, 2001).

This section will briefly outline a few of the methods that have been developed by researchers. The purpose of this section is to present the limited research on how to evaluate modular designs.

#### **2.4.1 Conjoint Method**

Conjoint is a powerful market research technique that can provide valuable information for new product development and forecasting, market segmentation and pricing decisions. It can be used to answer a wide range of product development question including:

- Which features or attributes of a product or service drive the purchase decision?
- Will changes in product design increase or decrease consumer preference and sales?

In short, conjoint analysis takes into account the fact that consumers do not make choices based on a single attribute and predicts what products or services people will choose and assesses the weight people give to various factors that underline their decision (Rice, Conjoint).

Drawing from the power of conjoint, Kevin Otto was able to propose a method for predicting the best product architecture based on market data (Otto, Work in Progress). The end result of Otto's work is a revenue model based upon conjoint data, and a cost model based upon cost-of-complexity factors of production. These two models are then set equal to each other and optimized. As far as the data used in the conjoint analysis and the cost analysis are correct, this method can accurately predict which product architectures will produce the greatest revenues.

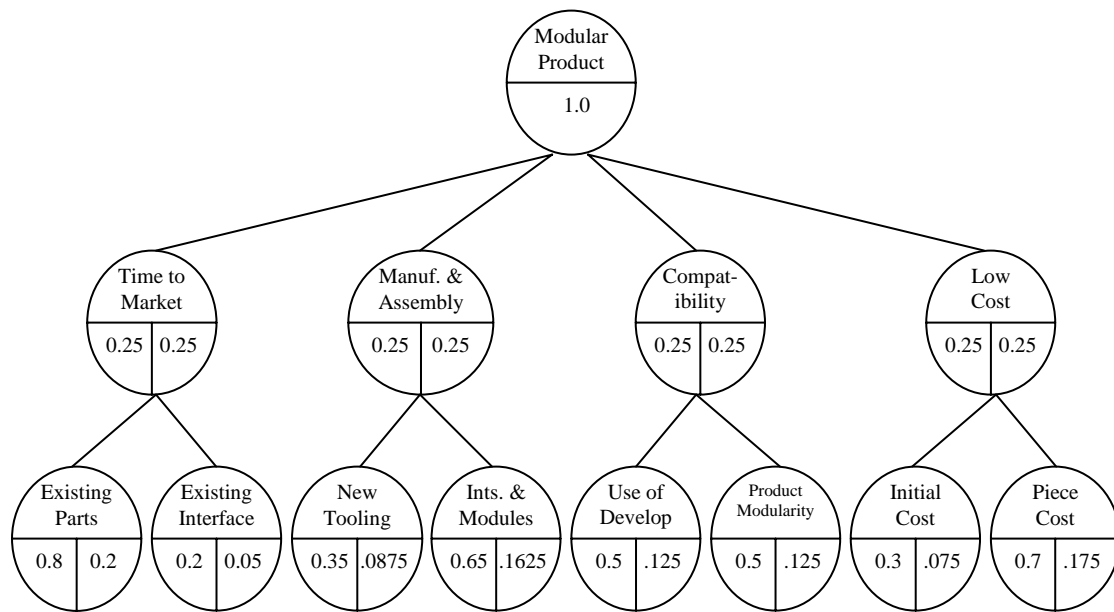
This concept of combining market research into product development is also supported by Gupta and Samuel (2001). Gupta and Samuel were also able to use conjoint analysis, combined with cost models, to predict the estimated demand for products based on performance attributes for the product architecture and the price for each product configuration. This method could be used to show the amount of revenue generated by a modular product based upon what modules were included in the final design.

## 2.4.2 Design Objectives Tree

Figure 2.12 shows an example of a decision tree as used by Mattson (2001) in his work on managing design decisions for modular consumer products. At the top of the



tree lies the overall objective. The next level down shows the individual product objectives and at the lowest level are the product sub-objectives. The numbers below the objective headings shows the relative weighting of each objective. The number to the right represents the weight of that item in the overall objective. The number on the left represents the weight of that item to the object one level up. As a check, all of the right most numbers at the product sub-objective level should sum to 1.



**Figure 2.12**  
Design Objective Tree  
(Mattson, 2001)

Once the objective tree is completed it can be used to develop a metric for the overall objective (MOO) of the product. This is done by matching each of the weights at the product sub-objective level to a metric that varies from 0 to 1. Metrics can be of any type. An example of two metrics that might be used are the modularity metric and the interface metric discussed in section 2.1.4. Equation (2.7) shows the MOO equation that would be used for figure 2.12. In this equation,  $\beta_1$  represents a metric that measures the

use of existing parts,  $\beta_2$  represents a metric that measures the use of existing interfaces, and  $\beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$  each represent their respective product sub-objectives as listed at the lower most level of figure 2.12. The weights that precede each metric are each product sub-objectives' weight relative to the overall objective.

$$MOO = 0.2\beta_1 + 0.05\beta_2 + 0.0875\beta_3 + 0.1625\beta_4 + 0.125\beta_5 + 0.125\beta_6 + 0.075\beta_7 + 0.175\beta_8 \quad (2.7)$$

By varying the product sub-objective metrics to reflect competing designs, a score can be obtained for each that shows how closely each design comes to satisfying the overall product objective. As demonstrated by Mattson, these scores can be used to evaluate a group of modular designs and decide which is best based on the MOO of designing a modular product.

## 2.5 CHAPTER CONCLUSIONS

This chapter outlines some of the previous research in the area of modular product design. As such, it describes the current boundary of knowledge surrounding the design of modular products as it pertains to this thesis. From this literature review it can be concluded that:

- Modularity comes at the expenses of other design objectives and is therefore coupled with every other design decision
- The benefits of modular design are such that they have fostered a significant amount of research in this area
- Further classification of cost and benefits is necessary to eliminate conflicting opinions
- Some basic tools have been developed for classifying, developing, and quantifying modularity, but very little work has been done to develop metrics to objectively evaluate modular designs

- Some definitions of modularity and related topics are conflicting and could use further development
- Concept evaluation and selection is one of the largest challenges when designing modular products
- Few tools exist to help designers manage the link between modularity and other product objectives
- While a few metrics have been developed to help quantify modularity, metrics that allow designers to effectively compare the tradeoffs of one modular design to another still remain to be developed
- Few tools exist for organizing functions into modules based on market strategies, consumer demand, etc.
- Most chunking methods are based on heuristics that only deal with product performance issues
- Most tools for the development of modular products assume that the design team is not starting from scratch developing a new product
- During the chunking phase of design performance considerations take precedence over all other considerations

From the conclusions listed above it can be shown that there are three areas of modular product research that still need significant contributions. Each of these three areas is consistent with the three fold objective of this thesis. They are:

1. Consolidation and unification of modular product classification methods and terminology.
2. The development of metrics which are suitable for use in classifying modular products.
3. The development of tools that can be used to evaluate a modular products potential to achieve performance and strategic objectives.

No matter how much work is done in developing modular designs themselves, it is all in vain if the tools do not exist for selecting the best modular design.



## **3.0 RESEARCH APPROACH**

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The purpose of this chapter is to present the method that will be used to accomplish the objective of this thesis, show how the results add to the current boundary of knowledge, and show how the success of this thesis can be measured. The critical components of this chapter will be revisited in the conclusion of this thesis (Chapter 8) when the results are compared to the thesis objectives.

### **3.1 APPROACH**

The approach used to accomplish the objective of this thesis is:

1. Understand the current state of knowledge as it pertains to modular product design.
2. Develop a new classification scheme that shows how one type of modularity relates to another.
3. Develop metrics and heuristics that can be used to classify modular products and discuss their relative strategic strengths and weaknesses.
4. Prove the usefulness of the metrics and classification scheme through examples and a case study.

Modular product design theory can be divided into three main areas of research – product modularity, process modularity, and organizational modularity. Much of the design research that has been done to date has focused on the first two types of modularity. Pahl and Beitz refer to these two areas of modularity as functional modules and production modules (Pahl and Beitz, 1996). While it is recognized that the topic of

modularity is broad in scope and covers such diverse areas as organizational behavior, supply chain management, etc., this thesis will focus primarily on product modularity as defined in Definition 3.1.

Definition 3.1 **Product Modularity:** the physical division of product functions into modules that result in a certain degree of interchangeability, flexibility, and standardization of components.

To allow for an even greater contribution to the current state of knowledge, this thesis will further focus on consumer phase modularity as defined in Chapter 2.

## **3.2 ADDITIONS TO THE CURRENT STATE OF KNOWLEDGE**

Chapter 2 outlined the current boundary of knowledge surrounding modular product design and several areas that could be expanded upon were discussed. By expanding the boundary of knowledge surrounding these areas, designers will be better able to effectively develop, design, and evaluate modular products more effectively. This thesis will focus on the following areas for further development.

### **3.2.1 Tools and Metrics for Modular Product Design**

Many of the tools developed over the past decade have focused on the decomposition of products and the most functional way to group product-functions into modules. Relatively little work has been done in the areas of quantifying modularity for the use of evaluating competing modular product designs, and understanding the relationships between the different types of modularity. By increasing the knowledge surrounding these two areas of research, designers will be able to select a single modular

product design from a pool of competing designs that more readily accomplishes their objectives.

### **3.2.2 The Design Process for Modular Products**

While there are many design process that can be used to guide designers through the development of a product, the implications of using these methods for the design of modular products is not fully understood. By discussing design processes under the light of modular products, designers will be better able to understand the unique considerations that must be weighed when developing a modular product. In addition, designers will better understand how current design tools fit into the overall design process and what assumptions the design tools make.

### **3.2.3 Tools for Evaluating Modular Product Designs**

Few tools have been developed to help designers evaluate competing modular designs concepts. By showing how the metrics developed in this thesis can be used in conjunction with new classification schemes developed in this thesis, designers will be able to accurately identify the design that will most readily meet its strategic objectives.

## **3.3 EVALUATING THESIS RESULTS**

This research targets the creation of Design for Modularity (DFMod) principles that:

- Focus on the selection of competing designs

- Are complementary to existing design processes
- Are available and applicable throughout the entire design process
- Are applicable to consumer phase modular products
- Are consistent with terms and processes familiar to design engineers
- Are based on strategic objectives
- Are both useful and repeatable

This research also targets the creation of modularity metrics that are:

- Related to both design and strategic objectives
- Simple, intuitive and consistent with definitions presented in this thesis
- Applicable to most consumer phase modular products
- Useful in making design and strategic decisions
- Measures modularity consistently

### **3.4 ASSUMPTIONS AND DELIMITATIONS**

This thesis does not focus on the re-creation of suitable modular design tools, nor does it attempt to repeat what has successfully been done in the past. Rather, the focus of this thesis is on the collection of existing design tools, the creation of missing design tools, and the forming of design for modularity guidelines and metrics that can be used by designers to successfully design modular products.

This thesis focuses on the use of modularity at the consumer phase for consumer products, not large scale systems. This thesis is not intended to be all inclusive, nor are the tools developed herein intended to fit the needs of every company. However, guidelines will be presented to help designers use the metrics developed in this thesis and successfully evaluate modular designs using those metrics.



### 3.5 CHAPTER SUMMARY

This chapter contains the research strategy that will be used to fulfill the objectives of this thesis. In summary, the strategy is to:

1. Understand the current state of knowledge by examining previously published research surrounding modularity
2. Expand the boundary of knowledge surrounding modularity by adding to the current state of knowledge. Will be accomplished by:
  - i. Organizing existing research to develop a new classification scheme for modular products
  - ii. Develop metrics and tools for the purposes of classifying modular products and discussing their relative strategic strengths and weaknesses
3. Illustrate conceptual ideas, tools and methods, through a case study.

The success of this thesis will be judged by comparing the results of the thesis to its objectives.



## 4.0 CLASSIFYING MODULAR PRODUCTS

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In order for a design team to efficiently work through the design process when designing a modular product they need:

1. A consistent vocabulary.
2. A scheme for classifying modular design concepts that provides the team with a framework for discussing the strategic strengths and weaknesses of designs.
3. An awareness of the hierarchy of needs present in the modular product design process.

Without these three things designers will be unable to communicate clearly, discuss and screen design concepts, and will be unable to efficiently manage the design process.

Therefore, the purpose of this chapter is to develop a consistent modular product vocabulary, develop a method for classifying modular products, and explain the hierarchy of needs present in the modular product design process.

This chapter will be split into three subsections. Because vocabulary is necessary for the formulation of a classification scheme, and visa versa, these two points of interest will be combined in the first subsection of this chapter. In this subsection the Modularity Type Matrix (MTM) will be developed and further expanded to the Modularity Type Space (MTS). The second subsection will discuss the hierarchy of needs present in the modular product design process. The last subsection will conclude with a summary of the chapter.

To discuss the above listed points it is necessary to establish the difference between a strategic and a performance objective. Establishing this difference will also be helpful in subsequent chapters. Therefore, the definitions of these two terms are:

Definition 4.1 **Strategic Objective:** objectives of a product that fulfill a global purpose and are not directly related to the product performance and function. Examples of such objectives might include low cost, high market penetration, upgradeability, etc.

Definition 4.2 **Performance Objective:** Objectives of a product that are ultimately fulfilled by the function of the product. Examples of such objectives might include speed, power consumption, size, etc.

## 4.1 MODULAR PRODUCT VOCABULARY

Product modularity can exist at different levels, phases, types and degrees (as shown in section 2.1). While various researchers have proposed different methods for classifying the varying levels, phases, types and degrees of modularity there exists a need to assemble all of these classifications in one place and provide an accompanying list of vocabulary. This section will provide designers with a common basis for the classification of modular products by showing how existing classification methods relate to one another and by providing a vocabulary list of terms relating to modular products.

This section will revisit the definitions listed in Chapter 2 with a three fold purpose: first, to eliminate ambiguity and contradicting definitions, second, to provide a new means for classifying modularity that shows the relationships between classifications, and third, to provide the vocabulary that will be used to discuss modularity throughout the remainder of this paper. As such, this section will begin with a discussion of the phases of modularity, move to a discussion of the types of modularity,

followed by a discussion of the degree to which a product is modular, and conclude with a discussion of types of modules.

#### 4.1.1 Phases of Modularity

The definitions of the three phases of modularity are useful but in their current state are too restrictive. For example, Mattson's definition of design phase modularity (Section 2.1.1) includes the statement that in order for a product to be considered modular at the design phase at least one module has to have been previously designed. This definition would exclude modular products that were not a redesign of an existing product. Because it is possible to design a modular product without starting from an existing design using design phase modularity, the definition of design phase modularity was changed to the following:

Definition 4.3 **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.

The definitions of manufacturing phase modularity and consumer phase modularity remain unchanged.

Definition 4.4 **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.

Definition 4.5 **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.

## 4.1.2 Types of Modularity

Section 2.1.2 lists definitions from Ulrich and Eppinger, Otto and Wood, and Stake. With some redundancy, each of these sets of definitions defines a type of modularity using two distinguishing factors.

1. The first is whether or not 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 4.10).
2. The second is 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 4.1 was generated as a means of showing the relationship between these existing definitions.

**Table 4.1 Modularity Type Criterion**

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

As can be seen in Table 4.1, Stake's definition of component-sharing modularity was excluded. This term was excluded because it deals more directly with product families and not with product modularity.

Looking at Table 4.1 it can be seen that the criterion on the vertical axis deals with interface type (standard vs. unique), and the criterion on the horizontal axis deals with the architecture (base vs. baseless). The definitions of the interface types are:

Definition 4.6 **Standard Interface:** An interface that allows any module to be attached to any interface on the product in question.

Definition 4.7 **Unique Interface:** An interface that requires modules to be attached to a specific interface on the product in question.

The definitions of the architecture types are:

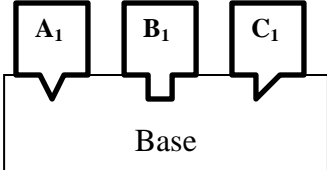
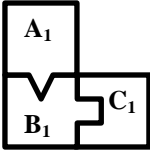
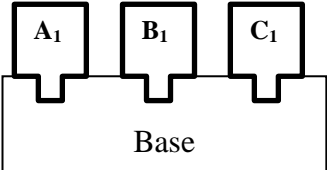
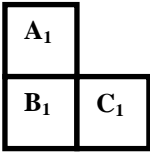
Definition 4.8 **Base Architecture:** An architecture that utilizes a base unit (see Definition 4.10 for description of base unit).

Definition 4.9 **Baseless Architecture:** An architecture that doesn't use a base unit (see Definition 4.10 for description of base unit).

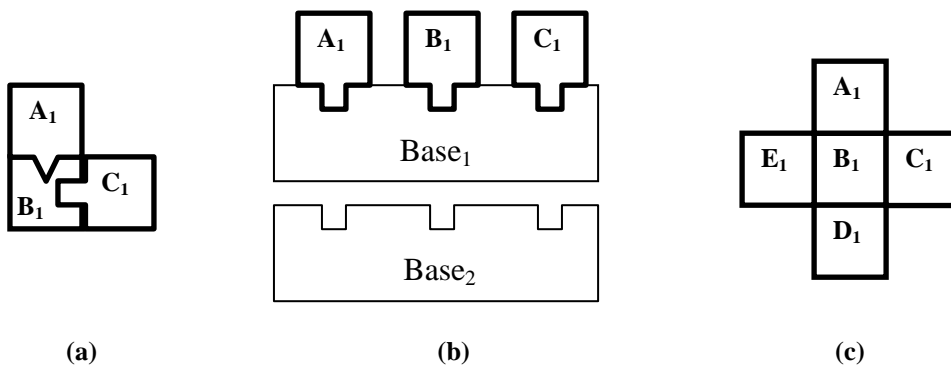
Using these new definitions and categories of criteria, Table 4.1 evolves into the Modularity Type Matrix (Table 4.2). Contained in the Modularity Type Matrix (MTM) are four types of modularity.

The distinction between a base and baseless can be made by defining the term base unit. The classification scheme of the modularity type matrix sufficiently describes the varying types of modularity; however it offers little insight into the definition of a base unit. In fact, when attempting to define a base unit, the information contained in Table 4.2 can be misleading. For example, it might seem appropriate to define a base unit according to the interface arrangement. The representation of Type I and III modularity shown in Table 4.2 shows the base unit as the component to which everything else plugs into. Unfortunately a definition of this type is not adequate.

**Table 4.2 Modularity Type Matrix (MTM)**

		Architecture Type	
		Base	Baseless
Interface Type	Unique	<i>Type I</i> 	<i>Type II</i> 
	Standard	<i>Type III</i> 	<i>Type IV</i> 

The following three examples will help illustrate the difficulty in defining the term base unit.



**Figure 4.1**  
 Variations on Module  
 Configurations Presented in the  
 Modularity Type Matrix



First, consider the arrangement of the interfaces. Figure 4.1a shows a slightly altered picture of the representation of Type II modularity in Table 4.2. The difference between these two pictures is that module  $B_1$  no longer plugs into  $C_1$ . Instead, both modules  $A_1$  and  $C_1$  plug into  $B_1$  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  $B_1$ ?

Second, consider how replaceable a component is. Figure 4.1b shows the same representation of Type III modularity that is contained in Table 4.2 except the base unit shown here 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?

Third, consider the number of modules plugged into a particular component. Figure 4.1c 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  $B_1$ . Does the fact that  $B_1$  now acts as a hub for the product constitute a change in its classification?

Because these questions have no clear answers, the term base unit is better defined leaving these questions aside. None of the three questions above deal with the function of components in question. All of the questions above deal with the physical appearance of the components in question. Therefore, the term base unit is more easily defined based on the function of the components in question. The definition of the term base unit is therefore:

Definition 4.10 **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.

The following five guidelines for identifying a base unit were extracted from the three examples above and from the heuristics for grouping functions into modules that are discussed in Section 2.3.2 of this document. These guidelines are to be used as indicators of what product components might be taken under consideration as possible base units. All possible base units identified using these indicators should be subject to Definition 4.10 in order to identify the base unit.

A product component might be a base unit if:

- It acts as a physical hub to which the majority of other modules attach
- It acts as a communication hub for the majority of other product components
- It acts as an energy hub supplying power to the majority of other components attached to it
- It acts as a material hub supplying materials to the majority of other components attached to it
- It does not have a replacement module readily available

While the focus of this document is the consumer phase of modularity, it is important to note that the base unit might be defined differently at each of the three phases of modularity. In fact, it is entirely possible that a product with no base unit at one phase might have a base unit at another phase. For example, a product might have a baseless architecture at the manufacturing phase but through some manufacturing steps certain modules are permanently attached forming a base unit at the consumer phase. Likewise, 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. Again, this would influence which module(s) is chosen as the base unit. Therefore, it is important to always take into consideration the phase of modularity. The following is a discussion that highlights and further explains Definition 4.10.

The blender shown in Figure 4.2 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.



**Figure 4.2**  
**Two Module**  
**Blender**

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 4.10.

**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 carryout 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 4.2 would be classified as having a base architecture with module one being the base.

To take the above example one step further, consider the same blender in Figure 4.2 except now it is composed of three modules instead of two. Module one remains the same. Module two is almost the same. The only difference being that the blades are now removable. The blades, bushing and interface all simply unscrew as a single unit from the bottom of module two (Figure 4.3). Module two is now just the container, and module three is composed of the blades, bushing, and interface. The functions of module one remain the same as above. The function of module two are to contain the material. The function of module three are to stir, blend, and or mix the material contained in module two.

**Blender Module One:**

1. Transform Energy – independent of any other module
2. Control – independent of any other module
3. Provide Support – independent of any other module

**Blender Module Two:**

1. Contain the Material – dependent on module three

**Blender Module Three:**

1. Stir, Blend, and or Mix – dependent on module one



**Figure 4.3**  
**Blade, Bushing and Interface**  
**Module**

In the case of the three module blender, there exists a hierarchy of functional dependency. Module two depends on module three to be able to contain any material. Without module three, module two is little more than a bottomless container. Module three depends on module one for the motion it needs to stir, blend, and or mix the material contained in module two. Module two is not the base unit because it is dependent on module three to carryout its primary function. Module three cannot be the base unit, despite the fact that module two depends on it to be able to carry out its primary function, because it is dependent upon module one to be able to carryout its primary function. Therefore, module one is the only module that could possibly be considered a base unit. For the same reasons as stated in the two module blender, module one is also the base unit in the three module example.

Before concluding the discussion about the blender it is important to point out a few things that the blender examples illustrate. First, as the three module example showed us, functionally dependent hierarchies can and do exist. These hierarchies might

be the result of coupled and decoupled designs as described by section 2.3.1 of this document. In more complicated products the likelihood of these hierarchies will increase and the possibility of having multiple hierarchies, nested or un-nested, in a single product becomes increasingly possible. To actually determine the possibility of having more than one base unit more research in this area will be required. In addition, to determine the correlation between coupled/decoupled designs and designs that incorporate a base architecture more research will be required. Both of these areas of research are beyond the scope of this document.

Second, Definition 4.10 does not rule out the possibility of functional interdependence between modules. The secondary function of module three in the three module blender example is to contain the material to be blended, stirred and or mixed because that is what it does when attached to module two. Taking this function into consideration, modules two and three can be classified as interdependent. Module three needs module two to be able to contain the material and module two needs module three to be able to contain the material. It is speculated that these interdependencies will offer little information with regard to whether a product uses a base or baseless architecture. As such, when determining if a product uses a base or baseless architecture efforts should be focused on functional dependencies rather than functional interdependencies.

Third, the 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

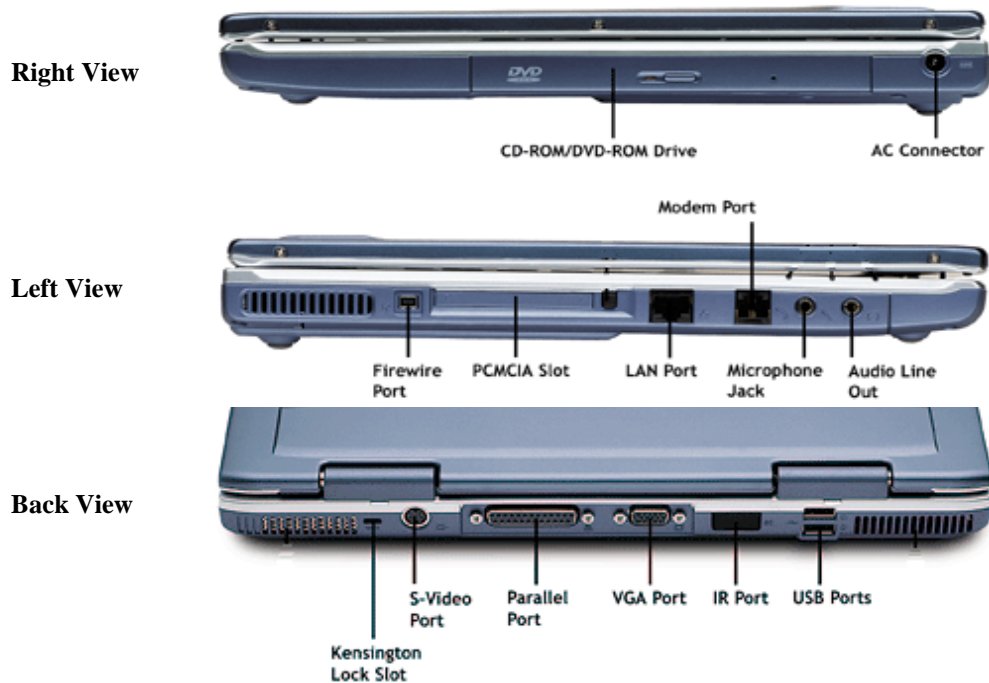
is not dependent on any module to carry out its primary function of supplying power. Should module three be classified as the base unit? The answer is no. Module one remains the base unit, while module three is classified as a module that the base unit requires for minimum configuration.

#### 4.1.2.1 Type I Modularity

Type I modularity as expressed in Table 4.2 is defined as:

Definition 4.13 **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 4.4 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 4.4 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 4.4 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, this product is not an example of Type I modularity at the extreme. This concept of varying levels of classification will be addressed in Chapter 5.



**Figure 4.4**  
**Type I Modularity**  
**“Laptop Computer Interfaces”**

#### 4.1.2.2 Type II Modularity

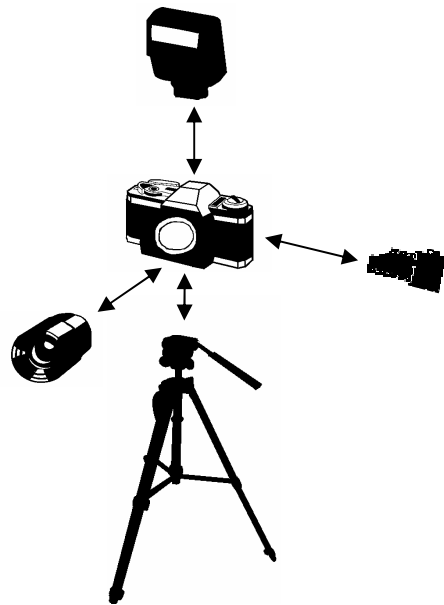
Type II modularity as expressed in Table 4.2 is defined as:

Definition 4.14 **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 4.5 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 4.5. 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 4.5 is a good example of Type II modularity.



**Figure 4.5**  
Type II Modularity  
“Photography Equipment”

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

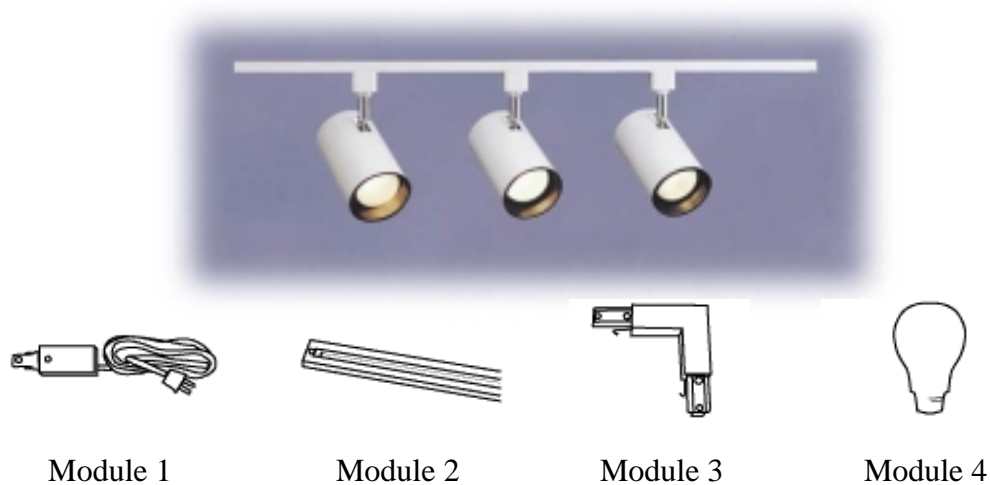
their functional independence. However, this example does put forth an interesting question. Is it possible that a product can be baseless in some respects and use a base in others? For example, perhaps the photography equipment is baseless with respect to module function but uses a base with respect to product control and product structure. Whatever the answer to this question, the photography equipment is a good example of Type II modularity as defined by Definitions 4.10 and 4.14. However, it is also obvious that the definition of a base unit (Definition 4.10) needs further development (see Section 8.3)

#### 4.1.2.3 Type III Modularity

Type III modularity as expressed in Table 4.2 is defined as:

Definition 4.11 **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 4.6 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 4.6 shows three module 4's of the same type attached to the base unit (modules 1 and 3 are not visible).



**Figure 4.6**  
Type III Modularity  
"Track Lighting"

#### 4.1.2.4 Type IV Modularity

Type IV modularity as expressed in Table 4.2 is defined as:

Definition 4.12 **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 4.7 shows two types of stackable containers. Figure 4.7a 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 4.7b 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.

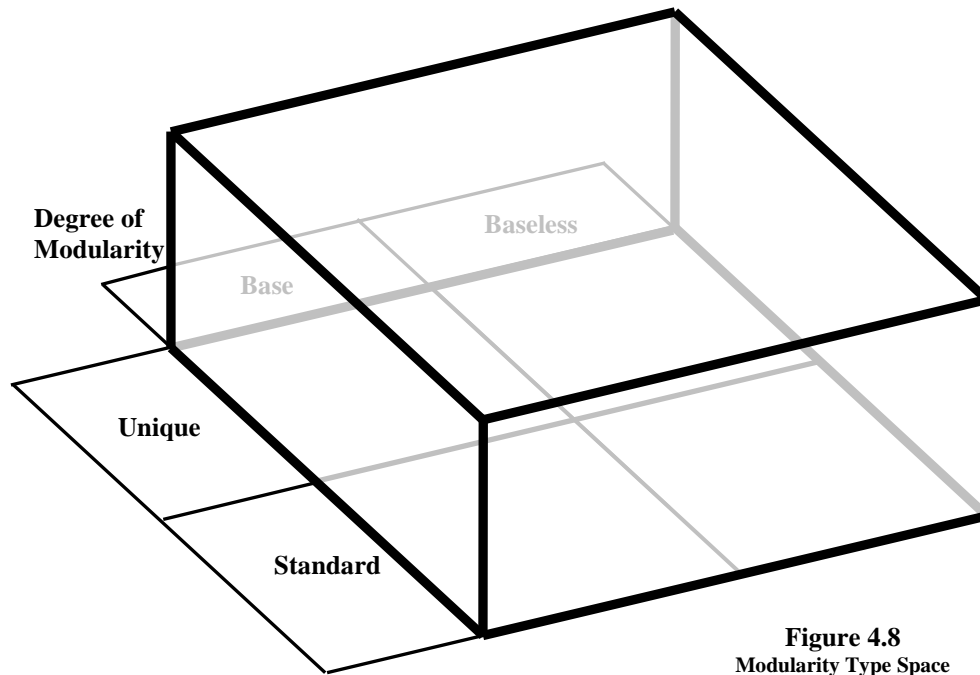


**Figure 4.7**  
Type IV Modularity  
“Stackable Storage”

### 4.1.3 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 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.

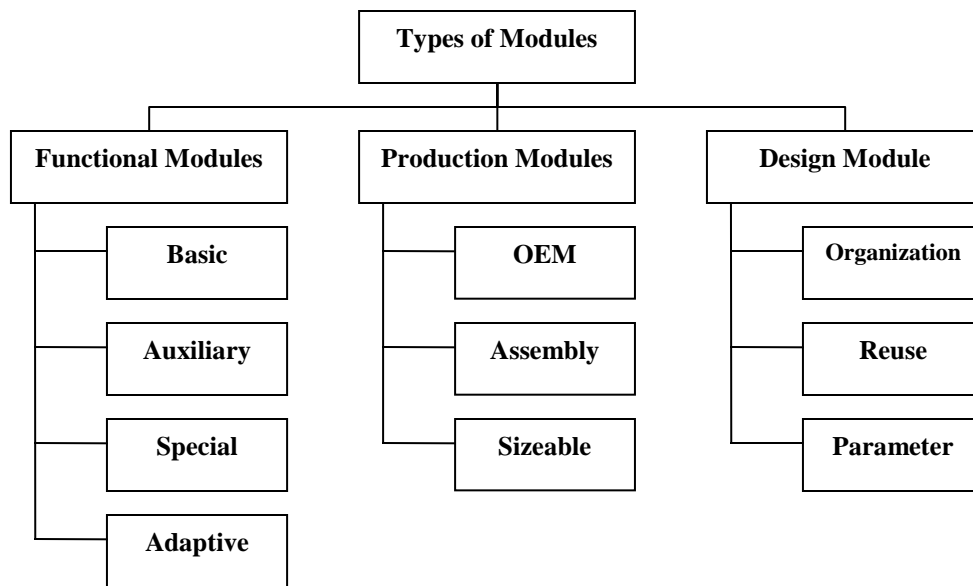
This question of the degree to which a product is modular adds a third dimension to the MTM. Therefore, the MTM is renamed the Modularity Type Space (MTS) and can be seen in Figure 4.3.



**Figure 4.8**  
Modularity Type Space  
(MTS)

#### 4.1.4 Types of Modules

Sections 4.1.1 and 4.1.2 each provided much needed clarification on the topics of phases and types of modularity. This section will provide the same clarification with respect to types of modules. Section 2.1.3 of this document presents two outlines to be used in classifying different types of modules. Although each of these outlines was developed by different researchers, each list compliments the others. Figure 4.9 was created by combining the two outlines mentioned above with other modular product concepts. The creation of this figure is discussed in the following paragraphs.



**Figure 4.9**  
Outline for the Classification of  
Module Types

Section 2.1.3 lists two main types of modules; functional modules and production modules. Functional modules are defined as:

Definition 4.15 **Functional Modules:** modules that are designed to implement technical functions independently or in combination with other modules.

Functional modules included all modules that are chunked based on functional considerations. To ensure that all modules function as designed, all modules must be considered functionally. In other words, all modules are functional modules that can be further classified using Definitions 4.18 – 4.21. However, sometimes the motivation for chunking product sub-functions is not strictly a functional decision. Sometimes product sub-functions are grouped based on production considerations. A module is classifiable as a production module, in addition to its default classification as a functional module, if it satisfies the following definition:

Definition 4.16 **Production Modules:** Modules that result from the chunking of product sub-functions based on production considerations.

A module that satisfies Definition 4.16 is further classifiable using Definitions 4.22 – 4.24.

Not only are product sub-functions sometimes grouped into modules based on production considerations, they are sometimes grouped based on design considerations. A module is classifiable as a design module, in addition to its default classification as a functional module, if it satisfies the following definition:

Definition 4.17 **Design Modules:** Modules that result from the chunking of product sub-functions based on design considerations.

A module that satisfies Definition 4.17 is further classifiable using Definitions 4.25 – 4.27. Design modules include modules of the following nature:

- Modules that are formed because they allowed for an easy division of labor among a design teams members.
- Modules that are formed because of a desire to reuse parts of a products design.
- Modules that are formed to ensure certain design parameters are not overlooked.

To explain the third bullet listed above, consider the example given at the conclusion of Section 2.3.3. In this example, a product contained both a heating unit and a cooling unit. According to design specifications, these two units must be placed at least three feet apart. To ensure that this design parameter is not overlooked, these two units could be chunked together into one module. Because this module was created based on a design consideration, it would be considered a design module.

The definitions for the terms that fall under the category of functional modules in the outline for classifying module types (Figure 4.9) are:

Definition 4.18 **Basic Modules:** modules that are fundamental to a product and can fulfill an overall function simply or in combination with other modules.

Definition 4.19 **Auxiliary Modules:** modules that are kept in step with the basic modules and are usually essential to the product's overall function. Modules required to satisfy the minimum configuration of a base unit can often be called auxiliary modules.

Definition 4.20 **Special Modules:** modules that carry out complimentary and task-specific sub-functions and are usually not essential to the products overall function.

Definition 4.21 **Adaptive Modules:** modules that are necessary for adaptation to other systems and to marginal conditions. Adaptive modules can be both essential and not essential to the products overall function.

The definitions for the terms that fall under the category of production modules in the outline for classifying module types (Figure 4.9) are:

Definition 4.22 **OEM Modules:** modules whose components or functions are grouped together simply because a supplier can provide them at less expense than they could be developed and manufactured in-house.

Definition 4.23 **Assembly Modules:** modules whose functions are grouped together to increase assembly ease.

Definition 4.24 **Sizeable Modules:** modules that are exactly the same except for their physical scale. These modules allow the physical scale of a system to be varied without changing the assembly process.

The definitions for the terms that fall under design modules in the outline for classifying module types (Figure 4.9) are:

Definition 4.25 **Organizational Modules:** modules that result from the chunking of functions based on an easy or logical division of labor.

Definition 4.26 **Reuse Modules:** modules that result from the chunking of functions based on the possibility of reuse in other product designs.

Definition 4.27 **Parameter Modules:** modules that are created to ensure that a design parameter is not overlooked.

Before concluding this discussion on module types, it is important to point out that none of the three basic types of modules (Definitions 4.15 – 4.17) is exclusive.



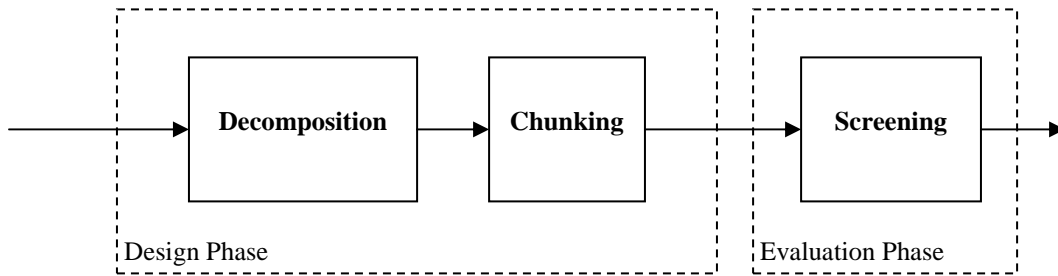
Every module is classifiable as a functional module. However, some modules will have secondary or even tertiary classifications as a production or design module depending on the motivation for chunking. For example, it is possible for a basic module to also be an OEM module.

## **4.2 THE DESIGN PROCESS**

Every product that has ever been produced, is being produced, or will be produced has undergone some type of development process. Although some of these processes were not well thought out and haphazard at best, others were meticulously planned taking into consideration every conceivable obstacle. Today there exists many different design processes that can be used and or altered to fit the specific needs of any given design team. However, regardless of the process that a design team chooses to follow, there are some commonalities that exist between all possible options. Each design process will go through some type of design phase, in which the detailed design of the product will be completed, and some type of evaluation phase. Some processes might perform these steps in a linear fashion, and others might do them iteratively. The important point is that all well researched and developed processes possess these steps. The process used to develop a modular product is no different.

Figure 4.10 is a simplified schematic of a modular design process that possesses the two steps mentioned above. In this example design process the design phase is composed of two steps. The first step is decomposition and the second step is chunking. It is assumed that at the conclusion of these two steps there exist multiple competing designs. These two steps are followed by a screening step in the evaluation phase to

select a final design from the competing possible designs. The specific methods used to perform decomposition, chunking and screening are not important. What is important is the hierarchy of design criteria that exists in the design process of a modular product.



**Figure 4.10**  
Simplified Modular Design  
Process

If a product cannot be decomposed and chunked to meet performance objectives, the question of whether or not it can meet strategic objectives is moot. As a result, during the design phase of Figure 4.10, performance objectives are most important, while strategic objectives play second chair. Once the design phase is finished and the team enters the evaluation phase, strategic objectives are more important than performance objectives. At this point in the design process it is assumed that all remaining designs meet basic performance objectives. Therefore, the design team focuses more on a products ability to meet strategic objectives than it does its ability to meet performance objectives to gauge the success of a product.

To help designers predict the ability of a product to meet certain strategic objectives new tools are required. Modular design tools are needed that will enable designers to predict earlier than the evaluation phase what designs will meet certain

strategic objectives and to help designers screen competing designs to select the one that will best meet the desired strategic objectives. The development of such a tool, based on the Modularity Type Matrix, will be the subject of the next two chapters.

### **4.3 CHAPTER SUMMARY**

This chapter began by discussing the three phases of modularity. The definitions of these three phases were altered to make them more applicable to all modular products. Three definitions resulted from this discussion. A discussion about the types of modularity then followed resulting in a new way of categorizing modularity types. Existing definitions were organized in a two-by-two matrix to better show how these four classifications of modularity types related to one another. Much of the discussion about this new method for classifying modularity types centered on the definition of a base/baseless architecture. Nine definitions resulted from this discussion that helped to better explain the MTM. Once the MTM was fully developed, a third dimension was added to the matrix that addressed the question of the degree to which a product is modular. The MTM therefore became the MTS. Section 4.1 then concludes by organizing existing definitions for module types into two existing classes and one new class. Thirteen definitions resulted from this discussion and a chart (Figure 4.9) that shows how they relate.

This chapter concludes with a brief discussion of the modular design process. In this discussion the need for tools that enable a design team to better predict what types of modular products will meet certain strategic needs was illustrated. These strategic

objectives and the tools for measuring them will be the subject of the remainder of this document.

## 5.0 CLASSIFYING PRODUCTS USING THE MTS

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Chapter 4 developed a new scheme for classifying modular products according to the type of modularity they use and the degree to which they are modular. This new classification scheme, the MTS, not only defines four types of modularity, it shows how these four types relate to one another. It is the purpose of this chapter to provide metrics and rules that can be used to show the relative position on the MTS of competing modular product designs. These metrics and rules will create a method for classifying competing modular product designs and showing their relative position on the MTS.

This chapter is split into three sections. The first section will discuss metrics and rules that can be used to locate a product on the interface axis of the MTS. The second section will discuss metrics and rules that can be used to locate a product on the architecture axis of the MTS. The third section will discuss metrics and rules that can be used to locate a product on the degree of modularity axis of the MTM. Following these three sections will be a summary section.

To eliminate the need for many hard to read three dimensional tables, the first two sections will ignore the degree of modularity axis and deal only in two dimensions. The third dimension will then be added in the third section. In doing so, it is important to remember that everything that is true for the MTM will be true for the MTS.

## 5.1 INTERFACE AXIS

The interface axis is located on the left side of the MTM (Table 5.1). When attempting to place a product on this axis it is important to remember that the MTM 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 MTM, 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 Definitions 4.6 and 4.7.

The only question the interface axis of the MTM addresses is that of interface reuse. At one extreme every interface on a product would be different. This situation corresponds to the end of the interface axis labeled unique (Table 5.1) and is defined in the following manner:

$$\begin{aligned}N_{\text{interface\_types}} &\equiv 1 \\N_{\text{it}} &\equiv 1\end{aligned}$$

At the other extreme, every interface on a product would be the same. This situation corresponds to the end of the interface axis labeled standard (Table 5.1) and is defined in the following manner:

$$\begin{aligned}N_{\text{interface\_types}} &\equiv N_{\text{interfaces}} \\N_{\text{it}} &\equiv N_{\text{i}}\end{aligned}$$

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

Equation (5.1) 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 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 (2.2), presented in Section 2.1.4 of this document.

$$I = \frac{N_{it} - 1}{N_i - 1} \quad (5.1)$$

Where,

$$\begin{aligned} N_i &\geq 2 \\ 1 &\leq N_{it} \leq N_i \end{aligned}$$

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 (5.1) 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 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.

These scores, and the manner in which they are to be used in conjunction with the MTM, can be seen in Table 5.1.

**Table 5.1 Modularity Type Matrix (MTM) with Interface Metric Values**

			Architecture Type	
			Base	Baseless
Interface Type	Unique	1	<p>Product design that uses perfectly unique interfaces.</p> <p>Mixture of standard and unique interfaces.</p> <p>Product design that uses perfectly standard interfaces.</p>	
		.5		
	Standard	0		

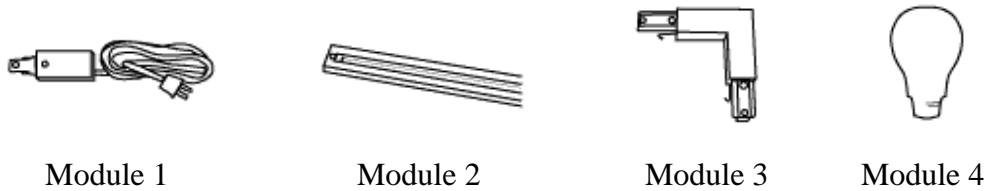
To illustrate how to use Equation (5.1) and the MTM consider the four examples given in Sections 4.1.2.1, 4.1.2.2, 4.1.2.3, and 4.1.2.4. It was in these four sections that the four types of modularity were defined and a product that exemplified each was discussed. The four products discussed were a track light system, modular bins, laptop computer interface array, and photography equipment. Each of these four products will be discussed in one of the following four subsections.



### 5.1.1 Track Lighting Example

For the track lighting system, as will be the case for many modular products, the number of interfaces used on a product is a function of the number of modules the product uses. For this example, the product is defined as a system containing the following modules (pictured in Figure 5.1):

- One power module (module 1)
- Three tracks (module 2)
- Three joiners (module 3)
  - Two modules that have two interfaces (pass through type)
  - One module that has one interface (terminator type)
- Eight lights (module 4)



**Figure 5.1**  
Track Lighting  
Modules

In order to give the track lighting system an interface score, the number of interfaces ( $N_i$ ) and the number of interface types ( $N_{it}$ ) must be known. Ascertaining the number of interfaces should always be done first to ensure that all interfaces are identified before any attempt to categorize them as unique or standard. When counting the number of interfaces care should be taken to ensure that interfaces are not double counted. Only the female or the male side of the interface should be counted, not both. In the case of the track lighting system, a system that uses a base architecture, the easiest

way to ensure that interfaces are not double counted is to count only the interfaces on the base unit. Therefore, the base unit must be defined for this product.

Referring back to Definition 4.10, and using the blender example from Chapter 4 as a guideline, the base unit for this product is recognized as needing a minimum configuration. In other words, the base unit is defined as the assembly of a power module, all three lengths of track, and all three joiners. This configuration yields three sections of track connected with the two pass through type joiners, terminated at one end with the terminator type joiner, and powered at the other end by the power module.

Because all remaining modules plug directly into the base unit, the number of interfaces present in this product can be ascertained by counting the number of interfaces on the base unit. However, because the base unit does not have any discrete interfaces, the number of interfaces must be ascertained through some other means. In this case, the number of interfaces can be calculated by dividing the length of track available for lighting modules by the average length of the interface required for each lighting module. This might not be the best or only method for ascertaining the number of interfaces on a product that does not have discrete interfaces, but it works well for this product. The MTM is only valuable for showing classifications of competing product designs relative to each other (this will be further explained in Section 5.1.5). Therefore, the question of how the interfaces are counted is not as important as being consistent in the manner in which they are counted. For this example, assume this calculated number of interfaces is equal to 9 for each section of track. Because there are three sections of track present in this product the total number of interfaces in this product is 27.

Having identified and counted the number of interfaces present on this product the next step is to find the number of interface types. This product only uses one type of interface. Knowing the values for the number of interfaces and the number of interface types the interfaces score can be calculated in the following manner:

$$I = \frac{N_{it} - 1}{N_i - 1} = \frac{1 - 1}{27 - 1} = \frac{0}{26} = 0$$

Therefore, the track light system would be classified somewhere along the dotted line labeled “A” in Table 5.2. The actual position of the product on that dotted line will be decided by tools developed in Section 5.2.

**Table 5.2 MTM with Interface Metric Product Scores**

			Architecture Type	
			Base	Baseless
Interface Type	Unique	1		
	Standard	0		

Before moving to the next example, it is important to note that the decision of what to call the base unit might change the outcome of the interface score. For example,

assume that instead of defining the base unit as the combination of the power module, track, and joiners (as was done above), that the base unit is simply defined as the power module. With this change there are a few things to consider. First, this is now a product that has module chaining. Module chaining is defined as:

Definition 5.1 **Module Chaining:** A situation in which all the modules of a product do not attach directly to any one module (or to the base unit). For example, the situation in which a module that is plugged into the base unit but that also has a module plugged into it would be considered a module chain.

This alters the interface score in the following ways. First, the number of interfaces changes. Previously there were 27 interfaces present on this product. This number must be increased to 33 to account for the lengths of track used up by the power module and the joiners that were previously not counted. In addition, the number of interface types must now be counted differently. Because the power module and the joiners will only attach to the ends of the track and the light modules will only attach to the middle, there are two different types of interfaces present on this product. There are 27 of one type (the type that the light modules attach to) and 6 of another type (the type that the power module and joiners attach to). Based on these new values for number of interfaces and interface types, the new interface score is 0.03. As can be seen by charting this value on Table 5.2, this change in base unit did not drastically change where this product falls on the MTM. As such, the question of how to count is not as important as being consistent when counting. This point will be further discussed in Section 5.1.5.

### 5.1.2 Modular Bins Example

The product in this example is pictured in Figure 5.2 and is defined as an assortment of 9 bins. It is interesting to note that if the product was defined as a single bin, it would not be classifiable on MTM because the number of interfaces would be equal to 1. One bin includes the male end of one interface and the female end of another interface. Counting these as separate interfaces would be the same as double counting an interface as was explained in the track lighting example. Therefore, each bin has one interface and a product defined as a single bin would fall outside the scope of the MTM.

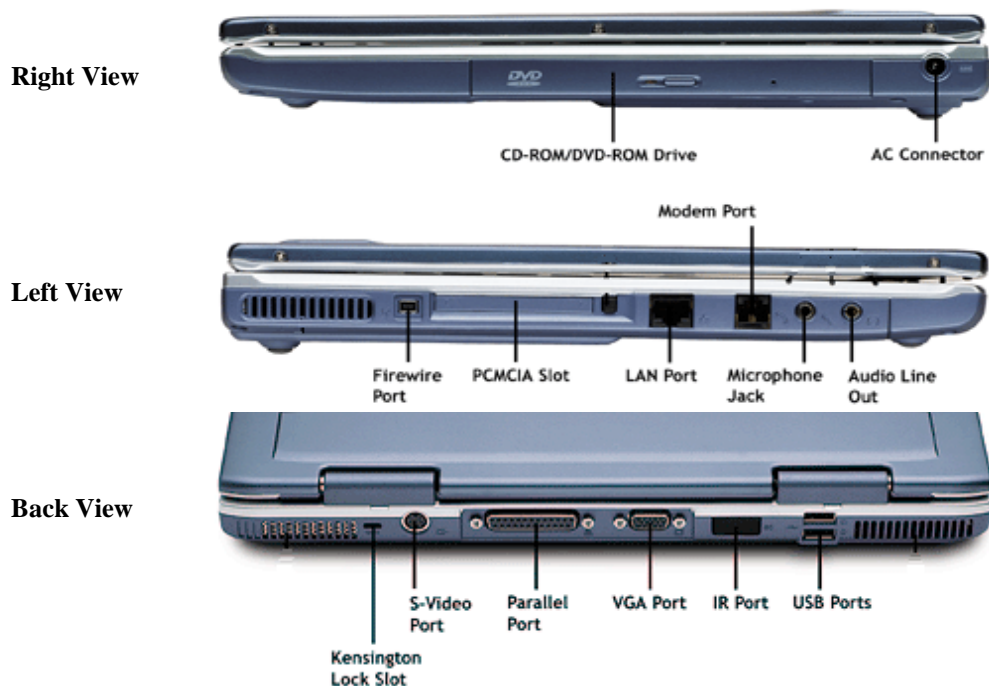


**Figure 5.2**  
Stackable Storage Bins

Because there are nine bins in this product, and each bin has one interface, the number of interfaces present on this product is 9. Also, because all the interfaces are the same, the number of interface types is 1. Using Equation (5.1), the interface score for this product is 0. Therefore, the modular bins would be classified somewhere along the dotted line labeled “A” in Table 5.2. The actual position of the product on that dotted line will be decided by tools developed in Section 5.2.

### 5.1.3 Laptop Computer Interface Array Example

This product is defined by Figure 5.3. As can be easily seen in the figure, there are 14 interfaces present. This number does not include the AC power connector because power is a minimum configuration requirement. As can also be easily seen in the figure, there are 14 interfaces and 12 types of interfaces present. Using Equation (5.1), this product receives an interface score of .85. Therefore, the laptop computer would be classified somewhere along the dotted line labeled “B” in Table 5.2. The actual position of the product on that dotted line will be decided by tools developed in Section 5.2.



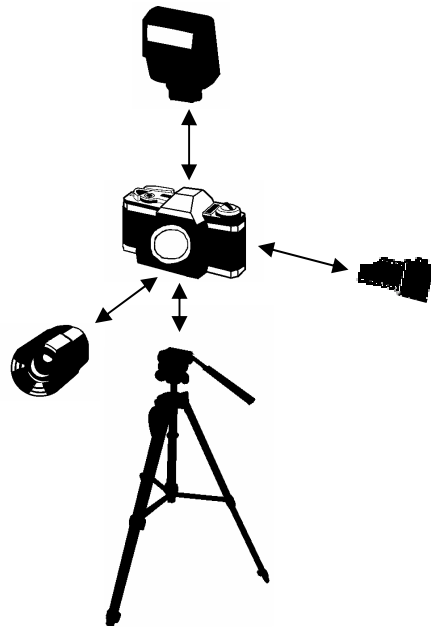
**Figure 5.3**  
Laptop Computer Interfaces

This product did not receive an interface score of 1 because it had two small groups of interfaces that were standard (one group of two USB ports, and one group of

two 1/8” microphone/speaker jacks). As the number of standard interfaces approaches the number of unique interface, and visa versa, the interface score will approach .5.

### 5.1.4 Photography Equipment Example

This product is defined by the systems seen in Figure 5.4. It consists of a camera, a flash, a lens, film, and a tripod. Between these five modules there exist four interfaces ( $N_i = 4$ ). Each of these interfaces is unique ( $N_{it} = 4$ ). Using Equation (5.1), this product receives an interface score of 1. Therefore, the photography equipment would be classified somewhere along the dotted line labeled “C” in Table 5.2. The actual position of the product on that dotted line will be decided by tools developed in Section 5.2.



**Figure 5.4**  
Photography Equipment

### 5.1.5 Method to using the Interface Metric

The above four sections described how to plot the position of a modular product on the interface axis of the MTM. As was exemplified in the previous four sections, there are often several ways to define a base unit, count interfaces and interface types. The method chosen often depends upon the product. Because of this fact, the MTM is not well suited as a means for classifying and comparing non-similar products or concept designs. While it is true that all modular products will plot on the MTM, there would be little value in doing. There is no way to consistently count interfaces, interface types and define base units when dealing with non-similar products. However, because consistency is possible when dealing with similar products, the real value of the MTM can be seen when it is used to compare competing modular product designs. For example, assume for a moment that Figure 5.1 shows only one example of three competing design options. With all four options plotted on the MTM using the Interface Metric (and the metric developed in Section 5.2), the relative position of each option can be seen. This will allow the design team to discuss the strengths and weakness of each design relative to the others. This is the subject of Chapter 6.

Keeping the idea of consistency in mind, the following are the steps that should be taken when attempting to find the interface value of a product:

1. Define the area of interest
  - Are you interested in an entire assembly or just a subset?
2. Count the number of interfaces
  - Do not double count interfaces
  - Count all interfaces
  - Deciding if the product uses a base or baseless architecture can be of help
3. Count the number of interface types
4. Calculate using the Interface Metric – Equation (5.1)



## 5.2 ARCHITECTURE AXIS

The architecture axis is located at the top of the MTM (Table 5.3). Placing a product on this axis is a binary decision. The following steps were derived from Definitions 4.8, 4.9, and 4.10, the blender example from Section 4.1.2, and Sections 4.1.2.1, 4.1.2.2, 4.1.2.3, and 4.1.2.4.

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

1. Define the product of interest (as was done in Section 5.1).
2. Identify all modules and list each module's primary function(s).
3. Check for functional dependency between modules by following the examples in Section 4.1.2.
  - a. In products with a large number of modules the five indicators of a base unit listed in Section 4.1.2 might help to narrow the search.
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 4.10 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 4.10 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 of Chapter 4. Some products might have more than one functionally independent module, or small clusters of functionally dependent modules that are independent of all others. In these cases the design team must make a judgment call. This need for a judgment call is an example of why the MTM is not well suited for classifying and comparing dissimilar products. When comparing similar products on the MTM, 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 and, therefore, the MTM would have little value in making such comparisons.

It is also important to note that only the primary functions are to be considered when identifying a product as base or baseless. In other words, at the consumer level the functions under consideration should be those that would be important to the consumer. Likewise, at the manufacturing and design phases, the functions under consideration should be those that are important at those phases. It is possible that the base unit be defined differently at all three phases.

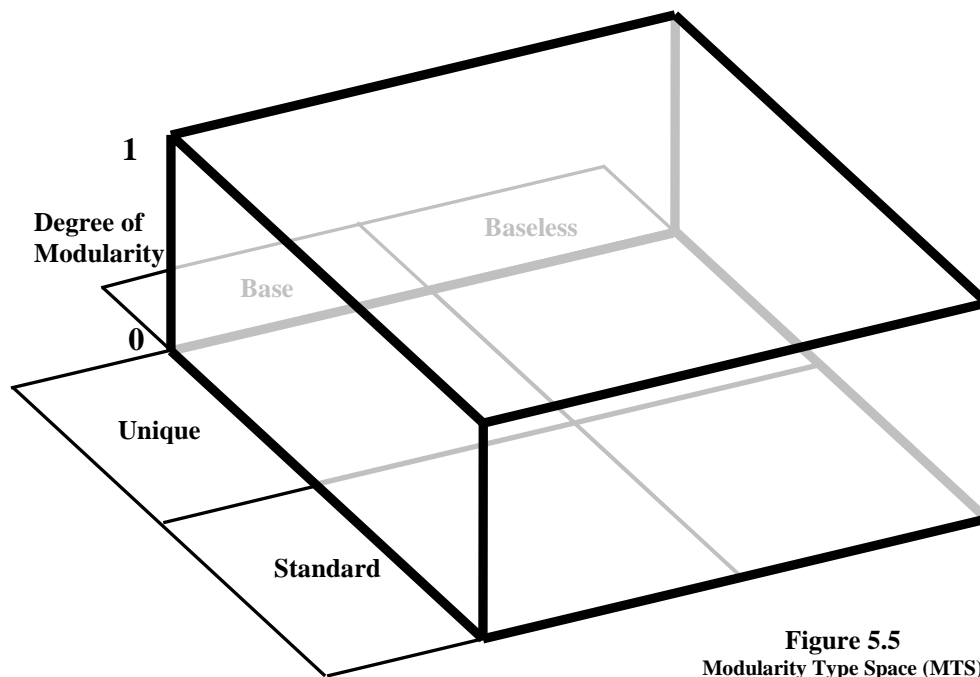
Using the steps developed above and Table 5.2, the position of each of the four products discussed in the previous section can be seen in Table 5.3. For a more detailed discussion of how each product was classified base or baseless see Sections 4.1.2, 4.1.2.1, 4.1.2.2, 4.1.2.3, and 4.1.2.4.

**Table 5.3 MTM with Product Plots**

			Architecture Type	
			Base	Baseless
Interface Type	Unique	1	Laptop Array	Photo Equip.
	Standard	0	Track Lighting	Modular Bins

### 5.3 DEGREE OF MODULARITY AXIS

The degree of modularity axis is located perpendicular to the plane created by the architecture and interface axes of the MTM (Table 5.3) and is oriented out of the page as shown in Figure 5.5. With the addition of this third dimension the MTM evolves into the MTS.



**Figure 5.5**  
Modularity Type Space (MTS)  
with degree of Modularity Score  
Values

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 (2.1) presented in Section 2.1.4 of this document, was developed:

$$M = \frac{N_{\text{modules}} - 2}{N_{\text{sub\_functions}} - 2} = \frac{N_m - 2}{N_{sf} - 2} \quad (5.2)$$

Where,

$$\begin{aligned} N_{sf} &\geq 2 \\ 2 &\leq N_m \leq N_{sf} \end{aligned}$$

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.

Equation (5.2) 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 5.5). 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 5.5).

An illustration of how to use Equation (5.2) in conjunction with the MTS can be found in Section 5.3.1. This section will only discuss the track lighting example from Sections 5.1 and 5.2 even though these two previous sections each discussed the track lighting example and three additional products. This is due to the fact that the tools needed to use the Modularity Metric, functional decomposition methods, were previously developed by other researchers. Due to the simple calculation, giving more than one example of how to calculate the Modularity Score would be redundant. Therefore, it is assumed that for the track lighting example in Section 5.3.1 the number of product sub-functions was discovered previously through the use of some functional decomposition method. Section 2.3 of this document contains a brief list of some popular methods for decomposing a product.

### 5.3.1 Track Lighting Example

In this discussion, the product in question is defined the same way it was in Section 5.1.1 of this document. In other words there are 15 modules present in this product ( $N_m=15$ ) that are depicted in Figure 5.1. To plot the position of this product on the degree of modularity axis of the MTS the modularity score must be calculated. In order to do this the Number of Modules ( $N_m$ ) and Number of Sub-functions ( $N_{sf}$ ) must be obtained. The Number of Modules present in this product was already determined to be 15. The following data was obtained through some type of functional decomposition (assumed to have been performed previously), and the Number of Sub-functions was calculated to be 46:

- Power module (module 1)
  - Supply power

Track module (module 2)

- Distribute power
- Support light modules
- Allow DOF for positioning of light modules
- Support joiner and power modules
- Provide attachment points for mounting and installation

Joiner module (module 3)

- Distribute power
- Provide attachment points for mounting and installation

Light module (module 4)

- Convert energy to light
- Focus light
- Provide DOF for aiming of light

The number 46 was calculated by multiplying the number of functions for each module by the number of respective modules and then summing the products. Knowing the value of the two variables contained in the Modularity Metric the modularity scores can now be calculated.

$$M = \frac{15 - 2}{46 - 2} = \frac{13}{44} = .3$$

Rather than attempting to represent this product's location in a three dimensional figure like Figure 5.5 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 5.4. By adding the Modularity Score beneath the plotted position of the product on the MTM, the MTS can be clearly represented without the need for a confusing three dimensional plot. Table 5.4 combines all the information of the Sections 5.1 and 5.2, pertaining to the track lighting example, with the information contained in this section to show the location of each of the track lighting product on the MTS.

It is important to note that the number of modules chosen to be included in the “product” will affect the modularity score and the placement of the product on the MTS.

This is another example of the fact that the MTS is not well suited for categorizing or comparing products that are not similar in design. The MTS is best suited as a tool for comparing competing product designs where consistent decisions of how to obtain the values of the variables  $N_m$  and  $N_{sf}$  can be made. See Section 5.4 for further discussion on this point.

**Table 5.4 MTS with Plot of Track Lighting Example**

Degree of Modularity			Architecture Type	
			Base	Baseless
Interface Type	Standard	0		
	Unique	1		

M=0.3  
Track Lighting

### 5.3 SUMMARY

In summary, there are a few key points from the chapter that will be reiterated here. First, because of the need to leave flexibility in the methods for plotting products on the MTS, design teams will sometimes find it necessary to make an arbitrary decision

about a product's characteristics. These sorts of decisions will affect the way a product is plotted on the MTS. Therefore, the methods developed in this chapter (and Chapter 6) are best used to plot and compare similar products where some consistency in decision making can be maintained. This makes the MTS particularly well suited for the selection of a final design concept from a group of competing product designs. Table 5.3 is not intended to provide any insight into comparing the products that are plotted. It is simply an example of how to plot products on the MTS.

Second, items such as the number of modules or the primary function of a module will change depending on the phase of modularity. These will affect the plotting of the product on the MTS. Therefore, the phase of modularity must always be taken into consideration.

Third, it is important to remember that when calculating the Modularity Score all product sub-functions are considered. When deciding if the product uses a base or baseless architecture only the primary functions of the product are considered.

This chapter built on the classification scheme developed in Chapter 4. By adding metrics and rules that can be used to plot a product's location on the MTS a classification method was developed. This method will allow a design team to plot competing product designs and plot their locations on the MTS. Once plotted on the MTS, the design team can then discuss each design's strategic strengths and weaknesses relative to one another. The concept of using the MTS to discuss the strategic strengths and weaknesses of competing product designs will be the subject of Chapter 6.



## 6.0 STRATEGY BASED CONCEPT SELECTION

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Every product or system is designed with some end in mind. As Definitions 4.1 and 4.2 illustrate, these ends can be grouped in two categories, strategic objectives and performance objectives. Although strategic and performance objectives are often closely related, this chapter focuses its discussions on strategic objectives so as not to deviate from the focus of this document. Performance objectives will only be discussed to the extent that they are needed to provide context for a discussion on strategic objectives.

The purpose of this chapter is to show how the MTS can be used as a tool for comparing the strategic strengths and weaknesses of competing product designs for reasons of concept selection. In doing so it will be important to show that a modular product's ability to achieve certain strategic objectives depends on the type of modularity used in the product and the phase at which the modularity is applied. This chapter will develop the MTS from a method for classifying modular products to a design tool capable of aiding designers in final concept selection through a comparison of strategic strengths and weaknesses.

This chapter will begin by illustrating that a modular product's ability to achieve certain strategic objectives depends upon the phase of modularity. Therefore, when comparing competing product designs it is important to consider each design's strategic strengths and weaknesses at each phase of modularity to ensure that no advantage or weakness is overlooked. The second section of this chapter will give an example, based

on the track lighting product discussed in the previous two chapters, to show how the MTS might be used as a design tool for selecting a final design from a group of competing designs. The third section will present a mathematical method that can be used in conjunction with the MTS for final concept selection. The chapter will conclude with a summary.

## **6.1 PHASE DEPENDENT STRATEGIC OBJECTIVES**

Although the physical embodiment of modules and interfaces look similar at all three phases of modularity, the advantages and disadvantages gained at each phase of modularity can be different. For example, a product that is Type I will always yield a design in which modules only fit into a specific slot (due to its use of unique interfaces) regardless of what phase of modularity it is applied, but the advantages and disadvantages gained at each of the three phases of modularity can be different. The Tomy Bit Char-g is a good example of a product that uses unique interfaces to gain a different strategic advantage at each phase of modularity.

The Bit Char-g, made by Tomy, is one of the worlds smallest radio controlled cars. Figure 6.1 shows the Char-g car assembled in front of its radio transmitter. The American quarter in the foreground helps show the relative size of the car.

Figure 6.2 shows the Char-g in its packaged form as it would be found on a store shelf. As can be seen in this figure, the Char-g comes with some assembly required. While the electronics have been previously attached to the chassis, the axels, tires, and other components have not yet been assembled.



Figure 6.1  
Tomy Bit Char-g Toy Car

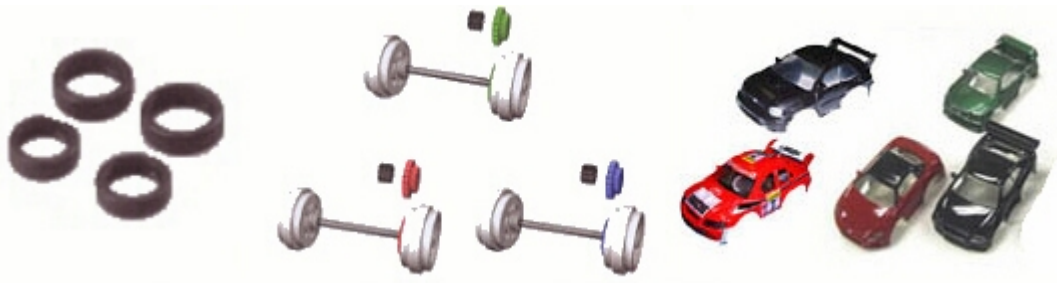


Figure 6.2  
Tomy Bit Char-g Toy Car in  
Retail Packaging

The Char-g car is a modular product that utilizes unique interfaces. The body of the car, the chassis, the tires, the axles, the motor, and the gears (each visible in Figure 6.2) all fit together (Figure 6.1) each with its own unique interface. The transmitter is

also partially visible in Figure 4.2, but is not a part of the car and will therefore be left out of this discussion.

It is not certain if the Char-g is modular at the design phase because the design of the product is not available for viewing. However, it can be concluded from Figure 6.2 that the Char-g is modular at both the manufacturing and consumer phases. By making the Char-g car modular there are two strategic advantages gained at the manufacturing phase. First, the need to assemble is greatly reduced during manufacturing. Because the interfaces facilitate easy assembly, the assemble step is delayed until the consumer phase. As a result, assembly during the manufacture of the Char-g consists of nothing more than placing the proper modules in the box. Second, custom orders are easily satisfied. For example, to satisfy the request for a faster car the only change required at the manufacturing phase is to substitute a different motor for the original. No specific tooling or change in the assembly process is required.



**Figure 6.3**  
Tomy Bit Char-g Upgrade and  
Add-on Parts

The strategic advantage at the consumer phase is illustrated by Figure 6.3. Figure 6.3 displays tires, axels and gears, and new car bodies for the Char-g. These are just a few of the upgrade and add-on parts that are available for the Char-g cars. Because the

Char-g cars are modular, and because consumers are familiar with how they are assembled, Tomy has created a market for upgrade and add-on parts. This helps extend the life of the Char-g product line, and creates an additional source of revenue for Tomy.

As was illustrated in the Char-g toy car example, modular products can and do have phase dependent strategic advantages. All of the strategic advantages discussed in the Char-g example are a direct result of its use of unique interfaces and base unit (Type I modularity). However, some of the strategic advantages discussed were specific to either manufacturing or consumer phase modularity. Therefore, when using the MTS to compare the strategic strengths and weaknesses of competing product designs for the purpose of selecting a final design (see Section 6.2), it is important that each of the three phases of modularity are considered to ensure that nothing is overlooked. By discussing the strategic advantages and disadvantages of modularity types within the context of the three phases of modularity, the MTS is given more depth and becomes a more powerful tool for designers.

Before demonstrating how the MTS can be used as a tool for selecting a final design concept from a set of competing product designs based on the strategic strengths and weaknesses of each concept, the relationship between the MTS and strategic strengths and weaknesses must be shown. This is the topic of the next section in this chapter.

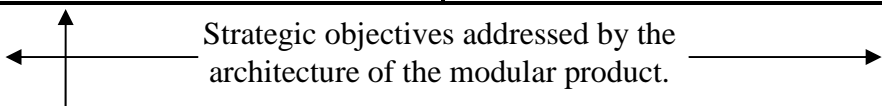
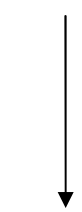
### **6.1.1 MTS and Strategic Objectives**

Each axis of the MTS addresses certain product characteristics. As was shown in Chapter 5, these characteristics can be used to plot the position of a product on the MTS.

Product characteristics also influence a product's ability to achieve strategic objectives. Therefore, not only can the axes be used to plot a product's position on the MTS for purpose of classification, once plotted, the MTS can serve as a framework within which the strategic advantages and disadvantages of a product can be discussed. When several similar products, or designs, are plotted on the MTS at the same time, the MTS can be used to show the strategic strengths and weaknesses of each product relative to all the other similar products plotted. This display of strategic strengths and weaknesses will be useful in helping design teams to select a final product concept from a set of competing design concepts on the basis of which products strategic strengths and weaknesses are best aligned with the strategic objectives of the product.

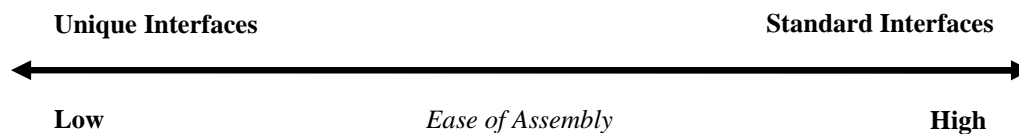
Using the MTS as a design tool for the selection of a final product concept involves two steps. The first step is to plot all competing product designs on the MTS. This was the subject of the last two chapters and therefore will not be discussed any further in this chapter. The second step is to list strategic objectives along the axes of the MTS (Table 6.1, does not show the Degree of Modularity Axis) for the purpose of comparing each concept to all the others. The final concept can then be chosen by selecting the concept with strategic advantages that best align with the overall strategic objectives of the product.

**Table 6.1 Strategic Objectives by MTS Axes (wo/ Degree of Modularity Axis)**

Degree of Modularity			Architecture Type	
			Base	Baseless
Interface Type	Unique	1		
		.5	Strategic objectives addressed by the interface of the modular product.	
	Standard	0		

For example, assume that the product of interest is a desktop computer. More specifically the design team is interested in examining the design of the PCI card slots on the motherboard. The design team is interested in evaluating the conventional design's ability to ease assembly at the manufacturing phase. The strategic objective ease of assembly can be addressed by the interface axis of the MTS. Because of the fact that a computer has the ability to recognize what cards are plugged into what slots and configure itself accordingly, the conventional design, which uses standard interfaces, has a high ability to ease assembly (Figure 6.4). The standard interfaces, combined with the computers self configuration ability, affords computers flexibility in assembly by allowing the cards to be plugged into any slot. On the other hand, if the PCI card slots on a desktop computer used unique interfaces, the assembly process of the desktop computer

would lose its flexibility. This loss of flexible assembly would require more stringent controls on assembly processes and ultimately hinder the assembly of each machine. Therefore, unique interfaces would result in low ease of assembly (Figure 6.4). In this scenario, because both Type III and IV modularity have standard interfaces and Type I and II do not, ease of assembly would be a strategic advantage for Type III and IV modularity and a strategic disadvantage for Type I and II modularity at any degree of modularity (Figure 6.4).

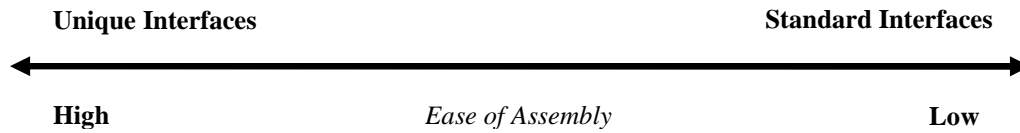


**Figure 6.4**  
Ease of Assembly for Self  
Configuring System at the  
Manufacturing Phase

It is important to note that the reason the question of ease of assembly could be addressed in the case of the computer PCI card slots was by answering the question of whether or not the computer was self configuring. Consider a computer that is not self configuring. If a computer did not have the ability to recognize what cards were plugged into what slots and configure itself accordingly, standard interfaces would have a low ease of assembly (Figure 6.5). In this scenario, every PCI card would have to be plugged into a designated PCI card slot. Standard interfaces would only confuse the assembly process by making it possible to plug cards into the wrong slots. Unique



interfaces would require that all cards be plugged into predetermined slots. Unique interfaces would have a high ease of assembly (Figure 6.5)



**Figure 6.5**  
Ease of Assembly for a Non-self  
Configuring product at  
Manufacturing Phase

In either case, self configuring or not, the strategic question of ease of assembly was answered by the Interface Axis of the MTS. The issue here is not the answer to the question of self configurability. The issue is that the MTS does not address all product characteristics. There are three important consequences of this point that are listed below:

- It is not possible to list all strategic objectives that can be addressed by each of the three axes of the MTS and there will be some strategic objectives that cannot be addressed by the MTS.
- In placing strategic objectives on an axis it is not possible to generalize which end of the axis should be labeled as high and which end should be labeled as low.
- Designers will be required to use their knowledge of the product to answer questions not asked by the MTS in order to use the MTS to answer questions of strategic performance.

In order for a design team to use the MTS, they must answer the questions asked by the three axes of the MTS and supply additional information that will be specific to the product in question. Because the MTS requires product specific information other than what is needed to plot the product's position, it is not possible to create generalized

lists of strategic objectives that would most appropriately fall on each axis of the MTS. In addition, as was shown in Figures 6.4 and 6.5, this additional product information also makes it difficult to generalize which end of an axis should be labeled as high and which end should be labeled as low. However, it is this need for additional information that makes the MTS a powerful design tool. Because the MTS does not address all product characteristics, it is a flexible tool that can be used to analyze all modular products. By supplying the additional information, which should be readily available to designers, the design team will be able to place strategic objectives on the axes of the MTS, label the highs and lows, and use the MTS to compare the strategic performance of competing product designs.

For matters of uniformity, when strategic objectives are placed on an axis of the MTS, they are worded so that a products ability to achieve that objective can be expressed in terms of the words “high” and “low.” This will be demonstrated in the following section.

## **6.2 CONCEPT SELECTION EXAMPLE**

This section will demonstrate how to place strategic objectives on the MTS and label the highs and lows. The track lighting example from the previous two chapters will be used to demonstrate these procedures. Although the following example will focus only on the consumer phase of modularity, this same procedure can be done for both design and manufacturing phase modularity. The strategic objectives discussed in this section are only listed for the purposes of discussion and are not intended to be complete.

Beginning from where the previous two chapters left off, the track lighting product has already been plotted on the MTS (Table 6.2). The product, as described in the previous two chapters is labeled Track Lighting – 1. It will be referred to as design 1 throughout the remainder of this chapter.

**Table 6.2 MTS with Plot of Track Lighting Example**

Degree of Modularity			Architecture Type	
			Base	Baseless
Interface Type	Unique	1		
		.5		
	Standard	0		
			<div style="border: 1px solid black; border-radius: 50%; padding: 5px; display: inline-block;">           M=0.3 Track Lighting - 1         </div>	

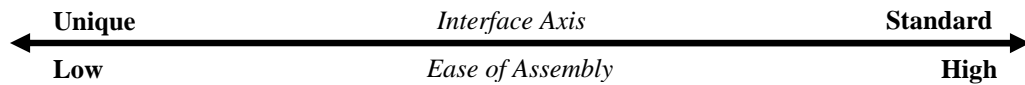
There are three steps to using in the MTS for the purposes of concept selection and screening. They are listed bellow:

1. List strategic questions along all axes of the MTS.
2. Examine each strategic question with regard to each axis to see if that axis provides any insight into that strategic question. If there is insight provided, proceed to the next bullet. If there is no insight provided, eliminate that strategic question from that axis.
  - To label the high and low ends of the axes.
    - i. Keep track of any additional information that was used to make such assignments to provide consistency in making future assignments
3. Select the concept that is best aligned with the overall strategic objectives of the product.

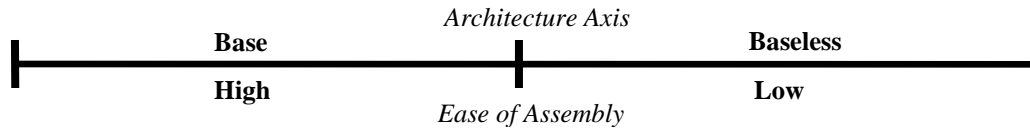
For this example, assume that the design team is concerned with the strategic questions of ease of assembly and product upgradeability both the consumer phase. The following paragraphs will show how this questions is addressed by following the three steps listed above.

Looking first to the question of ease of assembly in relation to the interface axis, it is clear that this product's ability to aid or hinder assembly changes as it moves along this axis. Design 1 uses one type of interface for the assembly of the base unit and a second type for the assembly of lighting modules. The number of lighting module interfaces far out number the other interface type. Because the track lighting product does not require that the lighting modules be plugged into any specific interface, in a sense, it is self configuring. This arrangement facilitates easy assembly. Therefore, the standard end of the interface axis is labeled as high with regard to ease of assembly and the unique end is labeled as low (Figure 6.6a). Because this product behaves as self configuring, unique interfaces would only complicate the assembly process.

The architecture axis also provides an insight into how easy it is to assemble the track lighting product. Whenever there is a base unit to which everything else attaches easy assembly is facilitated. This is a Design for Manufacturing principle applied to the consumer phase of modularity. In other words, because design 1 provides a base unit to which everything else attaches (there is no module chaining, see Definition 5.1), assemble is facilitated. Therefore, the base half of the architecture axis is labeled as high with regard to ease of assembly, and the baseless half is labeled as low with regard to ease of assembly (Figure 6.6b).



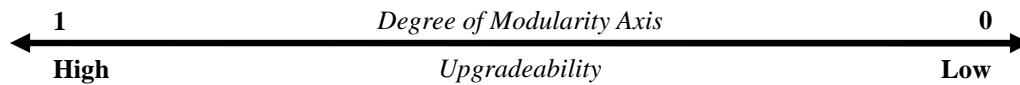
**Figure 6.6a**



**Figure 6.6b**

**Figure 6.6**  
**“Track Lighting”**  
**Ease of Assembly**  
**on the MTS**

The degree of modularity axis deals specifically with product sub-function density per module. Because product sub-function density has little to do with assembly it is concluded that the degree of modularity axis provides no insight into the ease of assembly of the track lighting product. However, product sub-function density does affect a products ability to be upgraded. In other words, the lower the density per module, the easier it is to upgrade product sub-functions independently of each other. A low density corresponds to a score of 1 on the degree of modularity axis. A high density corresponds to a score of 0 on the degree of modularity axis. Therefore, the 1 on the degree of modularity axis is labeled as high and the 0 is labeled as low with regard to the track lighting products ability to be upgraded (Figure 6.7). The other two axes offer no insight into the question of upgradeability.



**Figure 6.7**  
 “Track Lighting”  
 Upgradeability  
 on the MTS

Table 6.3 combines the information contained in Figures 6.6 and 6.7 into the MTS. Table 6.3 also shows two fictitious designs that were added for the purposes of discussion. As can be seen in Table 6.3, designs 1 and 3 are both well aligned with the strategic objective ease of assembly. Design 2 scores high on the architecture axis with regard to ease of assembly, but scores low on the interface axis. It can therefore be concluded that design 2 is not as well aligned with the strategic objective ease of assembly as designs 1 and 3. With regard to product upgradeability, design 3 has the best alignment, design 2 is the second best, and design 3 is the worst.

**Table 6.3 MTS with Strategies**

<i>Upgradeability</i> 0 = LOW 1 = HIGH		Base		Baseless
		HIGH <i>Ease of Assembly</i>		LOW <i>Ease of Assembly</i>
<b>Unique</b>	<b>1</b>	<b>LOW</b>		
	<b>.5</b>			
<b>Standard</b>	<b>0</b>	<b>HIGH</b>		
	<b>0</b>			

Having completed steps 1 and 2, the design team is now ready to choose the final design. Because the MTS only provides a context within which a products ability to achieve strategic objectives can be discussed and does not identify the best design, the design team must still choose the final design. In simple situations, such as the track lighting example, this can be done through simple observation of which product is best aligned to all the strategic questions. In this case, design 3 should be chosen as the final design because it is best aligned with all the strategic questions along all of the axes. However, for more complex situations in which there is no clear winner, the design team will have to use some other means of selection. Section 6.3 will explain one method that might be used in such a situation.

### **6.3 METHOD FOR FINAL DESIGN SELECTION**

Once the first two steps listed in Section 6.2 are completed, the design team is left to choose the final design concept. In many instances, there will be no clear winner that ranks high on every axis with regard to every strategic question (as was the case in with the track lighting example). The following explanation of how to choose a final design concept is based on the scenario described by Table 6.4. This explanation is not intended to exemplify the best or only method for selecting a final concept from the MTS. It is only intended to show one possible method for selection.

The scenario shown in Table 6.4 is derived from the track lighting example in Section 6.2. In this new scenario it is there is no clear winner in every category. While it is still true that design 3 ranks the highest on the interface and architecture axes with regard to ease of assembly, it no longer ranks the highest on the degree of modularity axis

with respect to upgradeability. On this axis, design 3 is out ranked by design 5 that is also rank the lowest on the architecture axis and the second lowest on the interface axis with respect to ease of assembly. To complicate matters even further, designs 2 and 4 each rank the same on the degree of modularity axis with respect to upgradeability, but each is lacking on either the architecture or interfaces axes with respect to ease of assembly. There are now clear winners in this scenario.

**Table 6.4 MTS with Concept Selection Scenario**

<i>Upgradeability</i> 0 = LOW 1 = HIGH		Base		Baseless		
		HIGH <i>Ease of Assembly</i>		LOW <i>Ease of Assembly</i>		
Standard	0	HIGH	Design - 2 M=0.5		Design - 5 M=0.8	
	.5				Design - 4 M=0.5	
Unique	1	LOW	Design - 3 M=0.6		Design - 1 M=0.3	

To select the winner the design team must weight each of the strategic questions (once for each axis that the question appears) relative to all the others. The weights, when summed, should total to 1. Therefore, in this example, three weights are required. One weight must be assigned for ease of assembly along the architecture axis, one for ease of assembly long the interface axis, and one for upgradeability along the degree of



modularity axis. Assume that the design team assigned the weights in the following manner:

- Ease of Assembly (Architecture) = .25 =  $W_{EoA\_Arch}$
- Ease of Assembly (Interface) = .30 =  $W_{EoA\_Int}$
- Upgradeability (Degree of Modularity) = .45 =  $W_{Up\_Mod}$

These weights can then be used to write the following equation:

$$DS = (W_{EoA\_Arch})(A) + (W_{EoA\_Int})(1 - I) + (W_{Up\_Mod})(M) \quad (6.1)$$
$$DS = (.25)(A) + (.30)(1 - I) + (.45)(M)$$

This equation was written by taking each weight and multiplying the respective score (interface, architecture, or modularity) that was used to plot the design on the MTS. The method for obtaining the interface and modularity scores has been discussed in previous chapters, but the method for obtaining the architecture score has not. To obtain the architecture score simply give a 1 to any product that falls in the column labeled as high and a zero to any product that falls in the column labeled as low. Using this method the product that is in the high column will score higher than the product in the low column.

It can also be seen in Equation (6.1) that the value of 1 is taken away from the Interface Score. This is done to reflect the fact that the in the scenario presented in Table 6.4, a 0 on the interface axis with respect to ease of assembly is labeled high, and the 1 is labeled as low.

Using the DS equation and the plot values of each design in Table 6.4 the following results were obtained:

- Design 1; DS = .69
- Design 2; DS = .54
- Design 3; DS = .82
- Design 4; DS = .48

- Design 5; DS = .65

Therefore, the order in which the designs should be considered for selection as final design based on strategic objectives, not performance objectives (see Definitions 4.1 and 4.2), is:

1. Design 3
2. Design 1
3. Design 5
4. Design 2
5. Design 4

## 6.4 SUMMARY

This chapter began by illustrating the point that a modular product's strategic strengths and weaknesses will vary depending on the phase of modularity. This illustration included a discussion on how the MTS could be used to express the strategic strengths and weaknesses of competing product designs. It also pointed out that due to product characteristics not addressed by the MTS, it is not possible to create a generalized list of strategic objectives, with corresponding high and low values, for each axis of the MTS at each phase of modularity. Section 6.2 presented a simple example of how to use the MTS to select a final design concept. Section 6.3 presented a method for selecting a final design concept in more complex situations.

Chapter 4 presented a new scheme for classifying modular products according to the type of modularity they use. This scheme also showed how classifications related to one another. Chapter 5 added to the scheme developed in Chapter 4 by providing metrics and rules that can be used to plot products on the MTS. This addition of metrics and rules moved the MTS from a simple classification scheme to a classification method.

Chapter 6 also added to the MTS. It presented how to use the MTS to discuss strategic strengths and weaknesses for the purposes of final concept selection. This final addition to the MTS moved the MTS from a method for classification to a design tool capable of aiding designers during the design process. Chapter 7 will present a complete case study of how this design tool can be used to make design decisions.



## 7.0 VACUUM CLEANER CASE STUDY

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The purpose of this chapter is to show how to use the tools developed in the last three chapters in the context of a design scenario. In doing so, this chapter will also show that these tools are valuable to anyone attempting to design a modular product.

This design process will begin with a functional decomposition, move to concept generation, followed by the plotting of competing designs on the MTS, and concluding with a selection of the final design concept based on strategic objectives. Because this is the first time that decomposition and concept generation have been discussed in the context of a design process using the MTS, these two sections will be followed by subsections that will discuss interesting findings related to each. The design scenario used in this case study is as follows:

Five mechanical engineers have been given the job of redesigning a vacuum cleaner for home use. At its highest functional level the vacuum cleaner must be able to clean common residential flooring. The team has been asked to design a modular vacuum cleaner that will best meet the following strategic objectives at the consumer phase:

- High potential for product add-ons and extensions
- Easy assembly
- High potential for product reconfiguration
- Easy to use
- Differentiable from other vacuum cleaners based on features

The vacuum was to include the following basic features:

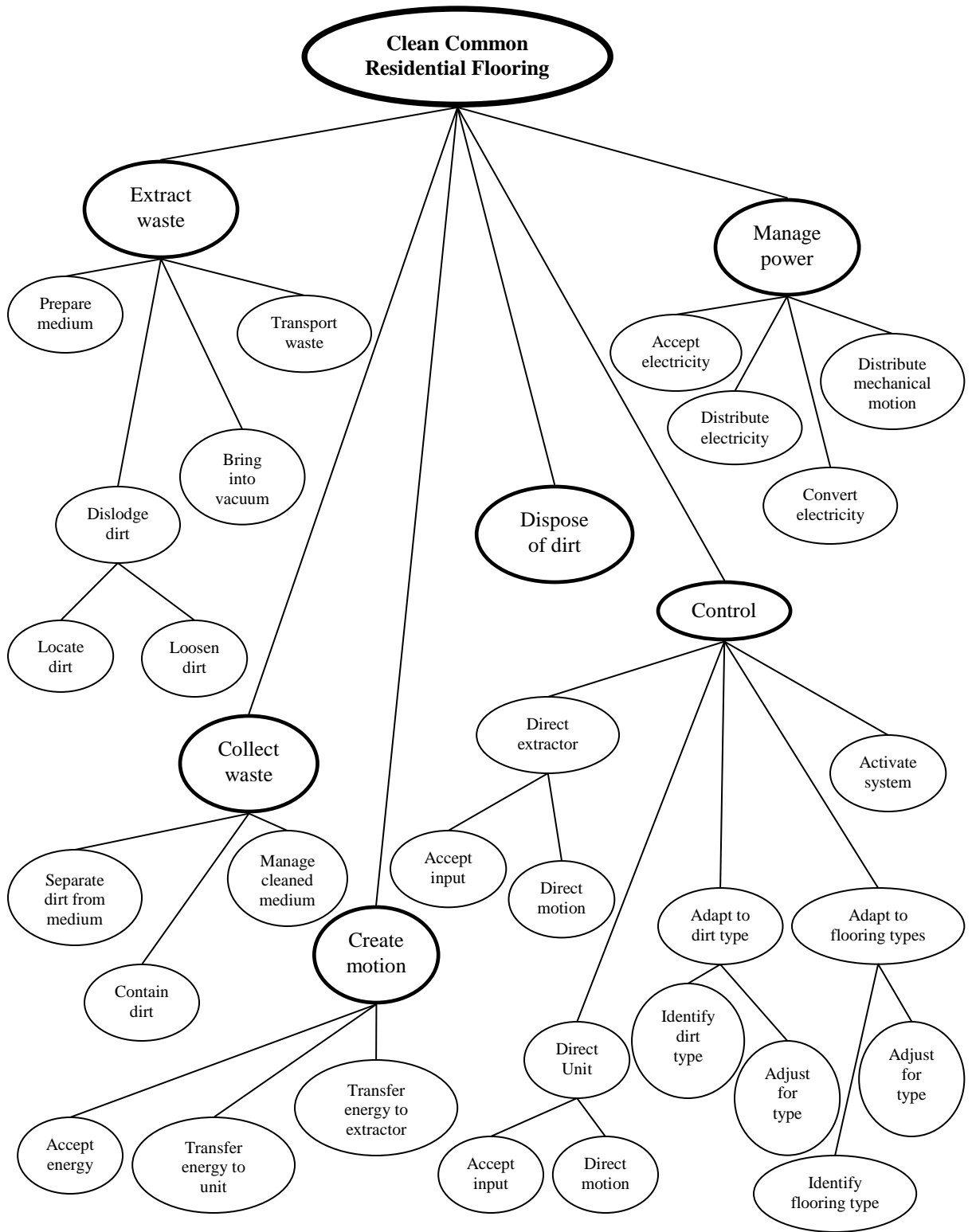
- Use air not water for the purposes of dislodging waste from flooring and transporting waste through the vacuum
- Is pushed/pulled and directed by the user (not self propelled and or directed)
- Uses standard 120 volt household power and interfaces with the home through a standard three prong plug

After presenting the design team with this information the first step they decided to take was to perform a functional decomposition of the vacuum cleaner they were to redesign.

## 7.1 DECOMPOSITION

The decomposition was performed for two reasons. The first reason was to gain a better understanding of the product to be designed by listing out the sub-functions of the vacuum cleaner in a hierarchical manner. The second reason was to establish the number of sub-functions that would later be used to calculate the Modularity Score for the purposes of plotting product concepts along the degree of modularity axis. Because the MTS only requires the number of sub-functions and because the design team was in a rush to get through the design process, sub function interactions such as material flow were not included in this functional decomposition. Sub-functions were simply listed beneath the overall function using a branching diagram.

As was stated earlier, the overall function of the vacuum cleaner was to clean common residential flooring. This function was placed at the top of the branched diagram and sub-functions were listed below it as shown in Figure 7.1.



**Figure 7.1**  
Functional Decomposition  
of Vacuum Cleaner

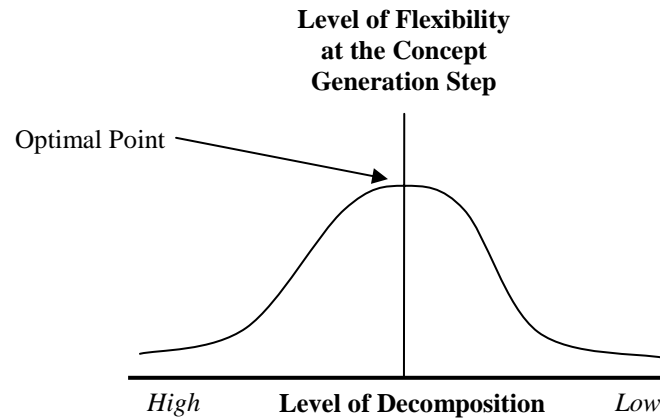
### 7.1.1 Decomposition Findings

During this case study, the design team made an important discovery about using function decompositions as a basis for concept generation. In this case study, the functional decomposition was done first to act as a guide for concept generation. To ensure the consistency in defining a product that the MTS demands in order to provide valid comparisons (as was discussed in previous chapters), the vacuum cleaner was decomposed to ensure that each product design contained the same sub-functions. Because the design team did not want to restrict too tightly the creative process of generating product concepts, a point was reached beyond which functional decomposition was counterproductive (Figure 7.2).

If the design team did not move beyond high level decomposition, product concepts would not be similar enough, as to what the sub-functions they contained, to allow any sort of comparison to be made using the MTS. If the design team went to low level decomposition, product concepts would be similar enough to compare on the MTS, but the design team would have little flexibility when it came to concept generation. The team realized that as long as all the product sub-functions were represented in the functional decomposition that were necessary to break the product into modules, adequate decomposition had been performed. In other words, as long the product concepts did not subdivide any of the design leaves shown in Figure 7.1 there was no need to decompose the product any further. However, realizing that there was no way to ensure that product concepts would not subdivide any of the design leaves in Figure 7.1 until concept generation had been completed, the team decomposed the product to what they felt was adequate, and then moved on to concept generation knowing that the



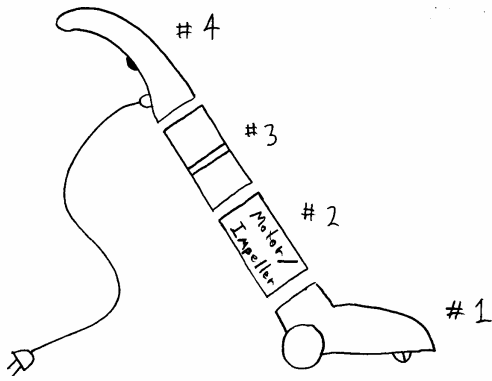
functional decomposition might need to be amended. It was also discovered that defining the functions that the vacuum cleaner will perform will help the design team know when they have adequately decomposed the product.



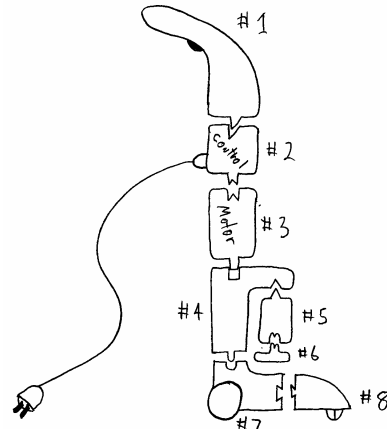
**Figure 7.2**  
Optimal Decomposition

## 7.2 CONCEPT GENERATION

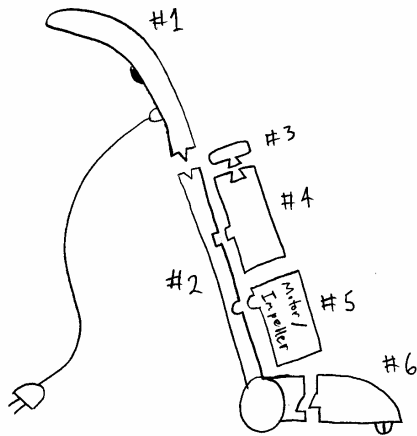
Concept generation was done first as a group. Different ideas were discussed and then the team split up to generate their own concepts. The team then held another meeting to bring their creative knowledge together and to select the ideas that they wanted to pursue further. There were five concept vacuum cleaners that the team decided to pursue. Sketches of these five concepts can be seen in Figure 7.3. See Appendix A for detailed information on each design.



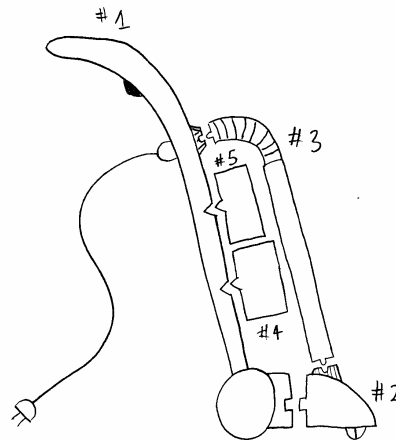
**7.3 a**  
**The Stick**



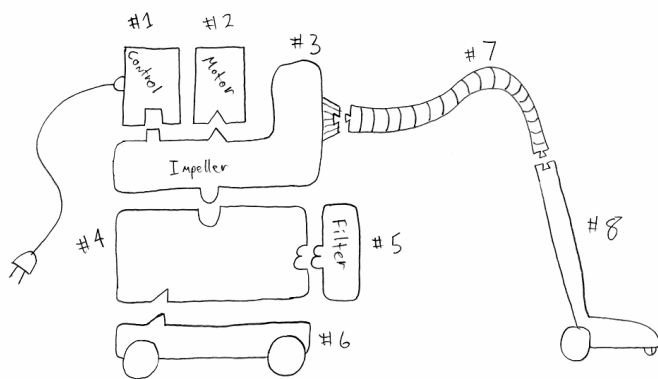
**7.3 b**  
**The Tower**



**7.3 c**  
**The Pistol**



**7.3 d**  
**The Wand**



**7.3 e**  
**The Dragger**

**Figure 7.3 (a-e)**  
**Vacuum Cleaner Concepts**

## 7.2.1 Concept Generation Findings

During concept generation some interesting discoveries were made with regard to the designing within the MTS. The design team made the following observations while generating modular vacuum cleaner concepts.

Type I modularity with a low Modularity Score is the easiest region to design in. Designing in this region requires little more than chunking a few sub-functions into modules and providing a unique interface for each. Type IV modularity with a high Modularity Score is the most difficult region to design in for reasons discussed below.

Changing a concept that is Type I modular into a Type II modular product (moving a product from base to baseless architecture) regardless of the Modularity Score can be easily accomplished by putting redundant functions in each of the modules. In other words, by putting the functions of the base unit into each module a baseless architecture can be achieved. This can be seen in Appendix A. Each of the concepts shown in Appendix A has a list of what sub-functions are included in each of its modules. At the end of that list is a number that represents the number of total listings for a given concept. The reason that some concepts have a higher number of listings than other concepts is due to the number of redundant functions that those concepts contain. The three baseless concepts have a higher number of function listings than the concepts that use a base architecture.

Changing a concept that is Type I modular into a Type III modular product (moving a product from unique interfaces to standard interfaces) regardless of the Modularity Score requires one of two things. It is assumed that the design team is following existing design for manufacturing (DFM) principles that dictate that all

configurations will yield a functional product. This can be accomplished by designing a product to be self configuring. This is easily accomplished in electrical/computer systems but more difficult in mechanical systems. This can also be accomplished by designing redundant interface capacity into every interface. In other words, provide that every interface has the capacity to handle all types of information, material, or energy flow regardless of whether or not the module that is plugged into it will use the entire capacity.

Changing a concept that is Type I modular into a Type IV modular product (moving along both the architecture and interface axes of the MTS) can be achieved by simultaneously doing the things discussed in the two paragraphs above. Because this requires two lines of simultaneous thinking, this is the most difficult region to design in. It was also observed that Type I modularity (with a Modularity Score of 0) offers the least amount of product configuration flexibility, while Type IV modularity (with a Modularity Score of 1) offers the greatest amount of product configuration flexibility.

### **7.3 PLOTTING THE MTS**

This section will show the plotting of the vacuum concepts on the MTS. It will start by first calculating a Modularity Score for each concept, followed by an Interface Score, and conclude with a discussion about how the base/baseless decision was made. Following these two calculations and one discussion, this section will conclude by showing the location of each of the five concepts on the MTS.

Table 7.1 contains the data used to calculate the Modularity Scores and the calculated scores.

**Table 7.1 Modularity Score Calculations**

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

Table 7.2 contains the data used to calculate the Interface Score and the calculated scores.

**Table 7.2 Interface Score Calculations**

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

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, there exists no single 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:

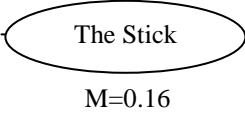
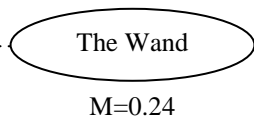
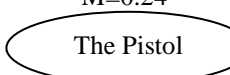
1. Modules 1 and 2 join to form the base unit that exclusively distributes the electrical power that almost all other modules are dependent upon to carry out their primary functions.
2. Modules 1 and 2 also exclusively manage and distribute the extraction medium that the vacuum system needs to function.

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 plotted on the MTS (Table 7.3).

**Table 7.3 MTS with Vacuum Plots**

Degree of Modularity		Architecture Type	
		Base	Baseless
Interface Type	Standard	0	
	Unique	.5	
		1	

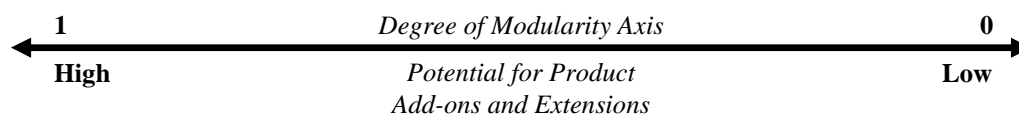
## 7.4 CONCEPT SELECTION

The beginning of this chapter lists the four strategic objectives that the vacuum cleaner concepts were to achieve. The team immediately realized that the last of these strategic objectives could not be addressed by the MTS and decided that it would have to be addressed by some other means. As such, they did not discuss it any further in the context of the MTS. However, the first three strategic objectives were broken down, re-written as strategic questions, and listed below:

- Potential for product add-ons and extensions?
- Ease of assembly?
- Potential for product reconfiguration?
- Ease of use?

Following the steps outlined in Section 6.2, the team selected a final concept in the following way.

The team first looked at the strategic question of potential for product add-ons and extensions. It was decided that the degree of modularity axis and the interface axis both provided insight into this strategic question. Low sub function density per module means that a individual sub-functions can be upgraded with more independence from other sub-functions. In other words, a product with low sub function density has a greater potential for product add-ons and extensions than does a product with high sun function density. Therefore, the “1” end of the degree of modularity axis is labeled as high and the “0” end is labeled as low with respect to the potential of upgrade (Figure 7.4).

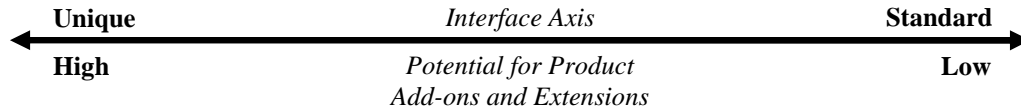


**Figure 7.4**  
Potential for Product Add-ons and  
Extensions on the Degree of  
Modularity Axis

It is difficult to design a mechanical system, such as a vacuum cleaner, to use standard interfaces and be functional regardless of module location and orientation. It is much easier to use unique interfaces that assure a certain location for each module. In other words, in the case of the vacuum cleaner, it would be harder to design product add-ons and upgrades for a concept with standard interfaces. Therefore, the standard end of

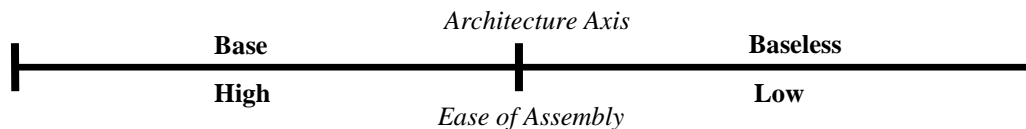


the interfaces axis is labeled low with respect to potential for product add-ons and extensions and the unique end of the axis was labeled high (Figure 7.5).



**Figure 7.5**  
Potential for Product Add-ons and Extensions on the Interface Axis

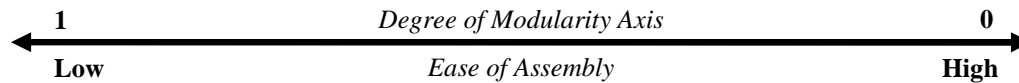
Next, the team looked at the strategic question of ease of assembly. It was decided that the degree of modularity axis and the architecture axis each provided insight into this strategic question. It is always easiest to assemble something when you have a foundation to build from. In other words, a product that uses a base architecture is easier to assemble than one that does not. Therefore, the base end of the architecture axis was labeled as high and the baseless end was labeled as low with respect to ease of assembly (Figure 7.6).



**Figure 7.6**  
Ease of Assembly and Reconfiguration on the Architecture Axis

When assembling a product, it is also true that the fewer the number of pieces the easier it is to assemble. A product with a low sub function density will have more modules than a product with a high sub function density. Therefore, the “1” end of the

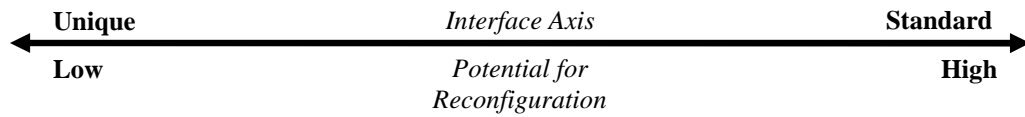
degree of modularity axis was labeled low and the “0” end was labeled as high with respect to the ease of assembly (Figure 7.7).



**Figure 7.7**  
Ease of Assembly on the Degree of  
Modularity Axis

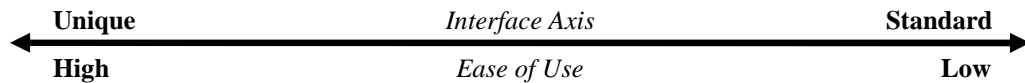
Although the interface axis would usually provide some insight into the question of ease of assembly, it does not provide any insight in the case of the vacuum cleaner. Vacuum cleaner concepts that use standard interfaces were designed to function regardless of module location and orientation. This means that they are easy to assemble because any configuration will yield a functioning system. On the flip side, all the vacuum cleaner concepts that use unique interfaces are easy to assemble because each module fits into only one interface.

Next, the team looked at the strategic question of potential for reconfiguration. It was decided that interface axis was the only axis to provided insight into this strategic question. A product that uses standard interfaces and was designed to function regardless of module location or orientation (such as all the standard interface concepts under consideration) will have a higher potential for reconfiguration than a product that uses unique interfaces. Unique interfaces, by their very nature, stifle reconfiguration. Therefore, the unique end of the interface axis was labeled as low with regard to the potential for reconfiguration and the standard end was labeled as high (Figure 7.8).



**Figure 7.8**  
Potential for Reconfiguration on the  
Interface Axis

Finally the team considered the strategic question of ease of use. The team agreed that the only thing that might be confusing to a consumer was assembling a standard interface vacuum to get the functionality they wanted. Therefore, the unique end of the interface axis was labeled as high with regard to ease of use and the standard end was labeled as low (Figure 7.9).



**Figure 7.9**  
Ease of Use on the  
Interface Axis

Having labeled all the highs and lows of each strategic question with regard to those axes that provided insight, the team was left with a list of strategic questions along their respective axes. That list and the weighting of importance that the design team gave to each can be seen below:

- Potential for product add-ons and extensions
  - Degree of Modularity Axis – .20
  - Interface Axis – .20
- Ease of assembly
  - Architecture Axis – .15
  - Degree of Modularity Axis – .15
- Potential for product reconfiguration
  - Interface Axis – .20

- Ease of use
  - Interface Axis – .10

Table 7.3 contains the scores of all five concepts under consideration for use in calculating which vacuum concept is best aligned with the strategic objectives.

**Table 7.3 Plot Values for all five Concepts**

Concept	Interface Score	Modularity Score	Architecture Score
The Stick	0	0.16	1
The Tower	1	0.32	1
The Dragger	1	0.32	1
The Pistol	1	0.24	0
The Wand	0.5	0.24	0

The equation used to calculate the design score of each of the five vacuum concepts was:

$$DS = (.15)(1 - M) + (.20)(M) + (.15)(A) + (.20)(I) + (.20)(1 - I) + (.10)(I)$$

Table 7.4 contains the design score for each of the five vacuum concepts as well as their relative ranking.

**Table 7.4 Design Scores and Relative Ranking**

Concept	Design Score	Ranking
The Stick	.51	2
The Tower	.62	1
The Dragger	.62	1
The Pistol	.46	3
The Wand	.41	4

Therefore, according to the weights the design team chose, there was a tie for the vacuum concept that was best aligned with the strategic objectives. The design team should choose either The Tower concept or The Dragger concept.

## 7.5 SUMMARY

This chapter has shown the usefulness of the design tools developed in this document. It has further demonstrated how these tools can be used to guide designers to a modular product concept that is best aligned with their strategic objectives. In completing this case study there are few interesting findings to discuss. Some of the findings were discussed in the Sections 7.1.1 and 7.2.1 of this document. One more will be discussed here.

It is interesting to note that the MTS did not distinguish between two of the vacuum concepts. According to the MTS, The Tower and The Dragger are identical products. However, after looking at the sketches of each in Appendix A, it is easy to see that these are in fact two very different designs. This is simply more proof that the MTS does not entirely characterize a product and can therefore not be the only means for final concept selection. Still, the MTS can point designers in the right direction so that their decision process is made simpler.

It is also important to mention that this case study focused only on strategic objectives at the consumer phase of modularity. This exercise should be repeated two more times, once for the manufacturing phase and once for the design phase, to gain even more insight into what concept should be selected as the final design.



## 8.0 THESIS CONCLUSIONS

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The conclusions to this document are presented in this chapter. The chapter begins with an overall summary of the research presented in this document followed by conclusions that can be drawn from this research. The chapter will conclude with suggestions for future work that builds upon the research in this document.

### 8.1 THESIS SUMMARY

The research presented in this document can be summarized as follows:

- An introduction that presented modularity as a way for achieving specific product objectives.
- A literature review that presented past research in the area of product design methods which provided the foundation for the modularity tools developed later in the document.
- A research approach that defined the scope of the research and delimitations, as well as laid out a method whereby the success of the thesis could be measured.
- Definitions and classifications for modularity types were consolidated to create the MTS. The classifications of module types and the modular design process were also discussed.
- Metrics and heuristics were developed for the purpose of plotting the position of a modular product on the MTS.
- The MTS is presented as a tool for comparing and screening competing modular product design concepts.
- A case study was given to illustrate how to use the MTS in a design setting and to validate its usefulness.

Chapter 3 presented the criteria that would be used to judge the success of this document. This thesis was to focus on the creation of Design for Modularity (DFMod) principles that:

- Focus on the selection of competing designs
- Are complementary to existing design processes
- Available and applicable throughout the entire design process
- Applicable to consumer phase modular products
- Consistent with terms and processes familiar to design engineers
- Based on strategic objectives
- Both useful and repeatable

This research also targeted the creation of modularity metrics that are:

- Related to both design and strategic objectives
- Simple, intuitive and consistent with definitions presented in this thesis
- Applicable to most consumer phase modular products
- Useful in making design and strategic decisions
- Measures modularity consistently

Each of the points listed above were achieved in the creation of metrics and heuristics, the consolidation and writing of definitions and classification schemes, and the creation of the design tools developed in this document. The next section will focus on conclusions that can be drawn from the research contained in this document.

## **8.2 THESIS CONCLUSIONS**

The schemes, metrics, and tools developed in this thesis are both valuable and useful to the designers of modular products. They provide designers with a systematic and repeatable method for discussing the relative strategic strengths and weaknesses of modular 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 heuristics included in this document for the purposes of plotting product concepts on the MTS are both functional and useful.
3. The MTS can help designers to select a final product concept based on strategic objectives.
4. The MTS does not fully characterize modular products and therefore should not be used as the only screening and selection criteria.
5. Additional tools are needed to manage the balance of strategic, performance, and other objectives for the purposes of screening and selecting a final concept.

It is the belief of the author of this document that the ideas and principles presented in this document have provided valuable tools that can be used by design teams today and that will provide a better foundation for the research of tomorrow. The next section will list areas of research that the author suggests will add to this work.

### **8.3 RECOMMENDATIONS FOR FUTURE WORK**

Researchers can add to the work contained in this document by focusing their work in the following areas:

1. Explore the link between coupled/decoupled designs and products that use base architectures.

2. Study modular products and develop generalized categories for all modular products (i.e., mechanical, electronic, etc.).
3. Develop generalized strategic strengths for each of the octants of the MTS for each generalized category of modular product at each phase of modularity.
4. Study the possibility of mapping the MTS for the optimal design locations for each of the generalized types of modular products.
5. Develop a highly repeatable and unambiguous method for identifying a base unit for the purposes of identifying base and baseless architectures.
6. Explore other uses of the MTS such as using it before concept generation as a method for focusing concept generation.
7. Perform design experiments with carefully chosen design teams that use the tools presented in this document and measure their success.
8. Explore the usefulness of the tools in this document at the manufacturing, and design phases of modularity.
9. Explore the usefulness of the tools in this document on large scale products such as airplanes, rocket boosters, and automobiles
10. Further develop the definition of the term “Base Unit.”
11. Explore the possibility of varying a modular products classification as base or baseless depending on different levels of architecture (i.e. structural level, control level, material level, power level, etc.)

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# APPENDIX A

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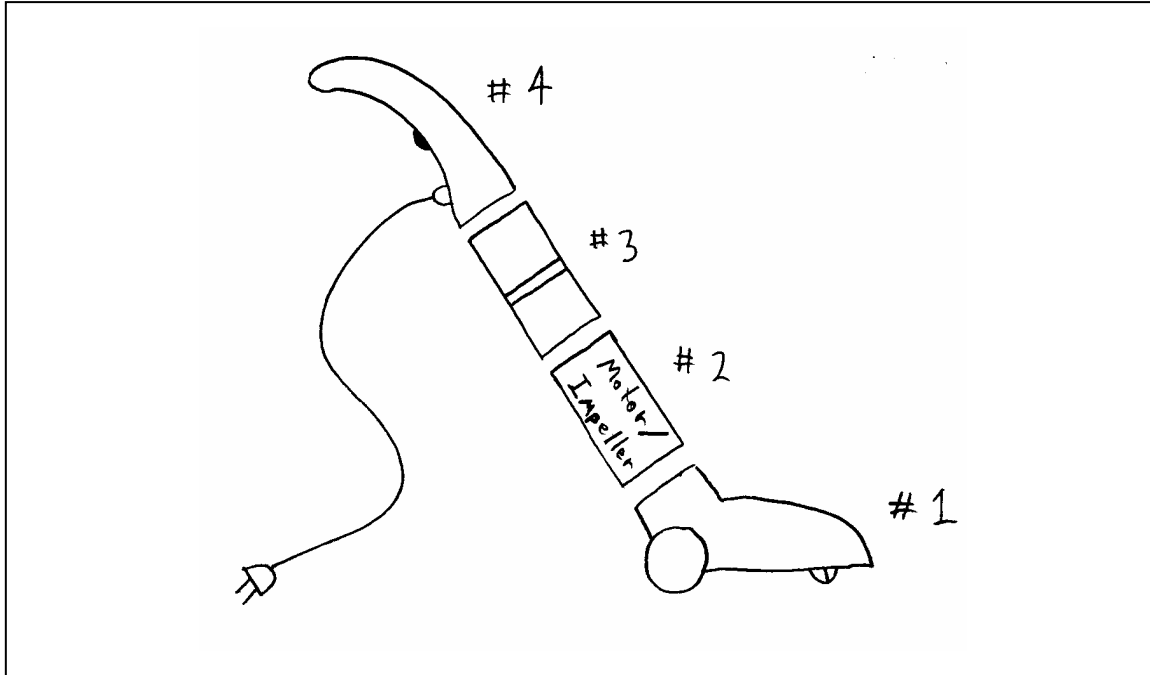
This appendix contains sketches and descriptions of the five vacuum cleaner concepts that are discussed in the case study of Chapter 7. Below is a list of the design leaves found in Figure 7.1.

## Design Leaves:

- Prepare extraction medium
- Locate dirt
- Loosen Dirt
- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Separate dirt from medium
- Contain dirt
- Manage cleaned medium
- Dispose of dirt
- Accept motion generating energy
- Transfer motion energy to unit
- Transfer motion energy to extractor
- Accept directional input for extractor motion
- Direct extractor motion
- Accept directional input for the unit motion
- Direct unit motion
- Identify dirt type
- Adjust extraction method for dirt type
- Identify flooring type
- Adjust for flooring type
- Activate system
- Accept electricity
- Distribute electricity
- Convert electricity
- Distribute mechanical motion

## Design: The Stick

### Sketch:



**Description:** This vacuum is baseless and uses standard, reversible interfaces. Standard and reversible means that all the interfaces are the same, and there is no distinction between a male and a female side of an interface (a module can be flipped 180 degrees and still attach to the same interface). Modules can be attached to one another at either end. Because of this design, the vacuum can be assembled in many different ways. Each configuration will yield different functionality. For example, module 4 can plug into module 1 creating a non-sucking device that uses the beater bar as a powered hand broom. Module 3 is the filter/dirt containment module. This module was made reversible by placing the filter in the middle of the containment space and placing a one way valve at each end of the container. There is a motor in module 1 to convert the electrical power into mechanical motion used to run the beater bar. There is a motor in module 2 to convert the electrical power into mechanical motion used to prepare the medium. See below for a list of what sub-functions are contained in which module.

### Sub-functions by Module:

*Functions given to the user:*

- Locate dirt
- Dispose of dirt
- Identify dirt type
- Adjust extraction method for dirt type
- Identify flooring type
- Adjust for flooring type

*Module 1*

- Loosen dirt



- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Direct extractor motion
- Direct unit motion
- Distribute electricity
- Convert electricity
- Distribute mechanical motion

*Module 2*

- Prepare extraction medium
- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Distribute electricity
- Convert electricity
- Distribute mechanical motion
- Direct extractor motion
- Transfer motion energy to extractor

*Module 3*

- Separate dirt from medium
- Contain dirt
- Manage cleaned medium
- Distribute electricity
- Direct extractor motion
- Transfer motion energy to extractor

*Module 4*

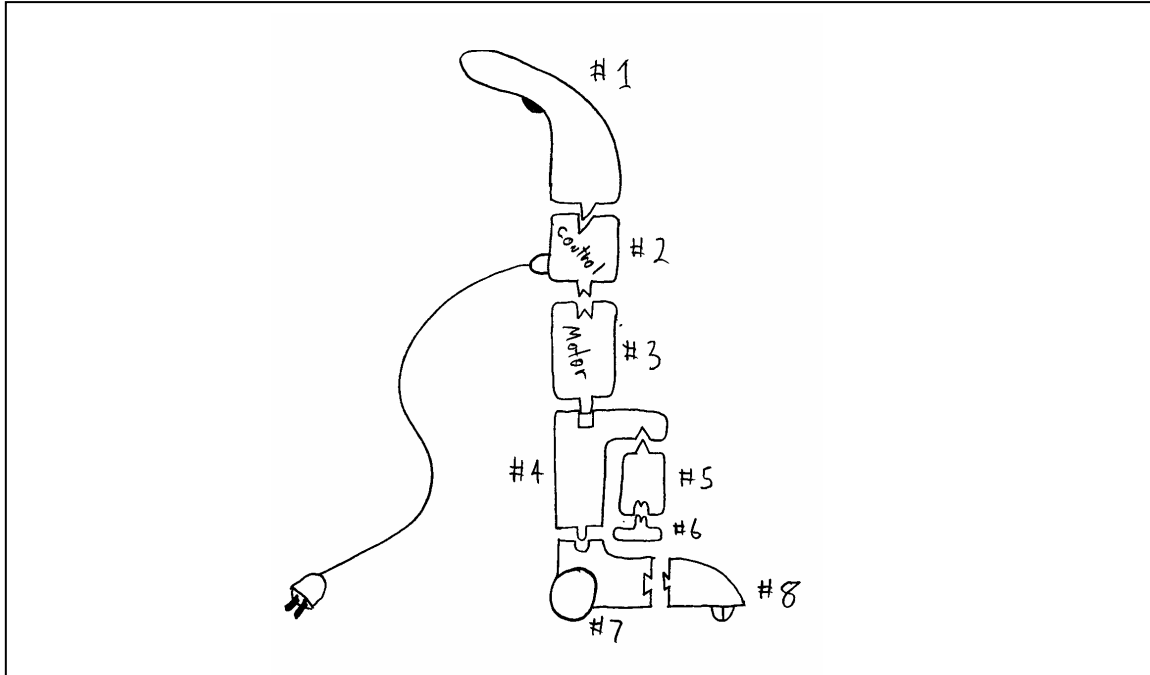
- Manage cleaned medium
- Accept motion generating energy
- Transfer motion energy to unit
- Transfer motion energy to extractor
- Accept directional input for extractor motion
- Direct extractor motion
- Accept directional input for unit motion
- Direct unit motion
- Activate system
- Accept electricity
- Distribute electricity

**Total sub function listings:**

39

## Design: The Tower

### Sketch:



**Description:** This vacuum uses a baseless architecture and unique interfaces. This design is similar to “The Dragger” but with one major difference. The extractor and the unit are not separate and cannot move with any independence. In addition, this design uses only one motor to convert electricity into mechanical motion. The motion need to turn the beater bar in module 8 is transferred through the adjoining modules. See below for a list of what sub-functions are contained in which module.

### Sub-functions by Module:

*Functions given to the user:*

- Locate dirt
- Dispose of dirt
- Identify dirt type
- Adjust extraction method for dirt type
- Identify flooring type
- Adjust for flooring type

*Module 1*

- Accept motion generating energy
- Transfer motion energy to unit
- Transfer motion energy to extractor
- Accept directional input for extractor motion
- Direct extractor motion
- Accept directional input for unit motion
- Direct unit motion

- Activate system
- Distribute electricity

*Module 2*

- Transfer motion energy to extractor
- Distribute electricity
- Accept electricity
- Activate system
- Direct extractor motion

*Module 3*

- Transfer motion energy to extractor
- Distribute electricity
- Convert electricity
- Distribute mechanical motion
- Direct extractor motion

*Module 4*

- Prepare dirt extraction medium
- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Transfer motion energy to extractor
- Distribute electricity
- Distribute mechanical motion
- Direct extractor motion

*Module 5*

- Contain dirt

*Module 6*

- Separate dirt from medium
- Manage clean medium

*Module 7*

- Transport waste (medium/dirt mixture)
- Transfer motion energy to extractor
- Direct extractor motion
- Direct unit motion
- Distribute electricity
- Distribute mechanical motion

*Module 8*

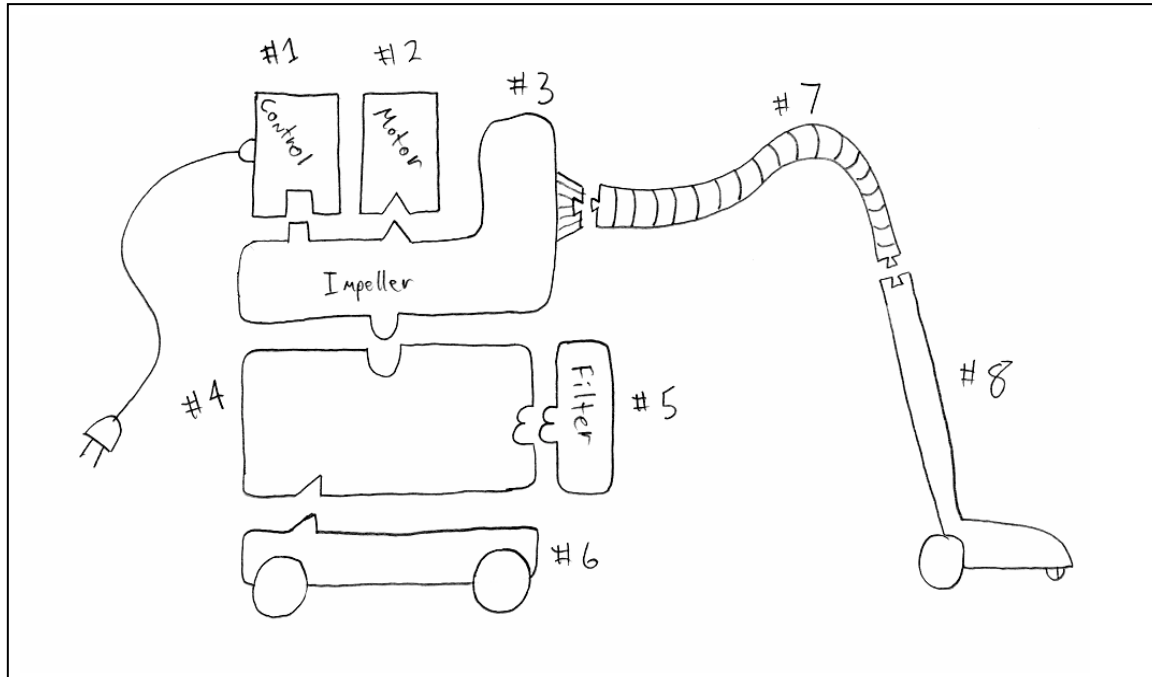
- Loosen dirt
- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Distribute mechanical motion
- Distribute electricity

**Total sub function listings:**

46

**Design:** The Dragger

**Sketch:**



**Description:** This vacuum uses a baseless architecture and unique interfaces. This design is similar to “The Tower” but with one major difference. The unit (made up of modules 1 -7) is separate from the extractor (module 8). They are free to move with some independence. See below for a list of what sub-functions are contained in which module.

**Sub-functions by Module:**

*Functions given to the user:*

- Locate dirt
- Dispose of dirt
- Identify dirt type
- Adjust extraction method for dirt type
- Identify flooring type
- Adjust for flooring type

*Module 1*

- Activate system
- Accept electricity
- Distribute electricity

*Module 2*

- Convert electricity
- Distribute electricity
- Distribute mechanical motion

*Module 3*

- Prepare extraction medium
- Bring dirt into vacuum
- Distribute electricity
- Distribute mechanical motion
- Transport waste (medium/dirt mixture)

*Module 4*

- Contain dirt
- Distribute electricity

*Module 5*

- Separate dirt from medium
- Manage cleaned medium

*Module 6*

- Accept directional input for unit motion
- Direct unit motion
- Distribute electricity
- Accept motion generating energy
- Transfer motion energy to unit

*Module 7*

- Transport waste (medium/dirt mixture)
- Transfer motion energy to unit
- Direct unit motion
- Distribute electricity

*Module 8*

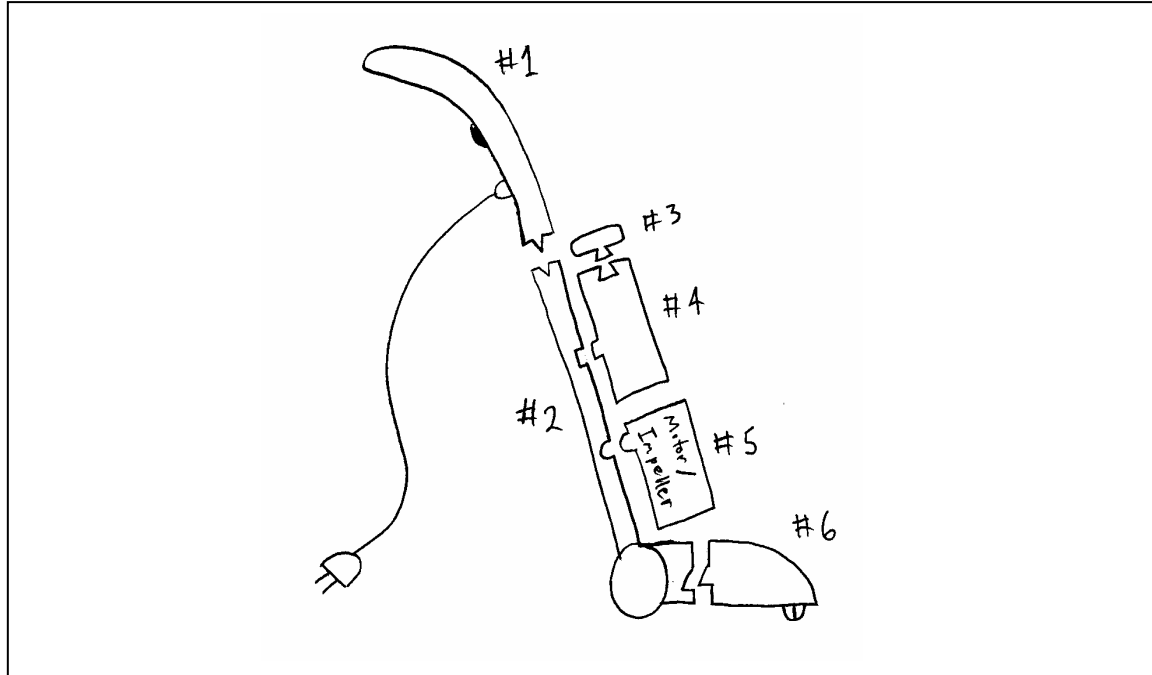
- Loosen dirt
- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Accept motion generating energy
- Transfer motion energy to extractor
- Accept directional input for extractor motion
- Direct extractor motion
- Accept directional input for unit motion
- Direct unit motion
- Distribute electricity
- Convert electricity
- Distribute mechanical motion
- Transfer motion energy to unit

**Total sub function listings:**

43

**Design:** The Pistol

**Sketch:**



**Description:** This vacuum uses a base architecture and unique interfaces. Modules 1 and 2 are joined to form the base unit (they are the minimum configuration). All other modules attach directly to the base unit except for module 3, the filter, which attaches to module 4, the dirt container. This design uses two motors to convert electricity into mechanical motion. One is located to in module 5 and the other is located in module 6. See below for a list of what sub-functions are contained in which module.

**Sub-functions by Module:**

*Functions given to the user:*

- Locate dirt
- Dispose of dirt
- Identify dirt type
- Adjust extraction method for dirt type
- Identify flooring type
- Adjust for flooring type

*Module 1*

- Accept motion generating energy
- Transfer motion energy to unit
- Transfer motion energy to extractor
- Accept directional input for the extractor motion
- Direct extractor motion
- Accept directional input for the unit
- Direct unit motion

- Activate system
- Accept electricity
- Distribute electricity

*Module 2*

- Transport waste (medium/dirt mixture)
- Transport motion energy to extractor
- Direct extractor motion
- Direct unit motion
- Distribute electricity

*Module 3*

- Separate dirt from medium
- Manage cleaned medium

*Module 4*

- Contain dirt

*Module 5*

- Prepare extraction medium
- Bring dirt into vacuum
- Convert electricity
- Distribute mechanical motion

*Module 6*

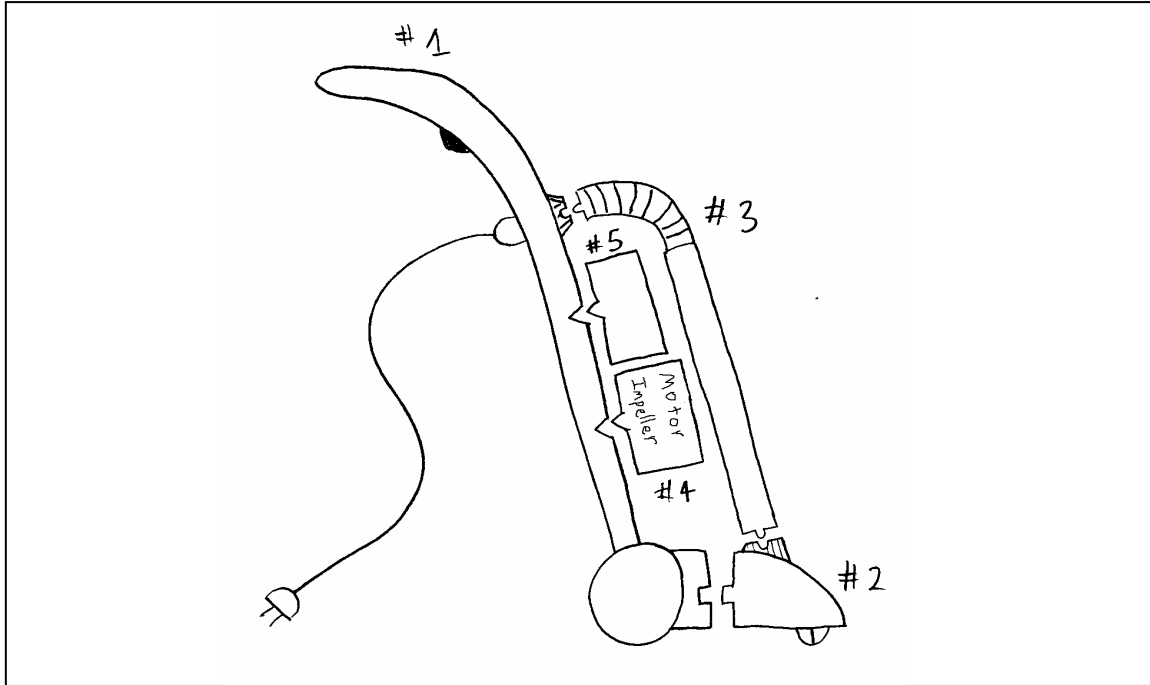
- Loosen dirt
- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Convert electricity
- Distribute mechanical motion

**Total sub function listings:**

33

## Design: The Wand

### Sketch:



**Description:** This vacuum uses a base unit and a mixture of unique and standard interfaces. Modules 4 and 5 attach to the base unit, module 1, with standard interfaces. Their positions are interchangeable. Module 2 attaches to the base unit through two interfaces. One of the interfaces supplies module 2 with power and information, and the other interface supplies it with material (vacuum air). This design uses two motors to convert electricity into mechanical motion. One is located in module 2 and one is located in either module 4. See below for a list of what sub-functions are contained in which module.

### Sub-functions by Module:

*Functions given to the user:*

- Locate dirt
- Dispose of dirt
- Identify dirt type
- Adjust extraction method for dirt type
- Identify flooring type
- Adjust for flooring type

*Module 1*

- Accept motion generating energy
- Transfer motion energy to unit
- Transfer motion energy to extractor
- Transport waste (medium/dirt mixture)
- Accept directional input for extractor motion



- Direct extractor motion
- Accept directional input for unit motion
- Direct unit motion
- Activate system
- Accept electricity
- Distribute electricity

*Module 2*

- Loosen dirt
- Bring dirt into vacuum
- Transport waste (medium/dirt mixture)
- Convert electricity
- Distribute mechanical motion

*Module 3*

- Transport waste (medium/dirt mixture)

*Module 4*

- Prepare extraction medium
- Bring dirt into vacuum
- Convert electricity
- Distribute mechanical motion

*Module 5*

- Separate dirt from medium
- Contain dirt
- Manage cleaned medium

**Total sub function listings:**

30

