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TOWARDS A THEORY OF MODULAR DESIGN

by

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DISSERTATION

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TOWARDS A THEORY OF MODULAR DESIGN

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DEDICATION

To God, my family and my friends for their love and support.

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TOWARDS A THEORY OF MODULAR DESIGN

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Modular design is a popular topic in industry today, though there is no systematic method in place that guarantees a modular design. This work presents a theory of modular design which represents a new tack on design methods. While it uses functional decomposition to describe the problem, it shifts the search for solutions to a modular level rather than looking for a solution to every individual sub-function. To accomplish this theoretical shift, a functional base set is developed to make function structure generation repeatable and to provide a consistent level of decomposition. The functional base set consists of a standard set of functions and flows, clearly categorized and defined. Three heuristic methods are introduced to define modules from such a function structure. The heuristics are verified through a set of hand held, mechanical and electromechanical consumer devices. A quantitative framework is developed to assess the customer need importance of identified modules and to provide a tool for grouping similar devices into device families.

Utilizing these components, an overall theory of modular design is stated. It is comprised of two parts: a modular design methodology and a development team formation methodology. Three case studies are presented which show the theory's application to original and reverse engineering design problems as well as the team formation problem. One case study, in particular, shows the utility of the modular design methodology to devices of larger scale than the verification set.

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CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

As children, especially those of us who grew up to be engineers, we often played with toys that allowed us to build physical incarnations of our wild imaginations. A popular toy of this type was the Tinkertoy™ collection. Think back to the sticks of varying lengths, the wheels and connectors and the plastic sliders, shown in Figs. 1.1 - 1.2. With these limited types of building blocks, we built thousands (or more) of creations. All the while we were identifying the type of building block necessary to serve the immediate functions of connecting two sticks, forming a right angle or rotating a wheel while working toward the overall goal of creating a car, building a sky scraper or setting up a windmill. An example of a windmill constructed from these basic sets is shown in Fig. 1.3. This very same process is indicative of a modular design, where we build up devices from a set of distinct components or modules. But how do we define the modules in a world unbounded by Tinkertoy™ shapes? This dissertation establishes a method that will do that very thing.

1.1.1 Theoretical Motivations

Modular devices may be defined as machines, assemblies or components that accomplish an overall function through combination of distinct building blocks or modules (Pahl and Beitz, 1988). Modules are defined as physical structures that have a one-to-one correspondence with functional structures (Ulrich and Tung, 1991). However, modularity in mechanical design is often an afterthought. Once a device is designed and developed, components of the device are observed to have other potential uses. This can lead to faster development and reduced costs in future device designs, but if modularity is identified and exploited in the initial conceptual or reverse engineering[1] effort, the immediate device design reaps benefits in reduced development time and costs (Congress, 1992). Increased batch sizes of building blocks lead to lower costs (Pahl and Beitz, 1988). Also, modules which are easily identified with a particular function are more easily combined, offering a reduction in development time.

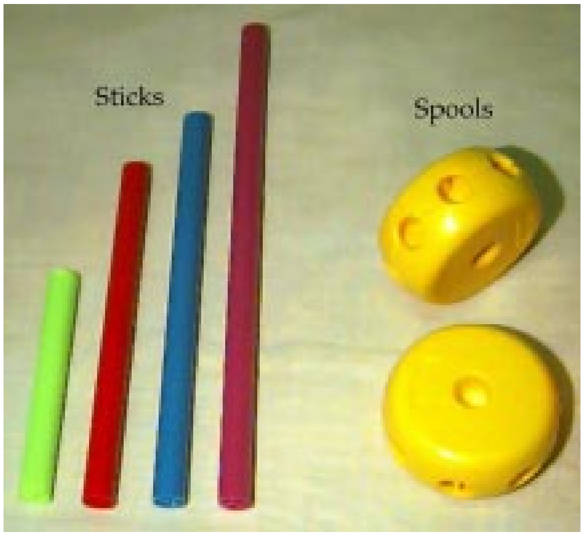

Figure 1.1 Connecting sticks of various sizes (left) and connection spools (right) are modules found in Tinkertoy™ sets.

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[1] Reverse engineering initiates the redesign process, wherein a device is predicted, observed, disassembled, analyzed, tested, "experienced," and documented in terms of its functionality, form, physical principles, manufacturability and assemblability (Otto and Wood, 1996).

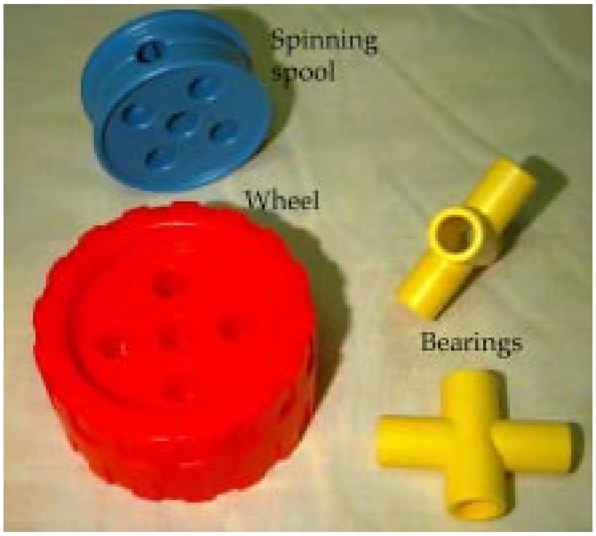


Figure 1.2 Wheels, spinning spools and bearings (clockwise from lower left corner) are additional modules in Tinkertoy™ sets.

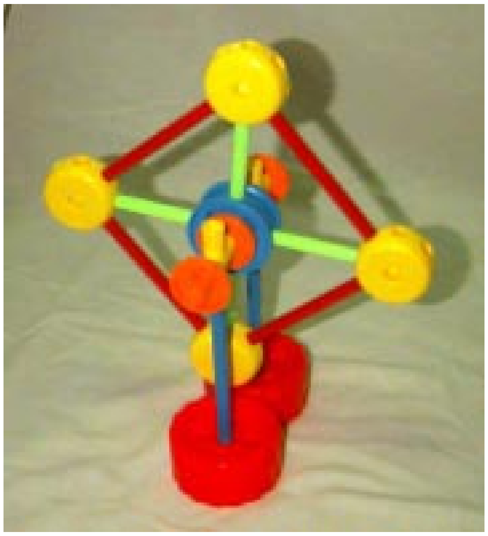


Figure 1.3 A windmill constructed of the basic modules found in the Tinkertoy™ set.

Combining components has been addressed in recent work addressing automated design techniques (Bradley and Agogino, 1994; Ward, 1989; Ward and Seering, 1993; Schmidt and Cagan, 1997a & b; Vadde et al., 1992). Ward developed a mechanical design compiler that transformed a high level design description into a more concrete lower level. The name 'compiler' is accurate because the program parses a device language into a computable form. Others have automated the catalog design problem, which is the process of selecting a fully specified element to perform some function in a larger design or assembly (Bradley and Agogino, 1994). Once the element or component needed is specified, a catalog design program evaluates the components in its database and presents a set that meets the specifications. In essence, these components are modules, or building blocks. In either case, the output of a design compiler or a catalog design program is a element or set of elements (or components) that satisfy some function. If a methodology exists which identifies modules early in the conceptual or reverse engineering design effort, then design compilers can be used earlier in the process. This is the direction of the work by Schmidt and Cagan (1995), who use a vocabulary of grammars to map an overall device function to actual components. Extending this further, once modules and their interface parameters are identified, then compilers could present a list of candidates to fulfill the module's function.

Another driving factor behind modular design theories is device design for the life cycle. This increases the ease with which components can be replaced after a certain amount of wear and also promotes recycling of spent components. For recycling, the grouping of components with similar recycling requirements makes the device easier and, thus, cheaper to recycle. Modules are formed based on material, service requirements and post-life intent (Newcomb et al., 1996;

Rosen, 1996; Marks et al., 1993). Research activities with auto makers explore this type of modular device development, spurred by recent device take-back legislation passed in Europe (Newcomb et al., 1996).

Modular design also realizes savings in manufacturing time. For modular devices, as the design of each module is finalized, it can be handed off for manufacture. Tooling and manufacture of module A can begin while the design of module B proceeds. This iterative overlapping (Krishnan et al., 1995) realizes lead time reduction in device introduction, a definite advantage in today's competitive markets. Krishnan et al. (1996) also develop a model of product development costs for devices based on common platforms. The common platform families are, in essence, modular devices. Gupta and Krishnan (1997) establish the optimal component and vendor selection problem as an integer program and present a mathematically based heuristic method that identifies near optimal solutions. Their work deals with combining existing components in well defined fields as opposed to determining what defines a module.

Returning again to the Tinkertoy™ analogy, recall how easy it was to make changes to our creation on the fly. For each type of Tinkertoy™, we knew its function and what interface it required to connect with other Tinkertoys™. These two pieces of information, function and interface requirements, defined the Tinkertoy™ module. For example, Fig. 1.4 shows a Tinkertoy™ connector with two sticks. Here, the module's function is its name - *connector*. The interface requirements are shown in Fig. 1.5. The *connector* connects two or more sticks together and requires a physical interface of holes to accomplish this function. With the module defined in this manner, it is possible to reconfigure the original creation to serve a new function. This is another benefit of modular design, ease of reconfiguration. In fact, Schmidt and Cagan (1997) use a method of grammar-based design that searches all the possible configurations of a set of components for the optimal design.

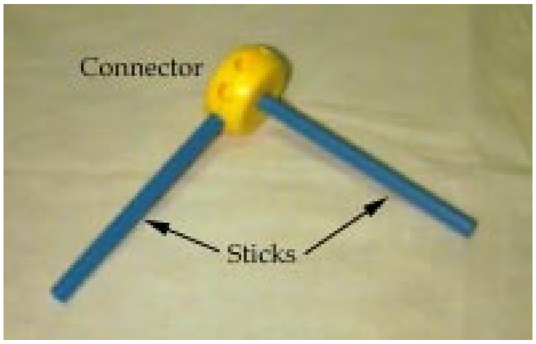


Figure 1.4 *Connector module* demonstrating its function of connecting two sticks together.

Figure 1.5 Interface requirements of the *connector module* dictate that holes exist to connect sticks together.

A systematic approach to development team formation can be based on modules or chunks of a device. Pimmler and Eppinger (1994) propose a design structure matrix technique for clustering functional elements into chunks or modules and basing development teams on those chunks. Complex design problems are typically broken into major systems and then further decomposed into a number of sub-systems. These divisions are largely based on existing industry structures or envisioned device architecture. If development teams are, instead, based on modules of device, then each team's responsibility and necessary interactions with other teams is clearly defined.

Though not strictly intended as a modular design tool, Ulrich and Seering (1989) describe a schematic synthesis problem and solution technique that generates designs by combining elements from a defined set. The technique uses a schematic description of a device to generate creative, feasible solutions to a limited set of mechanical design problems. The schematic description utilizes bond graph elements, such as idealized inertances, capacitances, resistances, transformers and gyrators, to describe separate components of a device within the dynamic systems domain. The schematic description is a more concrete representation of a device than a functional description. This work shows that bond graph methods can be implemented in the conceptual design process and motivates this work to include effort and flow descriptions into the modular design process.

1.1.2 Industrial Motivations

Theory is all well and good, but is there a real need for modular design methods in industry? The answer is a resounding yes! Industry is interested in modular devices for all the reasons mentioned in the theoretical section. The use of modular attachment methods and standardized components by Xerox has made their copiers easier to disassemble, modify and reassemble, resulting in savings of $200 million per year (Congress, 1992). Fiber optic cable splicer units by 3M also incorporate modules to provide sealing around the cables for a variety of enclosures as well as decouple the seals from the structural supports which hold the cables together (Jackson, 1997). Arrow Automotive Industries, a company that specializes in recycling (or remanufacturing) automotive modules such as starters, clutches and carburetors, has annual sales of approximately $100 million (Congress, 1992).

While there is industrial interest in creating modular devices, there is no systematic modular design methodology in place. Modular design has been a recognizable goal of industry for some time. A prime example is fixturing modules for use with machining operations which date back to the 1960s and 1970s. Conversely, systematic function based design methodologies are seeing increased use in industry (Jackson, 1997). Developed in Germany in the 1970s, function based design methodologies have seen adoption in Japan and the United States (Pahl and Beitz, 1988; Shimomura et al., 1996). Combining the two, function based design and modular design, is a definite industrial need, as evidenced by initial works of industrial design experts in the area of modular design (Cutherell, 1996; Jackson, 1997).

1.2 HYPOTHESIS AND OBJECTIVES

I have now motivated my interest in modular design. Its potential benefits, applications and current problems were listed in brief. Now, a formal statement of the work that follows in this dissertation is presented. First, my hypothesis concerning modular design is posed. The hypothesis is followed by a list of practical objectives of the work.

1.2.1 Hypothesis

Following a methodical, mechanical design approach, it is possible to identify modular components at the functional level of a conceptual or reverse engineering design. Direct benefits from identifying modules include greater use of common components in similar devices, a more logical method of organizing design teams and a reduction in development and manufacturing lead time of a device.

1.2.2 Objectives

Objectives of this dissertation:

1. Develop a formal method of identifying modules in a device based on existing design methodologies and show its incorporation into an overall design methodology.
2. Through quantitative means, show when modular design offers a benefit to the designer.
3. Provide physical verification of modules which exist in current devices and show how the module identification method predicts them.
4. Through case studies, demonstrate the application of the method to conceptual and reverse engineering design problems.
5. Predict, in one commercially available device, where a modular design will benefit the device.

1.3 SCOPE

This work is an attempt to establish a set of steps that will identify opportunities for the use of modules based on a function structure of the device. A function structure is simply a graphical method of breaking an overall problem into smaller sub-problems called sub-functions (Pahl and Beitz, 1988; Ullman, 1997; Ulrich and Eppinger, 1995). This includes conceptual designs of new devices, as well as reverse engineering of existing devices. It provides the designer with insight into what functions can be grouped as modules and how those modules may be solved by existing components or new technologies. Before, this insight was only gained through generations of device improvements. In reverse engineering design, the method's power is evident in the identification of opportunities for module sharing across different types of devices as well as ways to combine existing individual components into new modules. Furthermore, a quantitative framework is presented that arranges devices into families based on their functional similarity. This is especially useful for companies looking to expand their device offerings while capitalizing on their existing expertise.

As a measure of when modular design is appropriate, a quantitative framework based on customer needs is used. This framework determines the customer ranked importance of modules based on the customer need ranking of individual sub-functions that form a module. The basic idea is that if two or more sub-functions with high customer need ranking directly interact with each other, then combining the sub-functions into a module will meet the customer needs directly. This is verified through a study of consumer devices. The customer need identified modules are compared with the predicted modules of the method and then with any actual modules which exist in the device.

This work initially focuses on consumer devices, mainly of the household use variety. Reverse engineering techniques (Otto and Wood, 1996) are used to verify the modular design method with actual devices. Later, the method is shown to be applicable to original design as well.

An overall methodology for modular design ties all the pieces together. It gives a set of steps from customer needs to module identification to form layout. Case studies are used to show the application of the methodology. A reverse engineering, a one-off conceptual design of a new device and a development team formation example are presented.

It is also worthwhile to consider modular design’s applicability outside the field of mechanical engineering. The functional approach to solving design problems is easily applicable to other domains, including management, marketing and construction. Consider a marketing strategy for a new device launch. This strategy may include running some “teaser” ads as the device nears its official availability date. Knowing the device’s target consumer population, advertisements are placed in the appropriate newspapers, television stations and radio. Additionally, device demonstrations might be planned in areas with a large concentration of potential consumers. The device launch strategy could be viewed as a modular system, with its modules being the demographic research, advertising placement and device demos.

1.4 WHERE MODULE IDENTIFICATION FITS IN

To date, few attempts at forming a systematic method for modular design exist. It turns out, though, that module identification is easily integrated into function-based methodologies. Examples include the conceptual design methodologies of Pahl and Beitz and Ulrich and Eppinger and the reverse engineering methodology of Otto and Wood (Pahl and Beitz, 1988; Ulrich and Eppinger, 1995; Otto and Wood, 1996).

Modularity identification fits nicely within the functional decomposition portions of the above methodologies. Functional decomposition is simply the process of decomposing the overall device function into smaller, easier to handle problems. An iterative process, functional decomposition yields many sub-functions that each have a simple, realizable function. Ullman (1997) notes that the ability to decompose a problem is a characteristic of creative design. Once decomposed, each sub-function can be solved by a wide range of principles, known as solution principles. The many possible combinations of solution principles, known as concept variants, ensure a creative design. The module identification method will point out which of the sub-functions, and their associated solution principles, may be treated as a module.

Another approach by Ulrich and Eppinger (1995) and Cutherell (1997) addresses modularity from a device architecture standpoint. Neither provide a means of deciding when a modular architecture is better than an integral one. However, some of the pros and cons are listed in Table 1.1.

Additionally, both Cutherell and Ulrich and Eppinger present a four step process for defining a device architecture. My work provides a method to achieve their steps 2 and 4, clustering elements and defining interactions. Clustering elements is the process of determining which sub-functions can be grouped together as a module. I will present a heuristic and quantitative framework to do this. Defining interactions requires identification of the module boundaries, which the heuristic approach provides.

Table 1.1 Comparison of modular and integral architectures (adapted from Cutherell, 1996).

	Pros	Cons
Modular architectures	Improves device reconfigurability	May make devices look too similar
	Increases the device variety and speed of introduction for new devices	Makes imitation of device easier by competitors
	Improves maintainability and serviceability of device	Reduces device performance
	Decouples development tasks (and manufacturing, to some extent)	Modular design may be more expensive than integral design
Integral architectures	Harder for competitors to copy design	Hinders change of design in production
	Tighter coupling of team with less interface problems	Reduces the variety of devices that can be produced
	Increases system performance	
	Possible reduction in system cost	

1.5 HOW TO USE THIS DOCUMENT

Throughout this document, each chapter will begin with an overview containing a road map for the chapter and a list of new information within the chapter. A quick read of this first section will tell you specifically what's in store for that chapter. Also, a running analogy with the Tinkertoy™ set continues throughout most of the document. If you're new to design methodologies, Chapter 2 and 3 will provide an introduction to the methodology and some applications that won’t overwhelm you. The more quantitatively inclined will appreciate Chapter 4. Finally, for the applied folks, Chapter 5 and 6 will give you a brief method and several case studies of actual devices.

Chapter subject matter in brief:

Chapter 2 is for you if you are unfamiliar with formal design methodologies like Pahl and Beitz or Ullman. It describes functional decomposition and function structures more in depth. Also, it introduces the concept of a functional base set, function dependencies and flow ranking. These three concepts represent a significant contribution to functional decomposition techniques.

Chapter 3 presents the heart of this work, the module heuristics. Three module heuristics are introduced which identify modules from a function structure in functional base set form. Several examples are offered showing the heuristic’s application to function structures of existing devices. The devices are then examined to see if any identified modules exist or if the addition of such modules would make sense. Finally, the database of devices used to verify the heuristics is discussed.

Chapter 4 presents the quantitative framework for assessing the value of a module in terms of customer needs. It also presents a mathematical method for grouping devices into families, based on functionality and customer need rankings. Examples are presented which verify the module heuristics of Chapter 3.

Chapter 5 presents the overall theory of modular design. From customer need to identification of modules to form layout, the modular design methodology is applicable to both reverse engineering and original design. A natural extension of the modular design methodology concerns module-based development teams. A development team formation methodology is proposed here as well.

Chapter 6 contains three case studies. One is a one-off original design of a clinker clearer for a power generation plant. A teaming study for an automobile climate control system applies the development team formation methodology. Finally, a reverse engineering case study of the predicted and actual evolution of an iced tea brewer is presented.

1.6 SUMMARY

This chapter introduced the modular design problem under consideration in this dissertation. Along the way, several terms popped up that will form the vocabulary for this modular design work. Here I will summarize the key terms again.

Design methodology is an orderly arrangement of steps concerned with the application of engineering principles to solve a real problem. While design methodology is commonly associated with the creation or modification of devices, it is not limited to devices.

Modular devices are machines, assemblies or components that accomplish an overall function through the combination of distinct building blocks or modules.

Original design is the process of gathering customer needs, abstracting the problem, decomposing the overall function, generating concept variants, selecting a concept variant and embodying that variant for a new problem.

Redesign is the process of evolving an existing device at the subsystem, configuration, component or parametric level.

Reverse engineering is part of the redesign process, wherein a device is predicted, observed, disassembled, analyzed, tested, “experienced,” and documented in terms of its functionality, form, physical principles, manufacturability and assemblability.

Conceptual design refers to the part of either original design or reverse engineering where the overall function is decomposed and concept variants (for an entire device or only a part of a device) are generated and selected.

Catalog design is an automated process of searching a database of existing elements or components to select an element or set of elements that meet the provided specifications.

Design compilers are programs that transform a high level design description to a more concrete lower level.

Decomposition is the process of decomposing an overall problem or function into smaller parts or sub-functions. A *function structure* is a graphical method of decomposition.

Now you’re set. In the chapters that follow, we will explore the problem of modular design and add to your vocabulary.

CHAPTER 2

FUNCTIONAL BASE SET

2.1 INTRODUCTION

In function-based design methodologies, functional decomposition of the device is the most important step in the design process. By breaking the overall function of the device into small, easily solved sub-functions, the form of the device follows from the assembly of all sub-function solutions. But how do you define ‘small, easily solved sub-functions’? Is there a method that will lead to a repeatable functional decomposition between different designers? These have been two points of contention plaguing formal design methodologies such as Pahl and Beitz (1988) and Ulrich and Eppinger (1995).

Since engineers live to bring order to a chaotic world, the obvious engineering solution to the two problems posed is to impose a standard set of functions and flows. Attempts have been made to do this, as early as the 70s (Miles, 1972; Collins et al. 1976), and efforts have intensified since the proliferation of the Pahl and Beitz methodology (Kirschman et al., 1996; Hundal, 1990; Otto and Wood, 1997; Little et al., 1997). By standardizing a set of functions and flows, we will answer both questions. The latter, dealing with repeatability, is solved by limiting the possible sub-function description to a set with clear definitions. The former question of how far to decompose an overall function is answered also: decompose the overall function until all sub-functions may be described by the standardized set of functions and flows. This process is termed a function structure transform.

2.1.1 Road Map for This Chapter

This chapter continues with a description of functional decomposition and a survey of various techniques to decompose an overall function. Specifically, this document will use a function structure to decompose problems. Then the process of transforming a decomposed function structure into a functional base is presented with examples.

2.1.2 What's New Here

The original work for this chapter includes a consistent ordering of flows in the functional base set and creation of clear definitions for the flows. These two contributions increase the repeatability of function structure generation and define a means of stopping decomposition at equivalent levels for different design problems. The concept of functional dependency is introduced as a means of ordering a function structure consistently, further increasing the repeatability of function structure generation. Finally, a simple method of linking flows of a function structure to stated customer needs is given.

2.2 FUNCTIONAL DECOMPOSITION

Functional decomposition is the process of breaking the overall function or problem into smaller pieces, or sub-functions. A hierarchic decomposition, used in this work, systematically breaks the overall function into simpler functions (Allen and Mistree, 1993). Each successive simplification produces a layer below the parent function, moving from the abstract to the concrete. Once all the sub-functions have been simplified to the same degree, the bottom-most layer of the hierarchy represents the refined sub-functions.

The other part of the decomposition process not yet mentioned, but essential to any successful design, is the gathering of customer needs and the verification that the decomposed problem meets these needs. Many techniques for gathering customer needs are available, from interviews to focus group discussions. A more complete presentation of such methods is available in Urban and Hauser (1993). Once gathered the stated customer needs must be checked against the new sub-functions at every level of decomposition to verify that the needs are being met by some sub-function.

2.2.1 An Example of Hierarchical Functional Decomposition

As an example of hierarchical functional decomposition, consider a power screwdriver. Many such devices are on the market today, with manufacturers such as Black & Decker and SKIL. The decomposition process begins with a statement of the overall function of a power screwdriver. I choose the verb-object statement of *loosen/tighten screws.* This is shown in the black box description of Fig. 2.1 along with relevant flows of material, energy and signals that I can identify with the problem at this point. The black box description also defines the system boundary such that the bit is considered an input to the device.

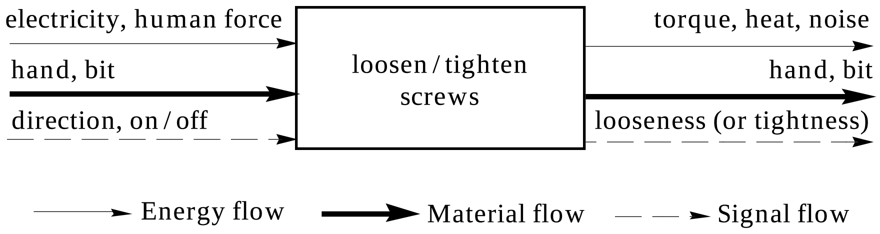


Figure 2.1 A black box representation of a power screwdriver. The overall function is shown in the box as *loosen/tighten screws*. Identified input and output flows are shown on the left and right sides of the box.

Next, customer needs are gathered for the problem. Here, interviews were conducted with nine customers, an appropriate sample size for small consumer products (Griffen and Hauser, 1993). The stated customer needs are compiled in Table 2.1 and listed in order of importance (on a 0 to 10 scale).

Table 2.1 Customer need statements and importance ranking for a power screwdriver.

Customer need	Importance
Powerful	9
Long lasting battery charge	9
Fast	8
Reversible, i.e. screw & unscrew capability	8
Lightweight	8
Short charging time	7
Able to use manually	7
Uses different (interchangeable) tips	7
Comfortable handle	6
Automatic shut off when not in use	6
Small size	5
Variable velocity	5
Maintenance free	4
Balanced weight	3

To continue the decomposition of the power screwdriver, the overall function of *loosen/tighten screws* is decomposed into smaller, simpler sub-functions. Figure 2.2 shows the next level of decomposition that I performed. Here, five sub-functions are identified to compose the overall function. For each level of decomposition, the customer needs are checked to make sure that some sub-function is meeting each need.

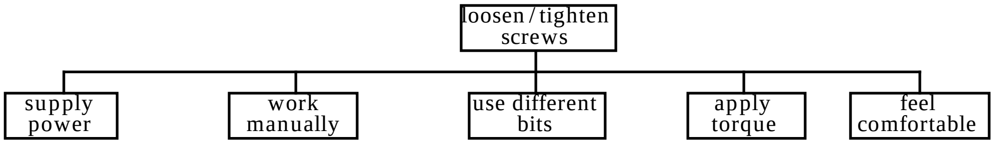


Figure 2.2 The first level of decomposition beneath the parent function (which in this case is the overall function) of *loosen/tighten screws* shows five sub-functions. These sub-functions all contribute to the overall function and meet stated customer needs.

The decomposition process for the power screwdriver continues through two more levels of decomposition before the problem is considered fully decomposed (or the sub-functions are considered refined). This hierarchy is shown in Fig. 2.3. While not apparent now, the reason the decomposition process is stopped will become clear in Section 2.3. For now, it is important to note that decomposition is an iterative process that results in a set of sub-functions that, taken together, solve the overall problem. These refined sub-functions are shown in the boxes with darker outlines.

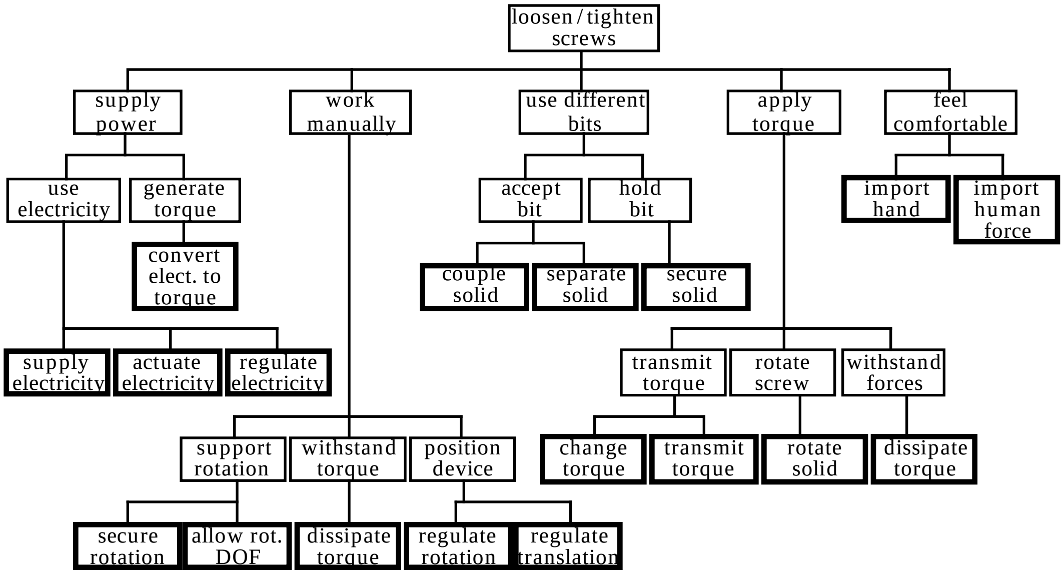


Figure 2.3 An example of a hierarchical decomposition of a power screwdriver. Boxes with heavy outlines indicate the refined functions.

2.2.2 Bringing Flows into the Functional Decomposition

Within the hierarchical category, there are many approaches to decomposition (Suh, 1990; Pahl and Beitz, 1988; Sturges et al., 1993; Mistree et al., 1993; Lai and Wilson, 1987). Pahl and Beitz (1988) decompose a problem based on flows of energy, material and signal. First, an overall function is stated in verb-object form and all input and output flows are identified. The overall function is broken into simpler sub-functions. Generally, a verb-object form is used to describe all sub-functions, but some deviations from this form may occur during decomposition. The refined sub-functions, however, are represented in verb-object form. For example, consider the sub-functions *work manually* and *feel comfortable* from Fig. 2.3. They are not in verb-object form, but the final refined sub-functions all are. These sub-functions trace the flow of energy and material through the device as depicted in Fig. 2.4. Sub-functions may be further decomposed as needed. The function flow arrangement that results after decomposition is called the function structure for the device. In this type of hierarchical decomposition, it is important to note that sub-functions of the same layer are related to each other through flows.

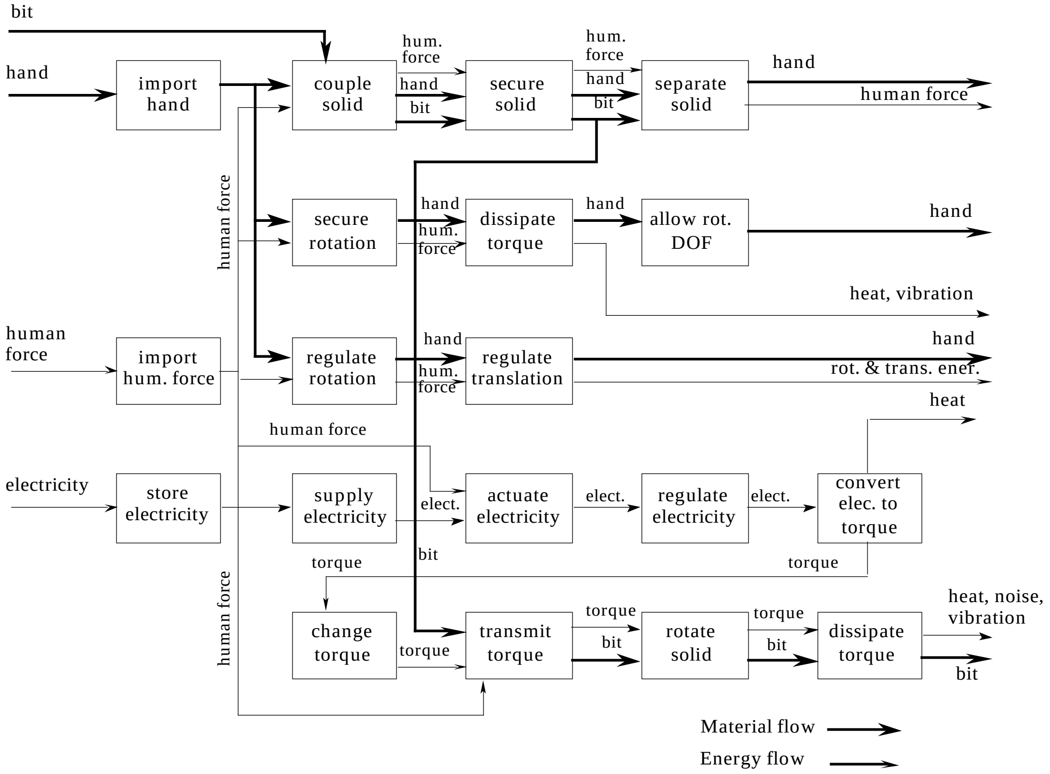


Figure 2.4 Power screwdriver function structure based on the hierarchical decomposition shown in Figs. 2.1 - 2.3.

Figure 2.4 shows the function structure for the power screwdriver that was decomposed in the previous sub-section's example. Note that the refined sub-functions from the hierarchical decomposition of Fig. 2.3 are now connected by flows. This provides more information about the problem in an easy to follow diagram.

A different hierarchical decomposition is given in Suh's (1990) axiomatic design. It decomposes the overall problem into layers of functional requirements which map directly to design parameters. The functional requirements within a layer are independent of each other. Each layer of the hierarchy represents a level of design. As the functional description becomes more detailed, the layers increase and the functional requirements become more specific. Thus, Suh decomposes problems into independent functional requirements rather than sub-functions related by flows.

In this document, functional decomposition will basically follow the flow-based Pahl and Beitz method. The flow-based method is chosen because of my belief that flows represent a more intuitive way of describing a design problem. We will, however, impose additional arrangement rules on the function structures that facilitate identification of modules. These arrangement techniques are presented in Chapter 3.

2.3 THE FUNCTIONAL BASE SET

Returning to our original questions of this chapter, neither the Pahl and Beitz nor Suh decomposition methods clearly indicate when a problem is decomposed sufficiently. Others have offered modifications (mostly to Pahl and Beitz) that suggest stopping points (Sturges et al., 1993), but they are still ambiguous in their definitions of supporting and basic functions, their triggers for stopping decomposition. Nor do any of the methods offer a standardized set of functions and flow descriptions. Hundal (1990) suggests a set of function classes and flow classes to describe all sub-functions. Listing six basic function categories and three basic flows, shown in Table 2.2, Hundal claims to encompass all mechanical functions. Kirschman et al. (1996) also present a method of classifying functions through a taxonomy of elemental mechanical functions. In both cases, the set of functions and flows provide a stopping point for decomposition. This set is an attempt to define a functional basis which provides two benefits: 1) a common vocabulary of functions and flows to improve repeatability of function structure development and 2) a level of detail that, when reached, stops the decomposition process.

Table 2.2 Hundal's (1990) basic function and flow categories.

Function Category	Basic Function	Flow Category	Basic Flow
Store/Supply	Store, Supply, Hold, Release, Stop	Material	
Connect	Connect, Compare, Mark, Valve, Switch, Pack, Mix, Add, Subtract, Multiply, Divide, AND, OR	Energy	Mechanical, Electrical, Thermal/Fluid, Miscellaneous
Branch	Cut, Branch, Count, Display, Separate	Signal	
Channel	Transmit, Transport		
Change Magnitude	Process, Crush, Form, Coalesce, Change		
Convert	Liquefy, Solidify, Evaporate, Condense, Integrate, Differentiate, Sense, Convert		

The standard list of functions and flows adopted here is derived from the Little et al. (1997) functional basis set. Little et al. note that Hundal lacked a separate function category for signals and for functions which firmly support an energy or material in a specific location. Therefore, Little et al. developed a functional basis of eight function classes and three basic flows. It is further noted in Little et al. that the derived functional basis set encompasses all of Hundal's basic functions and flows and the 30 basic functions found in the Theory of Inventive Problem Solving (TIPS). TIPS is a design method developed in the Soviet Union based on the review of over two million patents (Altshuller, 1984; Malmqvist et al., 1996). From this immense base of empirical evidence, 30 basic functions were found to describe all of the devices.

Little et al. (1997) refer to their set of functions and flows as a basis set. The mathematical definition of basis requires that a set (a) span the space and (b) be linearly independent. A common example of a basis set is the eigenvectors of a dynamic system. Basis sets are not unique, but some are more convenient to use than others. The set of functions and flows used here is, in spirit, a basis set. The intent is to develop a set of functions and flows, based on empirical studies, that describe the entire design space and are non-repetitive. Proving the set to be a mathematical basis is an enviable goal, but is not pursued here. In the remainder of the dissertation, I refer to the set of functions and flows as the base set. The base set is discussed below. Here I add definitions to the set of flows to clarify their meaning.

2.3.1 **Flow Classes**

The three flow classes are extended to form the vocabulary of standardized flows. The flow classes, energy, material and signal, conform to those flows used in Pahl and Beitz. The flow classes are shown in Table 2.3.

Table 2.3 Flow classes, basic and sub-basic flows and complements. See Appendix A for bond graph references.

Class	Basic	Sub-basic	Complements	
Material	Human		Hand, foot, head ,etc.	
	Gas			
	Liquid			
	Solid			
Signal	Status	Auditory	Tone, Verbal	
		Olfactory		
		Tactile	Temperature, Pressure, Roughness	
		Taste		
		Visual	Position, Displacement	
	Control			
			Bond graph based complement	
Class	Basic	Sub-basic	Effort analogy	Flow analogy
Energy	Human		Force	Motion
	Acoustic		Pressure	Particle velocity
	Biological		Pressure	Volumetric flow
	Chemical		Affinity	Reaction rate
	Electrical		Electromotive force	Current
	Electromagnetic	Optical	Intensity	Velocity
		Solar	Intensity	Velocity
	Hydraulic		Pressure	Volumetric flow
	Magnetic		Magnetomotive force	$\frac{d}{dt}$ magnetic flux
	Mechanical	Rotational	Torque	Angular velocity
		Translational	Force	Linear velocity
		Vibrational	Amplitude	Frequency
	Pneumatic		Pressure	Mass flow
	Radioactive		Intensity	Decay rate
	Thermal		Temperature	Heat flow
Overall increasing degree of specification ➠				

Within each class, flows may be broken into basic and sub-basic flows. In practice, a basic flow is described by a basic descriptor + its class. For example, *human energy* is a basic flow for the power screwdriver of the previous section. Sub-basic flows are described by a sub-basic descriptor + its class. An example is the flow *auditory signal*. Basic and sub-basic flows are further specified by adding a complement found in the fourth or fifth columns of Table

2.3. Here the flow description is formed by a basic (or sub-basic) descriptor + a complement. A more specific description of the *human energy* used by the power screwdriver is *human force.*

Energy flow complements are divided into effort and flow analogies in the final two columns. Only one of the complements is used to further specify a basic or sub-basic energy flow. A few special cases exist where energy complements stand alone in describing a flow. Stand alone effort or flow analogies in the last two columns are denoted by a gray background. Taking an engine, for example, we may be interested in the *torque* produced by the engine (as opposed to *rotational torque*). Note that the material and signal classes do not use the effort and flow analogies found in the energy class.

The degree of specification depends on the type of design and customer needs. Using a more general flow description produces a generic function structure and, thus, a wider range of concept variants. However, if customer needs dictate concreteness in flows, then an increasingly specific complement is more valuable. Another use of the flow set (and function set in the following sub-section) is to compare different devices on a functional level. In this case, the flows (and functions) should be expressed in their basic categorization to capture similarities between devices. Techniques for comparing device functionality are presented in Chapter 4.

Considering the material and energy classes, both have basic flows of human. The importance in human crossing of device boundaries merits this special inclusion. Often the requirement of human interaction is known at an early stage of design. By its specification, it will guide the design to appropriate solutions faster.

Signals, while in actuality either material or energy, receive their own class because their function is to carry information. Here, signals are treated as two basic flows used for sensing (status) or control purposes.

As mentioned earlier, basic flows of the energy class are divided into bond graph-based effort and flow complements. I label the energy flow complements as effort and flow *analogies*. Not every basic energy flow in Table 2.3 will have power as the product of its effort and flow analogies, as would a true bond graph effort and flow product. The effort and flow analogies' product is scalable to power, though. The effort and flow analogies were created because they provide a consistent categorization of flows, eliminating confusion when increasing specification is needed. They also identify variables that are important in future analysis. For instance, in a hand held power screwdriver, is the relevant flow out of the motor *angular velocity* or *torque*? Of course both exist, but I argue that *torque* is the correct choice to describe the situation because effort is the more important output of the power screwdriver, based on the customer need of inserting screws easily. When mathematical models of the device are created, a formulation for the output torque will be required as expressed by the function structure.

Not only is a consistent division of basic flows necessary, but also a clear definition for all flows. Flow definitions are given in Appendix A. These definitions, along with the division of the energy class according to effort and flow, are a new contribution to the decomposition literature. Combined with existing definitions of functions, the flow definitions provide a complete base set for repeatable functional decompositions. Furthermore, they provide a stopping point for the decomposition.

2.3.2 Function Classes

The function classes used in the functional base set are given in Table 2.4. The first column lists the function class (the eight described in Little et al. (1997)). These classes are extended to include basic flows in the second column. The third column lists functions that are only valid when used with an appropriate flow. For example, the function verb *transmit* cannot be used with a flow such as *liquid*. However, it is perfectly valid to use *transmit human force*. The last column lists synonyms for the basic functions. These are terms that commonly appear in non-base set function structures and aid in transforming a function structure.

Original definitions for the basic functions are given in Little et al. (1997). These definitions and examples are refined and presented in Appendix B for completeness.

2.3.3 The Transform

With clear definitions for functions and flows, our functional base set is complete. As I stated earlier, the functional base set serves two purposes: 1) to tell where (or when) to stop decomposition, and 2) to make function structure generation repeatable. Thus, the term function structure transform and the phrase transforming the function structure imply that the problem is decomposed and that the decomposition is repeatable.

Table 2.4 Function classes, basic functions and synonyms (Little et al., 1997). Repeated synonyms are italicized.

Class	Basic	Flow restricted	Synonyms
Channel	Import		Input, Receive, *Allow*, Form Entrance, *Capture*
	Export		Discharge, Eject, Dispose, Remove
	Transfer		
		Transport	Lift, Move, Channel
		Transmit	Conduct, Transfer, Convey
	Guide		Direct, Straighten, Steer
		Translate	
		Rotate	Turn, Spin
		Allow DOF	Constrain, Unlock
Support	Stop		Insulate, Protect, *Prevent*, Shield, Inhibit
	Stabilize		Steady
	Secure		*Attach*, Mount, Lock, Fasten, Hold
	Position		Orient, Align, Locate
Connect	Couple		Join, Assemble, *Attach*
	Mix		Combine, Blend, Add, Pack, Coalesce
Branch	Separate		Switch, Divide, Release, Detach, Disconnect, Disassemble, Subtract, Valve
		Remove	Cut, Polish, Sand, Drill, Lathe
	Refine		Purify, Strain, Filter, Percolate, Clear
	Distribute		Diverge, Scatter, Disperse, *Diffuse*, Empty
	Dissipate		Absorb, Dampen, Dispel, *Diffuse*, Resist
Provision	Store		Contain, Collect, Reserve, *Capture*
	Supply		Fill, Provide, Replenish, Expose
	Extract		
Control Magnitude	Actuate		Start, Initiate
	Regulate		Control, *Allow*, *Prevent*, Enable / Disable, Limit, Interrupt
	Change		Increase, Decrease, Amplify, Reduce, Magnify, Normalize, Multiply, Scale, Rectify, Adjust
	Form		Compact, Crush, Shape, Compress, Pierce
Convert	Convert		Transform, Liquefy, Solidify, Evaporate, Condense, Integrate, Differentiate, Process
Signal	Sense		Perceive, Recognize, Discern, Check, Locate
	Indicate		Mark
	Display		
	Measure		Calculate

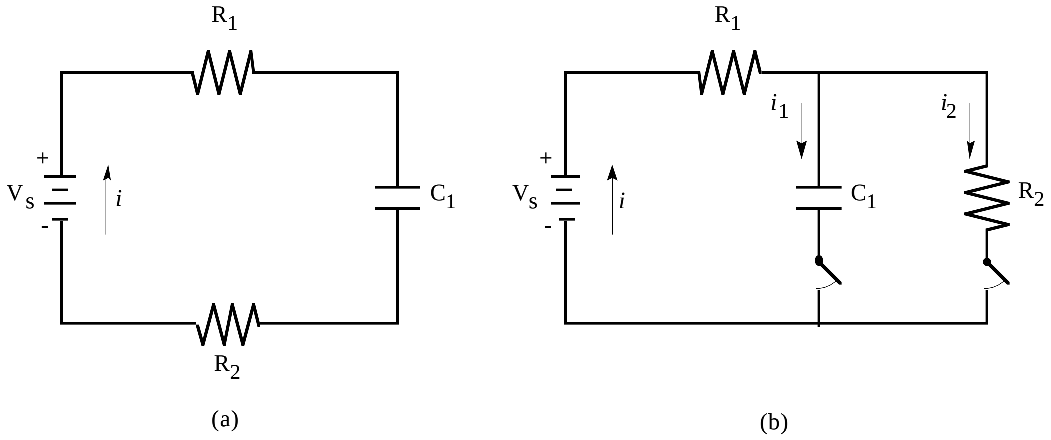
2.4 FUNCTION DEPENDENCIES

In function structures, *flow* refers to the energy, material or signal that travels through the sub-functions of a device. Decomposition techniques, like Pahl & Beitz (1988), trace flows through sub-functions without regard for the dependence of sub-functions on a specific order. Ulrich & Eppinger (1995), though, note that the order in which tasks are performed is important for product development processes. They define task dependencies as either parallel, sequential or coupled, where the tasks are analogous to sub-functions and the time and information resulting from each task are analogous to flows. Here I extend the concept of parallel and sequential dependencies to sub-functions and flows of a function structure. In each case, the dependencies are defined with respect to a given flow.

The benefit of classifying and ultimately arranging a function structure based on the dependencies of its flows and functions will become evident when the module identification method is presented in Chapter 3. For now, suffice it to say that for any design problem, regardless of the concern for modules, any additional information that can be contained in the function structure will expedite decisions in the conceptual phase.

2.4.1 Sequential Function Chains

In *sequential function chains,* the sub-functions must be performed in a specific order to generate the desired result. A flow common to all these functions is termed a *sequential flow*. This concept is directly analogous to a series circuit. In Fig. 2.5 (a), the resistors R_1 and R_2 and capacitor C_1 are analogous to sub-functions of a device. The current, *i*, is the flow common to all sub-functions. Because of the physical layout of the circuit, the flow (current *i*) must travel through each sub-function in a specific order (first R_1, next C_1 and finally R_2).



(a) (b)

Figure 2.5 Electrical circuit analogy with sequential and parallel sub-function chains. (a) Series circuit and (b) parallel circuit.

As an example of a sequential function chain in a real device, consider the palm-grip sander shown in Fig. 2.6. Its function structure is shown in Fig. 2.7. Following the flow of the *wood surface*, it travels through the sub-functions *remove solid, transport solid, secure solid, store solid* and *export solid* before exiting the device boundary. These sub-functions must occur in this specified order for the device to operate. The rough wood surface is removed, the wood debris is then transported away from the sanding surface, the debris is then secured in a dust bag and stored until some time when the dust bag’s contents are emptied. Another example of a sequential chain in the sander is the flow of *electricity* through the sub-functions *import electricity*, *actuate electricity*, *regulate electricity* and *convert electricity to rotation*.

Figure 2.6 The DeWalt palm grip sander.

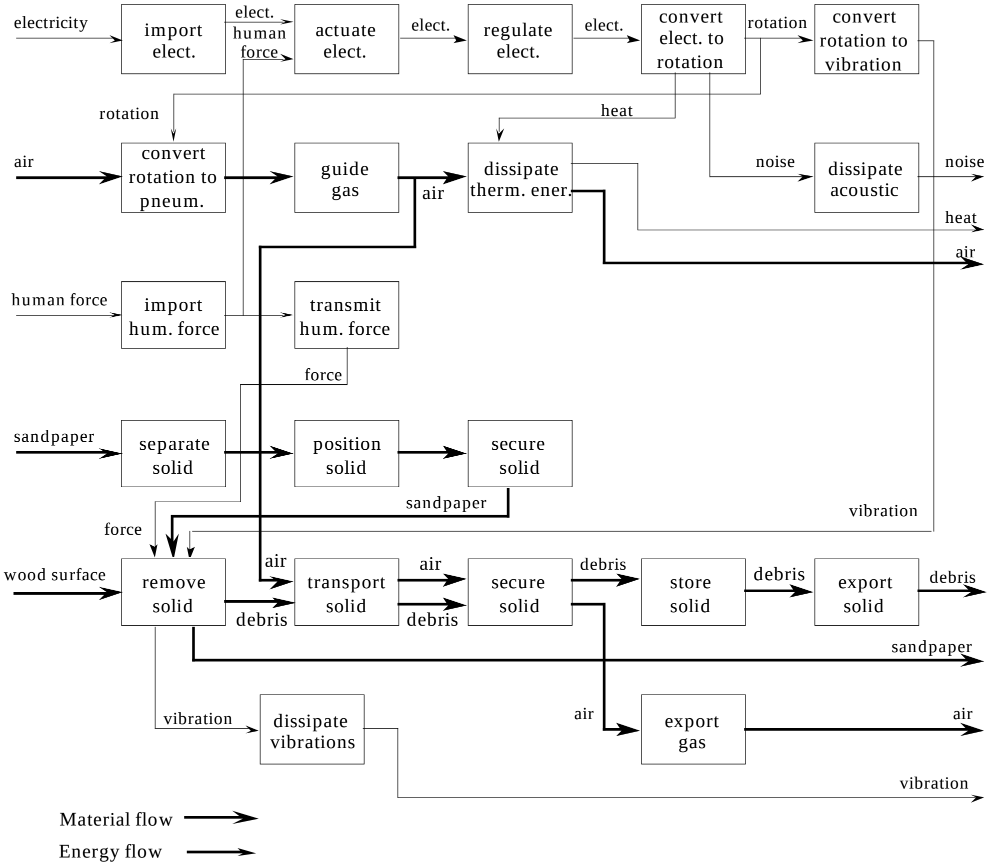


Figure 2.7 Palm-grip power sander function structure.

2.4.2 Parallel Function Chains

Parallel function chains consist of sets of *sequential function chains* sharing one or more common flows. Graphically, they are represented by branching flows in a function structure. The chains are called *parallel* because they all depend on a common sub-function and flow, but are independent of each other. Independence means that any one of the chains of the parallel function chain set does not require input from any other chain within the set. Physically, the parallel function chains represent different components of a device that may operate all at once or individually. The circuit in Fig. 2.5 (b) is analogous to the parallel function chains introduced here. As before, the resistors and capacitor act as sub-functions, but the voltage is the "flow." Sub-functions C_1 and R_2 are in parallel and thus experience the same flow of voltage potential. Both sub-functions C_1 and R_2 depend on the flow out of R_1, but do not depend on each other. Switches are included in the sequential legs of the parallel chain to indicate that either one or both of the sequential legs may operate at the same time. This is exactly the situation described by the parallel function chains above.

Returning to the example of the palm-grip sander and its function structure shown in Fig. 2.6, consider the following parallel function chain. The flow *human force* travels through the sub-function *import human force* and then splits to enter two separate sequential chains (one begins with *transmit human force*, the second with *actuate electricity*). Similarly, the flow of *air* splits after the sub-function *guide gas* and enters two sequential chains beginning with *dissipate* *thermal energy* and *transport solid*. In both cases, the parallel function chains are dependent on the function preceding the flow split, but not on each other.

2.5 FLOW RANKING

I briefly discussed customer needs and their role in functional decomposition in Section 2.2. Now, I introduce a technique called flow ranking which correlates customer needs with the flows of a function structure. While this concept is introduced as a stand-alone technique for the present, it will be utilized in Chapters 3 and 4 for module identification.

Flow ranking consists of a two step process and uses customer needs that are scaled between 1 (supporting) to 5 (must have). First, each stated customer need is associated with a flow or flows from the function structure that will meet that need. The final step produces a flow ranking for each flow, which is the sum of all the associated customer need importance values for that flow. Listing the flows in descending order by flow ranking value yields the ordered list of flows from most important to least important.

As an example, consider the power screwdriver introduced in Section 2.2. Table 2.5 shows the correlation of customer need and scaled customer need importance to flow.

Table 2.6 sums the importance values for each flow and ranks the flows from most important to least important. From the ranking, the flow of *electricity* is determined to be the most important flow according to customer need. This provides insight into the device that otherwise might have been overlooked. One’s intuition might suggest that rotational energy would be most important (since the overall function is to provide torque), but the flow ranking procedure reveals the importance of electricity in meeting the customer needs.

Table 2.5 Flow ranking based correlation for the power screwdriver example.

Customer need	Scaled cust. need importance (1 to 5)	Associated flow(s)
Powerful	5	electricity, rotational energy
Fast	4	electricity, rotational energy
Long lasting battery	5	electricity
Short charge time	4	electricity
Manual use capability	4	hand, human force
Reversible (screw and unscrew)	4	electricity, rotational energy
Lightweight	4	human force, electricity
Weight balance	2	human force
Small size	3	hand, electricity
Comfortable handle	3	hand
Automatic shut-off	3	electricity
Interchangeable tips	4	bit
Maintenance free	2	rotational energy, bit, human force
Variable velocity	3	electricity

Table 2.6 Flow ranking for the power screwdriver example.

Flow	Associated cust. need ratings	Cumulative flow rating
electricity	5, 4, 5, 4, 4, 4, 3, 3, 3	35
rotational energy	5, 4, 4, 2	15
human force	4, 4, 2, 2	12
hand	4, 3, 3	10
bit	4, 2	6

Also note from Table 2.6 that the resolution between the three flows *rotational energy, human force* and *hand* is small. How important are the differences in the flow ratings? The standard deviation of the set is 11.3, indicating that the flow rating only resolves two levels of customer need for this example. Therefore the standard deviation of the cumulative flow ratings can be used to determine levels of customer need for the set of flows.

2.6 SUMMARY

Recapping the topics of this chapter, functional decomposition methods were discussed while the concept of a functional base set was presented and refined. Specifically, a standard set of flows for the functional base set was developed and definitions presented to standardize their use. Bond graph based complements are added to the flow classes. The functional base set provides both a stopping point for decomposition and a vocabulary of function and flows that significantly increases the repeatability of function structures. This answers two of the major criticisms of formalized design methodologies such as Pahl & Beitz (1988).

Additionally, the concept of functional dependency in function structure arrangement was introduced. By defining sequential and parallel function chains, increased information is included in a function structure. This is a key part of the module identification method in the following chapters. It also presents the opportunity for increased accuracy in conceptual design decision making.

With the functional base set and functional dependencies defined, function structures can now be generated in a more systematic manner. The increased order of the function structure is necessary to define modules. A method of identifying modules from a transformed function structure is presented in the next chapter.

CHAPTER 3

MODULE HEURISTICS

3.1 OVERVIEW

Webster's dictionary defines a heuristic as "a method of education or of computer programming in which the pupil or machine proceeds along empirical lines, using rules of thumb, to find solutions or answers." Here is my working definition of module heuristics: A method of examination in which the designer uses a set of steps, empirical in nature, yet proven scientifically valid, to identify modules in a design problem. This definition requires another. "Proven scientifically valid" refers to a hypothesis, formulated after systematic, objective data collection, that has successfully passed its empirical tests. This is based on the scientific method.

Recalling the Tinkertoy™ analogy of Chapter 1, this chapter is providing you with additional building blocks or pieces in the form of module terminology and heuristic method. Think of the functional basis work in Chapter 2 as the tinker toy sticks. This chapter, then, represents the funny little connectors that allow the sticks to join together. At the end of this chapter, you will be able to start sticking all of the various pieces together to form your own creation.

3.1.1 Road Map for This Chapter

Chapter 3 begins by laying a foundation of terminology of modular products. Following that discussion, three heuristic methods of identifying modules from a function structure are presented. The heuristic methods assume you are familiar with functional decomposition and the functional basis described in Chapter 2. A problem decomposed and transformed into the functional basis is the starting point for the heuristic methods. Any function structure, whether transformed into the functional basis or not, can utilize the heuristic methods here. However, I use only transformed function structures to emphasize the benefit of repeatability that the functional basis provides. Finally, examples demonstrating the heuristic method are presented.

3.1.2 What's New Here

New information found in this chapter begins with the classification of modules within a device as either assembly, sizable or conceptual. The module heuristics that identify sub-functions that may be grouped together to form a module are new as well. In fact, this effort to define modules at the conceptual level is the heart of this dissertation. This is an attempt to formalize what some would describe as an intuitive gift. It is my belief that good design skills are not exclusively an innate gift, but that through a formal series of steps, good design skills are developed.

3.2 TERMINOLOGY

3.2.1 Device-Based Modularity

The benefits of modular design are discussed in Chapter 1. Two physical benefits are standardization of components and reconfigurability of devices. Based on these two attributes, modular devices may be classified as a member of one or more of six sets (Ulrich and Tung, 1991; Cutherell, 1996). These classes of modular devices do not form crisp categories. A particular device may exhibit qualities of more than one classification. The six classifications are defined below.

Component sharing modularity is the use of the same component across many different basic devices. This is associated with the concept of component standardization. Examples of component sharing modularity include Black and Decker's line of VersaPak power tools shown in Fig. 3.1. All of the tools utilize the same battery packs to provide power. Additionally, many use the same motors.

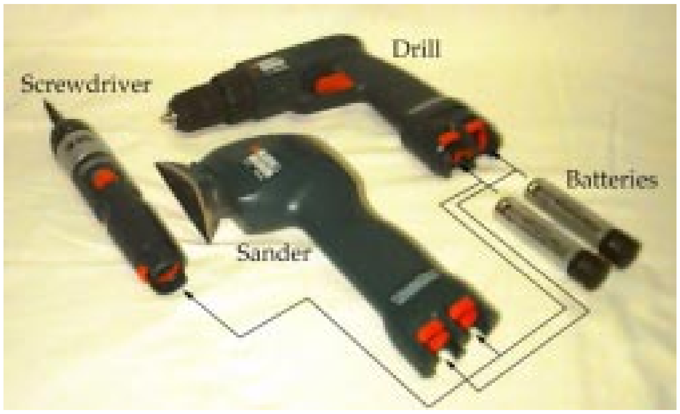


Figure 3.1 The three VersaPak power tools from Black and Decker represent examples of component sharing. All use the same batteries (2 are shown of the right side of the figure) as energy sources.

Component swapping modularity is the complementary case to component sharing. Here one basic device uses several different components to allow it to perform multiple tasks. Agricultural equipment provides an excellent example of component swapping modularity on a large scale. For instance, the same tractor (used here as the basic device) can use different components to cut hay, windrow hay and, finally, bale hay. On a smaller scale, the hand held power drill shown in Fig. 3.2 with its various bits (the components) is an example of a component swapping device. Component swapping is associated with reconfiguration of devices. It is important to note that component swapping and component sharing modularity are identical concepts. The difference lies in the definition of basic device and component.

Figure 3.2 The Black and Decker power drill uses different bits to screw and drill. The bits represent swappable components.

Fabricate to fit modularity involves the use of standard components with one or more variable components. Generally, the variations in components deal with physical dimensions that can be modified. Hydraulic cylinders, shown in Fig. 3.3, are examples of fabricate to fit modularity. Stroke length and bore diameter are two attributes that can be varied and used with other standard components such as hoses and fittings.

Figure 3.3 Hydraulic cylinders of varying bore diameter and stroke length are examples of fabricate to fit modularity.

Bus modularity describes a device with two or more interfaces that accepts any combinations of components from a set of component types. In most cases, the components have a standard interface that attaches to any of the common interfaces. Memory expansion slots in computers are an example of bus modularity and are shown in Fig. 3.4. Track lighting is another example. In this case the lights are the components and the track is the bus which accepts them.

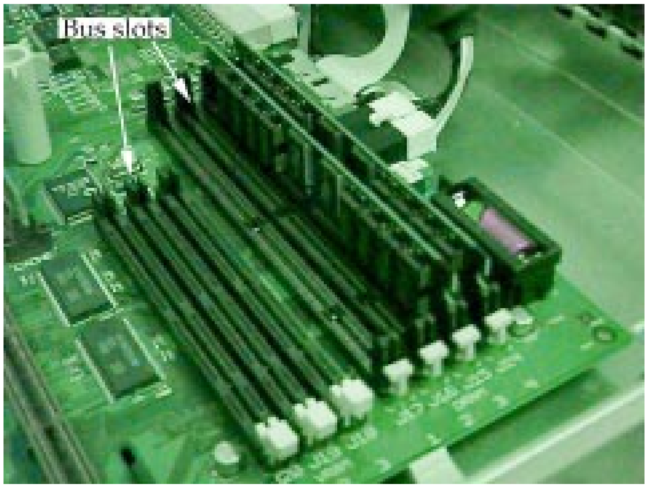
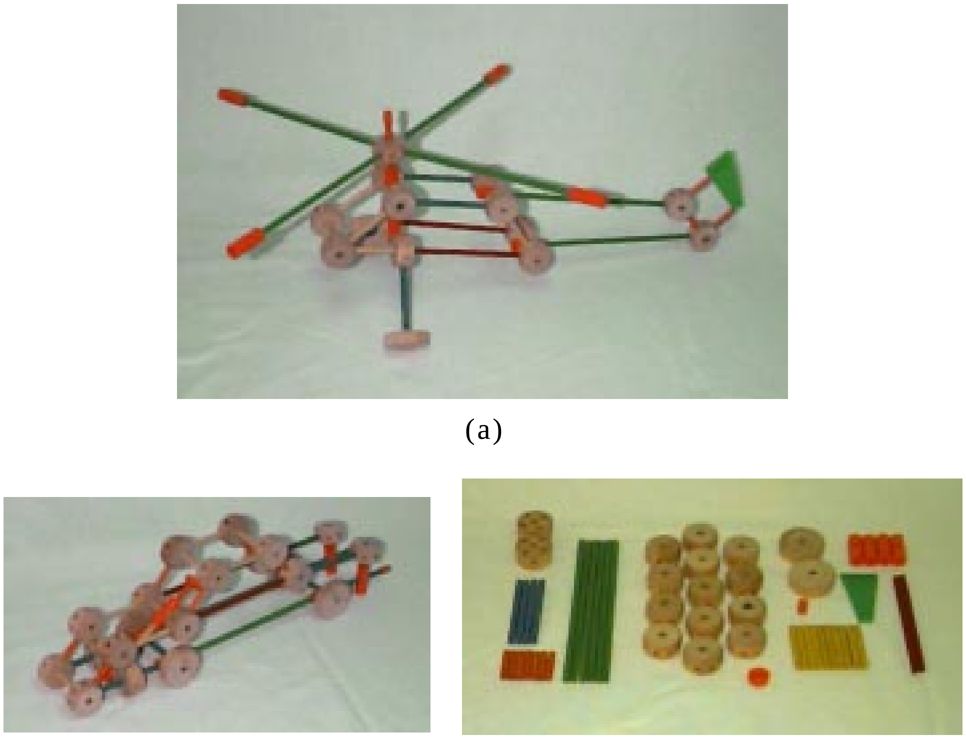


Figure 3.4 Computer DRAM expansion slots are examples of bus modularity. Here, two DRAM chips are inserted in the right-most bus slots with two more bus slots empty. The three empty bus slots on the left are VRAM slots.

Mix modularity combines several standard components together to create a new device. The beloved tinker toy set is an example of mix modularity. Its components combine to produce an almost endless number of new devices (in the form of toys).



(a)

(b)

(c)

Figure 3.5 Examples of mix modularity. The helicopter in (a) and car in (b) are made from the same set of standard components shown in (c).

Sectional modularity allows sections of a device to be configured in a variety of ways as long as the components are connected at their interfaces. Each component may have more than one interface. Cubical office furniture, consisting of interlocking panels, drawers and desktops, is an example of sectional modularity. The computer system shown in Fig. 3.6 is also an example of sectional modularity (Heid, 1992). Sectional modularity differs from mix modularity in that it does not create a new device, it simply gives a device a new physical layout and/or function.

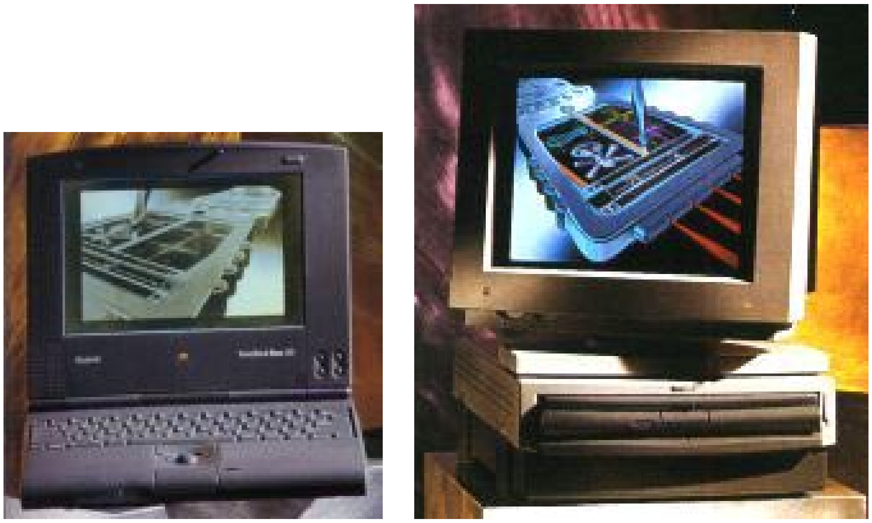


Figure 3.6 The Apple PowerBook Duo line of computers is an example of sectional modularity. The PowerBook Duo (left) can be used as a stand alone computer or can be used as the CPU section of the desktop system shown on the right. (Photo by Paul Franz-Moore.)

3.2.2 Implementation-Based Modularity

In addition to the device-based modularity descriptions above, three implementation-based modularity classes exist that describe the type of modules within a device (McAdams et al., 1997). These classes group modules based on how they are implemented and assembled. In fact, a device may accurately be classified by both a device-based and implementation-based modularity description. For example, a Black and Decker VersaPak power drill can be classified as a component swapping device (due to its use of different bits to drill, screw or ratchet bolts) while also exhibiting a implementation-based form of modularity (using the same motor and switch as a Black and Decker sander). The implementation-based modules are described next.

Assembly modules are components, or groups of components, that solve related functions and increase assembly ease. An example is the electricity to thermal energy module of a coffee maker. The module includes the electrical cord, switch contacts, electrical resistor heater, the water transport tube and the tube to water reservoir connectors. This module consists of several separate parts that are assembled together before final assembly of the entire device.

Sizable modules are components that are exactly the same except for their physical scale. Lawn mower blades are sizable modules as they vary in length depending on the width of cut of the mower cutting deck. Sizable modules can be manufactured by the same operations and machines.

Conceptual modules solve the same functions, but have different physical embodiments. Identification of conceptual modules in related devices provides an opportunity for component sharing between the devices.

3.3 THE METHOD OF MODULE HEURISTICS

Now, I move on to the method by which modules can be identified at a functional level. The method of module heuristics consists of three separate strategies to identify modules. The necessary starting point is a well refined function structure. For example purposes, function structures transformed into the functional basis presented in Chapter 2 are used.

The three heuristic methods introduced here offer surprisingly simple definitions of modules from transformed function structures. However, each of the methods may identify overlapping modules or modules which are subsets or supersets of other modules. The choice of which module to implement in that case is not always clear. The rule suggested here is to implement the module with the smaller number of sub-functions. This is in keeping with the philosophy that modules should be easily identifiable with a particular function. Ultimately, though, which module to implement requires some engineering judgment.

As the three methods are introduced, two consumer device function structures, in functional basis form, are used as physical examples. The devices are a SKIL Twist power screwdriver and a Presto hot air popcorn popper. The power screwdriver was chosen for the example series because it deals with several material flows. The hot air popcorn popper was chosen because of its energy flows and multiple energy conversions. Additionally, some of the modules identified by the methods appear as modules in the current devices and others offer areas for future modularity. The function structures were generated by the reverse engineering method of Otto and Wood (1996). I will show the identified modules for the two devices for each heuristic, discuss which ones exist and which ones present opportunities for a more modular design.

3.3.1 Dominant Flow

The dominant flow heuristic starts with the highest ranked, non-branching flow (from the customer needs based flow ranking procedure of Chapter 2) and groups the sub-functions the flow travels through until it exits the system or is transformed into another flow. The identified set of sub-functions define a module that deals with the flow traced through the system. The identified sub-functions form the boundary, or *interface*, of the module. Any other flows, in addition to the traced flow, that cross the boundary are *interactions* between the module and the remaining device. A dominant flow module is shown schematically in Fig. 3.7. To implement the module, conduits must be specified to carry the interactions across the interface.

Stated succinctly, the dominant flow proposition is:

> **Proposition 1:** The set of sub-functions which a flow passes through, from entry or initiation of the flow in the system to exit from the system or conversion of the flow within the system, define a module.

Screwdriver - Identified modules

In the SKIL Twist power screwdriver of Chapter 2, the highest ranked, non-branching flow is that of electricity. Electricity passes through four sub-functions as outlined by a dashed rectangle and shown in Fig. 3.8. *supply electricity*, *actuate electricity* and *regulate electricity* all have the flow electricity. The dominant flow heuristic identifies that these sub-functions could be combined as one module, here I'll name it the *electrical supply module.*

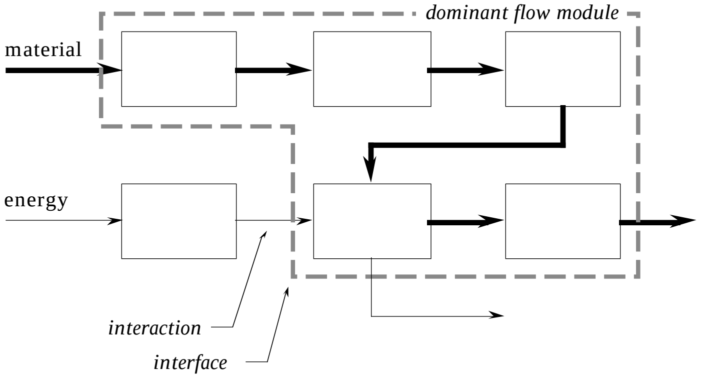


Figure 3.7 Dominant flow heuristic applied to a generic function structure.

The next flow to trace is the bit. It first enters the system and traces through the two sub-functions *couple solid* and *secure solid*. This set of sub-functions forms a module that I'll call the *coupling module*. The flow torque emerges from the *convert electricity to torque* sub-function and travels through the sub-functions *change torque, transmit torque, rotate solid* and *dissipate torque*. Here the heuristic identifies four sub-functions that form the *torque transmission module*.

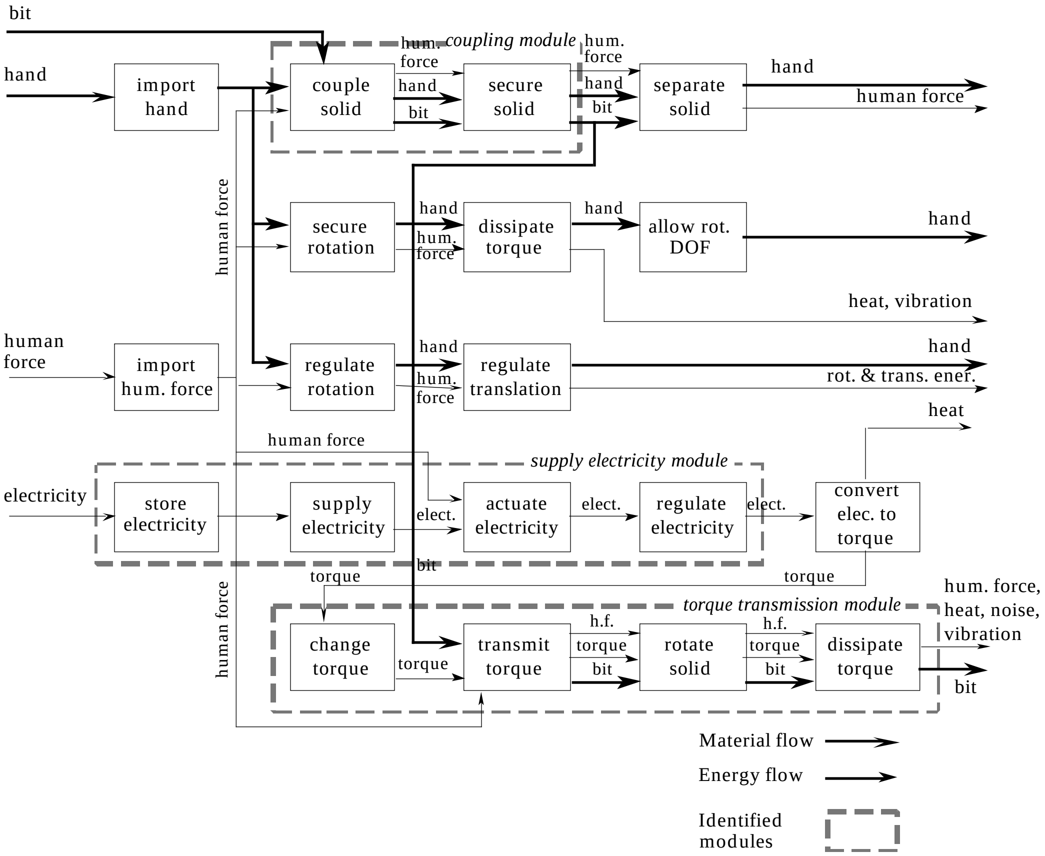


Figure 3.8 Modules identified by the dominant flow heuristic from a function structure of the SKIL Twist power screwdriver.

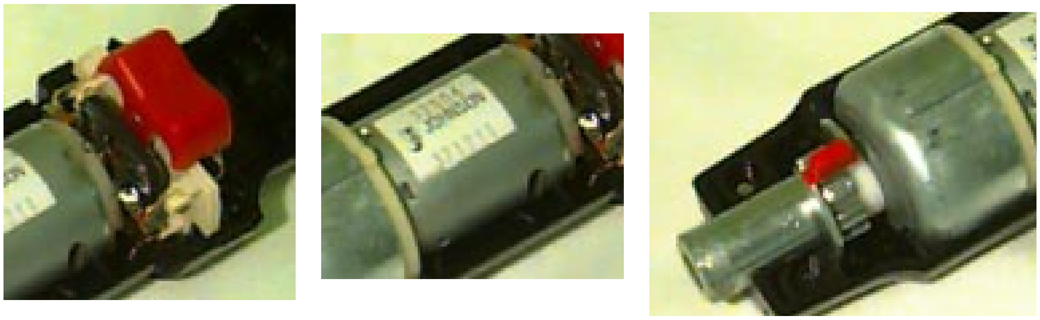
For the power screwdriver, the dominant flow heuristic identifies three modules, one for each purely sequential function chain. Not all device function structures will have a module associated with every non-branching flow. In some instances, flows may enter only one sub-function and then exit the system or be transformed, thus never forming a sequential function chain. Next, I discuss how the identified modules compare with existing modules and how others offer an opportunity for a more modular design.

Screwdriver - Actual modules

The identified modules are now verified by checking the actual device. Actual modules will be referenced with respect to the exploded view shown in Fig. 3.9. The module associated with the flow of electricity is actually found as two modules in the SKIL Twist power screwdriver. The *store electricity* and *supply electricity* sub-functions are embodied by a rechargeable battery, while the *actuate electricity* and *regulate electricity* functions form a switch module (to turn on as well as change the direction of the screwdriver). These two sub-modules are shown in Fig. 3.9 (c) and (f). In a sense, the heuristic method correctly identifies sub-functions that come together as a module. A possible device improvement, shown in Fig. 3.10, integrates the four sub-functions into a single component that stores, supplies and actuates electricity and interfaces with other drive units besides screwdrivers. The rechargeable battery solves the *store electricity* sub-function. The switch handles the sub-functions *actuate electricity* and *regulate electricity*. The contacts *supply electricity* for associated drive units. With this concept, the *supply electricity module*, would interface with different drive modules to create a mix modularity tool. For example, it could attach to a screwdriver, drill, detail sander or flashlight drive unit. This approach advances the modular battery powered hand tools available today a step further.

(a) Overview

(b) Exploded view



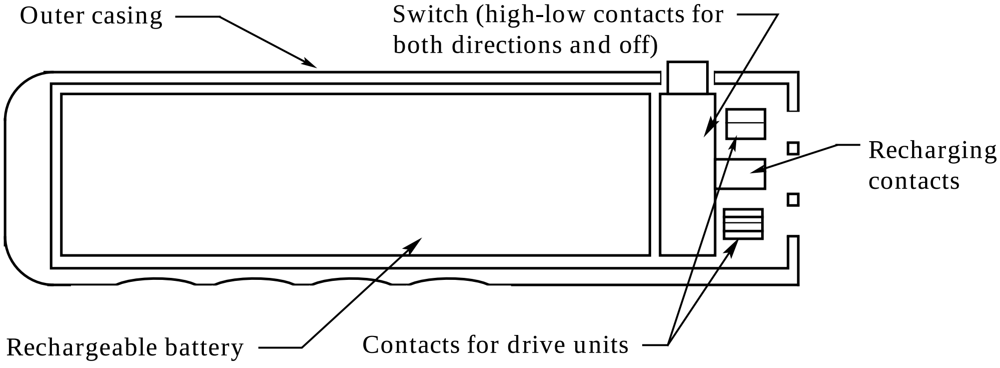
(c) Switch

(d) Motor

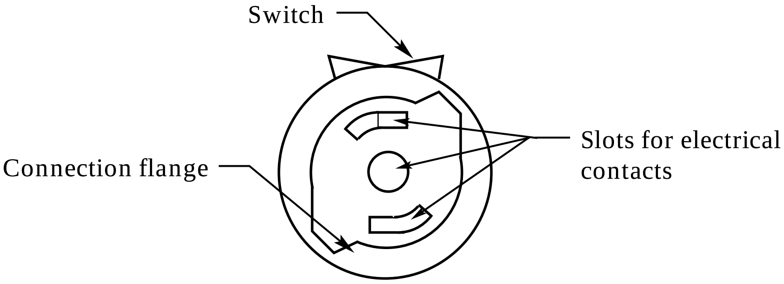
(e) Transmission and rotational lock

(f) Rechargeable battery

Figure 3.9 Views of the SKIL Twist power screwdriver.



(a) side view



(b) end view

Figure 3.10 Schematic of a possible *supply electricity module* for the SKIL power screwdriver. The side view is shown in (a) and the end view in (b). The rechargeable battery solves the *store electricity* sub-function. The switch handles the sub-functions *actuate electricity* and *regulate electricity*. *Supply electricity* is solved by the contacts for the drive units. With this concept, various drive units (such as a screw drive or a small sander) would attach with the *supply electricity module* through the connection flange.

Predicted modules associated with the flows bit and torque exist in the screwdriver as well. The *coupling module* and a subset of the *torque transmission module* (sans the *change torque* sub-function) are embodied by the same physical component (Fig. 3.9 (e)). Note that the dominant flow method does not identify this module sharing opportunity, i.e. the possibility of a single, physical module to embody two or more module concepts.

Thus, the dominant flow heuristic method predicts modules that exist in the screwdriver. In addition, it provides an innovative way of combining functions into one component that could be shared among devices. Another point to note about the dominant flow heuristic is that it defines functions that can be combined into assembly modules, i.e. parts that are best connected together before assembling the entire device.

Air popper - Identified modules

The Presto hot air popper is a popcorn popper that eliminates the need for oil in the popping process. This device evolved from such basic customer needs as wanting less mess when making popcorn and also from calorie conscious customers who did not want the extra calories introduced by the oil (though the option to lather the popcorn in butter is still present).

To begin the dominant flow analysis, the ranked flows are needed. Table 3.1 lists the customer needs and their correlation to flows. Table 3.2 then shows the ranked flows for the popper. In the Presto hot air popcorn popper, the highest ranked flow is air.

Figure 3.11 shows the function structure of the popper and the identified modules. The module associated with the air flow is the *air handling module.* It is comprised of the sub-functions *import gas, guide gas, convert rotational energy to pneumatic flow, transport gas* and *transmit thermal energy*. Note that the module stops prior to the flow split. Interactions of this module include *rotational energy, acoustic energy, thermal energy, pneumatic flow* and, of course, *air*.

Table 3.1 Customer need statements, importance rankings and their correlation to flows for the Presto hot air popcorn popper.

Customer need	Scaled cust. need importance (1 to 5)	Associated flow(s)
Short popping time	5	electricity, air, pneum. ener., therm. ener.
Easy to clean	4	butter, kernels
Simple operation	4	electricity, kernels, butter, air
Good taste	3	kernels, butter
Butter melts quickly	3	air, pneum. ener., therm. ener.
Make large batch	3	air, pneum. ener. therm. ener., kernels
Direct popcorn into bowl	2	air, pneum. ener., kernels
Easy to lift	2	electricity, therm. ener.
Keep popcorn warm	2	therm. ener., air, pneum. ener.
Easy to store	1	electricity
Easy to handle	1	electricity

Table 3.2 Flow ranking for the Presto hot air popcorn popper.

Flow	Associated cust. need ratings	Cumulative flow rating
air	5, 4, 3, 3, 2	17
kernels	4, 4, 3, 3	14
electricity	5, 4, 2, 1, 1	13
pneum. energy	5, 3, 3, 2	13
therm. energy	5, 3, 2, 2	12
butter	4, 3	7

The next ranked flow of kernels identifies the *kernel handling module.* Its member sub-functions are *import solid, store solid, transmit thermal energy, transport solid* and *export solid.* Interactions that cross the module boundary are *air, pneumatic flow, thermal energy* (of the *pneumatic flow*) and *kernels.*

The final module identified is the butter handling module with sub-functions *import solid, store solid, convert solid to liquid, store liquid* and *export liquid.* Here the interactions are *air, pneumatic flow, thermal energy* and *butter.*

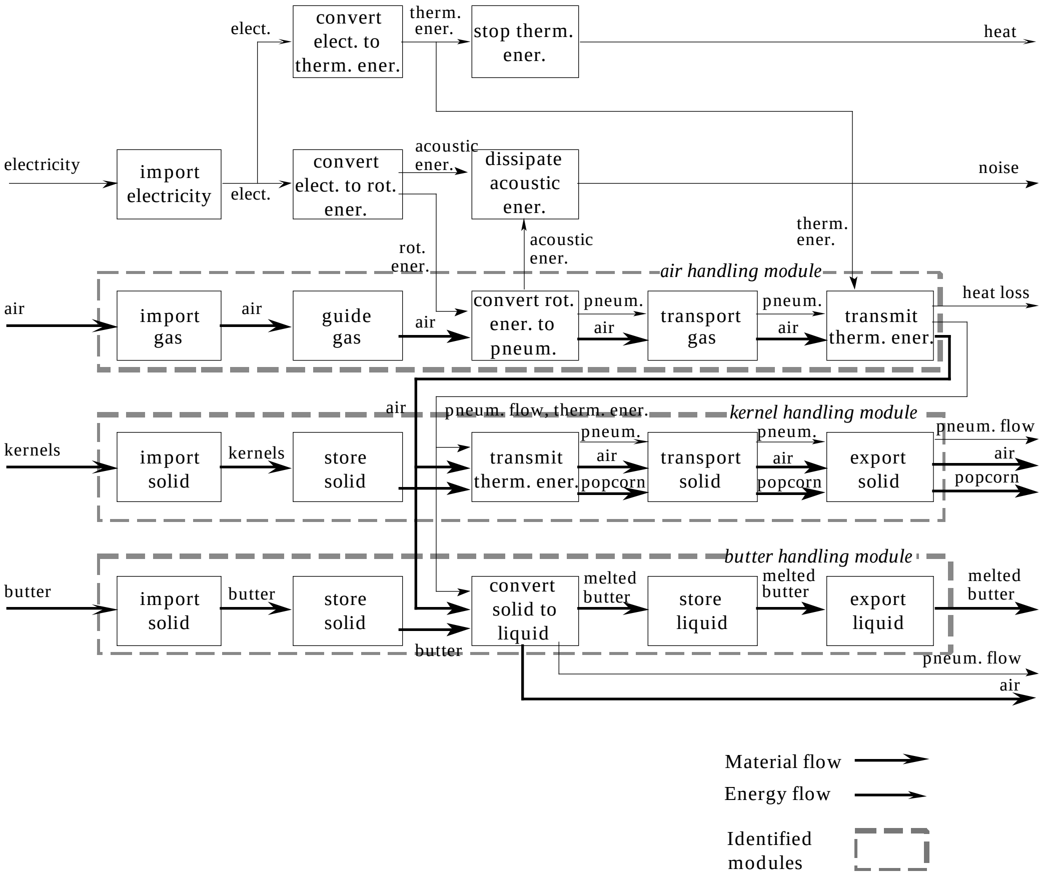


Figure 3.11 Modules identified by the dominant flow heuristic from a function structure of the Presto hot air popcorn popper.

Air popper - Actual modules

An exploded view of the Presto hot air popcorn popper is shown in Fig. 3.12. Modules will be referenced with respect to the exploded view. Considering the actual air popper, the identified *air handling module* does not exist as defined by the dominant flow heuristic. A subset of it, namely the *import gas* and *guide gas* sub-functions, is embodied by the outer housing of the popper (item 13 of the exploded view). The reason that this module does not fully exist will become apparent in Section 3.3.3, so bear with me until then.

The other two identified modules, *kernel handling* and *butter handling*, do exist. The *kernel handling module* is a cylindrical container with a screened hole in the bottom to hold the kernels and allow the hot air to flow through and transmit the thermal energy to the kernels. The container also transports and exports the popped kernels from the system. The module is realized as an assembly module consisting of items 2 - 5. The *butter handling module* is simply the butter cup that sits on top of the *kernel handling module* and holds the butter as the hot air below melts it (item 1). Note that both modules have physical conduits for their interactions of *hot air* and *pneumatic flow*.

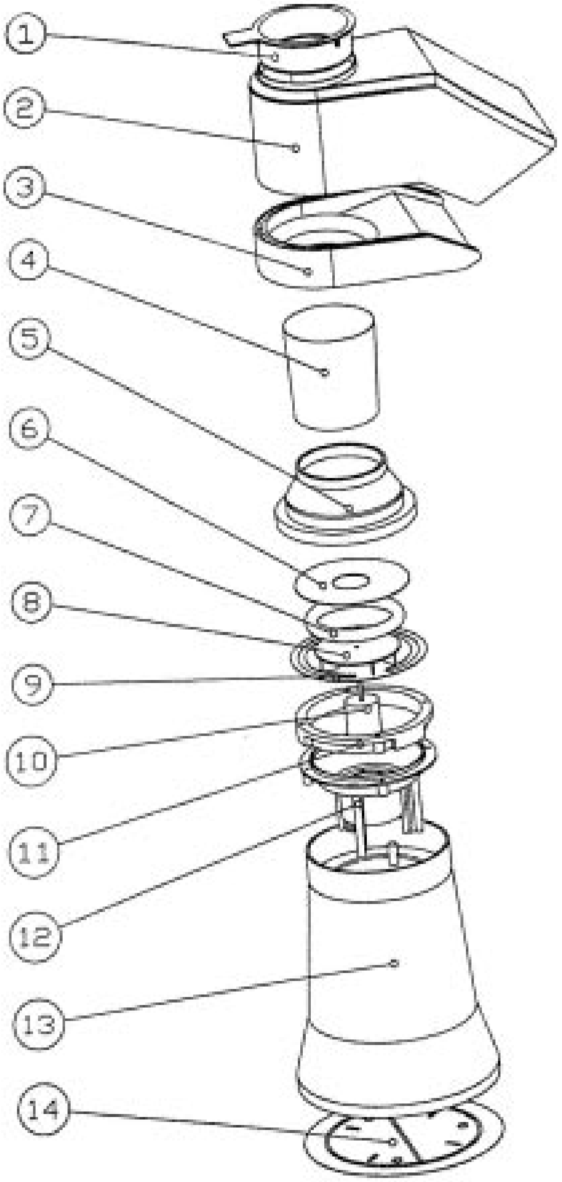


Figure 3.12 Exploded view of the Presto hot air popcorn popper. Bill of materials includes: 1-butter cup, 2-spout, 3-spout base, 4-container wall, 5-container bottom, 6-upper heating plate, 7-heating element, 8-impeller, 9-lower heating plate, 10-motor, 11-insulator ring, 12-motor housing, 13-housing, and 14-base plate.

3.3.2 Branching Flows

The method of the branching flow heuristic first requires identification of flows that branch into parallel function chains. Once identified, we will examine them in descending rank order. Each branch of the flow defines a potential module as shown schematically in Fig. 3.13. The module is formed of the sub-functions that make up the branch (each branch consists of a sequential function chain). All modules (one per branch) must interface with the device at the last sub-function before the flow branches. All flows that cross this interface are the interactions between the remaining device and the module.

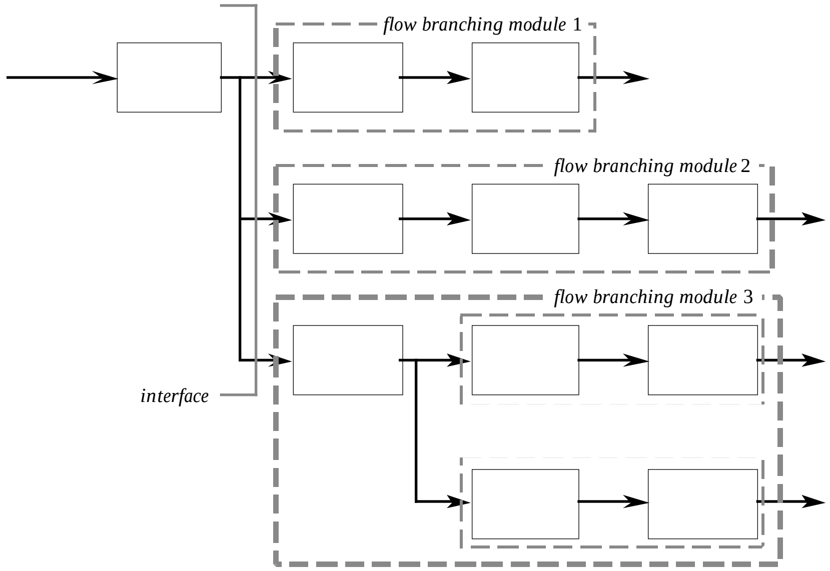


Figure 3.13 Flow branching heuristic applied to a generic function structure.

Note that branching flows will identify devices capable of component swapping or bus modularity. The interface boundaries defined are physical connections between module and device. In some cases they will be well-defined geometric connections, like various end mill attachments on a milling machine. Other times, the interface may be more fuzzy, like the differing interactions between the hand and the SKIL Twist power screwdriver.

The branching flow heuristic is stated formally as:

> **Proposition 2:** Parallel function chains associated with a flow that branches constitute modules. Each of the modules interface with the remainder of the device through the flow at the branch location.

Screwdriver - Identified modules

The power screwdriver has three flows which branch, the *bit, hand* and *human force*. Of the three flows, *human force* has the higher rank and will be examined first. Following the sub-function *import human force,* the flow branches into five limbs. Each branch represents a module as shown in Fig. 3.14. The five identified modules are the *coupling/decoupling, rotational lock, positioning, actuating* and *bit-torque transmission* modules. Note that a subset of the *coupling/decoupling* module was identified by the dominant flow heuristic. The *bit-torque transmission* and *actuate* modules are subsets of modules identified by the dominant flow heuristic. The *rotational lock* and *positioning* modules are new.

The second branching flow of the *hand* splits into three limbs. In this case two of the identified modules, *coupling/decoupling* and *positioning,* are the same as identified by the flow human force. The third module, named *manual use,* is a superset of the *rotational lock* module identified by the flow human force.

The branching flow of *bit* identifies two possible modules: *decoupling* and *bit-transmission*. The *decoupling* module, together with the *coupling* module of the dominant flow heuristic, constitute the *coupling/decoupling* module already identified. The *bit-transmission* module was previously identified as well.

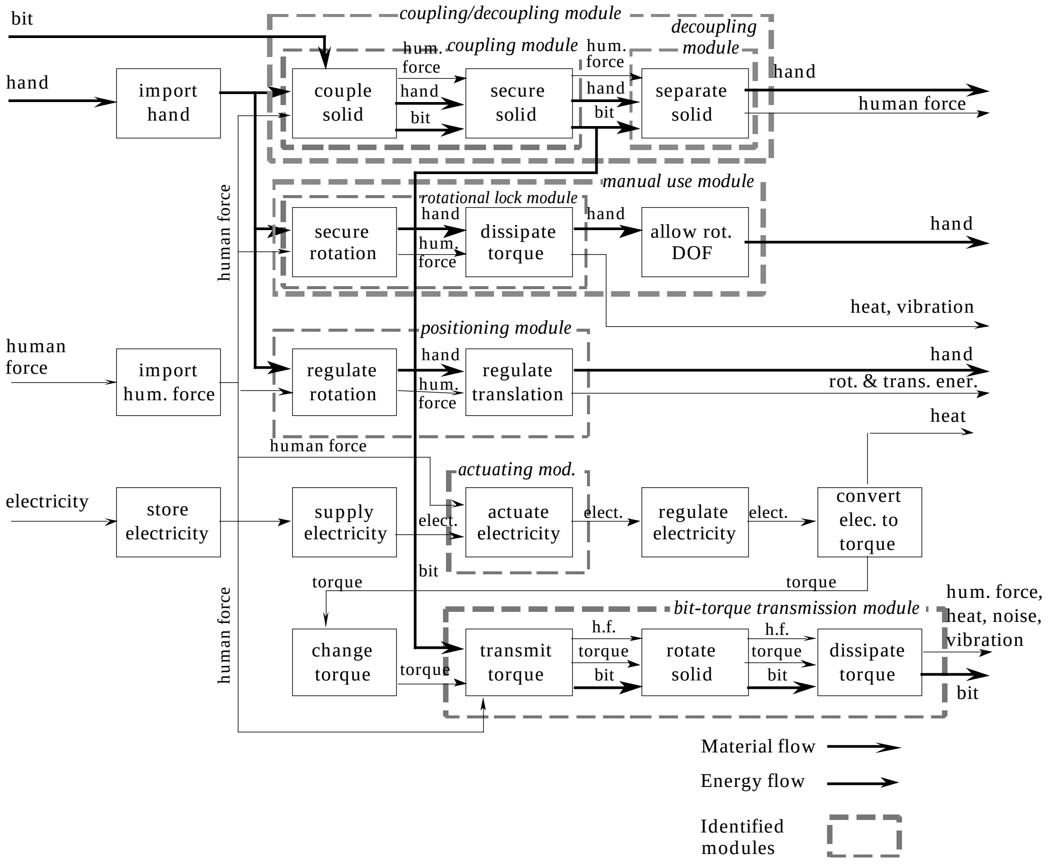


Figure 3.14 Modules identified by the flow branching heuristic from a function structure of the SKIL Twist power screwdriver.

Screwdriver - Actual modules

The branching flow heuristic identifies several modules that overlap with the modules from the dominant flow heuristic in addition to two new modules. The *coupling/decoupling* and *bit-torque transmission* modules are embodied by the same component as the *coupling* and *torque-transmission* modules of the previous section. The *actuating* module is a subset of the s*upply electricity* module. The *manual use* module is embodied by a tab that locks the screwdriver transmission in place and is shown in Fig. 3.9 (e). Also, the *positioning* module is essentially the plastic casing of the screwdriver.

A few remarks about the heuristics usage thus far are warranted. It is evident that they identify overlapping modules in some cases. At this point, we wonder about which module to implement in such a case. This will be addressed in Chapter 4, when customer needs are associated with modules. For now, I make the observation that the more ways a module is identified (in terms of heuristics and flows), the more important it is to implement.

Air popper - Identified modules

The branching flow modules for the air popper are shown in Fig. 3.15. Two flows, *pneumatic flow* and *air*, branch and identify modules. Since these flows trace the same route through the function structure, each identifies the same modules. The two modules, *kernel heating* and *butter heating*, deal with transmitting heat to a material and then moving it out of the system. Both of these modules interface with the rest of the device after *thermal energy* is transmitted to the *air* and *pneumatic flow*. These two flows combined with the material that enters the module are the primary interactions of the modules. You will notice that the modules are subsets of those predicted by the dominant flow heuristic.

Note that the flow electricity splits into two branches. However, in both cases the electricity enters a conversion sub-function. Thus, the flow never exits a sub-function and cannot be identified as a module by the branching flow heuristic. The next heuristic answers this problem.

Air popper - Actual modules

The two branching flow modules exist as subsets of the *butter handling* and *kernel handling modules*. So, for this particular device, the modules implemented are the larger set of sub-functions.

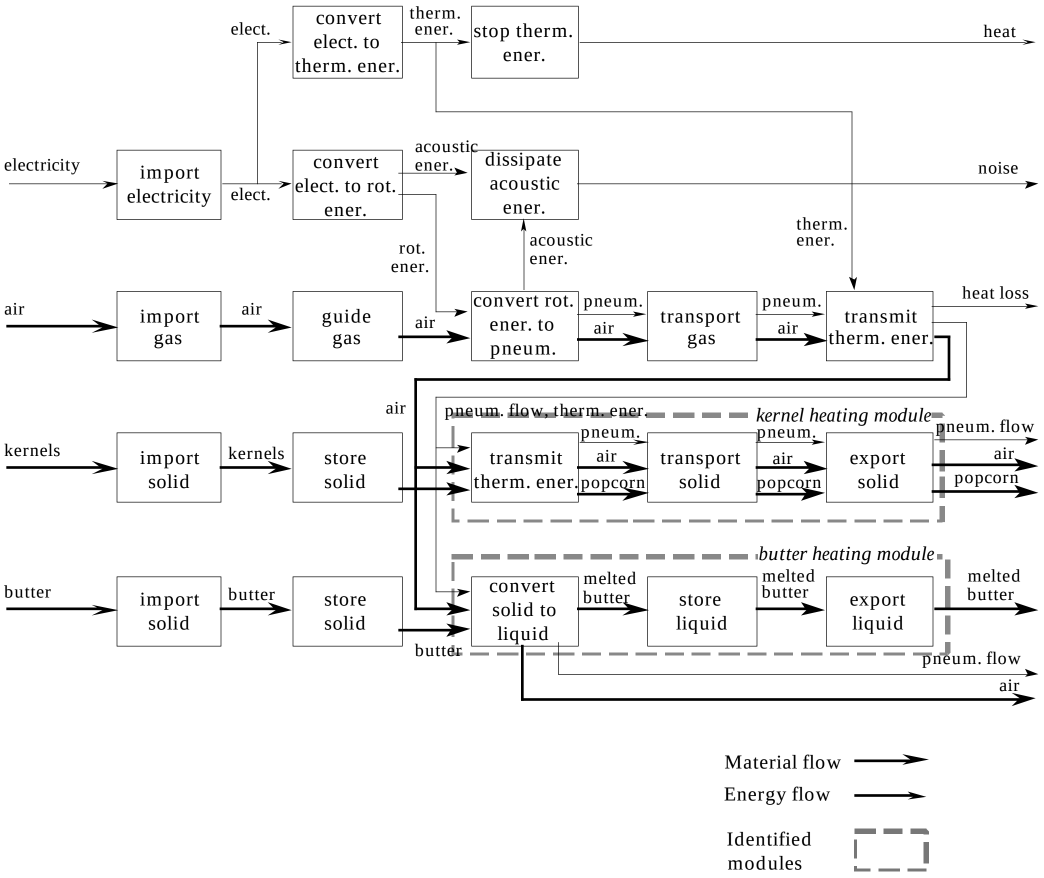


Figure 3.15 Modules identified by the flow branching heuristic from a function structure of the Presto hot air popcorn popper.

3.3.3 Conversion-Transmission Modules

The third heuristic method deals with conversion sub-functions and conversion to transmission chains. Conversion sub-functions accept a flow of material or energy and convert the flow to another form of material or energy. In many cases, these conversion sub-functions are already components or modules themselves. For instance, electrical motors, hydraulic cylinders and electrical heaters can all be represented by a single conversion sub-function and exist physically as a single component. If, additionally, the conversion sub-function exists in a chain with a transmit sub-function (or transport sub-function for material flow), then the chain presents an opportunity to form a module which converts an energy or material to another form and then implements (transmits or transports) that new form of energy or material.

The method of the conversion-transmission heuristic, shown schematically in Fig. 3.16, is simple. Identify conversion sub-functions and check for transmit or transport sub-functions downstream of the converted flow. If none exist, then the conversion sub-function is a module by itself. If transmit or transport sub-functions exist without any other sub-functions between them, then the convert-transmit (transport) pair represents a module. If other sub-functions exist between the convert and transmit (transport) sub-functions and those intermediate sub-functions only operate on the converted flow (i.e. the object in the sub-function verb-object pair is the converted flow), then the conversion-transmission (transportation) chain represents a module.

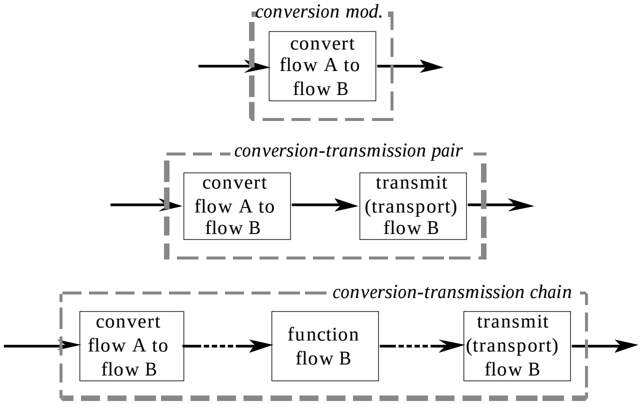


Figure 3.16 Conversion-transmission applied to a generic set of sub-functions.

Interfaces of a conversion-transmission module are defined in a similar manner as those for a dominant flow module. Two necessary interactions across the interface are the flow to be converted and then the exiting converted flow. Additional flows may also cross the interface.

The conversion-transmission proposition, stated succinctly is:

Proposition 3: A conversion sub-function or a conversion-transmission pair or proper chain of sub-functions constitutes a module.

Screwdriver - Identified modules

Consider the power screwdriver again, the conversion-transmission heuristic identifies one module as shown in Fig. 3.17. It consists of three sub-functions, the bounding *convert electricity to torque* and *transmit torque* and the intermediate sub-function *change torque*. The interface of the *electricity to torque* module is outlined in Fig. 3.17. The interactions are the two necessary flows of *electricity* and *torque* along with *heat* and *coupled bit*.

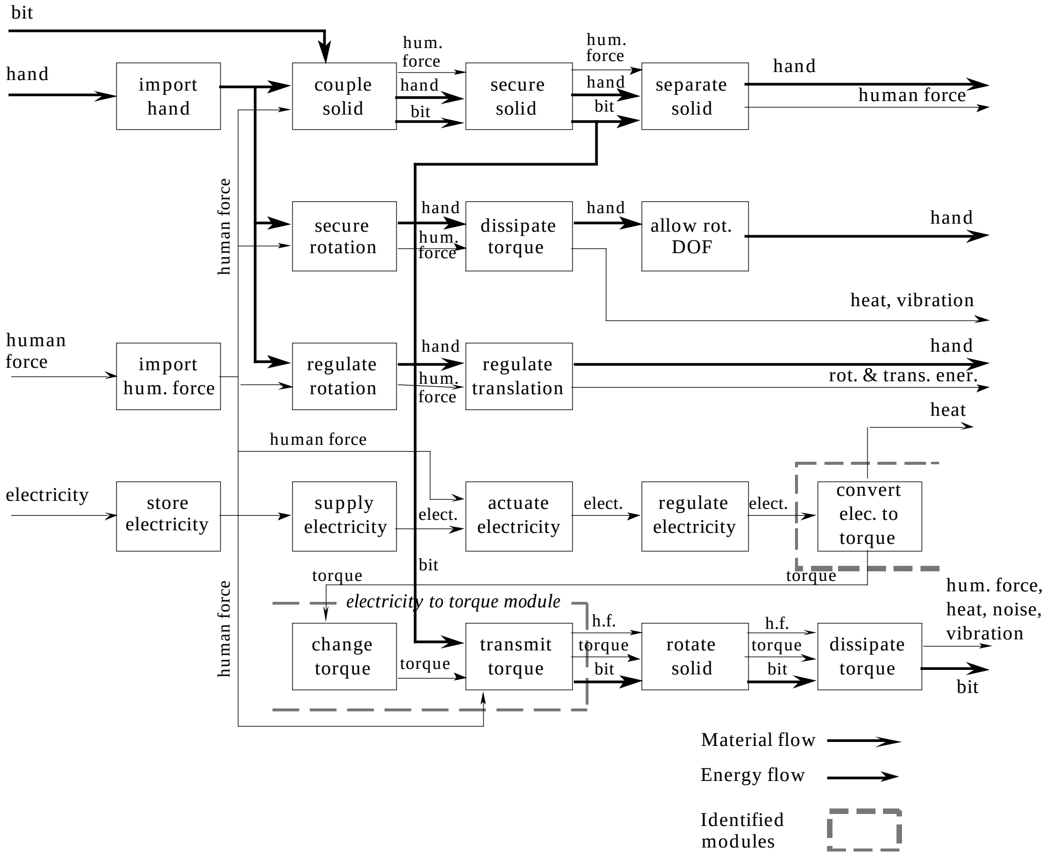


Figure 3.17 Module identified by the conversion-transmission heuristic from a function structure of the SKIL Twist power screwdriver.

Screwdriver - Actual modules

In the actual device, the three sub-functions are not embodied as a single module. The *convert electricity to torque* sub-function is a distinct component, shown in Fig. 3.9 (d) The *change torque* and *transmit torque* sub-functions, though, are part of the *torque transmission module* in Fig. 3.9 (e). In this case, the method provides an innovative approach to design of a module that incorporates a motor, transmission and drive-train. Recall the innovative *supply electricity* *module* of the screwdriver in Section 3.3.1. In concert with the *supply electricity module,* the *electricity to torque module* becomes the drive units in a mix and match set of power packs with switches and motor drive units.

Air popper - Identified modules

Returning one last time to the air popper, the conversion-transmission heuristic identifies three modules as shown in Fig. 3.18. The first is the *electrical to rotational energy module.* It is simply one sub-function: *convert electricity to rotational energy*. The interactions are the two necessary energy flows plus the by-product of *acoustic energy*. The *electrical to thermal energy module* is a convert-transmit pair. Besides the two necessary flows, the interactions are *excess heat, pneumatic flow* and *air*. The final module, this time a convert-transport pair, is the *rotation to pneumatic module.* Notable interactions are *air* and *acoustic energy*.

Recall in the air popper example of Section 3.3.2 that I noted that the flow of *electricity* branches, but did not apply the branching flow heuristic to it. The reason, though not apparent at the time, was *electricity* split and then entered two convert sub-functions. This is a more appropriate situation to use the conversion-transmission heuristic.

Air popper - Actual modules

In the air popper, the easiest identified module is the *electricity to rotational energy module* which is embodied by the motor (item 10 of Fig. 3.7). The two necessary interactions, *electricity* and *rotational energy*, require geometric conduits of electrical leads and a shaft, respectively. The other interaction, *acoustic energy,* does not require a physical conduit. An impeller is the incarnation of the *rotation to pneumatic module* (item 8). The *electrical to thermal energy module* is present in the air popper as well. It consists of a heating element and heating plates with a passageway for transmission of heat to the air flowing through the module (items 6-9). The passageway is the conduit for the interaction of *air* and *pneumatic flow*. The necessary interactions of *electricity* and *thermal energy* require physical conduits supplied by electrical leads and the surface of the heating element and plates.

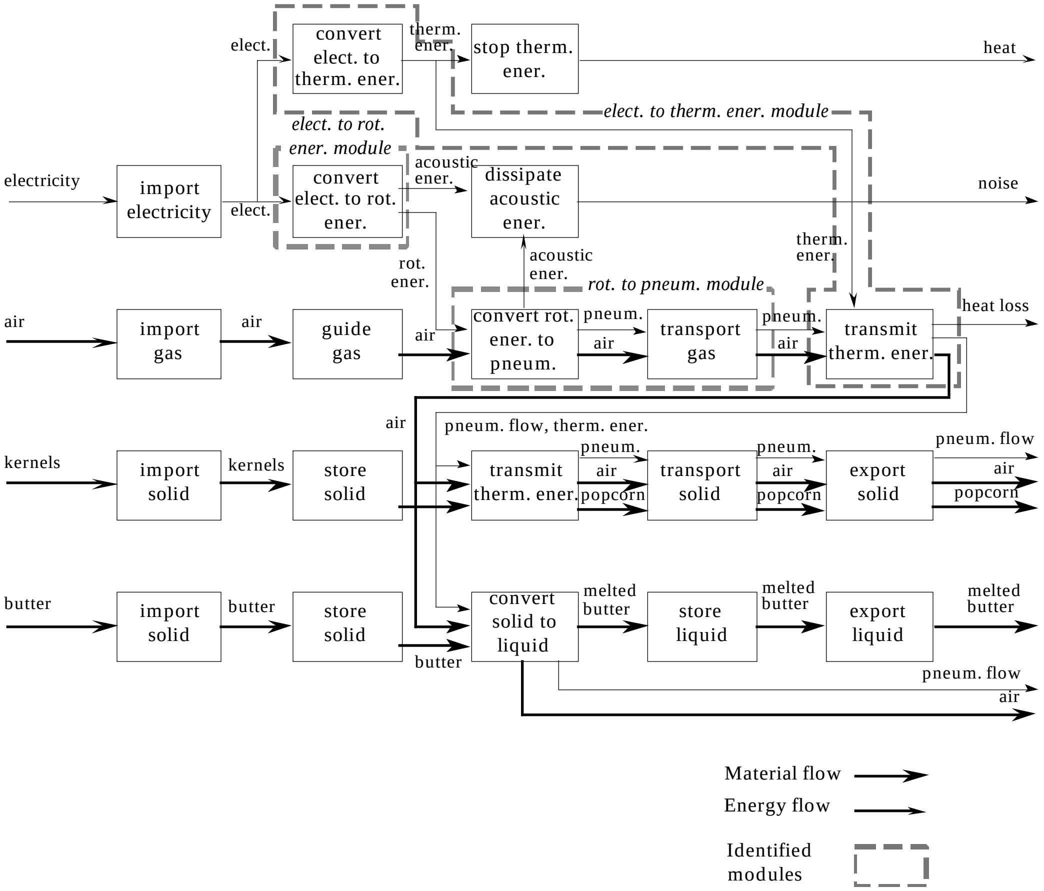


Figure 3.18 Module identified by the conversion-transmission heuristic from a function structure of the Presto hot air popcorn popper.

3.4 VERIFICATION OF HEURISTIC METHODS

The three heuristic methods introduced in Section 3.3 were presented with two examples. The heuristics were verified more rigorously using a database of 70 devices, of which the two example devices are a part. The devices represent a wide range of consumer applications, customer needs and overall functions. The mechanical or electromechanical devices include small construction tools, small kitchen appliances, automobile accessories, small household appliances and toys. This set of devices represents over 100 person years of work in reverse engineering and redesign and is the same set used in recent papers by Little et al. (1997) and McAdams et al. (1997). The redesigns and case studies are the result of course work and research at The University of Texas at Austin.

Of the 70 devices, 18 are transformed into the functional basis described in Chapter 2. The 18 devices are representative of the wide range of consumer applications in the entire database. Two types of devices, an iced tea brewer and a power screwdriver, are repeated (same type of device, different manufacturer) to examine the differences in competing products. All device function structures produce modules when the three heuristic methods are applied. Table 3.3 presents the results. The device function structures are included in Appendix C. The devices are listed in column one followed by three columns that indicate the number of modules identified by each of the three heuristic methods: dominant flow, branching flow and conversion-transmission. The next three columns indicate the actual modules found in the devices, associated with the three heuristic methods. Since it is possible for the different heuristic methods to identify overlapping modules, the final two columns give the number of unique modules possible and then the actual number of modules found in the device.

Table 3.3 Statistical comparison of identified modules and actual modules in 18 devices.

Device	Identified modules			Actual modules			Unique module poss.	Actual module total
	Dom. flow	Branch. flow	Conv.-Trans.	Dom. flow	Branch. flow	Conv.-Trans.		
Mr. Coffee iced tea/coffee brewer	6	4	1	5	3	1	7	6
West Bend iced tea/coffee brewer	6	4	1	4	3	1	7	5
Mr. Coffee coffee maker	5	3	1	3	1	1	6	3
B&D screwdriver	3	6	1	2	3	0	6	4
SKIL screwdriver	3	6	1	3	4	0	6	5
DeWalt sander	4	4	3	4	3	3	9	7
Bissel hand vacuum	5	3	2	4	2	2	6	6
Pencil sharpener	3	2	1	3	2	1	4	4
B&D electric knife	3	4	2	2	2	2	6	4
Presto air popcorn popper	3	2	3	3	2	3	8	6
Krups cafe trio	3	2	1	3	1	1	6	5
B&D sander	5	2	3	3	2	3	7	6
Dazey fruit/veggie peeler	5	3	2	3	2	2	7	4
Dremel engraver	3	4	1	2	2	1	5	3
1974 Chevy tailgate	3	6	1	2	3	1	5	3
B&D VersaPak trimmer	4	2	1	4	2	1	5	5
Cadillac visor	2	0	2	2	0	2	4	2
Super Maxx ball shooter	3	2	2	3	0	2	6	3
Average	4	3	2	3	2	2	6	4

It is important to note from the final two columns of Table 3.3 that the number of unique modules possible is always greater than (or equal to for three of the devices) the actual number of modules implemented in current devices. This strongly supports the heuristic methods' validity as a tool to identify all possible modules in a device. For this database of consumer, largely hand-held devices, four to nine unique modules are possible. The actual devices, though, incorporate between two to seven modules, with some exhibiting an impressive degree of modularity. As a comparison, the clinker clearer (a more complex device explained in Chapter 6) has a unique module possible count of 14 for its two subsystems studied. For consumer devices with 15 to 30 sub-functions, we now know that, on average, six unique modules are possible.

Two case studies follow; one compares the two iced tea brewers (different manufacturer, similar product) and the other is a comparison of the iced tea brewer and coffee brewer (same manufacturer). These case studies provide additional support for the module heuristics presented in Section 3.3. In the case of the apples to apples comparison of the iced tea brewers, the degree of modularity of the devices is compared. The apples to crab apples comparison of the Mr. Coffee iced tea brewer and coffee brewer shows how modules may be used across different, but related devices.

3.4.1 Apples to Apples Case Study

In this comparison, I examine the possible and actual modules of two iced tea brewers by manufacturers West Bend and Mr. Coffee. The function structure for both devices, represented in functional basis form, is shown in Fig. 3.19. Since the devices are functionally equivalent, one function structure is representative of both. As Table 3.3 shows, the module heuristics identify six dominant flow modules, one branching flow capable of producing four modules and one conversion-transmission module. These are shown schematically in Fig. 3.19.

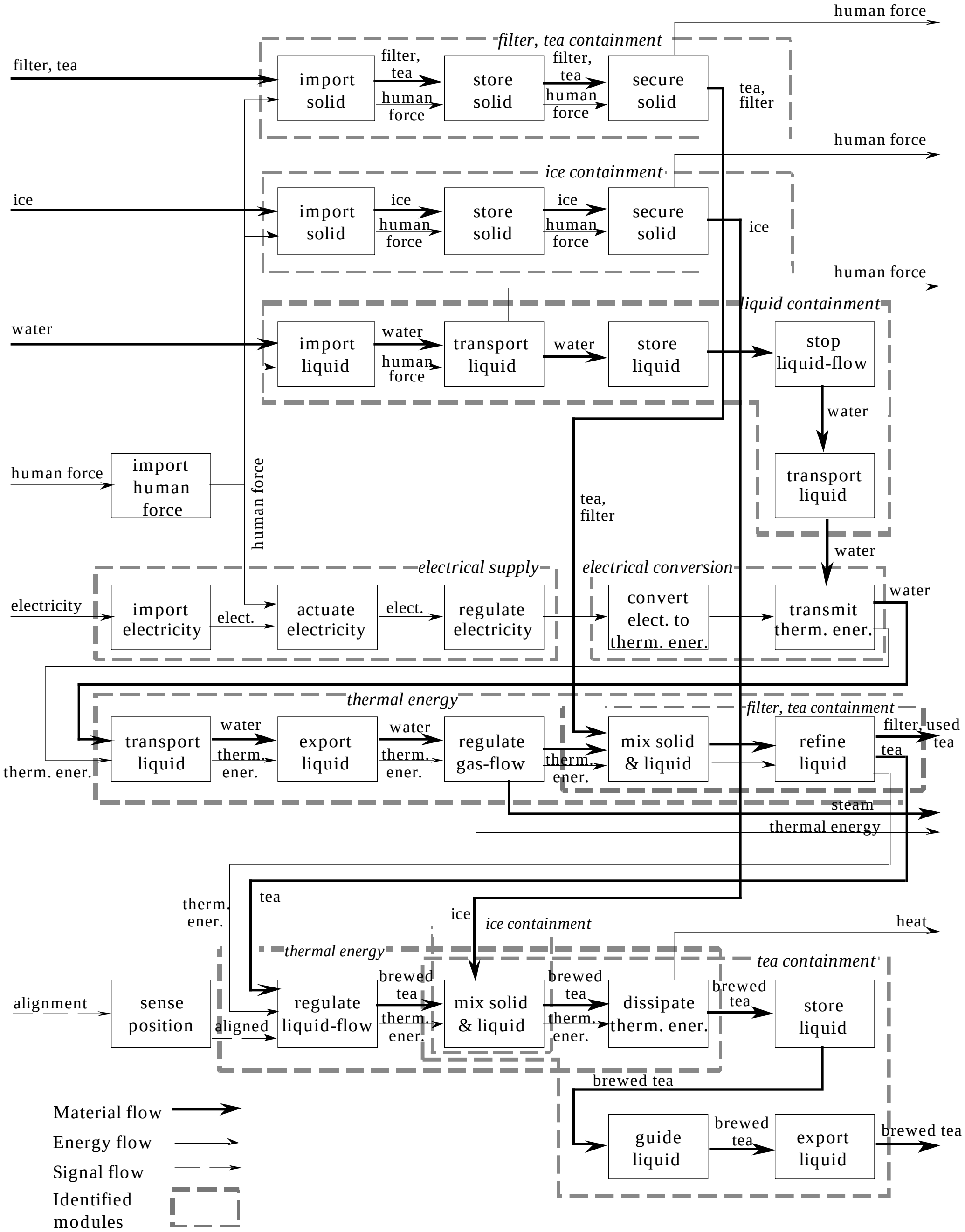


Figure 3.19 Function structure for both the Mr. Coffee and West Bend iced tea / coffee brewers.

Five modules were found in the Mr. Coffee device while only four were found in the West Bend device. Table 3.4 lists the actual modules and the functions they solve. In the first column, the name of the module from Fig. 3.19 is given. Only modules that exist as defined by the heuristics are included. The second column lists the heuristic or heuristics that identified the module along with the relevant flows. Columns three and four report if the module appears in the device, and column five lists the figure that shows the module.

Table 3.4 Actual modules found in the apples to apples case study of iced tea brewers.

Identified module: *functional description*	Identifying heuristic (*flow*)	Mr. Coffee	West Bend	Assoc. Fig.
electrical supply: *import electricity, actuate electricity, regulate electricity*	Dominant flow (*electricity*) Branching flow (*human force*)	exists	exists	3.20
electrical conversion: *convert elect. to thermal energy, transmit thermal energy*	Conv.-trans. (*elect. , thermal*)	exists	exists	3.20
ice containment: *import human force, import solid, secure solid, mix solid & liquid*	Dominant flow (*ice*) Branching flow (*human force*)	exists	exists	3.21
tea containment: *mix liquid & solid, dissipate thermal energy, store liquid, guide liquid, export liquid*	Dominant flow (*brewed tea*)	exists	exists	3.21
filter & tea containment: *import solid, store solid, secure solid, mix solid & liquid, refine liquid, regulate liquid-flow, export solid*	Dominant flow (*tea, filter*) Branching flow (*human force*)	exists	does not exist as a module	3.22

The *electrical supply* and *electrical conversion modules* are shown in Fig. 3.20. The two modules are combined into an assembly module in the tea brewers, though they are still distinct components. It can further be identified as an example of component sharing modularity.

The third and fourth modules, *ice containment* and *tea containment*, respectively, are embodied by the same component. Shown in Fig. 3.21, the pitcher solves the *ice containment* module in full. It also solves the *tea containment* module identified by the dominant flow brewed tea. Additionally, the *tea containment module* is used to import liquid (water) into the iced tea brewer. Marks on its side indicate the amount of water necessary, as well as the amount of ice.

Figure 3.20 West Bend (left) and Mr. Coffee (right) *electrical supply* and *electrical conversion modules* present in the iced tea brewers.

Figure 3.21 West Bend (left) and Mr. Coffee (right) *ice containment* and *tea containment modules* present in the iced tea brewers.

The fifth module, *filter & tea containment*, is predicted fully by the dominant flows of *tea* and *filter* and is a superset of the module predicted by the branching flow *human force*. As shown in Fig. 3.22, the Mr. Coffee iced tea brewer has this module while the West Bend does not.

Figure 3.22 Mr. Coffee *filter & tea containment module* in the iced tea brewer. This module is not present in the West Bend device.

What does this case study prove? Several things. It serves as an additional physical verification of the heuristics' validity. It shows a surprising degree of similarity of devices made by different manufacturers, suggesting that, while not formalized, some level of modular design exists in industry today. In addition, it shows an opportunity for increased modularity in the West Bend tea brewer. Which leads me to an interesting conjecture, that a higher degree of modularity translates to a better product. That means that the Mr. Coffee iced tea brewer is the better product in this case. This assertion is supported by customer surveys as well.

3.4.2 Apples to Crab Apples Case Study

Here, the Mr. Coffee iced tea brewer of Section 3.4.1 is compared with a different, yet similar, device: a Mr. Coffee coffee maker. Again, the goals of this case study are to verify the heuristic methods and to examine the possibility of using modules across different products.

The function structure for the coffee maker is shown in Fig. 3.23, complete with modules identified by the three heuristic methods. Recall that the iced tea brewer's function structure is shown in Fig. 3.19. Note that, as one expects, the two function structures are similar and that the coffee maker predicts essentially the same modules except for the *ice containment* module of the tea brewer.

Three actual modules are found in the coffee maker (of the six unique modules possible), as compared to the five that exist in the tea brewer. The interesting aspect is how similar the modules are between the two different products. Figure 3.24 shows the *electrical supply* and *electrical conversion modules* for both devices. Using the terminology of this chapter, the *electrical conversion module* represents a sizable module. In both products, the *electrical conversion module* is made from the same extruded tubing. The actuate electricity function solution of the *electrical supply module* is slightly different, due to the automatic shut-off feature of the tea brewer as opposed to the rocker switch of the coffee maker.

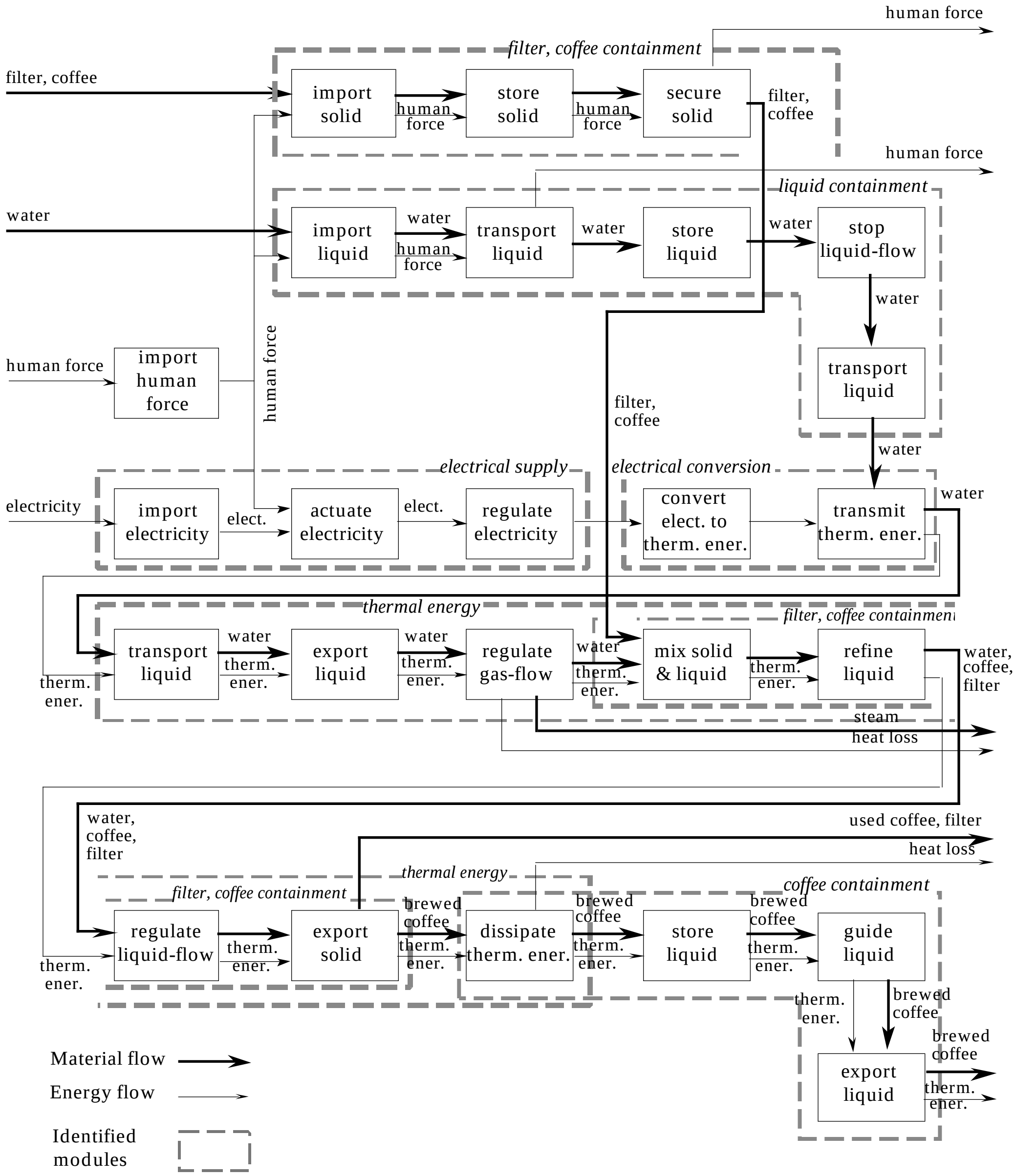


Figure 3.23 Function structure for the Mr. Coffee coffee maker with identified modules.

Figure 3.24 Mr. Coffee iced tea brewer (left) and coffee maker (right) *electricity to thermal energy modules*.

The third module that the two devices share is the *tea* and *coffee containment* module. This module is a conceptual module, as it uses the same solution principle in both devices, but the physical incarnation is different. The tea brewer utilizes a plastic, cylindrical pitcher while the coffee maker employs a glass, almost spherical pitcher.

Another module exists in the two devices. It is a subset of the *liquid containment* module. Here, both devices use the same component to solve the functions *stop liquid-flow* and *transport liquid* as shown in Fig. 3.25. This is an example of component sharing modularity.

For this case, three modules exist between the Mr. Coffee iced tea brewer and coffee maker. This, again, validates the methods presented in this chapter. The method also identifies opportunities for further modularity. For example, the iced tea brewer and the coffee maker both have the *filter & tea containment* module as identified by the heuristics. The module is physically incarnated in the iced tea brewer and could also be incarnated in the coffee maker. Within families of similar devices, the heuristic methods identify modules that can be shared across the family.

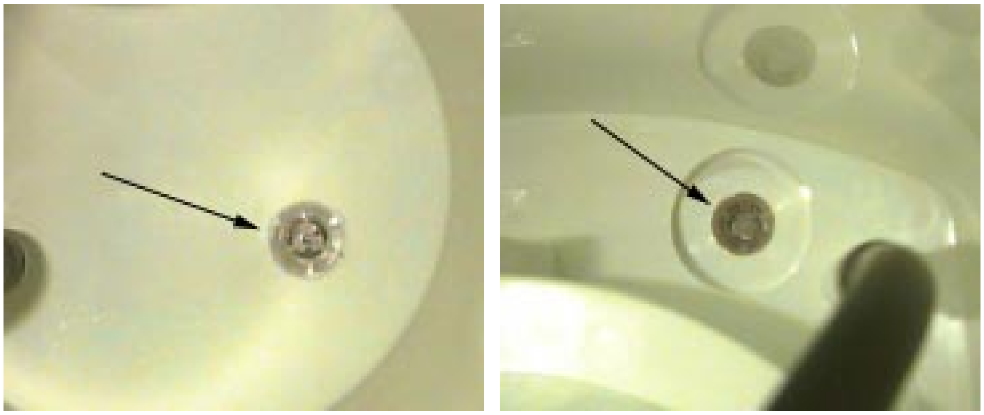


Figure 3.25 Mr. Coffee iced tea brewer (left) and coffee maker (right) subset of the *liquid containment module* (sub-functions *stop liquid*+t*ransport liquid*). These photos are of the bottom of the water tanks of the respective devices. The module transports water into the heating chamber and then stops the water from entering until the water in the chamber is hot and ejected.

3.5 SUMMARY

Chapter 3 is an information packed chapter! I started by reviewing and introducing a terminology of modular design. Six types of device modularity were reviewed: component sharing, component swapping, fabricate to fit, bus, mix and sectional modularity. Additionally, three types of manufacturing-based modularity descriptions were introduced: assembly, sizable and conceptual modules.

The heart of the dissertation followed the terminology. I introduced the three heuristic methods of dominant flow, branching flow and conversion-transmission functions. These three methods provide a systematic approach to identifying modules of a device using a function structure. While their application is elegantly simple, their utility is immense. The methods were verified using a 70 device database of consumer products. The methods always identified modules that currently exist in the products and, more importantly, identified opportunities for increased device modularity as the last two columns of Table 3.3 show. Finally, two case studies further verified the heuristic methods and demonstrated that some type of informal modular design exists in industry today.

The fact that competing devices and device families use similar or exact components lends much credence to my effort to formalize a modular design methodology. Application of the three heuristics shows that even popular consumer products overlook opportunities for modules. The three heuristic methods answer this problem in a simple, yet scientifically valid, manner. Quantitative support for these methods exists, as well. That, as you will discover, is the subject of the next chapter.

CHAPTER 4

QUANTITATIVE FRAMEWORK FOR ASSESSING MODULES

4.1 OVERVIEW

Throughout this document, I use Tinkertoys™ as a simple example of modular design. With Tinkertoys™, each piece's function is easily identifiable with one's need. For example, if I wanted to put wheels on a vehicle, I would need an axle, two wheels per axle and a way to connect the axle to the vehicle. The toy pieces that meet those needs are a stick, two disks (each with a hole for either end of the stick to insert in) and two bearings that float on the stick and allow an attachment point for the vehicle. This is shown in Fig. 4.1.

Figure 4.1 Tinkertoy™ pieces (left) that are examples of modules associated with a clear customer need. The assembled device appears on the right.

But how do we associate a module with customer needs when the correlation is not as direct as the Tinkertoy™ example? The functional base set of Chapter 2 provides a common language to describe functionality across different devices. The Chapter 3 heuristics then define modules in terms of their sub-functions, but functionality alone does not give a complete description of a device or a module. We bring customer needs into the module identification methods through the flow ranking technique, which loosely relates modules to customer needs. However, a better method is desired. Coupling customer need information with the functional description paints a more complete picture of a device. In fact, a customer need weighted functional description of a device can be represented as a vector, and a domain of devices can be compared by collecting all of the device vectors into a matrix. Manipulation of this matrix can tell us two important points concerning customer needs and modularity: 1) if devices are similar to each other and 2) if a group of sub-functions that comprise a module are meeting customer needs. Now, through this quantitative method, we can say with certainty whether or not a module meets customer needs.

4.1.1 Road Map for This Chapter

In Section 4.2, I present a quantitative framework for identifying modules based on customer needs. Note that “customer” refers not only to the consumer, but also to any entity that deals with the device, such as manufacturing. This framework, known as quantitative module assessment and based on the functional interdependence and product similarity method of McAdams et al. (1997), identifies sub-functions that can be combined into modules based on flow relationships to better meet customer need. The quantitative method also identifies device families based on the inner product of device vectors.

Verification of the module heuristics by the quantitative method is provided in Section 4.3. The 70 device database described in Chapter 3 is used for verification purposes. Specifically, the two case studies in Section 3.4 are shown to be supported by the quantitative method.

4.1.2 What's New Here

All of the theory presented in this chapter is the result of recent work in the area of relating customer needs to sub-functions at The University of Texas at Austin. What's new is the application of this theory to module identification and the use of customer need indexes as a measure of a module's utility. In a time when corporate resources are no longer viewed as unlimited, justification of module development by customer need is essential.

Specifically, notice the two methods for making the correlation between customer needs and sub-functions. One relies more heavily on engineering judgment. The second, new method tries to reduce that dependence on judgment.

4.2 QUANTITATIVE MODULE ASSESSMENT

So far I have used a base set to transform function structures and three heuristic methods to identify sub-functions that can be grouped together as a module. Customer needs were discussed briefly in Chapter 2 as a means of ranking flows. These ranked flows determine the order of flow examination in two of the heuristic methods: dominant flow and branching flow.

When it comes to quantifying the value of modular design methodology versus integral or non-modular methodologies, customer needs play a key role.

There is no better measure than that of customer needs. Meeting customer needs is already a primary component of decomposition based design methodologies (Pahl & Beitz, 1988; Ulrich and Eppinger, 1995; Ullman, 1997). Thus, the customer need ranking becomes our metric to evaluate the utility of a module.

The quantitative module assessment method that follows relates customer needs to sub-function groupings that constitute modules. This procedure originated with Little et al. (1997) as a means of exploring device and function relationships by producing a device-function matrix of normalized customer needs. It was later extended by McAdams et al. (1997) to include identification of functional relationships through a function-function matrix. This method was noted to present clear applications for module identification. Here, I summarize the method and modify it specifically for module identification.

4.2.1 The Device-Function Matrix

The first part of the functional interdependence method creates the device-function matrix and assumes that a number of devices are being studied. For each device, a function structure in functional basis form (as presented in Chapter 2) and a list of rated customer needs is required.

Correlating the customer needs to sub-functions

Next, customer need ratings are scaled to the range of 1 (optional) to 5 (must have) (Otto and Wood, 1997; Ulrich and Eppinger, 1995). The scaled customer need ratings are then correlated with the sub-functions of the device function structure to produce a device vector. This correlation is not direct, but two different methods exist to complete the correlation. The first presented is the method used in Little et al. (1997). The second utilizes the flow ranking concept introduced in Chapter 2. The two methods represent a philosophical difference in customer need to sub-function correlation. The Little method relies more heavily on the intuition of the designer. The flow ranking method attempts to make the correlation more systematic, though it still requires some engineering judgment.

The result of either of the customer need correlation methods is an unnormalized device vector of weighted sub-functions. Some sub-functions of a device may not be directly associated with any customer need, though they are essential to the mechanics of the overall function. These sub-functions are termed *supporting functions*. The sub-functions that do have a direct correlation are called *carrier functions*. So that the supporting functions are not neglected in the arithmetic manipulation that follows, they are given a value of 1. The eventual goal is to arrange a domain of device vectors into a matrix. Therefore, sub-functions that do not exist in the device are given the value of zero. To maintain the five point resolution of the customer needs ranking, a value of 1 is added to the carrier functions. Now the scale is 1 to 6, where a value of 1 denotes a supporting function and a value of 6 denotes an essential or highly important function. Note that values greater than 6 can exist when a sub-function relates to more than one customer need.

Little method (from Little et al., 1997). This method is a two step process. First, each customer need is associated with a flow or set of flows. Then, by following each flow through the function structure, sub-functions are related to flows and receive the original customer need rating. However, not every sub-function receives the customer need rating. Here judgment is used to determine if the sub-function is really addressing the customer need associated with the flow.

Example: Correlation by Little method

An example of the customer need rating to sub-function correlation is shown in Table 4.1. This example draws upon the SKIL power screwdriver of Chapter 3. The first and second columns list the customer needs and their scaled rating. The third column identifies the flows which directly affect the stated customer need. The relation between sub-function and flow is often evident, but inevitably some engineering judgment is required. The final column is where engineering judgment is definitely required. By following the flows through the function structure, shown in Fig. 4.2, we identify the sub-functions which directly meet the customer need.

Consider the customer need powerful. It is associated with the flows *electricity* and *torque*. Following the flow of *electricity* through the function structure, we identify the sub-function *convert electricity to torque* as directly impacting that need. Looking at the flow *torque*, it affects the screwdriver's power through the sub-function *change torque.*

Once the associated sub-functions are identified, each receives the value of the original customer need rating. This effectively assigns a customer need rating to those sub-functions which are viewed as directly affecting the associated customer need. These customer need ratings are then summed to produce the value of the weighted sub-function as shown in Table 4.2. Note that the third column of Table 4.2 forms the device vector for the SKIL power screwdriver.

Table 4.1 Little method correlation for the SKIL power screwdriver example.

Customer need	Scaled cust. need rating (1 to 5)	Associated flow(s)	Associated sub-function(s)
Powerful	5	electricity, torque	convert elect. to torque, change torque
Fast	4	electricity, torque	convert elect. to torque
Long lasting battery	5	electricity	store electricity
Short charge time	4	electricity	store electricity
Manual use capability	4	hand, human force	import human hand, import human force, secure rotation
Reversible (screw and unscrew)	4	electricity, torque	actuate electricity
Lightweight	4	human force, electricity	import human force, convert elect. to torque
Weight balance	2	human force	regulate rotation, regulate translation
Small size	3	hand, electricity	import human hand
Comfortable handle	2	hand	import human hand
Automatic shut-off	3	electricity	actuate electricity
Interchangeable tips	4	bit	secure solid
Maintenance free	1	torque, bit, human force	dissipate torque, store solid
Variable velocity	3	electricity	regulate electricity

Flow ranking method. The flow-ranking-based correlation method removes the engineering judgment necessary in the second step of the judgment method. First, each customer need is associated with a flow, and the sum of the customer needs for each flow is computed (called the flow rank). This, as you recall, is the same as the flow ranking procedure of Chapter 2. Then the flow rankings are assigned to each sub-function that the related flows pass through. Since it is possible for multiple flows to pass through a sub-function, each sub-function receives the cumulative flow rating from the flows.

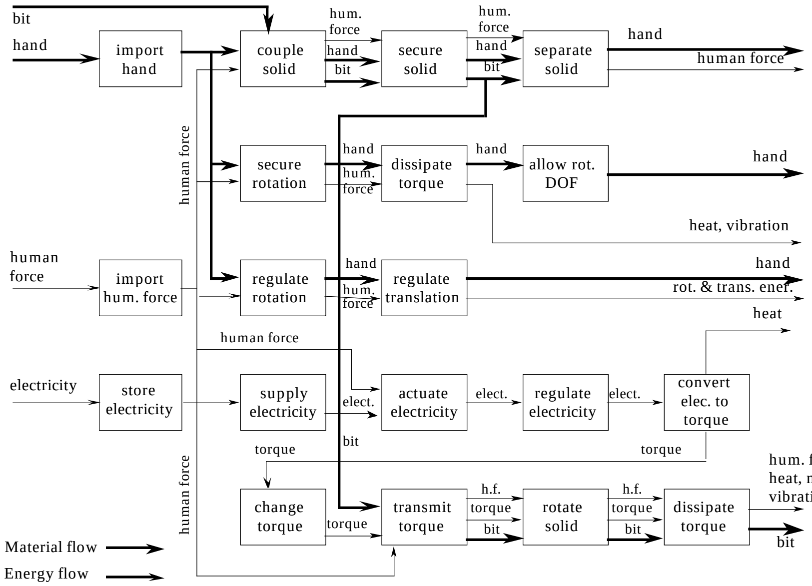


Figure 4.2 Function structure of the SKIL power screwdriver.

Table 4.2 Weighted sub-function values for the SKIL power screwdriver using the Little method.

Sub-function	Associated customer need ratings	Weighted cust. need rating
actuate electricity	4, 3, 1	8
allow rot. DOF	1	1
change torque	5,1	6
convert elect. to torque	5, 4, 4, 1	14
couple solid	1	1
dissipate torque	1,1	2
import hand	4, 3, 2, 1	10
import human force	4, 4, 1	9
regulate electricity	3, 1	4
regulate rotation	2, 1	3
regulate translation	2, 1	3
rotate solid	1	1
secure rotation	4,1	5
secure solid	4,1	5
separate solid	1	1
store electricity	5,4,1	10
supply electricity	1	1
transmit torque	1	1

Example: Correlation by flow ranking method

The customer need to sub-function correlation for the SKIL power screwdriver is now completed with the flow ranking method. Table 4.3 shows the first step of relating needs to flows.

The customer need related flows are listed in Table 4.4 with their cumulative customer need rating and associated sub-functions which they enter. Finally, the correlation is completed in Table 4.5, where the sub-functions receive their weighted customer need rating.

Note that the two methods generate different device vectors, as is evident in Tables 4.2 and 4.5. As long as the entire device domain is generated by the same method, the outcome (the normalized device-function matrix) is consistent and can be employed for the quantitative module assessment.

Table 4.3 Flow ranking based correlation for the SKIL power screwdriver example.

Customer need	Scaled cust. need rating (1 to 5)	Associated flow(s)
Powerful	5	electricity, torque
Fast	4	electricity, torque
Long lasting battery	5	electricity
Short charge time	4	electricity
Manual use capability	4	hand, human force
Reversible (screw and unscrew)	4	electricity, torque
Lightweight	4	human force, electricity
Weight balance	2	human force
Small size	3	hand, electricity
Comfortable handle	2	hand
Automatic shut-off	3	electricity
Interchangeable tips	4	bit
Maintenance free	1	torque, bit, human force
Variable velocity	3	electricity

Table 4.4 Flow ranking for the SKIL power screwdriver example.

Flow	Associated cust. need ratings	Cumulative flow rating	Associated sub-function(s)
electricity	5, 4, 5, 4, 4, 4, 3, 3, 3	35	*store electricity, supply electricity, actuate electricity, regulate electricity, convert elect. to torque*
torque	5, 4, 4, 2	15	*change torque, transmit torque, rotate solid, dissipate torque*
human force	4, 4, 2, 2	12	*import human force, couple solid, secure solid, separate solid, secure rotation, dissipate torque, regulate rotation, regulate translation, actuate electricity*
hand	4, 3, 3	10	*import hand, couple solid, secure solid, separate solid, secure rotation, dissipate torque, allow rot. DOF, regulate rotation, regulate translation*
bit	4, 2	6	*couple solid, secure solid, separate solid, transmit torque, rotate solid, dissipate torque*

Table 4.5 Sub-function to customer need correlation via flow ranking for SKIL power screwdriver example.

Sub-function	Associated flow ratings	Weighted cust. need rating
actuate electricity	35, 12, 1	48
allow rot. DOF	10, 1	11
change torque	15, 1	16
convert elect. to torque	35, 1	36
couple solid	12, 10, 6, 1	29
dissipate torque	12, 6, 1	19
dissipate torque	15, 12, 10, 6, 1	23
import hand	10, 1	11
import human force	12, 1	13
regulate electricity	35, 1	36
regulate rotation	12, 10, 1	23
regulate translation	12, 10, 1	23
rotate solid	12, 6, 1	19
secure rotation	12, 12, 1	25
secure solid	12, 10, 6, 1	29
separate solid	12, 10, 6, 1	29
store electricity	35, 1	36
supply electricity	35, 1	36
transmit torque	12, 6, 1	19

The two correlation methods produce different device vectors, in the sense of differing overall magnitudes and individual component magnitudes. However, each device vector will have the same sub-functions represented. Each simply represents a different view of capturing customer needs in the device-function matrix. Only one method should be used to generate a device-function matrix, though. No determination is made in this work as to the superiority of one method. The Little method is less cumbersome if you have a good knowledge of the type of devices being considered. If the domain of devices you are considering is less familiar to you, then the flow ranking method reduces the risk of arbitrarily assigning customer needs to the sub-functions. The flow ranking method only requires engineering judgment in correlating customer needs to flows, which is often the easier task. Both methods are shown as examples, but subsequent examples utilize the Little method.

Forming the matrix

The device vectors are arranged into a *mxn* (*m* total different sub-functions, *n* products) device-function matrix, Φ. Each element ϕ_{ij} is the cumulative customer need rating for the *ith* function of the *jth* device. To compensate for variations in detail and customer enthusiasm for a given device, Φ is normalized across the entire device space. The philosophy used to normalize the device function matrix relies on two complimentary points:

1. all devices are of equal importance, and

2. devices with more sub-functions are more complex; therefore the customer need ratings must be normalized to account for varying complexity.

The first point is realized by scaling the customer need rating of each sub-function so that the sum of a given device's sub-function customer need ratings is equal to the average sum of the customer need rating for all devices. This normalization expresses each sub-function customer need rating as a fraction of the average sum of customer need ratings for all devices. The complexity issue of the second point is addressed by scaling each device sub-function by the ratio of the number of sub-functions in that device to the average number of sub-functions per device. Thus, more complex devices (ones with more sub-functions) receive a higher normalized customer need rating.

Once implemented, the normalized version of Φ, $\mathbf{N}$, has elements

$$\nu_{ij} = \phi_{ij}\left(\frac{\overline{\eta}}{\eta_j}\right)\cdot\left(\frac{\mu_j}{\overline{\mu}}\right), \tag{4.1}$$

where the average customer need rating is

$$\overline{\eta} = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\phi_{ij}\,, \tag{4.2}$$

the total customer need rating for the *jth* device is

$$\eta_j = \sum_{i=1}^{m}\phi_{ij}\,, \tag{4.3}$$

the number of functions in the *jth* device is

$$\mu_j = \sum_{i=1}^{m}H\left(\phi_{ij}\right), \tag{4.4}$$

and the average number of functions is

$$\overline{\mu} = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}H\left(\phi_{ij}\right). \tag{4.5}$$

H is a Heaviside function, n is the number of devices and m is the total number of different sub-functions for all devices.

Normalizing the Φ matrix provides a level playing field on which to compare the devices within a domain. The averaging and scaling technique defined above is an intuitive way to make this relative comparison.

The matrices Φ and $\mathbf{N}$ for the 70 device database used for verification in this dissertation are presented in Appendix D.

4.2.2 Generating Device Families

The functional interdependence method can be used to identify modules within a group of devices. Opportunities for component sharing and swapping modularity are increased if the devices within a group are similar. Here I refer to such a group as a device family. One method to identify device families is a device hierarchy based on the primary flow of energy and energy conversions through the device system (Little et al., 1997). Another method, the device similarity method presented here, uses the device-function matrix defined in the previous section.

Device families are generated based on customer weighted sub-function similarity across a set of devices. The device similarity method uses the device-function matrix $\mathbf{N}$, which is a collection of device vectors in sub-function space. The device vectors that result from Eq. 4.1 are renormalized such that their norm is 1. The renormalization is strictly for convenience, as you will see later. To create the device family, one device is chosen as the generating device. This is the device against which all other devices will be compared. Then the inner product is calculated between the normalized generating device vector and each of the remaining normalized device vectors. Forming the inner product between the generating device *a* and another device *b*, $a \circ b$, gives the projection of the device *b* on the generating device *a*. The inner product of a device with itself (the completely similar device) is 1 and the inner product of a device with one that shares no sub-functions in common is zero.

Matrix multiplication allows all the projections for all possible generating devices to be obtained in a compact form. This matrix of projections is

$$\Lambda = \hat{N}^T \hat{N}, \tag{4.6}$$

where $\hat{N}$ is the matrix of unity normalized device vectors (each vector of **N** is renormalized to one), similar to **N**. Each element of Λ, λ_{ij}, is the projection of the *ith* device on the *jth* device. Λ is denoted as the device similarity matrix.

The similarity matrix Λ is customer need based. Another method to determine similarity is to examine sub-function commonality without regard to customer needs. Here we use a binary form of **N**, called **B**, where each component of the matrix receives a 1 if the device has the sub-function or a zero if it does not. Substituting **B** for $\hat{N}$ in Eq. 4.6 produces a matrix with elements that list the percentage of sub-functions the two devices have in common.

Therefore, the similarity matrix Λ and its binary counterpart produce different device family rankings. Λ includes customer needs in its formulation. Thus, it not only identifies common sub-functions, but also devices with similar levels of customer needs. The binary similarity ranking is also shown in the example that follows for comparison.

The similarity matrix Λ for the 70 device database used in this dissertation is included in Appendix D.

Example of a device family

The normalized device-function matrix, **N**, for the 70-product database is used to generate a device family with the SKIL power screwdriver as the generating device. Following the outlined procedure, **N** is renormalized such that the device vectors each have a norm of 1. Then Λ is formed and the column corresponding to the SKIL power screwdriver is sorted in descending order. The top ten devices most similar to the SKIL screwdriver are listed in Table 4.6.

Table 4.6 Device family with SKIL power screwdriver as the generating device.

Device	Similarity index, λ_{ij}	% of sub-functions in common
SKIL power screwdriver	1.0000	100
B&D cordless screwdriver	0.7652	95
Braun hand blender	0.7430	42
Durabuilt hand vacuum	0.6615	53
B&D weed trimmer	0.6469	37
Krups cheese grater	0.6460	47
Mini Pro hair dryer	0.6354	32
DeWalt sander	0.5816	42
Radio controlled truck	0.5796	37
Battery operated toothbrush	0.5668	53

There are several things to note from Table 4.6. First, as expected, the similarity index for the SKIL power screwdriver compared with itself is 1. Also, agreeing with our intuition, the Black & Decker cordless screwdriver is the most similar device to the SKIL power screwdriver. This makes sense as the two devices compete for the same customer and appear physically similar. The subsequent devices' similarity, though, is increasingly less obvious. For instance, would you think that the SKIL screwdriver is similar to a cheese grater? Indeed they are, sharing 64% of the same customer need weighted sub-functions and approximately half of the actual sub-functions. Note that the percentage of sub-functions in common does not decrease as the similarity index. Coupling functionality and customer needs provides a clearer picture of how devices relate to each other.

Recall the example of Section 3.3.1 where the dominant flow heuristic identified an electrical supply module. This device family presents a list of potential devices that could utilize such a module. The universal electrical supply module could provide the electricity and actuation of electricity to drive units that function as screwdrivers, blenders, vacuums, graters, small sanders, trimmers, toys or toothbrushes. The method provides greater insight into the relationships between different devices.

4.2.3 The Function-Function Matrix

The similarity matrix provides a new way to group devices into families based on customer needs and functionality. We still desire a method of assessing how well (or if) a module is meeting customer needs, though. The function-function matrix is introduced now as a means to assign a customer need importance to a module. The function-function matrix identifies repeatedly occurring sub-function combinations (the definition of a module) within a device domain and computes the combinations' customer need importance. The function-function matrix can be generated from the entire device domain or from a device family determined from the device similarity matrix.

The first step in forming the function-function matrix ***S*** is to form the unscaled function importance matrix ***S′***. Let

$$\boldsymbol{S}' = \mathbf{N}\mathbf{N}^T. \tag{4.7}$$

Each element of ***S′*** is

$$s'_{ij} = \sum_{p=1}^{n} v_{ip} v_{jp}\,, \tag{4.8}$$

where *n* is the number of devices. Note that the indices of the second term are *jp* (as opposed to *pj*) due to the result of multiplication by the transpose of **N**. Thus, each term in the sum of Eq. 4.8 is the product of the *ith* function and the *jth* function for the *pth* device. A non-zero contribution to the function importance s'_{ij} relies on the existence of both sub-functions in a device.

To maintain the customer need scale of 6, the square root of the product $v_{ip} v_{jp}$ is taken. The sum is divided by the number of products, *n*. Equation 4.8 becomes

$$s_{ij} = \frac{1}{n}\sum_{p=1}^{n} \sqrt{v_{ip} v_{jp}}\,. \tag{4.9}$$

The elements s_{ij} form a *mxm* matrix ***S***. ***S*** is the coupled function importance matrix, or the function-function matrix. Each s_{ij} is the customer importance of the combination of the *ith* function and the *jth* function in a device domain. The measure of s is still on a 6 point scale. For example, if s_{25} has a value of 6, the combination of sub-functions 2 and 5 is a “must” for all devices in the analyzed domain.

Categorization by flow interactions

The function-function matrix produces a set of sub-function combinations that are ranked by s_{ij}. To ease the interpretation of these combinations, I categorize them by their flow interaction. The three categorizations are defined next.

Common flow sub-function combinations are those in which each sub-function operates on a common basic flow. Distinctions between the order of the sub-functions are not made. Common flow combinations with a high customer importance are those most suitable for function sharing, modularity, function solution optimization, and function interaction analysis (McAdams et al., 1997). With respect to the heuristic approach of Chapter 3, common flow sub-function combinations support the modules identified by the dominant flow and conversion-transmission methods.

Flow independent, causally linked sub-function combinations are those with an obvious flow link, though not all of the functions operate on the same flows. In some cases, the existence of one function necessitates the other. In other cases, the functions may be linked by control or prevention relationships. This category is identified most closely with the branching flow heuristic. Determining which sub-function combinations are causally linked requires examination of a function structure that is in functional basis form, including the parallel and sequential function chain arrangement. As an example, consider the function structure in Fig. 4.2. A flow independent, causally linked sub function combination is that of *import human force+couple solid*, as is *import human force+actuate electricity*.

Independent flow, non-causal sub-function combinations share no common flow, operate separately from each other, and often result from distinct customer needs. These combinations indicate functions that should not be grouped together into modules. The function combinations may indicate module boundaries where interface issues become important. For example, modular casings can be constructed where function solutions can be “plugged” in using bus modularity techniques, similar to the fashion in which automobile manufacturers handle option cutouts on a dashboard. Here, a single housing could provide the interface for different modules.

The resolution of $\mathbf{s_{ij}}$

Customer need ratings initially have a resolution of 1, on an 6 point integer scale. Equations 4.1 - 4.9 generate values of *s* that are not integers. The sensitivity of the customer importance of combinations, *s*, to a change in initial customer need rating of one point is evident in the second decimal place (McAdams et al., 1997).

Example of the function-function matrix for module identification

Looking at the device family generated from the SKIL power screwdriver in the previous example, the function-function matrix for the ten devices (for two sub-function combinations as given in Eq. 4.9) in the SKIL family is generated. It is presented in Appendix D. The sub-function combinations are divided according to their flow relationships and then sorted by the coupled customer importance rating, *s*. This information is presented in Table 4.7. The first column lists the sub-function combinations. Column two gives the customer importance rating and column three gives the percentage of devices in the family which share the sub-function combination.

Table 4.7 Two sub-function combination for the device family based on the generating device SKIL power screwdriver.

sub-function combination	s	%
Common flow		
convert elect to rotation+store electricity	5.39	50
change rotation+convert elect to rot	4.85	50
actuate electricity+convert elect to rot	4.14	80
import human force+secure solid	3.66	60
actuate electricity+import human force	3.57	80
import human hand+secure solid	3.50	50
import human force+remove solid	3.26	40
import human force+import solid	2.82	70
actuate electricity+store electricity	2.55	50
change rotation+transmit rotation	2.25	60
convert elect to rotation+transmit rotation	2.22	50
import human hand+separate solid	2.14	40
convert elect to rotation+supply electricity	2.05	50
convert elect to rotation+regulate electricity	1.92	50
guide solid+import human force	1.85	30
import human force+position product	1.79	30
import human force+separate solid	1.71	40
store electricity+supply electricity	1.67	40
remove solid+secure solid	1.64	30
clean product+import human force	1.63	30
allow DOF of solid+import human force	1.51	30
Flow Independent, Causally Linked		
import human force+import human hand	7.14	90
convert elect to rotation+import human force	6.81	80
convert elect to rotation+remove solid	3.46	40
import human force+transmit rotation	2.88	70
convert elect to rotation+dissipate vibrations	2.76	50
import human hand+import solid	2.25	60
import human hand+remove solid	2.25	30
Flow Independent, Non-causal		
change rotation+import human force	5.41	70
change rotation+import human hand	5.07	70
dissipate translation+import human force	4.52	80
import human force+store electricity	3.96	50
dissipate translation+import human hand	3.90	70
convert elect to rotation+dissipate translation	3.65	60
change rotation+dissipate translation	3.52	60
import human hand+store electricity	3.47	40
convert elect to rotation+secure solid	3.35	50
actuate electricity+import human hand	3.12	70
change rotation+store electricity	2.94	30

Note that the common flow category deals with manipulating electricity and solids. This makes sense, recalling the fact that the flow ranking from Section 4.2.1 ranked the flows electricity, hand and human force as most important for the SKIL power screwdriver. The coupled customer importance rating supports these combinations as modules. All combinations with values of s greater than 2 indicate that the need is expressly stated by the customer (i.e. more than a combination of supporting functions).

Recalling the SKIL power screwdriver examples from Section 3.3, you will see that the common flow sub-function combinations support those modules identified by the dominant flow and conversion-transmission heuristics. The flow independent, causally linked sub-function combinations tend to support the flow branching heuristic by identifying the sub-function before the branch and a sub-function in one of the branches.

4.2.4 Quantitative Module Assessment Method Summary

The quantitative module assessment method presented here provides a customer need based quantitative metric for (or with respect to) device families. While the mathematics are not overly complex, the series of steps involved may seem confusing at first glance. Table 4.8 presents a summary of the steps of the quantitative module assessment method.

The quantitative method is viewed as having three steps which follow the order given in Table 4.8. The first step produces a normalized device-function matrix which allows a comparison of sub-functions shared by a wide domain of devices. Using the normalized device-function matrix, **N**, step two produces the device similarity matrix, Λ. This identifies device families. Step three requires the output of both steps one and two. It produces the function-function matrix, **S**, which calculates a customer need rating of grouped sub-functions. These groupings of sub-functions are potential modules. Their customer importance rating provides a metric for evaluation of the heuristically identified modules.

Table 4.8 Summary of quantitative module assessment method.

Step	Input	Output	Uses
1	1. List of rated customer needs 2. Function structure in functional basis	Normalized device-function matrix, **N**	Places a wide domain of devices on equal footing in terms of customer need ratings and device complexity. Allows comparison of functions shared by variety of devices.
2	1. Normalized device-function matrix 2. Generating device for family	1. Device similarity matrix, Λ 2. Device family ranked with respect to the generating device	Identifies device families which share common sub-functions and the possibility for shared modules.
3	1. Normalized device-function matrix 2. Device family of interest	1. Function-function matrix, **S** 2. Customer need rating of sub-function groups (modules)	Gives function to function relationship across entire device domain based on customer needs. Within **device families**, it identifies the sub-functions which may be grouped as modules while satisfying customer need. The method is applicable to the entire device domain, but focusing on device families sharpens the distinctions between modules.

4.3 VERIFICATION OF HEURISTICS

In Chapter 3, I presented two case studies to support the three heuristic methods introduced in that chapter. There I used a reverse engineering analysis to compare actual modules with those predicted by the heuristics. Now, with the theory behind the quantitative module assessment method in place, I will use it to further validate the heuristic methods on a quantitative basis.

4.3.1 Apples to Apples Case Study Revisited

Recalling the apples to apples case study, it looked at two similar iced tea brewers manufactured by Mr. Coffee and West Bend. In Section 3.4.1, actual modules were found which correspond to those identified by the heuristic methods. Now, I will explore if the heuristically identified modules are supported by customer needs, as determined by the quantitative method of this chapter.

To begin the analysis, the 70 device database is used to generate a device family with the Mr. Coffee iced tea maker as the generating device. The family is shown in Table 4.9.

Next the function-function matrix for the device family of Table 4.9 is constructed. The sub-function combinations are listed in Table 4.10 and ranked according to the coupled customer need index shown in the second column. The percent occurrence of the combination in the device family is noted in the third column.

Table 4.9 Device family with Mr. Coffee iced tea maker as the generating device.

Device	Similarity index, λ_{ij}	% of sub-functions in common
Mr. Coffee Iced Tea Brewer	1.00	100
West Bend Iced Tea Brewer	0.75	88
Mr. Coffee Coffee Maker	0.74	92
Krups Café Trio	0.60	67
Hot Glue Gun	0.60	50
Humidifier	0.51	42
Presto Popcorn Popper	0.46	25

Table 4.10 Customer need index and % occurrence for two function chains in the Mr. Coffee iced tea maker device family.

sub-function combination	s	%
Common flow		
convert elect to heat+transmit heat	7.45	100
mix liquid and solid+transmit heat	5.09	57
mix liquid and solid+store liquid	4.76	57
import solid+mix liquid and solid	4.19	57
refine liquid+transmit heat	3.86	57
import solid+secure solid	3.79	71
import solid+store solid	3.74	71
import liquid+store liquid	3.64	71
refine liquid+store liquid	3.62	57
mix liquid and solid+refine liquid	3.58	57
Flow Independent, Causally Linked		
import human force+store liquid	7.28	86
convert elect to heat+import human force	7.09	100
import human force+import solid	6.77	86
import human force+store solid	4.34	86
import human force+import liquid	4.01	71
import electricity+transmit heat	3.50	100
import human force+secure solid	3.35	71
actuate electricity+import human force	3.10	71
actuate electricity+transmit heat	2.94	71
convert elect to heat+import electricity	2.90	100
Flow Independent, Non-causal		
import human force+transmit heat	8.94	100
store liquid+transmit heat	6.98	86
import solid+transmit heat	6.86	86
import human force+mix liquid and solid	5.79	57
convert elect to heat+store liquid	5.70	86
import solid+store liquid	5.36	71
convert elect to heat+import solid	5.32	86
import human force+refine liquid	4.42	57
store solid+transmit heat	4.42	86
convert elect to heat+store solid	3.87	86
convert elect to heat+mix liquid and solid	3.69	57
store liquid+store solid	3.66	71
import liquid+transmit heat	3.65	71
secure solid+transmit heat	3.38	71
import solid+refine liquid	3.36	57
import electricity+import human force	3.26	100
secure solid+store liquid	3.26	71
import electricity+import solid	3.11	86

With the quantitative analysis complete, Table 4.11 compares the modules identified by the heuristic methods with the sub-function combinations of functional interdependence method. To verify the heuristic methods, the quantitative method must identify entire modules or subsets of the modules and associate a customer need importance with them. The first column of Table 4.11 lists the heuristic identified module and the sub-functions that comprise it. In the second column, the sub-function combinations from the quantitative method that support that module are listed. The third column lists the coupled customer need index that the module meets.

As you can see, the functional interdependence method supports all of the modules identified by the three heuristics. The common flow combinations verify modules identified by the dominant flow and conversion-transmission heuristics. The flow independent, causally linked combinations support those modules formed from the branching flow heuristic.

It is possible that the quantitative method may not generate a customer need index for every module. This is a reflection that the sub-functions comprising such a module are largely supporting functions. Thus any sub-function combinations from such a module receive a low coupled customer need index and could fail to exceed the threshold for reporting (which in this case was 2.0).

An additional point to note from Table 4.10 is the combinations of sub-functions from both the electrical supply and electrical conversion modules that appear. This suggests that combining these two modules into a larger chunk will better meet the customer needs. This is not in conflict with the heuristics; it simply reinforces the idea that the two energy domains the modules deal with are closely related through the energy conversion process.

Table 4.11 Comparison of the modules identified with the heuristic method and the quantitative method for the Mr. Coffee and West Bend iced tea brewers (reference the function structure in Fig. 3.10).

Heuristic modules: *functional description*	Quantitative sub-function combinations	Coupled cust. need index	Average index
filter, tea containment: *import solid, store solid, secure solid, mix solid & liquid, refine liquid*	import solid+store solid	3.74	4.25
	import solid+secure solid	3.76	
	import solid+mix solid & liquid	4.19	
	import human force+import solid	6.77	
	import human force+store solid	4.34	
	import human force+secure solid	3.35	
	mix solid & liquid+refine liquid	3.58	
ice containment: *import solid, store solid, secure solid, mix solid & liquid*	import solid+store solid	3.74	4.36
	import solid+secure solid	3.76	
	import solid+mix solid & liquid	4.19	
	import human force+import solid	6.77	
	import human force+store solid	4.34	
	import human force+secure solid	3.35	
liquid containment: *import liquid, transport liquid, store liquid, stop liquid-flow, transport liquid*	import human force+store liquid	7.28	4.98
	import liquid+store liquid	3.64	
	import human force+import liquid	4.01	
electrical supply: *import electricity, actuate electricity, regulate electricity*	import human force+actuate electricity	3.10	3.10
electrical conversion: *convert electricity to thermal energy, transmit thermal energy*	convert electricity to thermal energy+transmit thermal energy	7.45	7.45
thermal energy: *transport liquid, export liquid, regulate gas-flow, mix solid & liquid, refine liquid, regulate liquid-flow, mix solid & liquid, dissipate thermal energy*	mix solid & liquid+refine liquid	3.58	3.58
tea containment: *mix solid & liquid, dissipate thermal energy, store liquid, guide liquid, export liquid*	mix solid & liquid+store liquid	4.75	4.75

The apples to apples case study shows that the quantitative module assessment method associates a customer need index with the heuristically defined modules. The case study verifies that the heuristically identified modules do meet customer needs. Further, the quantitative module assessment provides the quantitative measure that answers the question, “What benefit am I receiving from identifying modules?” By grouping sub-functions into modules, you can meet multiple customer needs at once and simplify the design process.

4.4 SUMMARY

Another information packed chapter! This chapter takes you from customer need rankings and function structures to sub-function groupings that are ranked by a coupled customer need index. The sub-function groupings identify possible modules based not only on functionality, but also on their ability to solve customer needs. It is the coupled customer need index that gives a quantitative measure to justify a modular design.

The quantitative module assessment method is presented as it applies to module identification. The overall steps produce a device-function matrix, a similarity matrix and a function-function matrix. The device-function matrix provides a normalized look at a domain of devices with different functions and different levels of customer enthusiasm. This, in essence, allows customer needs to be gathered by many individuals and organized into a cohesive database. The similarity matrix produces sets of devices which are closely related in terms of functionality and customer need. These sets are called device families and are noted to offer opportunities for various types of modularity, especially component sharing, component swapping and bus modularity. Within the device family, the function-function matrix produces sub-function combinations with coupled customer need indexes. These indexes quantify how the combination of the sub-functions satisfies customer needs.

The groupings of sub-functions that emerge from the function-function matrix support the three heuristic methods for identifying modules presented in Chapter 3. The SKIL power screwdriver was carried through the chapter as an example of the functional interdependence method. Also, a reprise of the apples to apples comparison of Chapter 3 verified the modules identified by the heuristics.

Taken together, the heuristic method and the quantitative module assessment method provide a way to identify modules and then assign a customer need index to those modules. This tells the designer which sub-functions make sense to combine into modules and, then, which ones to focus on to meet the customer needs.

CHAPTER 5

A THEORY OF MODULAR DESIGN

5.1 OVERVIEW

A *theory* is a formulation of apparent relationships or underlying principles of certain observed phenomena which has been verified to some degree. In this chapter, I bring all of the preceding parts of the dissertation, my underlying principles which have been empirically verified, into a cohesive theory of modular design.

The functional base set, the flow rankings, the three module heuristics and the quantitative method are all analogous to the pieces that make up the Tinkertoy™ set. Now, how do we put them together as a useful creation? Well, we could rely solely on intuition and hope that the outcome serves our purpose, or we could follow a plan – much like we followed the diagrams on the side of the Tinkertoys™ canister to guide our reproduction of a plane, a truck, a spaceship, etc. The theory offered here presents a series of steps, from customer needs to concept generation to development team formation, that form my theory of modular design.

Many methodologies have emerged in recent years that deal with design problems ranging from original design to parametric design to redesign (Pahl and Beitz, 1988; Otto and Wood, 1996; Ulrich and Eppinger, 1995; Ullman, 1997). However, most can be described by the generic structure shown in Fig. 5.1. All have conceptual development, system-level design, detail design, testing and refinement and production phases. Generic design tasks and responsibilities for each phase are listed in Table 5.1. In general, the referenced design methodologies all require a large amount of work and design decisions at the front end of the process, denoted schematically in Fig. 5.1 by the area of each phase's floor. The methodologies are also viewed as sequential processes.

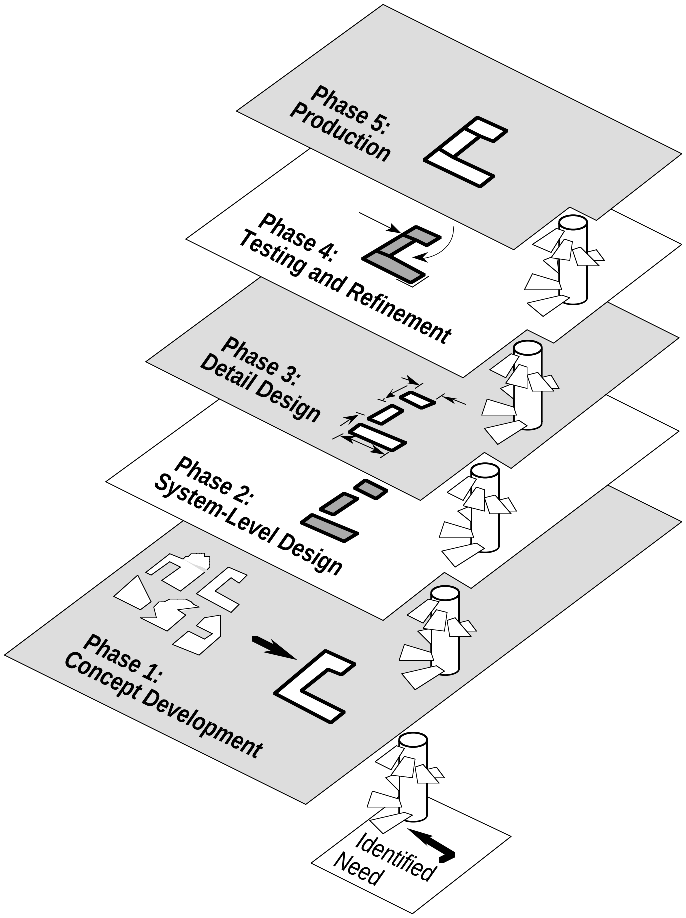


Figure 5.1 Phases of a generic design process. Each spiral staircase leading to the next level represents the steps of the design methodology for a given phase. The area of each phase's floor is proportional to the number of decisions required in each phase.

Table 5.1 Design tasks and responsibilities for a generic development process (adapted from Ulrich and Eppinger, 1995).

Concept Development	System-Level Design	Detail Design	Testing and Refinement	Production
Phase 1: • Investigate feasibility of device concepts • Develop industrial design concepts • Build and test experimental prototypes	Phase 2: • Generate alternative product architectures • Define major sub-systems and interfaces • Refine industrial design	Phase 3: • Define part geometry • Choose materials • Assign tolerances • Complete indust. design control documentation	Phase 4: • Do reliability testing, life testing and performance testing • Obtain regulatory approvals • Implement design changes	Phase 5: • Evaluate early production output

The benefit of the modular design methodology presented here is to transform the sequential process into a concurrent one. To realize the concurrent benefits of the modular design methodology, manufacturing concerns need to be considered as early and often as possible in the conceptual design process. Expanding the conceptual development team to include manufacturing engineers allows manufacturing processes, limitations and possibilities to be examined at each step of the design methodology. Finally, Phases 2 - 5 of Fig. 5.1 and Table 5.1 become parallel processes in a concurrent design process. Each module, once detailed, can be tested and produced before the entire device design is complete.

The idea of concurrent design leads to another issue: how to define sub-systems and teams for a project. The modular design methodology is carried out by a core conceptual design team. After the modular concept for development is selected, the core team then expands and assigns members to teams with responsibility for various sub-systems of the device. The device itself is modular, so it makes sense to base the development teams on the device modules. The modular design methodology provides a basis for such a teaming method.

5.1.1 Road Map for This Chapter

This chapter presents two components of my theory of modular design. The modular design methodology is based on the work of Chapters 2 - 4. The second part of the theory is an extension of the modular design methodology to development team formation. Both may be used as stand alone methods or integrated into existing methodologies, such as the original design methodology by Ulrich and Eppinger (1995) and the reverse engineering methodology by Otto and Wood (1996).

Section 5.2 presents the steps and tasks of the modular design methodology. Section 5.3 introduces the method to break complex devices into sub-systems and use those sub-systems to form development teams based on the module heuristics of Chapter 3. A summary of both components of the chapter is given in Section 5.4.

5.1.2 What's New Here

New material in this chapter includes the theory of modular design. This theory represents a new tack on design methods. It adds to the body of design methods by taking a new viewpoint of the design process. The modular design methodology incorporates the methods of the previous chapters into a single, cohesive set of steps to produce a modular device. The methodology for development team formation based on modules extends this methodology to include teaming problems.

5.2 MODULAR DESIGN METHODOLOGY

Let me set up two scenarios that will benefit from a theory of modular design.

Scenario A:

Company A has identified a need for a new device, driven either by changing customer attitudes or new technology. Currently no other devices are on the market that meet this need, or even come close, for that matter. As a creative designer for company A, you have determined that your problem requires an original design. In addition, you are interested in producing a device that is modular so that it is easy to reconfigure and uses as many standard parts as possible. Company A makes other devices, so you hope to capitalize on that existing knowledge as well. Since you are familiar with function based design methods, you want a method that examines modularity based on device functionality.

Scenario B:

Company B makes a variety of consumer power tools, many of which are battery powered. This is a competitive market, and you are looking to redesign several of your products to set them apart from competitors. Among the battery operated power tools, you suspect that several components can be shared across different tools, including batteries. You need a way to relate existing customer needs to this modular approach and a systematic way to identify what constitutes a module.

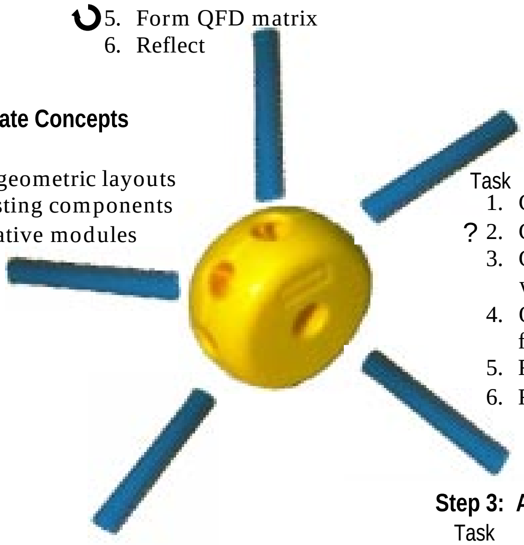
The modular design methodology is presented next. Following each step of the methodology, we will see how Company A and B might apply it and what their respective benefits might be.

5.2.1 The Method

As stated earlier, the modular design methods of the previous chapters are analogous to Tinkertoy™ pieces that fit together to form a larger creation. Here, I present a modular design methodology that unifies the pieces of Chapters 2 - 4. This method can be used as a stand alone process to identify possible modules to implement in a device, or it can be seamlessly integrated into other conceptual design methods.

An overview of the methodology is given in Fig. 5.2. The Tinkertoy™ connector and the sticks emanating from it provide a reminder that the methodology is a connection of all the previous pieces of the dissertation. Each of the steps is discussed in greater detail below. A table accompanies each step which details the tasks, required input, output and use and impact of the process.

A reminder – the design methodology offered here should not be viewed as a rigid sequence that must be followed, but as a starting point, a set of guidelines, by which the design process begins.



Step 1: Identify Customer Needs

Task
1. Gather raw data from customer
2. Interpret customer need
3. Organize needs into a hierarchy
4. Establish relative importance of needs
5. ↻ Form QFD matrix
6. Reflect

Step 2: Decompose Problem

Task
1. Create a black box description
2. ? Create a function hierarchy
3. Create a function structure with basis set flows and functions
4. Order function structure with functional dependencies
5. Rank flows
6. Reflect

Step 3: Apply Module Heuristics

Task
1. Dominant flow
2. Branching flow
3. Conversion-transmission
4. Reconcile overlaps
5. Reflect

Step 4: Conduct Quantitative Module Assessment

Task
1. Establish device domain
2. Compute device-function matrix
3. Generate device family
4. Compute function-function matrix
5. Reflect

Step 5: Generate Concepts

Task
1. Create rough geometric layouts
2. Search for existing components
3. Search for creative modules
4. Reflect

Figure 5.2 The five steps of the modular design methodology, part of the concept development phase of the design process.

Step 1: Identify Customer Needs

Identifying customer needs is the most critical part of the design process. Customer needs form the basis for device functionality and specifications. The tasks involved in Step 1 are listed in Table 5.2. The source of customer needs is customer interviews. For small consumer devices, nine or more customer interviews will provide approximately 90% of all customer needs (Griffen and Hauser, 1993). For more complex devices, a larger number of customer interviews is required, but is typically less than 50 (Ulrich and Eppinger, 1995). There are also different classes of customers, such as consumer and manufacturer. Both classes must be considered throughout the design. The two classes may be merged into one set of customer needs or kept separate. If the needs are considered separately, then two sets of customer needs must be carried through all five steps and conflicts reconciled at the end.

Table 5.2 Step 1: Identify Customer Needs.

Task	Input	Output	Use/Impact
1. Gather raw data from customer	Market need Customer demo-graphics Similar devices Questions	Raw data in voice of customer	• *The* foundation for development of the device • Identification of key business goals, markets, assumptions and stakeholders
2. Interpret raw data in terms of customer needs	Raw customer data	Interpreted customer needs	• Forms the basis for functional decomposition, engineering specifications and module assessment
3. Organize needs into a hierarchy	Interpreted customer needs Cards, post-it notes	Hierarchy of customer needs	• Primary and secondary needs by which device design is judged
4. Establish the relative importance of the needs	Hierarchy Customer or team input	Ranked customer needs	• Customer need importance values that are used n flow ranking and module assessment
5. Form QFD matrix ↻	Ranked customer needs Competing devices	QFD matrix relating customer need and engineering specifications	• Continual evaluation of target specifications and how they relate to customer needs
6. Reflect	All of the above output	Refined customer needs and QFD	• Provides a check for thoroughness and consistency of the customer needs gathering process

The customer needs are interpreted and organized by the design team. The needs are then subjectively ranked by the team or the customers. A more complete discussion of the customer need collection is given in Ulrich and Eppinger (1995).

The fifth task listed is an ongoing one throughout the design process, as denoted by the symbol ↻. Here we use a Quality Functional Deployment matrix to organize and record customer needs and engineering specifications (Otto, 1996; Hauser and Clausing, 1988). The matrix is started here and refined as the concepts evolve through later steps.

One final point about Step 1 which I cannot stress enough: this is *the most vital* step of the modular design methodology. Without accurate customer needs to guide development, the rest of the design is futile. As an example of the application of this step, review the ranked customer needs in Table 2.1 of the power screwdriver example.

Relation to scenarios. At the end of Step 1, Company A would have a set of customer needs for an original device. Company A designers use the closest devices in function to generate customer input, whether that is a competitor's device or one which they manufacture. They also have sketched out the device's target engineering specifications in a QFD matrix. Company B is redesigning its existing device, so it gathers customer needs relating to improvements or modifications to the device. Since the Company B device has competition in the market, benchmarking data (specifications as well as customer comment) is gathered for use in the QFD matrix as well. At the conclusion of Step 1, both companies have the customer needs that will direct the remainder of their design.

Step 2: Decompose the Problem

The result of Step 1 is ranked customer needs in the voice of the customer. Now, in Step 2, we decompose the problem, one of the characteristics of a creative designer (Ullman, 1997). The tasks of Step 2 are listed in Table 5.3.

First, we abstract the overall function of the device. Recall the example of the power screwdriver from Chapter 2 (and Fig. 2.1). The overall function is stated as “loosen/tighten screws.” This is the most abstract description of the power screwdriver. It should not indicate any of the internal workings of the device, simply the planned use of the device over its entire range. Next, we determine the input and output flows to the black box. These flows should be prompted by the customer needs from Step 1. Again recalling the power screwdriver, all input and output flows meet a customer need. Finally, we produce the black box diagram (as shown in Fig. 2.1).

Task 2, creating a function hierarchy, is noted to be optional (?). Some people may prefer to start directly with the function structure. The function hierarchy is there for those who need an additional method to spur the decomposition process without worrying about flows up front. The power screwdriver example of Chapter 2 provides an example of the purpose and results of the hierarchy development process in Figs. 2.2 and 2.3.

Task 3 is the heart of Step 2: creating a function structure in functional basis form. Here we decompose the black box description (or used the refined sub-functions of the function hierarchy) into sub-functions connected by flows of energy, material or signal. The functional basis set of flows and functions given in Tables 2.3 and 2.4 are used as a means of stopping decomposition and making function structure creation more repeatable among different designers.

Task 4 orders the function structure into sequential and parallel function chains. This is the final task in preparing the function structure for application of the module heuristics.

The simple flow ranking procedure of Chapter 2 is the fifth task. This associates customer needs with the flows of the function structure. Put simply, the highest ranked flow is the one that meets the most customer needs. This information is later used in the module identification and assessment steps.

The last task, Task 6, is a reminder that function structure creation is most often an iterative task. Here we check to see that all customer needs have been met by identifying the sub-function chains (from Task 4) that address them. Now, for each sub-function that is meeting a customer need directly, can its output be measured? If the answer is yes, then your decomposition process is complete. Otherwise, add sub-functions to the function structure that meet the customer need and are measurable.

Relation to scenarios. Both companies will have an overall description and a functional description of their respective devices after completing this step. The functional description will be a function structure in the functional base set with sub-functions that address all of the customer needs. The flows of each device will be identified and ranked in terms of customer needs importance.

Table 5.3 Step 2: Decompose the Overall Function.

Task	Input	Output	Use/Impact
1. Create a black box description - State overall function - Identify input and output flows	Ranked customer needs	Black box diagram Overall function Customer need based input and output flows	• Documents the overall function, input and output flows of the device, without regard to its internal workings • Facilitates knowledge of device over its full range of operating conditions • All flows directly or indirectly related to customer needs • Establishes the technical difficulty of input-output conversions
2. Create a function hierarchy ?	Black box description Ranked customer needs	Function hierarchy with multiple levels of decomposition	• The bottom level of the hierarchy represents the refined sub-functions • Provides a basis for creating the function structure
3. Create a function structure using the functional basis set flows and functions	Function hierarchy OR black box Functional basis set flow and function descriptions Ranked customer needs	Function structure in functional basis form	• Function structure is decomposed to a proper level and expressed in a standard set of flows and functions • Function structure creation is less subjective
4. Order function structure with functional dependencies	Function structure	Function structure with sequential and parallel function chains	• Identifies independent and dependent sub-functions • Places the function structure in the proper form for the module heuristics
5. Rank flows	Function structure Ranked customer needs	Flows with a customer need based ranking	• Orders flows based on customer needs, i.e. the highest ranked flow is the one that meets the most customer need • Provides a systematic way to look for modules in Step 4
6. Reflect	Function structure Ranked flows	Refined output	• Iterative evaluation of functional decomposition • Check of whether all customer needs are being met by a measurable sub-function

Step 3: Apply the Module Heuristics

With the function structure transformed, we apply the module heuristics in Step 3. The detailed tasks are listed in Table 5.4. The first three tasks consist of applying the module heuristics and are well described in Chapter 3, complete with numerous examples. For function structures with many flows (> 8), my observation is that the top half of the ranked flows will sufficiently identify the important modules. For each identified module, list the interactions. The precedence of the tasks is important. The dominant flow heuristic is applied first, as it may identify sequential sub-function chains prior to a flow branching. This can be thought of as identifying the base module, on which the branching flow modules will connect. Therefore, the branching flow heuristic is applied second. The conversion-transmission heuristic is applied last, as it identifies modules that convert energy or material to another form and typically connect the above modules.

Task 4 was implicitly covered in the examples of Chapter 3, but never explicitly stated. Here we reconcile the overlapping modules that can occur after application of all the modules. In the case of two or more flows or heuristics identifying the same module, we simply keep one of the modules in our set of possible modules to implement. The other case is where a module is a subset of another module. For this situation the recommendation is to keep both modules through the concept generation step and use a concept selection process to determine which to implement. For example, recall the hot air popcorn popper of Chapter 3. In Fig. 3.6 the dominant flow heuristic identifies a *kernel handling* *module* and in Fig. 3.10 the branching flow heuristic identifies a *kernel heating module*. The latter is a subset of the former. Generating concepts for both increases the variety of design variants and ultimately produces a more creative design.

Table 5.4 Step 3: Apply the Module Heuristics.

Task	Input	Output	Use/Impact
1. Apply dominant flow heuristic	Ranked flows Function structure	Groups of sub-functions that are possible modules Interactions of the module	• Identification of a module based on flows • Reduction of incidental flow interactions between modules
2. Apply branching flow heuristic	Ranked flows Function structure	Groups of sub-functions that are possible modules Interactions of the module	
3. Apply conversion-transmission heuristic	Function structure	Groups of sub-functions that are possible modules Interactions of the module	• Modules that are based on the conversion of material or energy from one form to another and its subsequent transmission
4. Reconcile modules and interactions	Identified modules from the three heuristics	A set of unique modules Module-interaction list	• Removes repeated modules and identifies modules that are subsets of others • Sets the stage for concept variants
5. Reflect	Identified modules	Refined set of modules with interactions	• Checks for thoroughness of interaction identification • Eliminates any clearly infeasible modules

Also in Task 4, we generate a module-interaction list. This is a list of interactions, classification of the interactions, spatial requirements and interfaces for each module. In addition to identifying interactions as energy, material or signal, we further specify if the input and output spatial requirements of the interaction with other modules or parts of the device. The spatial type is checked for the interaction if the module must be placed in close proximity to another module in order to prevent a flow from degrading. The detailed interaction information in the module-interaction list sets the stage for the concept generation step. As an example, a segment of the module-interaction list for the hot air popcorn popper of Chapter 3 is shown in Table 5.5. Note that the input and output interactions of air, pneumatic energy and thermal energy require special spatial consideration in order to keep the interaction from degrading between modules.

Table 5.5 A segment of the module-interaction list for the hot air popcorn popper.

		Interaction type			Interfaces in: modules or		Interfaces out: modules or	
Module	Interactions	M	E	S	Sp	(external systems)	Sp	(external system)
kernel handling	kernels	•				(user)		
	air	•			•	air handling	•	butter handling (environment)
	pneumatic energy		•		•	air handling	•	butter handling (environment)
	thermal energy		•		•	air handling	•	butter handling
	popcorn	•						(environment)

Finally, Task 5 reviews the modules. For each module, recheck the list of interactions to ensure all are documented. At this point, any clearly infeasible modules are eliminated. This sets you up for the final two steps.

Relation to scenarios. Step 3 provides both companies with a set of modules that comprise their devices. For Company A, the modules define work packages that can be developed concurrently. They also identify opportunities to use off the shelf components for the Company A designers. Company B is able to look at its existing device’s components and compare with the heuristically identified modules. The modules may offer a more creative way to build up their device.

Step 4: Conduct Quantitative Module Assessment

Step 4 uses the quantitative module assessment method (from Chapter 4) to assign a customer need based rank to each module identified in Step 3. This step relies on the accurate identification of customer needs from Step 1. The tasks are listed in Table 5.6.

To form the matrix Φ in Task 1, we need a database of devices from roughly the same domain, i.e. if the device to be designed is a hand-held consumer device, then the database domain is other small consumer devices; if the new device is a larger, heavy duty machine, then the database domain covers heavy duty machinery. Task 2 normalizes the Φ matrix across device complexity and customer need. With the normalized matrix $\mathbf{N}$, we compute a device family based on the device to be designed in Task 3. Then, in Task 4, we calculate the $\boldsymbol{S}$ matrix for the device family and order the customer need ranked sub-function combination values, s. Recall that s is based on two sub-function combinations. For modules with more than two sub-functions, the s values for all combinations of two sub-functions are averaged. This gives all modules an average customer need rank and indicates which modules will meet the most customer needs for the investment.

As with all other steps, the final task is to reflect on the process. Here we can assess the value of the modules identified in Step 3 based on customer needs. List the identified modules in order of customer needs. This ordering shows which modules most directly meet the stated customer needs. An example of Step 4 is given in Section 4.3.1 of Chapter 4.

Table 5.6 Step 4: Conduct Quantitative Module Assessment.

Task	Input	Output	Use/Impact
1. Establish a domain of related devices	Function structures (in functional basis form) of related devices Ranked customer needs for each device	Matrix of devices and weighted sub-functions, $\mathbf{\Phi}$	• The matrix compares functionality of a wide domain of devices
2. Compute the device-function matrix	$\mathbf{\Phi}$	Normalized device-function matrix, **N**	• Compares the domain of devices in a normalized measure of complexity and customer need • Sets the stage for determining devices with similar functionality and customer needs
3. Generate device family based on similarity to a selected device	**N** Selected device	Similarity matrix, Λ A ranking of the entire device domain's similarity to a chosen device	• Top ranked devices form a *device family* that represents devices with similar function and customer need • Identifies devices for component sharing or markets for a manufacturer to enter based on current strengths
4. Compute function-function matrix	Subset of **N** for a device family	Function-function matrix, $\boldsymbol{S}$ Ranking of the customer weighted importance of sub-function combinations	• Ranks sub-function combinations based on customer need • The weighted sub-function combinations (modules, essentially) direct the design efforts to modules that meet the most customer need for the investment
5. Reflect	Identified modules from Step 4	Ordered list of modules by customer need	• Focuses efforts on modules that make an impact with customers

Relation to scenarios. Company A is developing an original device. However, by looking at related devices it has identified components that meet customer needs similar to its own device. These components can now be considered as possible solutions which saves development time. Company B can see how the competition differs from its own device through the similarity matrix and look at components in competing devices that help meet its new customer needs. Company B designers can now present quantitative proof to the bean counters that the required investment will bear fruit with the customer need importance index for each module. For both companies, evaluation of competing or related devices helps them refine target specifications for their respective devices.

Step 5: Generate Concepts

In Step 5 we generate concepts based on the modules identified from Steps 3 and 4. These modules are identified based on their flow interactions, a departure from other product architecture techniques (Cutherell, 1996; Ulrich and Eppinger, 1995). The tasks of concept generation are listed in Table 5.7.

Table 5.7 Step 5: Generate Concepts.

Task	Input	Output	Use/Impact
1. Create rough geometric layouts - Establish spatial relationships - Assign rough dimensions where possible	Identified modules Interactions Ranked customer needs	Rough form layout concepts	• Produces a rough layout of the device's form • Guides the search for module solutions in terms of scale
2. Search for existing components	Vendors Published literature Patents Experts Device database (from quantitative assessment method)	Module concepts	• Incorporating an existing component is cheaper and easier than developing a new one • Allows creative focus on aspects of design that are truly unique
3. Search for creative modules - New modules manf. internally - Vendor	Team Open mind	Module concepts	• Generate new forms for the identified modules • Truly novel modules could be used in other devices as well
4. Reflect	Module concepts	Refined module concepts	• Continuous evaluation of concepts

The first task is to generate rough geometric layouts of the device. We've answered how the flows interact between modules, but this task takes into account the spatial interactions between modules. First, lay out the modules as they will physically be connected in block form. Roughly scale the blocks to their anticipated physical size. Then, assign overall dimensions to the layout based on information from customer needs. Several rough geometric layouts should be generated for eventual comparison. This allows varying layouts of the same modules as well as different sets of modules (in the case of overlapping modules from Step 3).

Tasks 2 and 3 search for solutions to the modules of the rough geometric layouts from Task 1. Here I break the search into external and internal components. The ultimate extension of the modular design method is that a device would be built up from a collection of existing modules, and Task 2 would be the only search required. But the reality is that the device will incorporate existing modules and creative modules that are manufactured internally to the company.

At the end of this step, we have a number of modular device concepts. We first should reflect on the concepts to check their feasibility. From the set of feasible concepts, apply a decision making process to select one for further development and production.

As an example of Step 5, recall the iced tea brewer from the Apples to Apples Case Study in Chapters 3 and 4 (Sections 3.4.1 and 4.3.1). The function structure for the iced tea brewer with identified modules is given in Fig. 3.13. The quantitative module assessment method provides the customer need rank of the modules in Table 4.11. From this we know the ordered importance of the modules: *electrical conversion, filter & tea containment, ice containment, liquid containment, electrical supply and thermal energy*. A rough geometric layout is shown in Fig. 5.3. Note that the flows between components are identified and that modules with spatial requirements are placed adjacent to each other. If a module is not butted directly to another module, then the module is a completely separate component not intended to be permanently assembled to the rest of the device. An overall dimension of the product is given. The dimensions are based on similar devices within the iced tea brewer family. Though this specification is not set in stone, it gives an upper bound for the overall dimension of the device. These two actions guide the spatial layout and help to focus our search for module solutions to the right scale.

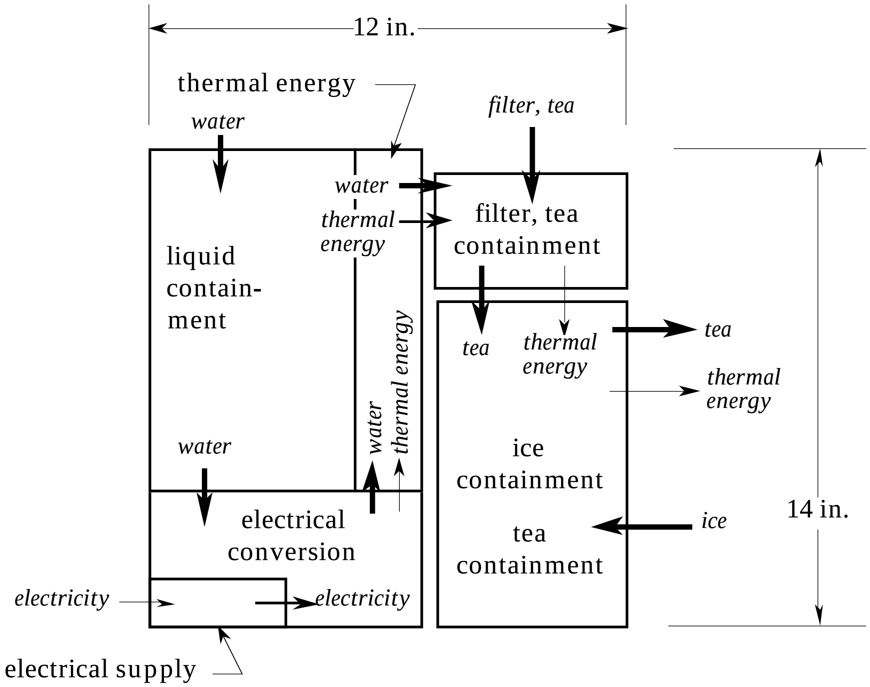


Figure 5.3 A rough geometric layout of the iced tea brewer.

Relation to scenarios. At the close of Step 5, Company A has several modular concepts for its original device. The concepts incorporate off the shelf components, components from its own line of devices, as well as creative, internally produced modules. The rough geometric layouts which this method facilitates show how the different modules will connect and which interactions present the most challenge. Now Company A can select a modular concept for further development and begin to prototype and test subsystems concurrently. Company B also has modular concepts which represent a modification of their existing power tool. The concepts incorporate many of the same components of the existing device, some new modules and even a module used by one of their fiercest competitors - a universally rechargeable battery. Company B can now fine tune its models of the power tool and select the concept for development.

5.2.2 Summary of the Modular Design Theory for Original Design

This section introduces a modular design methodology for the conceptual development phase of the design process. The five steps presented represent a stand alone methodology that can be applied to both original and reverse engineering design. Recall the two scenarios of Company A and B. Both Company A, looking to develop an original device, and Company B, looking to redesign its line of battery powered hand tools, can use this method. The flexibility of the method allows Company A to look for component sharing between the new device and the other devices it manufactures. Company B can do the same thing in addition to incorporating competitors modular efforts into Step 3 and 4 for comparison.

This work is part of a new theory of modular design and a departure from the conventional practice of dealing with modules after the concept is chosen. For organizations interested in modular devices, this theory provides a systematic approach to achieving customer need based modules. While it uses functional decomposition to describe the problem, it shifts the search for solutions to a modular level rather than looking for a solution to every individual sub-function. As a final reminder, view this not as a rigid set of steps to follow, but a starting point for developing a modular device and improving the design process.

5.3 MODULE BASED DEVELOPMENT TEAMS

Now I turn to the second component of my theory of modular design – the formation of development teams based on device modules. I will use one final scenario to motivate this work.

A large company, the pioneer of the plain-paper copier market, had an established product architecture and development team structure that propelled it to the top of its market. In the 1970s this company faced competitors that were producing smaller and more reliable copiers than their own. The competing products implemented very little new technology and even used the core technologies invented by the pioneering company. Despite this fact, it took the company nearly a decade to introduce a competitive product into the market. In that time, it lost half of its market share. That company was Xerox. The lack of modularity and unresponsiveness of the established development team to change are cited as reasons for Xerox's problems (Congress, 1992; Clark, 1988; Henderson and Clark, 1990).

Since the time of Xerox's problems, industry has invested in concurrent engineering practices and differing team structures. One popular practice is Integrated Product Teams, an approach that forms teams of members with various areas of expertise to develop, manufacture, market and support a product (Prasad, 1997). While there is literature supporting team interaction and duties in such an environment, there are still few formal methods for defining the sub-systems of a complex device.

Here I propose using the module heuristics to identify device modules and define the responsibilities of the development team. By definition, the identified modules are physical structures that have a one-to-one correlation with functional structures. Thus it makes sense for the modules of a device to define its development teams. Their interactions are also clearly identified, which denote the necessary lines of communications between other teams.

One caveat, before I proceed. The focus of my work is not on teams, but the issue of teaming is an obvious extension of the basic work with potential for innovation. The method presented here offers a technique to form development teams which is an application of the modular design work of the preceding chapters.

5.3.1 The Method of Forming Module Based Development Teams

A few product architecture techniques exist which can define development teams (Cutherell, 1996; Ulrich and Eppinger, 1995; Pimmler and

Eppinger, 1994). However, most define modules or “chunks” without regard to flow information. Flows, which describe the interactions between modules, are only considered at the end of the process. The module heuristic approach to forming development teams uses flow information to identify modules. By doing so, this minimizes the incidental interactions between modules, keeping the important flow interactions within the module.

The method is simple. In fact, much of it may already be complete after the completion of the modular design methodology. Table 5.8 lists the steps, required input and output of the development team method.

Table 5.8 Steps of the development team method.

Step	Input	Output
1. Decompose system on a functional level.	Description of the system (e.g. black box)	Function structure
2. Apply module heuristics and quantitative module assessment method	Function structure Device database	Identified modules Module-interaction list Ungrouped sub-functions
3. Associate ungrouped sub-functions with existing modules or each other - Use customer weighted sub-function combinations - Consider connecting flows	Function structure Identified modules Interactions	Regrouped modules Identified areas which require communication between teams
4. Assign teams to develop modules. Maintain a mix of designers and manufacturing personnel on teams	Modules for teaming Identified areas which require communication between teams	Development teams Concurrent design process for remainder of project

Step 1 is the now familiar decomposition process. A function structure, as developed in Step 2 of the modular design methodology, is the result of this step.

In Step 2, we apply the module heuristics to the function structure to identify modules. As an additional part of this step, the quantitative module assessment method can be applied to associate a customer need ranking to the identified modules.

Step 3 associates any ungrouped sub-functions from Step 2 with related modules or each other. Following the application of the heuristics, there may be ungrouped sub-functions. At this point we use two pieces of information to group these components: the customer weighted sub-function combinations of the quantitative module assessment method and the flows connecting these sub-functions. Lone sub-functions that have a high customer weight with another sub-function (from the quantitative module assessment) are associated with that sub-function. That may mean adding a sub-function to an existing module or grouping a set of lone sub-functions into a pseudo-module. The alternative is to group lone sub-functions to modules if they have connecting flows (other than the flow that defined the module).

In Step 4, we use the results of Step 3 – the list of modules with known interactions – and assign teams to develop the modules. The interactions define the lines of communications between groups that are necessary. Also, overlapping modules indicate that two teams must closely collaborate on the aspect of the design that solves the sub-functions they share.

An example of the development team method is presented as Case Study 3 in Chapter 6.

5.3.2 Summary of the Development Team Method

Engineers are well known for developing the "how to" of problem solving, but the "why" is often not evident. So, why use this method for development team formation? It gives organizations a method to define development teams based on the actual modules of a device. Thus, industry is not confined to historical team structures. Market leaders have been noted to lose market share when confronted by competing devices with different architectures (Henderson and Clark, 1990). This method provides a way to adapt teams and device architecture. It also builds on the information gained from the modular design methodology of Section 5.2. If the modular design methodology has been used, then much of the work to form development teams is complete.

This method represents a device architecture or module based approach to development team formation. Further, it departs from existing methods by considering the flow interactions as a means of forming modules and teams. It has the potential to minimize incidental interactions between modules and reduce the conflict between teams.

5.4 SUMMARY

The theory of modular design presented here represents a new tack on design methods. It looks at the design process from the standpoint of building up an overall device out of modules. It also is envisioned as a concurrent process, in terms of developing modular concepts and detailing and producing modules in parallel. The preceding chapters presented components of the theory.

They found cohesion in the two methods of the theory: modular design and development team formation.

Three case studies in Chapter 6 demonstrate the application of the theory of modular design. They show that the theory is more than a simple academic exercise, but a useful tool in real world applications.

CHAPTER 6

CASE STUDIES

6.1 OVERVIEW

The Tinkertoy™ analogy runs throughout this dissertation. The Tinkertoy™ pieces are noted to be modules. Their manner of connection is given as an example of module interfaces and interactions. All are appropriate analogies to the theory presented. But now, I want to look at some applications of the module heuristics. For the sake of the analogy, it's time to empty out the box of Tinkertoys™ and start building.

6.1.1 Road Map for This Chapter

This chapter examines three case studies using the theory of modular design espoused in Chapter 5. The first study, in Section 6.2, examines an one-off, original design problem by employing the modular design methodology. The second study, in Section 6.3, looks at an industrial teaming issue and applies the development team method. The final case study, in Section 6.4, examines a device that has evolved over time to become more modular and offers a prediction for what its next incarnation might be.

6.1.2 What's New Here

The new material here is the application of the theory of modular design to three distinct cases: original design, reverse engineering design and development team cases.

6.2 ONE-OFF, ORIGINAL DESIGN - THE CLINKER CLEARER

This section applies the modular design methodology to original design. Most of the examples presented earlier are based on reverse engineering techniques. This is, of course, necessary for verification purposes. The heuristic methods are equally valid for original design. They not only identify modules of the overall device that can be designed and fabricated separately, but they also identify areas of the device that can be assigned to teams for development, if the scale of the problem is large enough. The example presented next is considered a one-off device. As its name implies, this type of original design produces only one, or a very few, devices for a specialized need. One-off design is common in industrial, government and academic research settings. The academic and industrial settings are the source of the clinker clearer example that follows (Seo et al., 1997).

Following the problem introduction, the modular design methodology of Chapter 5 is used to generate a conceptual design for a portion of the overall problem. Each step of the methodology is summarized.

6.2.1 Problem Introduction

A Houston Industries Power Generation (HIPG) plant in Jewett, Texas, produces electricity via a lignite fueled boiler. Lignite is best described as a dirty coal. The dirtier the coal, the more residue produced during the burning process. Residue collects in the bottom of the boiler, known as the hopper. A cross sectional view of a typical boiler bottom is depicted in Fig. 6.1. This residue, called a clinker, is a glass-like substance that typically forms in large chunks, depending on the lignite quality. Clinkers must be removed from the hopper periodically to maintain full power generation capability. Ideally, the grinder system, a set of rotating cylinders with protruding teeth, crushes the clinkers into smaller chunks that can be flushed out of the boiler. In practice, however, the clinkers are too large to enter the grinder and require fragmenting.

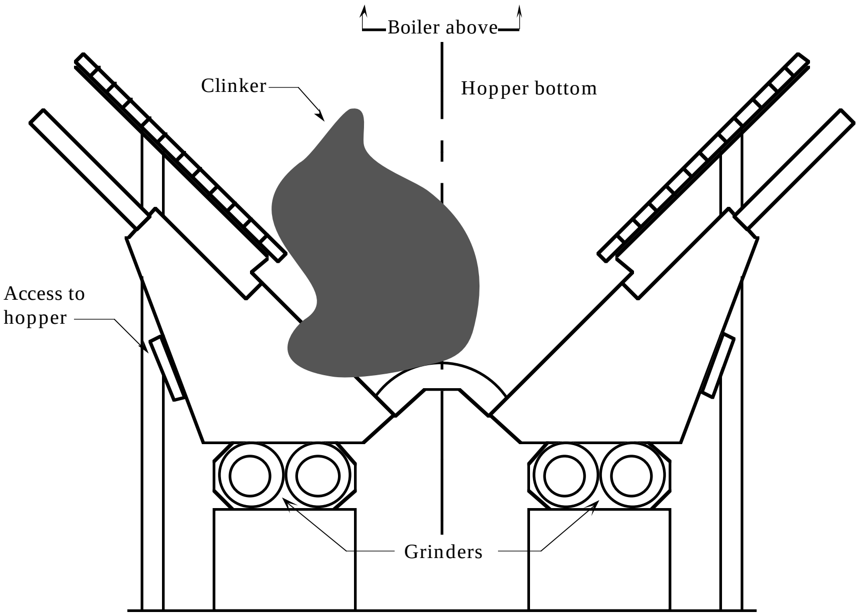


Figure 6.1 Schematic of HIPG boiler bottom.

HIPG contracted with the University to develop a device, tele-robotic in nature, that can enter the hopper through an access door and fragment clinkers so that they can be removed by the grinder or flushed through the access door. Currently, clinkers are fragmented in a dangerous, manual operation. While the fragmentation process is carried out, the boilers must operate at a lower power generation level. Thus, the manual operation is costly on both human and financial levels. A device capable of clearing the clinkers is the proposed solution to the problem. The device should be automated where feasible and should keep HIPG personnel a safe distance from the hopper during fragmentation. With the problem sketched out, we move to Step 1 of the modular design methodology.

6.2.2 The Modular Design Methodology

Step 1 - Identify Customer Needs

Customer needs for the clinker clearer were gathered through a series of interviews and group meetings at the HIPG plant. The group was comprised of approximately 15 personnel, from maintenance and operation hourly workers to salaried engineers and managers. Need collection also benefited from site visits and video of the manual clinker clearing process the device is to replace. The collected customer needs appear in Table 6.1. They are ranked on a 1 (supporting) to 5 (must have) scale.

Table 6.1 Customer need and importance data for the clinker clearer problem.

Customer Need	Importance
Break and clear clinkers from boiler hoppers	5
Operate in high temperature	5
Portable	5
Short clinker clearing cycle (time)	4
Probe will break away in case of impact	4
Removable after failure	4
Human interaction with manipulator is safe	4
Quick set up time	3
Easily secured	3
Probe supports different end effectors	3
Reach up to the cricket	2
Compatible with hopper MAPS (existing sonar system)	1

Step 2 - Decompose the Problem

With the customer needs in hand, a black box description of the overall problem is formulated. Figure 6.2 is a black box representation of the clinker clearer. The overall function of the device is to clear (or fragment) clinkers. Energy, material and signal input and output flows are identified at this early stage to guide customer need collection.

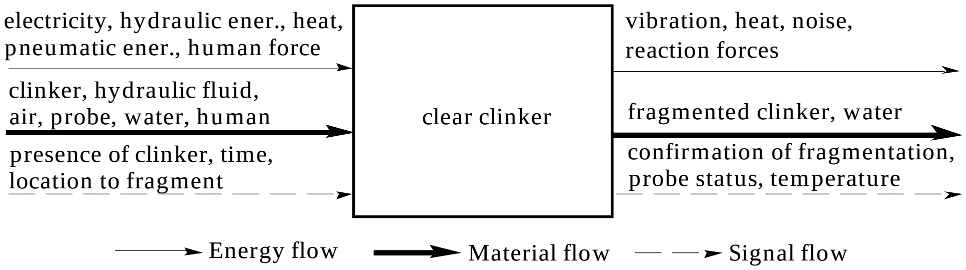


Figure 6.2 A black box model of the clinker clearer device showing overall function and the identified input and output flows following initial problem formulation from HIPG.

The hierarchical approach is used to decompose the overall function of *clear clinker* into four sub-functions as shown in Fig. 6.3. At each level of decomposition, all customer needs must be met by the sub-functions. In Fig. 6.3, for example, *locate clinker* meets the customer needs of breaking and clearing clinkers, short clinker clearing time, safe human interaction and MAPS compatibility.

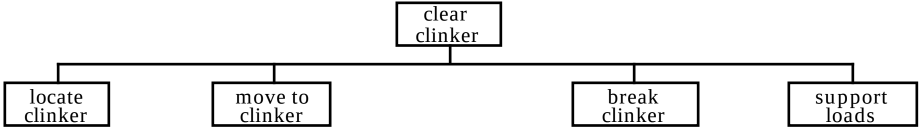


Figure 6.3 Initial hierarchical decomposition of the clinker clearer device into four sub-functions.

Since the clinker clearer device is a complicated animal, I now will focus on two key mechanical design areas for further decomposition. The sub-function *move to clinker* from Fig. 6.3 is decomposed two more levels as shown in Fig. 6.4. The bottom level of the hierarchy is decomposed sufficiently that the sub-functions may be represented in the functional base set, so decomposition ceases. Note that the sub-function *supply power* is further decomposed into form specific sub-functions. In general, conceptual design techniques do not encourage form solutions this early. However, for this problem, given the abundance of electrical energy and the required forces to manipulate any probe, electrical and hydraulic energy are specified to advance the design solution more quickly.

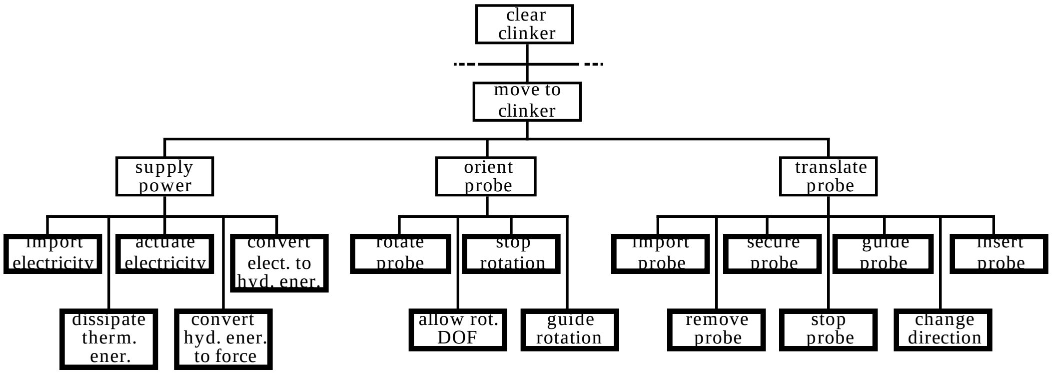


Figure 6.4 Decomposition of the *move to clinker* area. At each level, the customer needs of Table 6.1 are checked to see if decomposed sub-functions are meeting the needs.

The second mechanical design area I look at is the *break clinker* sub-function. Its decomposition is shown in Fig. 6.5. Again, the bottom level of the hierarchy is decomposed to the point where the sub-functions can be represented in functional basis form, the trigger for stopping decomposition.

The next step is to associate flows with the decomposed functions of Figs. 6.4 and 6.5 in a function structure and transform the sub-functions into the functional basis. The function structure for the clinker clearer (more specifically, the two functions of *move to clinker* and *break clinker*) is shown in Fig. 6.6. Note that creating the function structure reveals that additional sub-functions are needed for a complete description of the device. For example, the *supply power* sub-function of Fig. 6.4 deals with the requirements for converting electricity to hydraulic energy. Not until we consider the flow of a hydraulic fluid do we realize that additional sub-functions of *import liquid* and *store liquid* are needed.

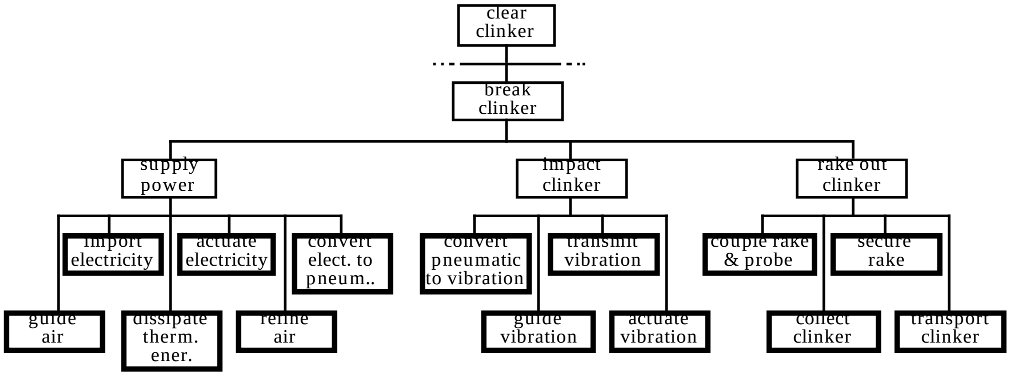


Figure 6.5 Decomposition of the *break clinker* sub-function. Subsequent levels of decomposition are checked to insure the sub-functions meet stated customer needs of Table 6.1.

The flow ranking for the clinker clearer is presented in Tables 6.2 and 6.3. The first step of correlating the customer needs to the flows is shown in Table 6.1. Then the flows are ranked in Table 6.2. From the ranking, it is evident that the probe is by far the most important flow in this subset of the device. Vibrational energy is the next important flow. The remaining flows have essentially the same importance, based on the stated customer needs.

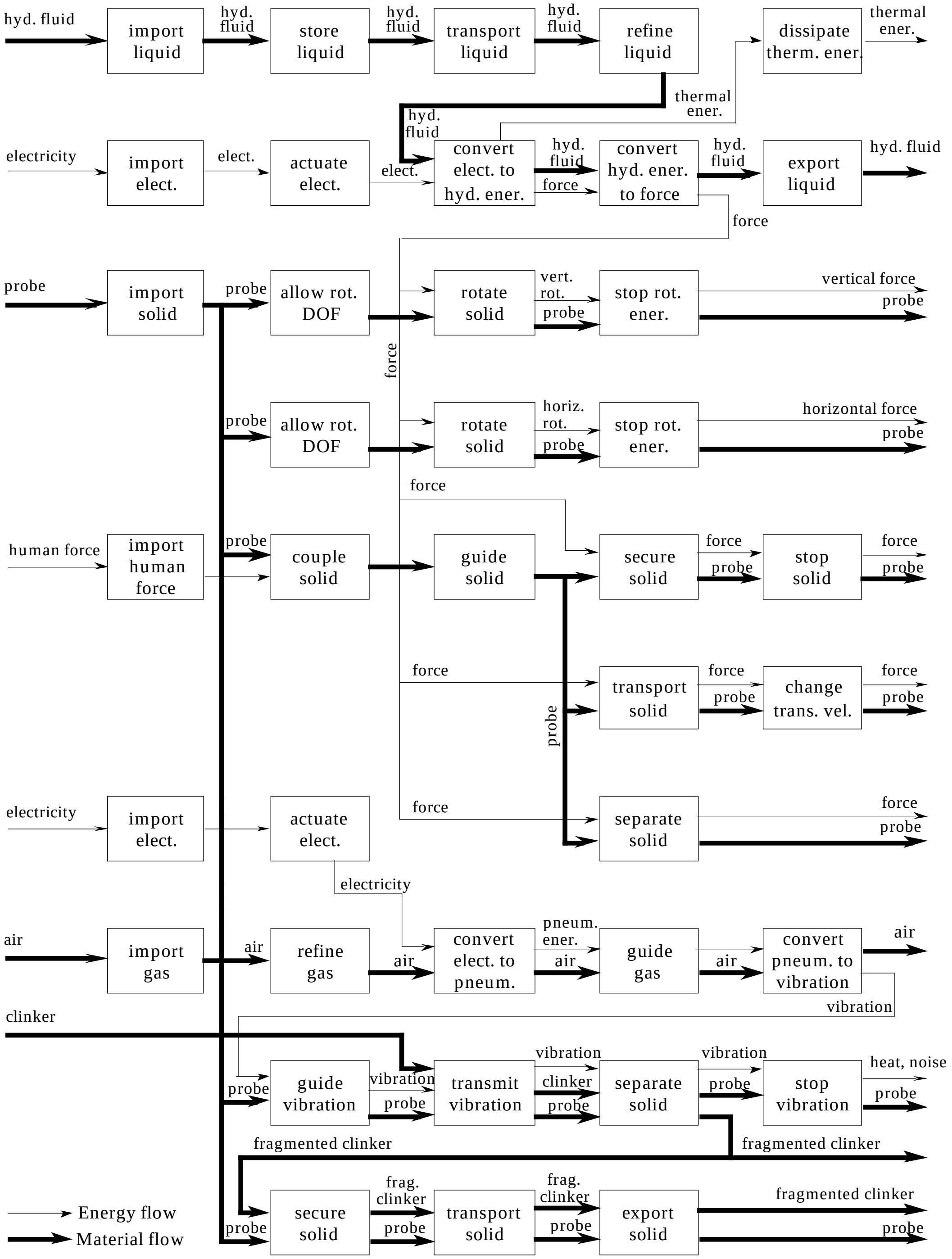


Figure 6.6 Function structure for the *move to clinker* and *break clinker* parts of the clinker clearer device.

Table 6.2 Customer need to flow correlation for the clinker clearer (step 1 of the flow ranking process).

Customer need	Scaled cust. need importance (1 to 5)	Associated flow(s)
Breaks and clears clinkers from boiler hoppers	5	probe, air, pneumatic ener., vibration
Operate in high temperature	5	probe
Portable	5	hydraulic fluid, electricity
Short clinker clearing cycle (time)	4	force, pneumatic ener., vibration
Probe will break away in case of impact	4	probe
Removable after failure	4	probe, force
Human interaction with manipulator is safe	4	human force, fragmented clinker
Quick set up time	3	human force, probe, electricity, hydraulic fluid, air
Easily secured	3	probe, human force, vibration
Probe supports different end effectors	3	probe, vibration
Reach up to the cricket	2	probe, force
Compatible with hopper MAPS (existing sonar system)	1	n/a for this sub-problem

Table 6.3 Flow ranking for the clinker clearer (step 2 of the flow ranking process).

Flow	Associated cust. need ratings	Cumulative flow rating
probe	5, 5, 4, 4, 3, 3, 3, 2	29
vibration	5, 4, 3, 3	15
human force	4, 3, 3	10
pneumatic energy	5, 4	9
electricity	5, 3	8
air	5, 3	8
hydraulic fluid	5, 3	8
fragmented clinker	4	4

Step 3 - Apply Module Heuristics

Now we are ready to apply the module heuristics of Chapter 3 to the clinker clearer function structure. What will we gain from this? First, we get an indication of whether the device is suitable for a modular design, i.e. are there any modules identified. Second, the identified modules present an opportunity to arrange design teams around the modules. With the interfaces and interactions of the modules identified by the heuristics, the connections that must be standardized between the modules are immediately known.

I begin the analysis by applying each heuristic to the function structure. Following that, I will compare the identified modules with those that exist in the device. Since this device represents an ongoing project at the University, not all components are fabricated and much of the design work was completed before this methodology was available for application. However, we should see areas where the heuristics and actual design agree since this work was the genesis for module heuristics method.

Dominant flow heuristic

The dominant flow heuristic is applied to the function structure in Fig. 6.7. Six modules are identified by this heuristic. Per the dominant flow heuristic, we examine the function structure one flow at a time in order of the flow rank. In this case, the top rated flow of *probe* appears as a splitting flow, so we proceed down the list of ranked flows and examine the remaining flows.

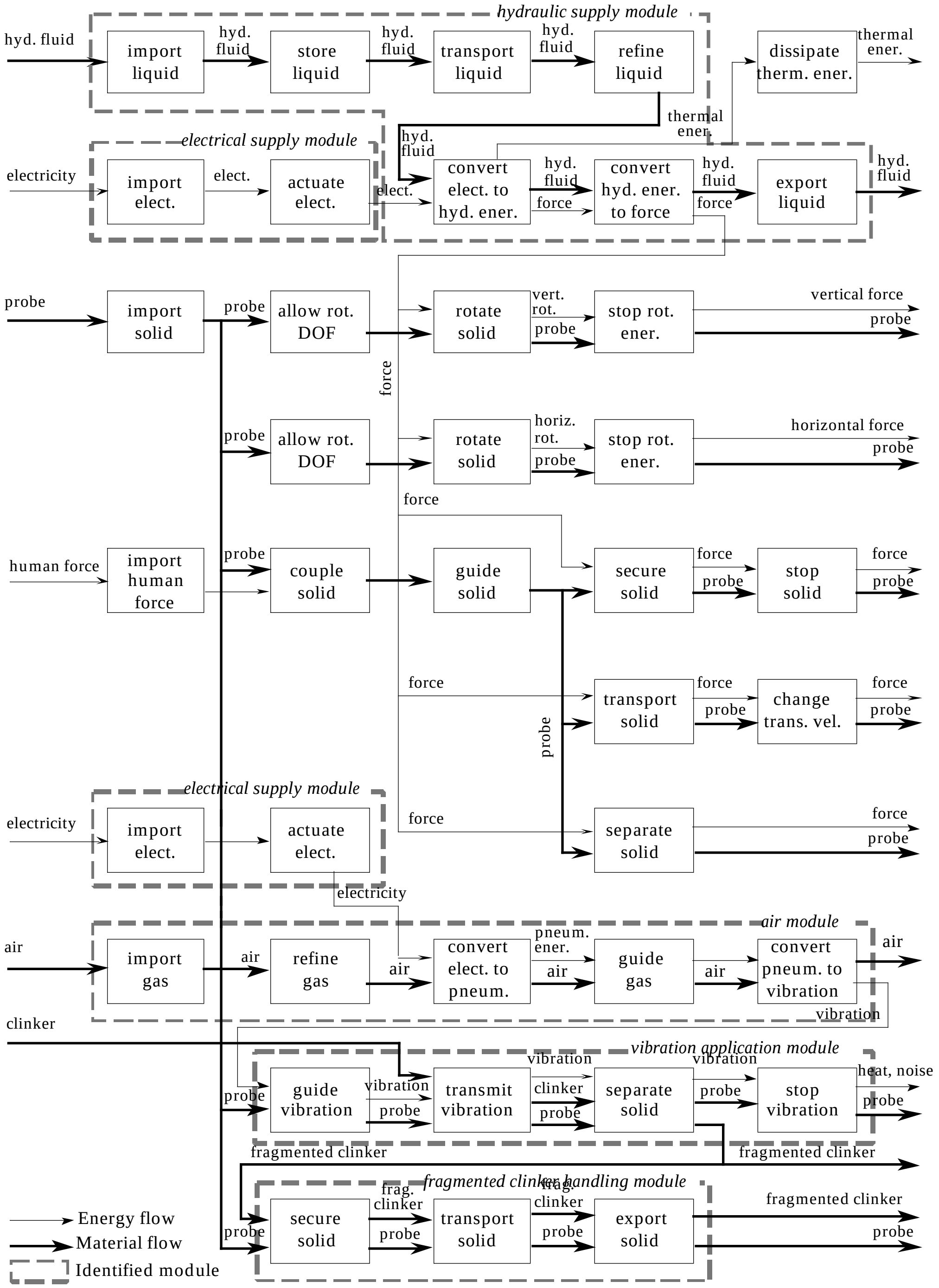


Figure 6.7 Modules identified by the dominant flow heuristic for the clinker clearer.

The *hydraulic supply module* handles the hydraulic fluid and the conversion of electricity to hydraulic energy and then to force. Its interactions across the module boundary are hydraulic fluid, electricity, force and thermal energy. The *electrical supply module* appears twice as a means of supplying electricity for conversion to hydraulic and pneumatic energy with electricity as its only interaction. An *air module* handles air intake and refinement and its ultimate conversion to vibrational energy. Associated interactions are air, electricity and vibration. Following the flow of vibration identifies the *vibration application module* which, as its name implies, applies vibrational energy to the clinker. The interactions here include vibration and the material interactions of probe and clinker, suggesting that geometric concerns will dominate this interface. The final module is the *fragmented clinker handling module*. It is concerned with removing the clinker fragments from the hopper. Its interactions are similar to the *vibration application module*.

Branching flow

The branching flow heuristic is applied to the clinker clearer function structure shown in Fig. 6.8. The highest ranked flow of *probe* branches and forms all of the modules identified for this heuristic. The flow of *force* also branches, but it identifies subsets of the *probe* identified modules. Four main modules are identified by the flow of *probe*. Two deal with probe motion and the remaining two address clinker manipulation.

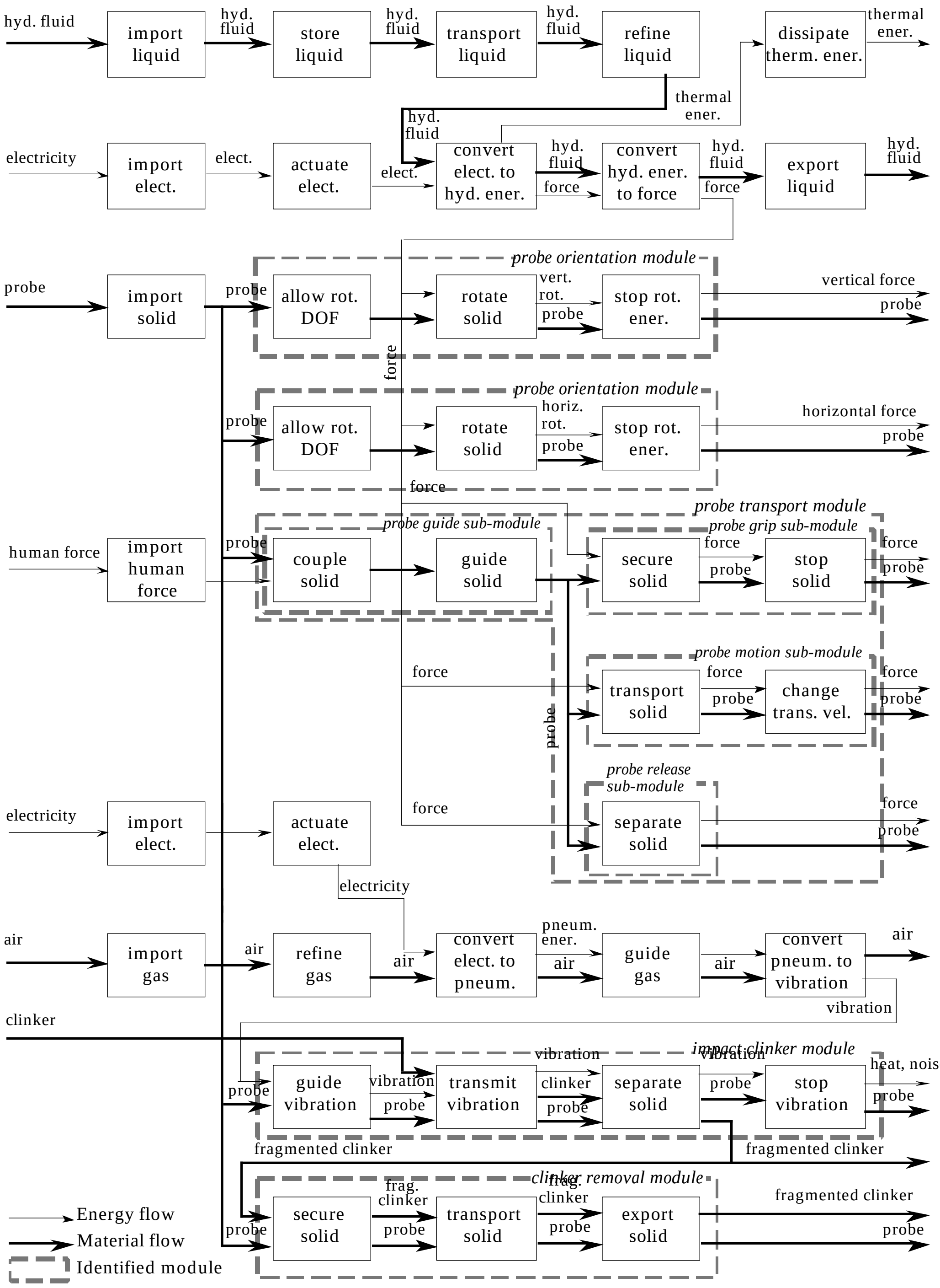


Figure 6.8 Modules identified by the branching flow heuristic for the clinker clearer.

Looking individually at the four modules, the first, *probe orientation*, deals with rotating the probe about specified axes. The next module, *probe transport*, has four sub-modules which guide the probe, grip the probe, translate the probe and release the probe. Both the *probe orientation* and *probe transport modules* have interactions of probe and force. The *impact clinker module* directs and applies the vibrational energy to the clinker for fragmenting. Its interactions are probe, clinker and vibration. Note that this is the same module identified by the dominant flow of vibration. The final module is the *clinker removal module*, also identified by the dominant flow heuristic. The probe and fragmented clinker are important interactions here. It is important to note that since all the modules have the material flow probe crossing the interface, geometric concerns will dominate these modules' connections.

In this case, the branching flow heuristic predicts modules of major importance to the clinker clearer device. The four identified modules fall into two categories: probe positioning and clinker handling. Therefore, the heuristic also identifies a logical separation of design work for different teams.

Conversion-transmission heuristic

The conversion-transmission heuristic is applied to the clinker clearer function structure in Fig. 6.9. It identifies four modules. The first two, *electricity to hydraulic* and *hydraulic to force*, are single sub-function modules and also a subset of the *hydraulic supply module* of the dominant flow heuristic. The third module, *electricity to pneumatic*, is a single sub-function and a subset of the *air module* as identified by the dominant flow heuristic.

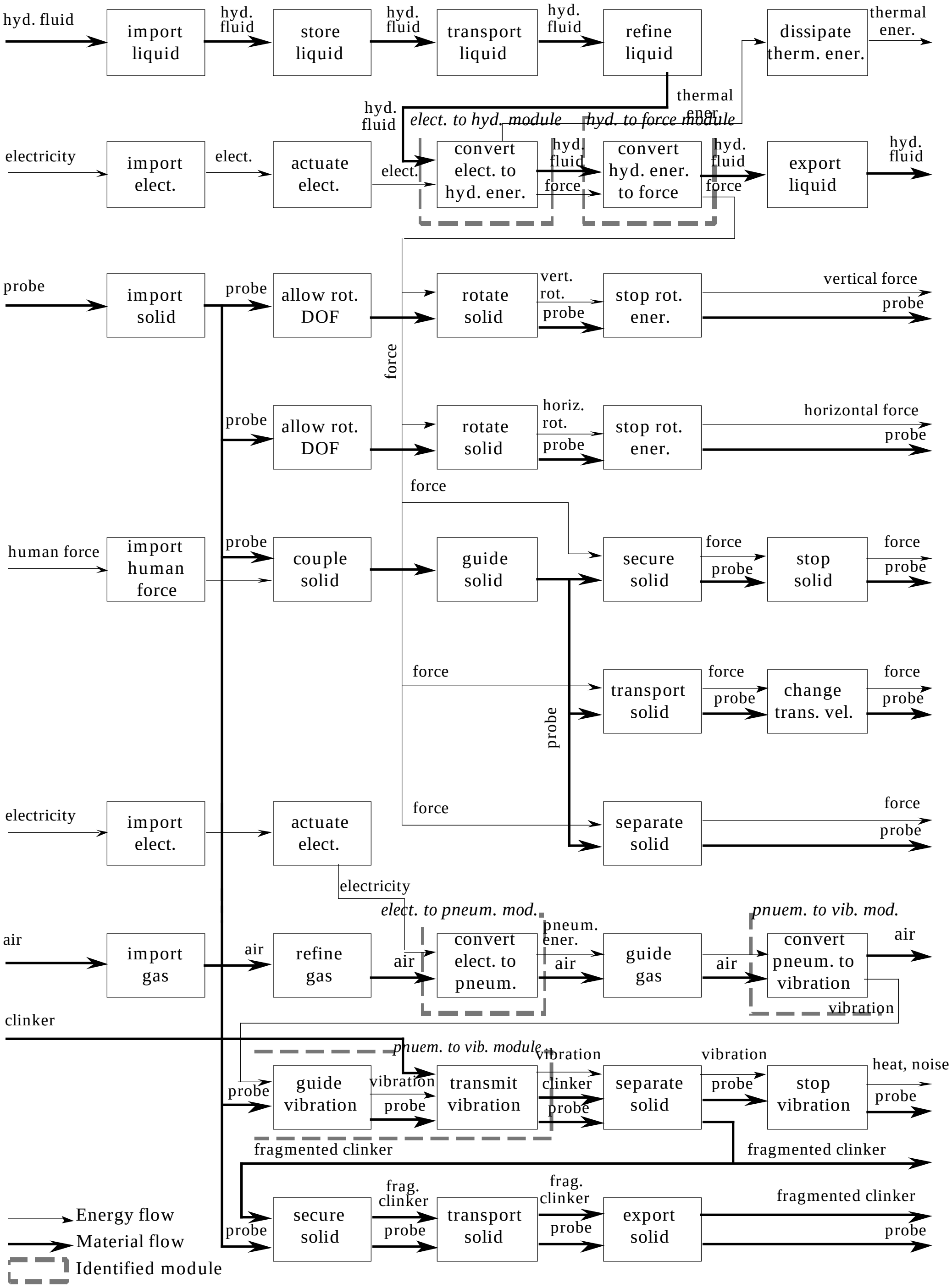


Figure 6.9 Modules identified by the conversion-transmission heuristic for the clinker clearer.

The fourth module is the *pneumatic to vibration module*, and it is a convert-transmit chain of sub-functions. While the other modules' interactions were non-remarkable, this module has an important interaction in the flow clinker. As with the other heuristics, the material flow suggests that the important interface issues will be geometric ones.

Step 4 - Conduct Quantitative Module Assessment

With the modules identified by the heuristic method, the next step in the methodology is the quantitative module assessment. For this problem, Step 4 was skipped due to the lack of an adequate device database of similar devices. The requirements of forming a database of similar, large scale, industrial maintenance devices was too lengthy and expensive for this particular project.

Step 5 - Generate Concepts

Three different rough geometric layouts of the *pole transport module* are shown in Fig. 6.10. We will focus on this particular module for Step 5. Since the *pole transport module* consisted of several sub-modules, layouts of the sub-modules are used to determine the configuration of the overall module. Then, the overall module is integrated with the remaining modules of the device.

In Fig. 6.10, you will notice the introduction of *pole* in the place of the flow *probe*. Through a separate decision making process, a pole was selected as the solution for the probe function. This represented a solution the customers were familiar with from the manual clearing procedure and has proven effective at reaching critical areas of the hopper. So, the additional concreteness of the pole is represented in the rough geometric layouts.

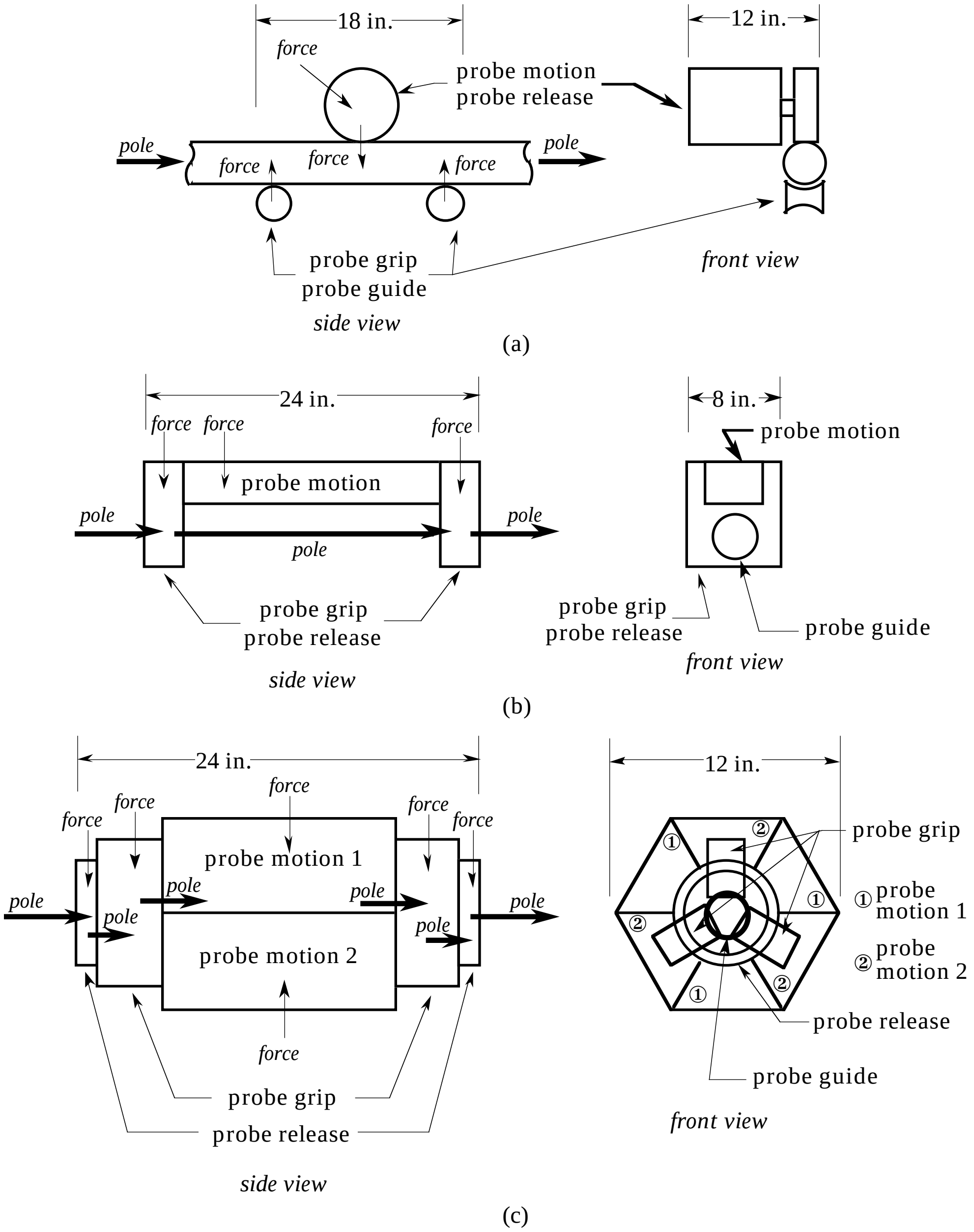


Figure 6.10 Rough geometric layouts of the probe transport module for the clinker clearer.

The first geometric layout, shown in Fig. 6.10 (a), is basically a pinch roller setup where a rotary motor is used to move the pole. In the second layout, refer to the side view of (b), the *probe grip module* on the left end grabs the pole and the *probe motion module* moves both to the right. The left *probe release module* then releases the pole and the *probe grip* and *probe release modules* return to the original position while the right *probe grip module* holds the pole and begins the cycle over again. In (c), two *probe grip, probe release* and *probe motion modules* (each similar in concept to (b)) work together to move the pole. Here, the modules are arranged to surround the pole to keep the load symmetrically distributed.

A mix of commercially available and custom designed components are explored for the rough geometric layouts of Fig. 6.10. Eventually the concept of Fig. 6.10 (c) is selected for the *probe transport module*.

6.2.3 Prototyping Efforts

A total of 14 modules were identified by the modular design methodology for this subset of the clinker clearer function structure. Many of the modules were implemented in the actual design. Table 6.4 lists the identified modules and the ones implemented. Of the modules that the design implements, the most complex is the *probe transport module*. An early prototype of the module is shown in Fig. 6.11. This module is best described as an assembly module that incorporates all four of its sub-modules. In practice, it became known as the insertion device and gained an additional sub-function of *convert hydraulic energy to force*. As mentioned earlier, and is evident in Fig. 6.11, the interaction between the module and the probe is a geometric issue. For the *probe transport module*, the probe passes through the center of the module where it is guided and alternately gripped, transported and released.

Table 6.4 Heuristically identified modules and their implementation status in the clinker clearer.

Module	Implemented?	Comments
hydraulic supply	yes	Commercial hydraulic power pack
supply electricity (2)	no	Subsumed within other modules
air	yes	Implemented minus the convert pneum. to vibration sub-function
vibration application	yes	Combined with pneum. to vibration module. Implemented as an interchangeable end effector for probe.
fragmented clinker handing	yes	An interchangeable end effector for probe
probe orientation	yes	As an assembly module
probe transport	yes	*convert hyd. ener. to force* sub-function added to identified module
impact clinker	yes	Same as vibration application module
clinker removal	yes	Same as fragmented clinker handling module
electricity to hydraulic	no	Subsumed by hydraulic supply module
hydraulic energy to force	yes	Commercial hydraulic cylinders
electricity to pneumatic	no	Subsumed by air module
pneumatic to vibration	yes	Merged with vibration application module

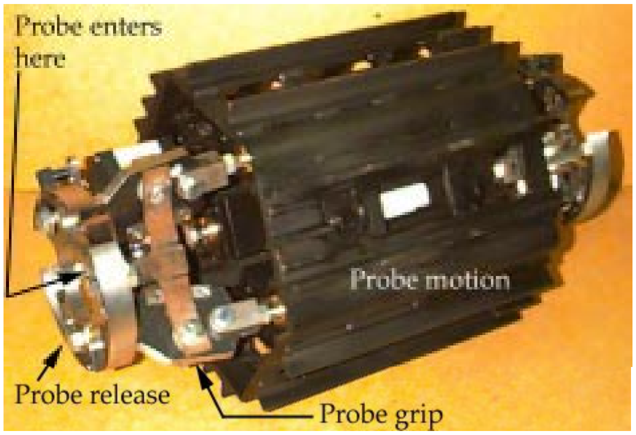


Figure 6.11 An early prototype of the *probe transport module* for the clinker clearer with sub-modules marked. Note that the pole will pass through the center of the structure (refer to Fig. 6.10 (c)).

You will note that several implemented modules were subsumed by other modules or merged with other modules. For instance, the vibration application and pneumatic to vibration modules are merged together in practice. The merged module creates an end effector for the probe that is interchangeable with the clinker removal module. This is an example of how overlapping modules are reconciled. Thus, overlapping modules present opportunities to further combine sub-functions into larger modules.

6.2.4 Clinker Clearer Summary

Overall, this case study shows that the module heuristic method is applicable to original design. It identifies modules, that in practice, are achievable and can be implemented. It also serves as a tool for task assignment within a design group.

Only a portion of the clinker clearer design is presented here. For the subset of the overall problem considered here, the customer need, functional decomposition, module heuristic and concept generation steps are shown. The concept selection process of determining the actual modules is not included, for the sake of brevity. Methods for completing this step are widely available (Pahl and Beitz, 1988; Ullman, 1997; Ulrich and Eppinger, 1995). The case study does show, however, the utility of the module design methodology for a typical one-off, original design problem.

6.3 MODULE BASED DEVELOPMENT TEAMS

One of the motivations for the theory of modular design is the ability to define development teams based on module groupings. Now, in that vein, I consider a climate control system for an automobile. This example was examined in Pimmler and Eppinger (1994). They used a design structure matrix technique to cluster components of the climate control system into modules. These modules then define the development teams and identify the interactions necessary between the groups.

Using the development team method of Chapter 5, modules of the climate control system are identified. These modules are compared with the design structure matrix modules of Pimmler and Eppinger. I argue that the module heuristics method provides a more intuitive means of grouping components together and, due to the inclusion of flow information, provides a clearer indication of interactions between modules.

6.3.1 Description of the Climate Control System

The climate control system is shown schematically in Fig. 6.12. This figure shows the components of the system at a form level, i.e. the actual forms of the solutions that solve the overall function of *control climate*. The climate control system has two main functions: heat and cool the air in the passenger compartment.

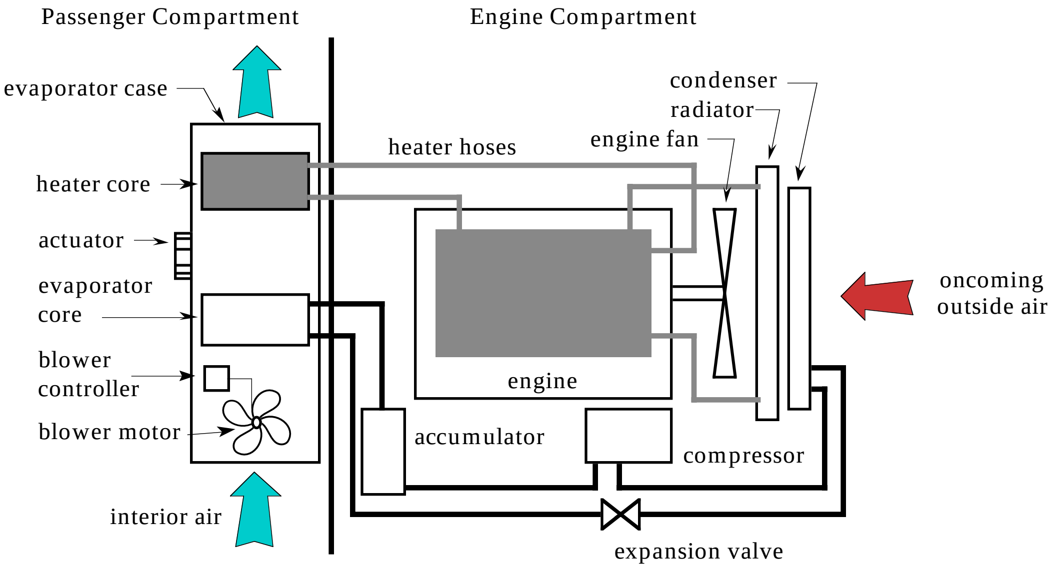


Figure 6.12 Schematic of an automotive climate control system (adapted from Pimmler and Eppinger, 1994).

Heating is provided by the circulation of hot engine coolant through heater hoses through the heater core (which is a heat exchanger). Since the heater core is a secondary system for dissipating thermal energy from the engine, hot engine coolant also circulates through the radiator (another heat exchanger) to dissipate thermal energy to the outside air.

Cooling of the passenger compartment air is achieved through the use of a refrigeration loop with five main components: compressor, condenser, evaporator, expansion valve and accumulator. The compressor accepts low pressure refrigerant gas and provides high pressure gas to the condenser. The condenser (a heat exchanger) condenses the gas, dissipating the thermal energy to the outside air. The high pressure liquid refrigerant then flows through an expansion valve, which maintains the pressure difference in the loop, to the evaporator. The refrigerant expands in the evaporator as the thermal energy of the passenger compartment air is absorbed (the evaporator is another heat exchanger). As the refrigerant exits the evaporator, it is a mixture of gas and liquid. The accumulator stores the liquid, allowing only the low pressure gas to pass to the compressor, which completes the cycle.

6.3.2 The Method of Forming Module Based Development Teams

Step 1 - Decompose system on a functional level

A function structure of the climate control system is given in Fig. 6.13. Note that the components are now represented as a sub-function or set of sub-functions which the component solves. If the team formation is following the modular conceptual design, then this step is already complete.

Step 2 - Apply the module heuristics

The three module heuristics are applied to the climate control system function structure next. The resulting modules are shown collectively in Fig. 6.14. As with Step 1, if the modular design methodology was followed, then this step is already complete.

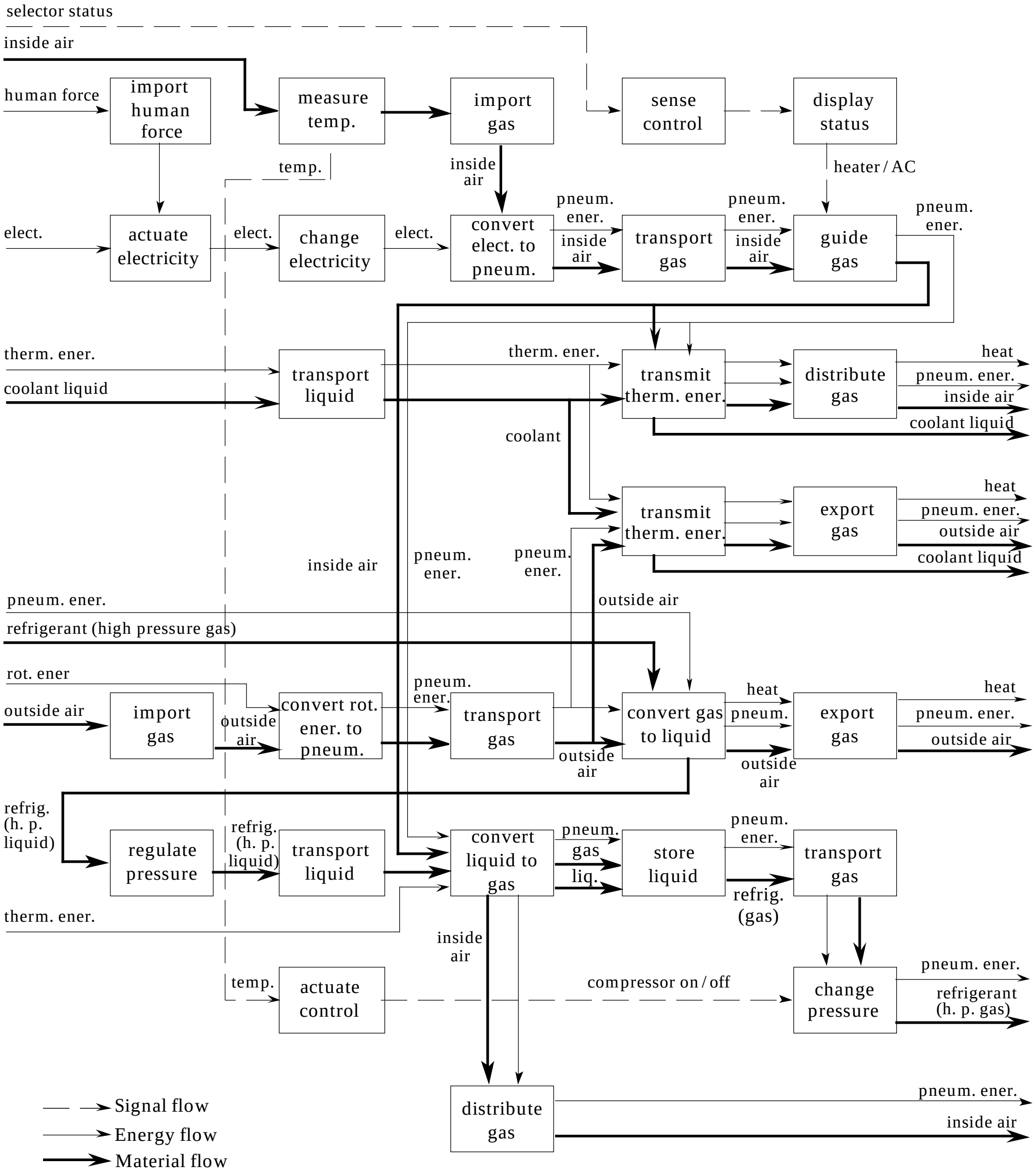


Figure 6.13 Function structure of the climate control system.

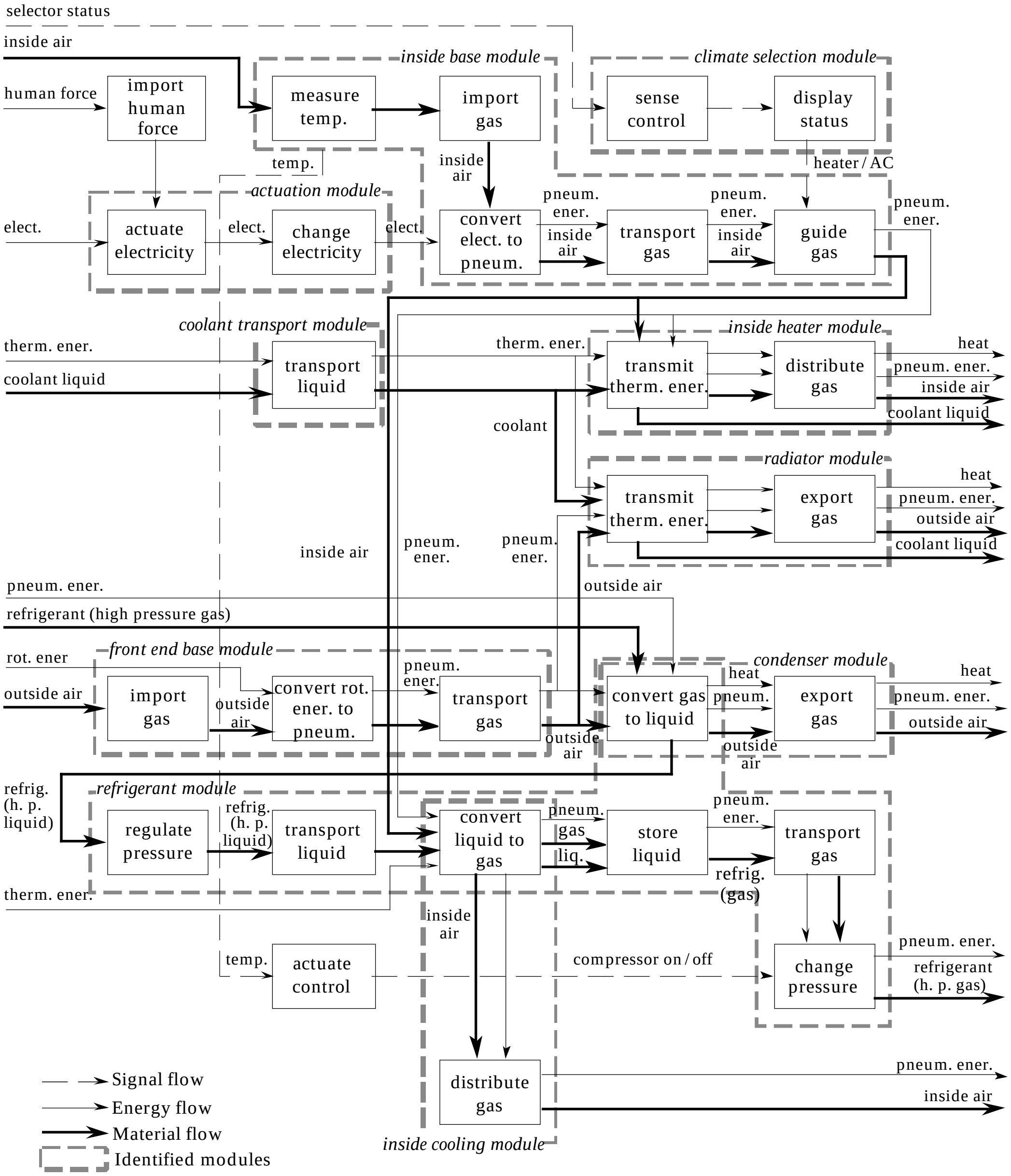


Figure 6.14 Identified modules of the climate control system by the dominant flow and flow branching heuristic.

Looking first at the dominant flow heuristic, we follow the flow *inside air* from entrance of the system until it splits. This group is called the *inside base module*. Next, we follow the flow of refrigerant through the system. It traverses through seven sub-functions labeled as the *refrigerant module*. The flow of *outside air* defines the *front end base module* before it splits. The flows *coolant liquid* and *thermal energy* (exhibiting the material-energy duality of the engine coolant) define the *coolant transport module* before they split. *Electricity* and the signal *selector status* identify the *actuation* and *climate selection modules*, respectively.

For the branching flow heuristic, three main flows branch: *inside air* (and its associated *pneumatic energy*), *outside air* (and its associated *pneumatic energy*) and *coolant liquid* (and its associated *thermal energy*). Note that all three of these flows have modules associated with them based on the dominant flow heuristic as applied before they branch. The flow *inside air* splits and forms two additional modules, denoted by *inside heater* and *inside cooling module*. In fact, these two modules are the heater core and the evaporator. The flow *outside air* splits to form two modules, the *condenser* and *radiator module*. The *coolant liquid* flow also identifies two modules that were previously identified by the flows *outside air* and *inside air*.

For this example, the conversion-transmission heuristic identifies modules that are all subsets of the modules identified by the dominant flow and branching flow heuristic. They are not discussed here since the development team application is searching for broader modules as opposed to the narrower modules the conversion-transmission heuristic predicts in this case.

The module-interaction list is given in Table 6.5. Each module and its interactions, the flows crossing the module boundary, are listed in the first two columns. The interactions are classified according to type in columns three through five. The basic flow classes of **M**aterial, **E**nergy and **S**ignal are represented. The final four columns list the input and output interfaces associated with the interaction as well as the **Sp**atial requirement between the modules. The spatial interaction, as used in Pimmler and Eppinger (1994), is an indication of whether components must be placed in close proximity to each other in order to successfully transfer material, energy or signal flows. In this table, the spatial column is simply a binary indication of the need for the module to be located in close proximity to another.

Table 6.5 List of modules identified by heuristics for the climate control example.

Module	Interactions	Interaction type			Interfaces in: modules or		Interfaces out: modules or	
		M	E	S	Sp	(external systems)	Sp	(external system)
actuation	electricity		•			(electrical system)		inside base
	human force		•		•	(human hand)		
inside base	inside air	•			•	(passenger compartment)	•	inside heater, refrigerant, inside cooling
	electricity		•			actuation		
	pneumatic energy		•				•	inside heater, refrigerant, inside cooling
	temperature			•				(actuate control)
	heater / AC			•		climate selection		
inside heater	inside air	•			•	inside base	•	(passenger comp.)
	pneumatic energy		•		•	inside base	•	(passenger comp.)
	thermal energy		•			coolant transport	•	(passenger comp.)
	coolant liquid	•				coolant transport		coolant transport
inside cooling	inside air	•			•	inside base	•	(passenger comp.)
	pneumatic energy		•		•	inside base	•	(passenger comp.)
	thermal energy		•		•	(passenger comp.)		
	refrigerant	•				refrigerant		refrigerant

Table 6.5 (Continued) List of modules identified by heuristics for the climate control example.

		Interaction type			Interfaces in: modules or		Interfaces out: modules or	
Module	Interactions	M	E	S	Sp	(external systems)	Sp	(external system)
front end base	outside air	•			•	(environment)	•	refrigerant, condenser, radiator
	rotational energy		•		•	(engine)		
	pneumatic energy		•				•	refrigerant, condenser, radiator
radiator	coolant liquid	•				coolant transport		coolant transport
	thermal energy		•			coolant transport	•	(environment)
	pneumatic energy		•		•	front end base	•	(environment)
	outside air	•			•	front end base	•	(environment)
condenser	thermal energy		•				•	(environment)
	pneumatic energy		•		•	front end base, refrigerant	•	(environment)
	outside air	•			•	front end base	•	(environment)
	refrigerant	•				refrigerant		refrigerant
refrigerant	refrigerant	•						
	pneumatic energy		•		•	front end base, inside	•	inside cooling, condenser
	thermal energy		•		•	(passenger comp.)	•	condenser
	outside air	•			•	front end	•	condenser
	inside air	•			•	inside	•	inside cooling
	compressor on / off			•		(actuate control)		
coolant transport	thermal energy		•			(engine)		inside heater, radiator
	coolant liquid	•				(engine)		inside heater, radiator
climate selection	selector status			•		(passenger comp.)		
	heater / AC			•				inside

Note in this example, I did not apply the quantitative module assessment method to associate a customer need ranking with each module. It was skipped due to the lack of an adequate device database of similar devices.

Step 3 - Associate ungrouped sub-functions

After applying the heuristics, any ungrouped sub-functions must be lumped into an existing module or a new one. This step ensures their assignment to a development team. In this example, we will assign the ungrouped sub-functions to the modules that their flows directly affect. For the sub-function *import human force,* the flow *human force* affects the *actuation module* and is lumped with it. The other ungrouped sub-function *actuate control* is lumped with the *refrigerant module,* the one to which it sends a control signal.

Step 4 - Assign teams to develop modules

Now we assign the development teams to the identified modules of Table 6.5. Teams are now defined based on function and interaction as indicated in the table. Instead of traditional, mutually exclusive teams, these teams share responsibility for components that affect more than one module. There are many ways to populate development teams once their responsibilities are defined by the module based development team method. One such method is to arrange teams based on personality type, as determined by the Meyers-Briggs Type Indicator (MBTI) tool. Accounting for type differences and, more importantly, making team members aware of other’s different strengths eases tension between the differing member types (Wankat and Oreovicz, 1993).

6.3.3 Comparison with Design Structure Matrix Technique

The module heuristic development team method identifies ten modules for the climate control system. This method identifies modules similar to the design structure matrix technique of Pimmler and Eppinger, but my modules are narrower in their focus (or may be viewed as having greater resolution). Pimmler and Eppinger identify three major modules and a fourth module which is a catch-all for the remaining components. The two techniques' modules are compared in Table 6.6.

Table 6.6 Comparison of module heuristic and Pimmler and Eppinger modules.

Development team method	Pimmler and Eppinger (1994) modules	Comment
inside base	inside chunk	Development team method provides greater resolution of modules
inside heater		
inside cooling		
actuation		
front end base	front end chunk	Development team method provides greater resolution of modules
radiator		
condenser		
refrigerant	refrigerant chunk	Same
coolant transport	controls / connections chunk	P&E simply lump remaining components together
climate selection		

As with the Pimmler and Eppinger technique, my method represents a departure from standard industry practice. It emphasizes team formation, hence product architecture, based on function and interaction concerns. Other product architecture techniques worry with interactions only *after* an architecture is selected (Ulrich and Eppinger, 1995; Cutherell, 1996).

Distinguishing the two methods, the development team method is a graphical method that includes flow information to identify modules. The matrix technique represents this information, but it is not as intuitive as the graphic connection of sub-functions or components with flows. The design structure matrix requires clustering algorithms to group sub-functions, while the development team method groups sub-functions through the simple application of the three module heuristics.

6.3.4 Summary

The development team method provides a useful tool for organizing development teams based on device modularity. The method is well suited to complex devices where identification of interactions between the device and teams is critical. It allows industry to adjust its development teams based on the device instead of being confined to a traditional corporate structure that might not be the most suitable for the device.

6.4 REVERSE ENGINEERING - EVOLUTION OF A TEA BREWER

The final case study looks at the evolution of the Mr. Coffee Iced Tea Pot. This case study was envisioned as an opportunity to predict the next generation iced tea brewer based on the modular design methodology. While that work was in progress, another iced tea brewer from Mr. Coffee surfaced on store shelves. It looked extremely similar to one of the modular concept variants of my work. Here, I present the evolution process that I went through using the modular design methodology in conjunction with the reverse engineering methodology of Otto and Wood (1996).

6.4.1 The Modular Design Methodology and Reverse Engineering

You will recall the iced tea brewer case studies that were examined in Chapters 3 and 4. In those case studies, the Mr. Coffee brewer was found to be more modular than the West Bend model. Could the Mr. Coffee brewer be further improved, though? Here is where we use the reverse engineering methodology to determine what can be altered about the device to improve it or to target another part of the market. Then the modular design methodology is applied to produce a modular concept variant. The steps of the modular design methodology are summarized below.

Step 1 - Customer Needs

Step 1 of the reverse engineering methodology identifies customer needs for the redesign of the iced tea brewer. Those customer needs are used in Step 1 of the modular design methodology as well, and are presented in Table 6.7.

Additionally, columns three and four indicate whether the existing iced tea brewer meets the customer need and, if not, whether the redesign will address it. In gathering customer needs, an existing iced tea brewer (Mr. Coffee model TM1) was used to solicit responses. That model was well received, but suggested improvements included a smaller operating footprint and an easier alignment process for the pitcher and the brewer, where the 'brewer' is considered the device minus the pitcher (customer need statements: compact and align pitcher to catch tea). These two needs are the impetus for the redesign. The other customer needs listed were addressed in earlier redesign efforts (Little, 1997).

Table 6.7 Customer need and importance data for the iced tea brewer.

Customer Need	Importance	Need met in current device?	Fix it?
Easy to add ice	5	yes	
Marks on pitcher denote fill levels	5	yes	
Easy to add tea	5	yes	
Stronger tea	5	yes	
Compact	4	no	yes
Water tank is accessible	3	yes	
Dishwasher safe pitcher	3	yes	
Brewer does not clog	3	yes	
Top for pitcher	3	yes	
Align pitcher to catch tea	3	no	yes
Brew larger amount of tea	2	no	yes
Brewer contains steam	2	yes	
Simple to turn on	1	yes	

Step 2 - Decompose the Problem

The decomposition step is aided by the concrete experiences of Step 2 of the reverse engineering methodology. Disassembly of the tea brewer, the bill of materials, the subtract/operate procedure and device experimentation contribute to the refined function structure of the tea brewer (Otto and Wood, 1996). First, though, the black box description of the tea brewer is shown in Fig. 6.15. The important input and output flows are shown. Note that an alignment signal is incorporated to address the customer need of aligning the pitcher to the brewer. In fact, each flow is associated with a stated customer need.

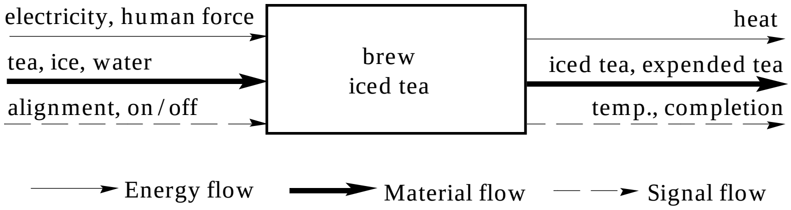


Figure 6.15 Black box description of the iced tea brewer.

The disassembly of the existing tea brewer yields an exact functional representation of the current device. Since the goal of redesign is to modify the device, we must see if new sub-functions are needed or if existing ones must be removed to meet the new customer needs. The customer need of compact size is addressed by existing sub-functions such as *import solid, store solid, import liquid, store liquid*, etc. However, the sub-function *sense position* is added to deal with the alignment of the pitcher and brewer. The function structure of the tea brewer is given in Fig. 6.16. Now we are ready to identify modules.

Step 3 - Apply Module Heuristics

The module heuristics are applied to the tea brewer function structure in Fig. 6.17. Six modules are identified by the dominant flow heuristic: *filter & tea containment; ice containment; liquid containment; electrical supply; thermal energy;* and *tea containment*. One branching flow (*human force*) identifies four modules that are previously identified by the dominant flow heuristic. One conversion-transmission module is identified: *electrical conversion*.

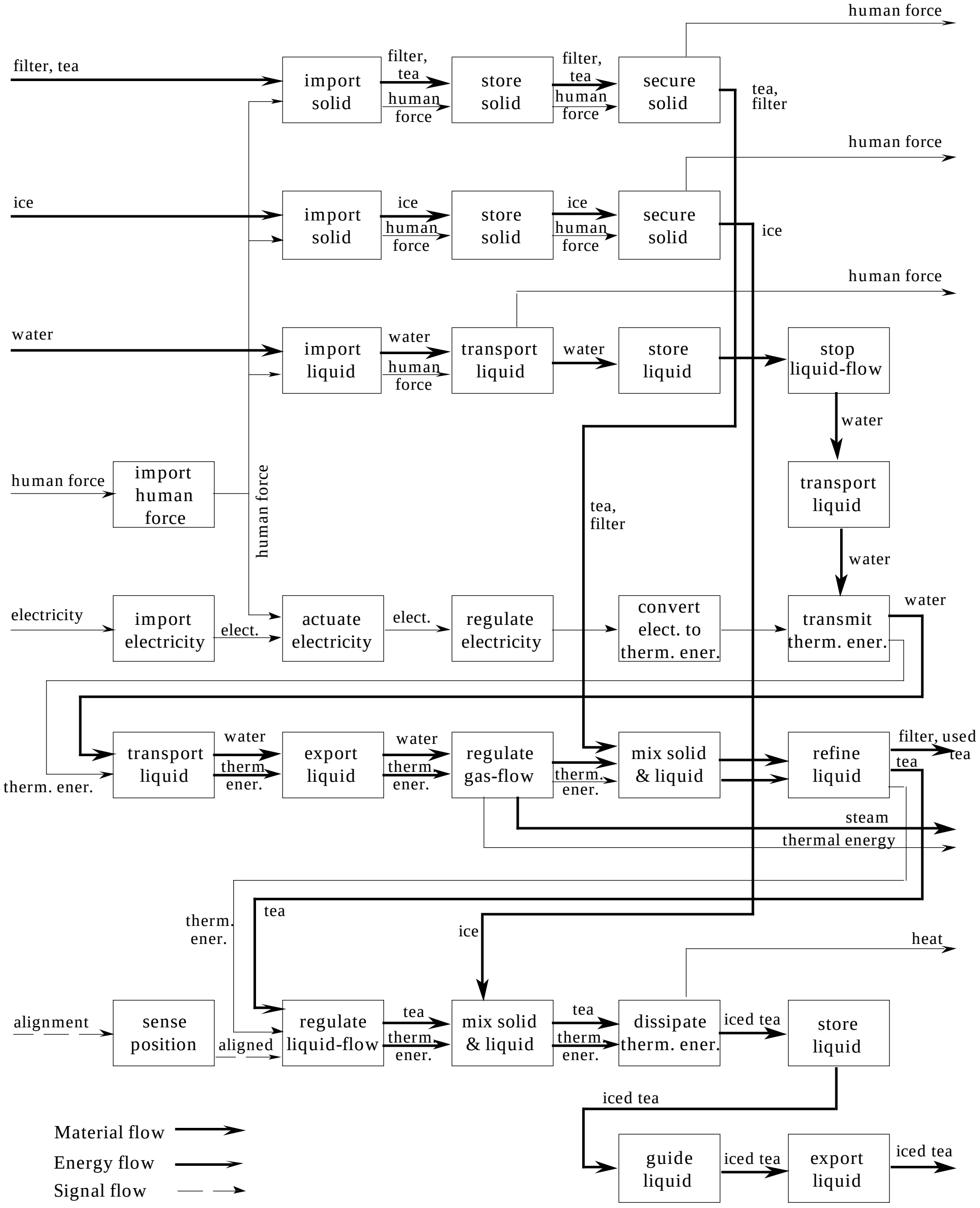


Figure 6.16 Function structure of the iced tea brewer considered for redesign.

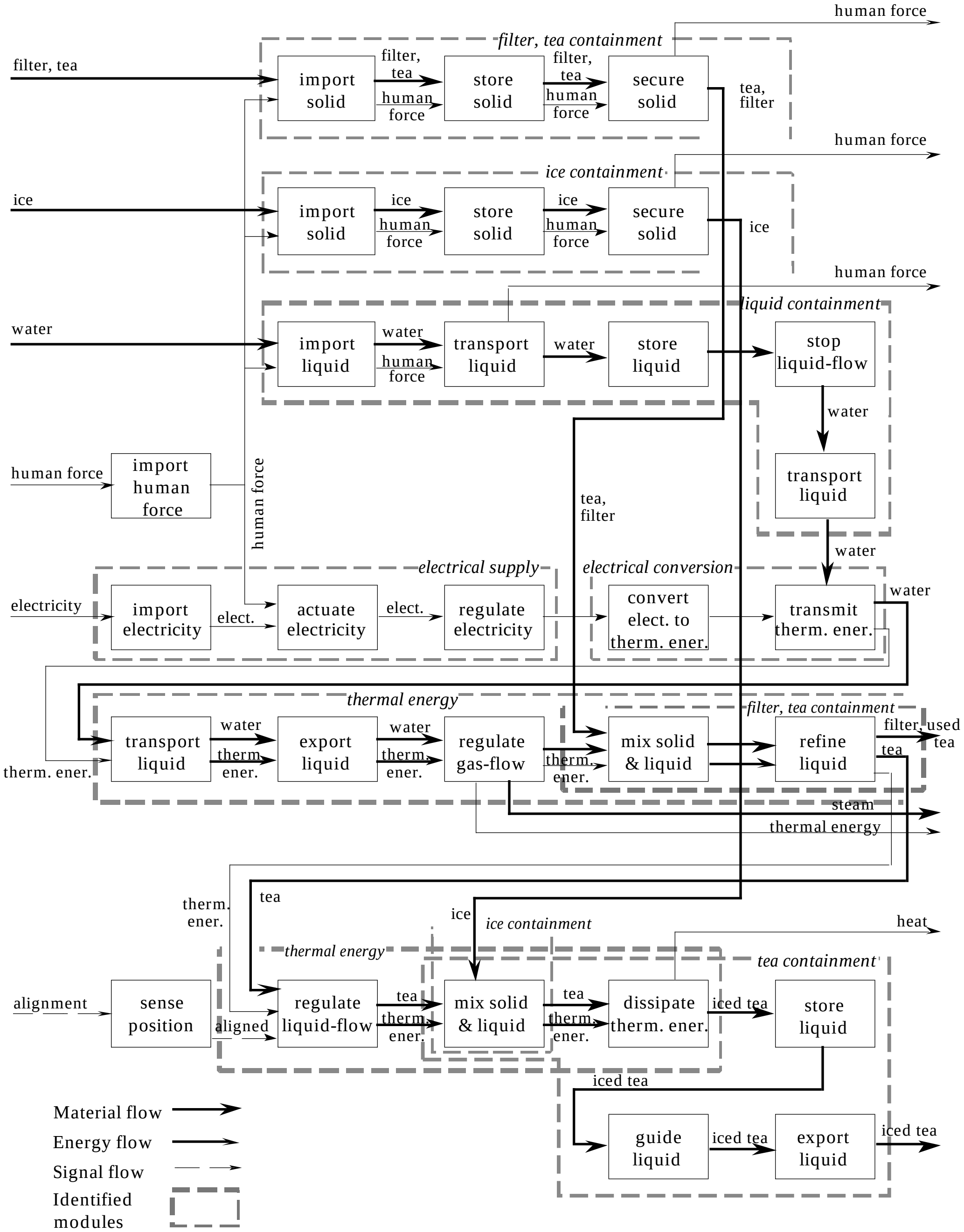


Figure 6.17 Identified modules for the iced tea brewer.

The interactions of the modules are listed in Table 6.8. The type of interaction is denoted as well. This task prepares us for the generation of concepts later in Step 5. Note that the spatial column indicates that the modules will have largely geometric interface concerns.

Table 6.8 Modules and interactions of the iced tea brewer.

		Interaction type			Interfaces in:			Interfaces out:
Module	Interactions	M	E	S	Sp	modules or (external systems)	Sp	modules or (external system)
filter & tea containment	filter, tea	•				(human)		(human)
	human force		•		•	(human hand)		(environment)
	thermal energy		•		•	thermal energy	•	thermal energy
	water	•			•	thermal energy		
	tea	•					•	thermal energy
ice containment	ice	•				(human)		
	human force		•		•	(human hand)		(environment)
	brewed tea	•			•	thermal energy		tea containment
	thermal energy		•		•	thermal energy		tea containment
liquid containment	water	•				(faucet)	•	electrical conv.
	human force		•		•	(human hand)		(environment)
electrical supply	electricity		•			(wall socket)		electrical conv.
	human force		•		•	(human hand)		
electrical conversion	electricity		•			electrical supply		
	water	•			•	liquid contain.	•	thermal energy
	thermal energy		•				•	thermal energy
thermal energy	water	•			•	electrical conv.		
	thermal energy		•		•	electrical conv.		(environment)
	tea, filter	•			•	filter & tea cont.		(human)
	steam	•						(environment)
	ice	•			•	ice contain.		
	brewed tea	•					•	tea contain.
	aligned			•		(sense position)		
tea containment	brewed tea	•			•	thermal energy		(environment)
	thermal energy		•		•	thermal energy		(environment)
	ice	•			•	ice contain.		

Note that several of the modules overlap with each other, though no one module is a subset of another. In this case, we keep all modules for future consideration. This will ensure a greater variety of concept variants.

Step 4 - Quantitative Module Assessment

Step 4 calculates the customer need importance value for each module and identifies similar devices. The first task is to form the device vector for the iced tea brewer and add it to the device database. Using the Little method from Chapter 4, the ranked customer needs and function structure are transformed into the device vector shown in Table 6.9.

Table 6.9 Device vector for the iced tea brewer.

Sub-function	Cumulative customer need rating
actuate electricity	1
convert electricity to thermal energy	3
dissipate heat	4
export liquid	1
guide liquid	1
import electricity	1
import human force	12
import liquid	9
import solid	16
mix liquid and solid	8
refine liquid	6
regulate electricity	1
regulate gas	6
regulate liquid	7
secure solid	6
sense position	4
stop liquid	1
store liquid	14
store solid	17
transmit thermal energy	6
transport liquid	4

Next we generate a device family based on the iced tea brewer. The device family represents a group of devices that are similar on a functional and customer needs level. The device family is shown in Table 6.10. Using the seven devices in the family, the function-function matrix is generated, showing the customer need importance values for combinations of sub-functions. The ranked sub-function combinations are shown in Table 4.10 of Chapter 4 and are not repeated here.

Table 6.10 Device family with Mr. Coffee iced tea maker as the generating device.

Device	Similarity index, λ_{ij}	% of sub-functions in common
Mr. Coffee Iced Tea Brewer	1.00	100
West Bend Iced Tea Brewer	0.75	88
Mr. Coffee Coffee Maker	0.74	92
Krups Café Trio	0.60	67
Hot Glue Gun	0.60	50
Humidifier	0.51	42
Presto Popcorn Popper	0.46	25

The ranked sub-function combinations are then used to assign an average customer need index to each of the modules from Step 3. The customer need index of a module is simply the average of all the sub-function combination customer need indices that represent the functionality of the given module. This is shown for the tea brewer family in Table 6.11. Note that all the modules address some set of customer needs. The *electrical conversion module* is the most important, from the customer's standpoint. Since all modules have an index greater than one, implementation of all modules is justified by customer need. If that is not feasible, then the average index allows the modules to be ranked. For instance, part of the *filter & tea containment module* is contained within the *thermal energy module*. The *filter & tea containment module* is ranked higher. So it would make sense to incorporate the *filter & tea containment module* before the *thermal energy module* if resources were unavailable to do both.

Table 6.11 Customer need importance values for the iced tea brewer modules identified in Step 3.

Heuristic modules: *functional description*	Quantitative sub-function combinations	Coupled cust. need index	Average index
electrical conversion: *convert electricity to thermal energy, transmit thermal energy*	convert electricity to thermal energy+transmit thermal energy	7.45	7.45
liquid containment: *import liquid, transport liquid, store liquid, stop liquid-flow, transport liquid*	import human force+store liquid	7.28	4.98
	import liquid+store liquid	3.64	
	import human force+import liquid	4.01	
tea containment: *mix solid & liquid, dissipate thermal energy, store liquid, guide liquid, export liquid*	mix solid & liquid+store liquid	4.75	4.75
ice containment: *import solid, store solid, secure solid, mix solid & liquid*	import solid+store solid	3.74	4.36
	import solid+secure solid	3.76	
	import solid+mix solid & liquid	4.19	
	import human force+import solid	6.77	
	import human force+store solid	4.34	
	import human force+secure solid	3.35	
filter, tea containment: *import solid, store solid, secure solid, mix solid & liquid, refine liquid*	import solid+store solid	3.74	4.25
	import solid+secure solid	3.76	
	import solid+mix solid & liquid	4.19	
	import human force+import solid	6.77	
	import human force+store solid	4.34	
	import human force+secure solid	3.35	
	mix solid & liquid+refine liquid	3.58	
thermal energy: *transport liquid, export liquid, regulate gas-flow, mix solid & liquid, refine liquid, regulate liquid-flow, mix solid & liquid, dissipate thermal energy*	mix solid & liquid+refine liquid	3.58	3.58
electrical supply: *import electricity, actuate electricity, regulate electricity*	import human force+actuate electricity	3.10	3.10

It is important to remember that the customer need index for the sub-function combinations is based on a family of related devices. This gives the added assurance that the modules are justified not just by the iced tea brewer, but also by a wider domain of devices. It shows that any investment in a modular system for the iced tea brewer can see a return in other devices. Or, conversely, the iced tea brewer can benefit from other devices in its family if they already have a modular design.

Step 5 - Generate Concepts

Now we are ready to generate concepts for the iced tea brewer modules. The two customer needs that are driving the redesign are a compact size and a pitcher to brewer alignment method. The rough geometric layouts must address these needs. Two possible concepts are shown in Fig. 6.18. The (a) concept is similar to the current iced tea brewer model, utilizing a side by side design. An alignment foot is shown and the overall dimensions are smaller to address the customer needs. Concept (b) is a stacked design, departing from the existing iced tea brewer configuration. It has a small footprint and incorporates an alignment notch in the layout. Both layouts show the interactions between the modules.

With the modular concepts in rough layout form, we can now search for existing components and creative solutions to embody the modules. Since this is a redesign, many of the same components from the existing device may be incorporated into the redesigned device. For example, the *electrical supply* and *electrical conversion modules* are solved by a readily available component that is used in virtually all coffee makers and iced tea brewers. This component is shown in Fig. 6.19. On the other hand, such modules as the *liquid containment module* are typically brand and model specific, requiring a creative solution.

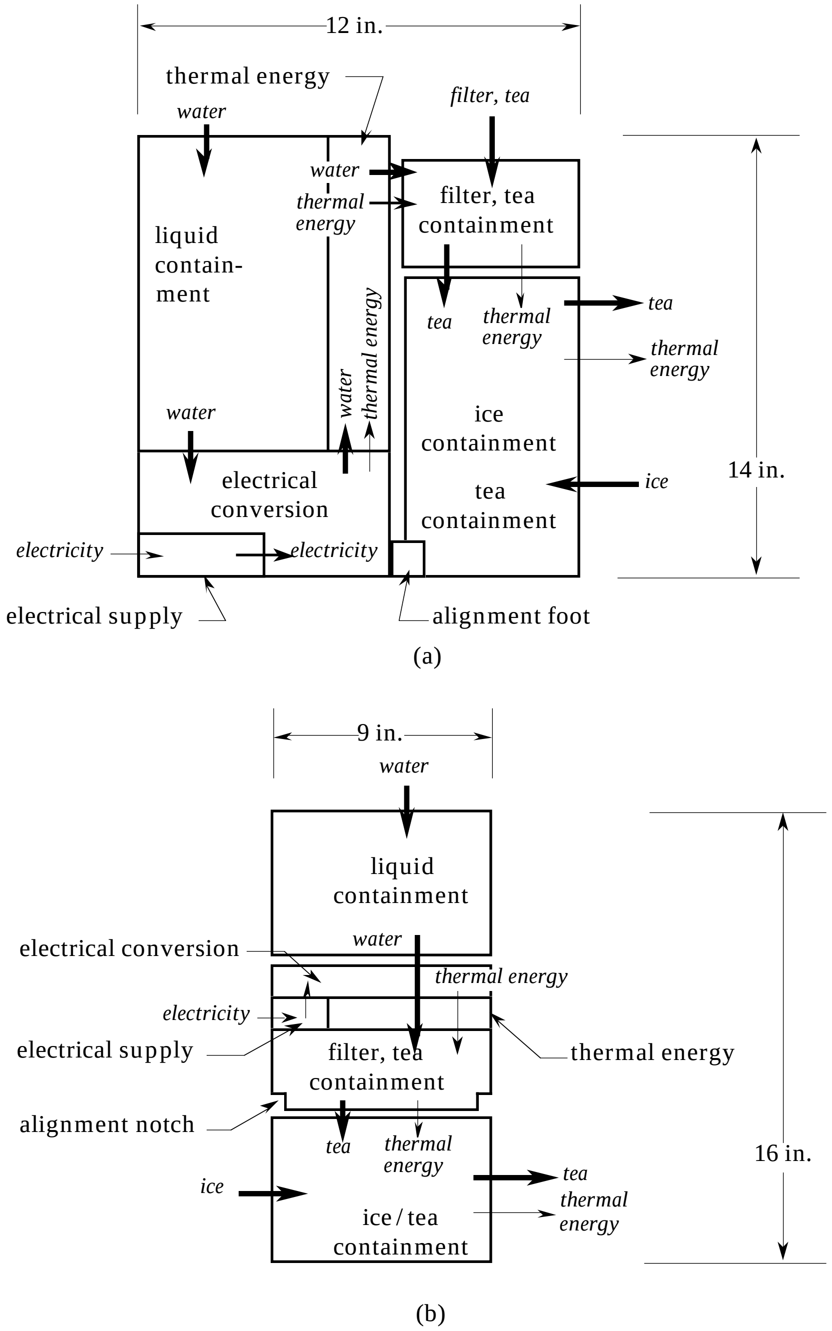


Figure 6.18 Rough geometric layouts for the iced tea brewer redesign. The layout in (a) is the traditional side by side design while the layout of (b) features a stacked concept.

Figure 6.19 Examples of existing components that solve the *electrical supply* and *electrical conversion modules* for the iced tea brewer. These modules are used in iced tea brewers and coffee makers.

Completing the Redesign

Following the concept generation step, the concepts are then selected through some selection process. These selection processes are well documented and the choice is left to the designer (Pahl and Beitz, 1988; Ulrich and Eppinger, 1995; Ullman, 1997). Without belaboring the point, the concept screening method employed selects the stacked concept of Fig. 6.18 (b) for development.

Now the modular design methodology is completed. Returning to the reverse engineering methodology of Otto and Wood (1996), we pick up at their Step 5 to firm up engineering specifications and metrics. This is usually accomplished by generating a House of Quality (or Quality Functional Deployment) matrix to arrange the specifications and metrics (Otto, 1996). The redesign is completed through the generation of detailed models and prototypes and the eventual production of the next generation iced tea brewer.

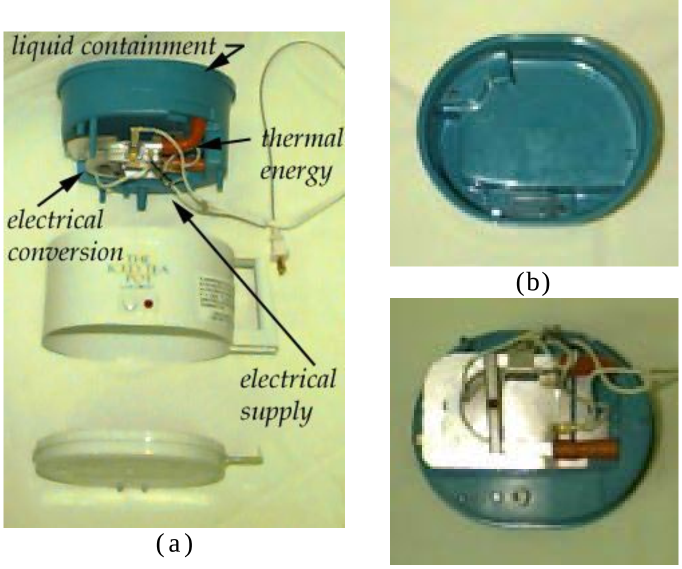
6.4.2 The Evolved Iced Tea Brewer

After rough geometric layouts were developed for this case study, a new model of the Mr. Coffee Iced Tea Brewer was discovered on local store shelves. The new model, along with the original side by side version, is shown in Fig. 6.20. Note the similarity to the selected stacked concept from the above steps.

Figure 6.20 Comparison of two Mr. Coffee Iced Tea Brewers. The model on the left is the older, side by side version. The model on the right, is very similar to the stacked concept presented in Section 6.4.1.

While the stacked iced tea brewer model by Mr. Coffee and my modular design work are two independent designs, it does offer strong support for the modular design methodology. The stacked model is a modular device, and it answers the customer needs that drive the redesign study of Section 6.4.1: a compact design (footprint) and a method to align the pitcher and brewer. Many of its modules are contained together in the top assembly module, shown in Fig. 6.21. The *liquid containment, thermal energy, electrical conversion* and *electrical supply modules* are aggregated together, similar to the arrangement shown in Fig.

6.18 (b). The main difference, though, is the absence of a f*ilter & tea containment module*. This module's functions are solved instead by requiring the use of tea bags and merging the sub-functions of *mix liquid & solid* and *refine liquid* into the *liquid containment module*. Here, the tea mixture is heated and recirculated through the *liquid containment module* until the tea mixture reaches a set temperature. Then the tea is dispatched from the *liquid containment module* into the *ice* and *tea containment modules*.



(a) (b) (c)

Figure 6.21 Modules from the stacked Mr. Coffee Iced Tea Brewer. (a) An exploded view of the *liquid containment, thermal energy, electrical supply* and *electrical conversion modules*. (b) The top view of the *liquid containment module*. (c) The bottom view of the *liquid containment module* and the interfaces between it and the other modules listed in (a).

6.4.3 Reverse Engineering Summary

This case study of the Mr. Coffee Iced Tea Brewer shows that the modular design methodology is easily integrated into a reverse engineering design process. The quantitative module assessment step is particularly useful in this case. In addition to associating a customer need importance with modules, it provides a means of drawing on the knowledge of other existing, related devices. This case highlights another strength of the modular design method: the ability to begin the search for solutions at the modular level rather than the functional level. This reduces the number of solution principles that must be found, but does not diminish the opportunity for creative modular concept solutions. The modular design methodology's incorporation into an existing reverse engineering methodology is summarized and a real world analog of this redesign is discussed.

6.5 SUMMARY

Three case studies are presented in this chapter: an original, one-off design; a reverse engineering design; and a development team formation case. Each of these demonstrate how the theory of modular design is applied in real situations. The clinker clearer device (original, one-off design) is the genesis of the modular design methodology. It shows that modules can be identified and then detailed separately. This allows parallel development and manufacture of the modules. The iced tea brewer (reverse engineering) case shows how the modular design methodology can improve or modify an existing device to meet changing customer needs. The rough geometric layouts of the tea brewer allow the design to begin at the component level rather than returning to the functional level. The teaming study (development team formation) extends the theory of modular design to cover personnel issues by establishing a method for forming development teams and the required lines of communication.

The theory represents a valuable tool for designers. This chapter shows that it is not simply a self serving creation of the academic world. Instead, it has practical applications exemplified in the three case studies.

CHAPTER 7

CONCLUSIONS & FUTURE WORK

7.1 OVERVIEW

No body of research is ever really complete. This dissertation is no exception. It does, however, prove the stated hypothesis and meet the listed objectives. The answers to the questions posed in Chapter 1 and their greater impact to the field of design methodology are summarized in the conclusions section. These same answers also spur additional questions and additional avenues for continued research. Such topics are covered in the future work section.

7.2 CONCLUSIONS

Following a methodical, mechanical design approach, it is possible to identify modular components at the functional level of a conceptual or reverse engineering design. The approach is formalized in the theory of modular design of Chapter 5. Direct benefits from identifying modules include greater use of common components in similar devices, a more logical method of organizing design teams and a reduction in development and manufacturing lead time of a device.

Recall the stated objectives of this dissertation:

1. Develop a formal method of identifying modules in a device based on existing design methodologies and show its incorporation into an overall design methodology.
2. Through quantitative means, show when modular design offers a benefit to the designer.
3. Provide physical verification of modules which exist in current devices and show how the module identification method predicts them.
4. Through case studies, demonstrate the application of the method to conceptual and reverse engineering design problems.
5. Predict, in one commercially available device, where a modular design will benefit the device.

Every objective is met in this work. Objectives 1 and 2 are met through the theory of modular design in Chapter 5. The third objective is met through the verification studies presented in Chapters 3 and 4. The final objectives are addressed through the case studies of Chapter 6.

Along the way to formulating the overall theory, a functional base set is developed. The functional base set defines a set of functions and flows which describe the design space. The functional base set makes function structures more repeatable among different designers and provides a consistent level at which to stop decomposition, thus answering two major criticisms of formalized design methodologies. The functional base set has implications far beyond that of modular design to the very core of function based design methods. Flow ranking is also introduced as a technique to relate customer needs to device flows.

The function structure becomes the foundation for heuristic and quantitative methods of identifying modules. Three heuristic methods provide a systematic approach to identifying modules of a device using a function structure. Their application is elegantly simple, but their utility is immense. The quantitative module assessment method relates customer need rankings to modules through their functionality. This provides a metric with which a module's importance can be assessed. The quantitative assessment method also evaluates device similarity based on customer needs and functionality, providing a new tool for companies looking to expand into a related market or glean information from competing devices.

The theory of modular design represents a new tack on design methods. Two complementary parts of the theory of modular design are formulated: modular design and development team formation. Both look at the design process from the standpoint of building up an overall device out of modules. The theory is also envisioned as a concurrent process, in terms of developing modular concepts and detailing and producing modules in parallel. The theory provides a systematic approach to achieving customer need based modules. While functional decomposition is used to describe the problem, the theory shifts the search for solutions to a modular level rather than looking for a solution to every individual sub-function.

The new approach to modular design is welcomed, based on conversations with industry design experts (Jackson, 1997). Also a survey of current device offerings confirms that modular devices are a goal of industry. Consider Black and Decker's VersaPak line of power tools. All share a common rechargeable battery module and many share switches and motors. The battery module makes the device line reconfigurable, standardized and less expensive (assuming one set of batteries is used to power multiple devices) for the consumer. The common switch modules and motors allow Black and Decker to order in large batches, thus, lowering manufacturing cost. The modular design method offers a systematic way of describing the modular devices on the market. More importantly, though, the modular design methodology advances the topic of modular design by offering innovative modules that are not present in current devices (recall the *supply electricity* module of the SKIL power screwdriver that could interact with different drive modules in Chapter 3).

Likewise, the development team formation method advances the teaming issue. It upends the current product architecture techniques which group functions together and then worry about interactions between modules. Instead, it uses the flows (which are interactions) to define modules and teams. The method also identifies the necessary communication lines between concurrent development teams and forms a framework for future study in the teaming area.

The work here represents my contribution to the field of mechanical design theory. It is a substantial contribution, and it sets the stage for future work in the modular design area.

7.3 FUTURE WORK

The theory of modular design proves the hypothesis of this dissertation. It also points to areas where further work is needed. I close this dissertation with brief discussions of those avenues for future work.

7.3.1 Educational Research and Application

The systematic approach of the theory of modular design is perfectly suited for incorporation into an engineering design course. Common complaints by students in traditional design courses reflect their desire for a method that provides guidance throughout the design process (this is my personal experience as well when I was an undergraduate in my capstone design sequence). The modular design methodology can be integrated into function based methodology courses. An interesting experiment would be to compare the design of one device by two groups, one which used the modular design methodology and the other a standard methodology such as Pahl and Beitz (1988).

7.3.2 Standardized Set of Modules

In the analysis of the 70 product database used to verify the module heuristics, certain modules appeared time and time again. Just as the functional base set brings a standard list of functions and flows, a standard list of modules would speed functional decomposition of a design problem. A hybrid form of function structure would combine modules with other sub-functions. This could simplify the decomposition process and the search for solution principles, since modules indicate a component solution already exists, while sub-functions identify parts of the device that require original design.

7.3.3 Module Compiler

Utilizing the standardized set of modules, a module-aware design compiler could be constructed. Module compilers, similar to the design compiler developed by Ward and Seering (1989), could transform a high level representation of a device (like a rough geometric layout, perhaps) into concrete components from a database of actual components. The database would require physical components to be classified into a standard set of modules. Each component would be specified by their geometric, material, energy and signal interactions. This idea for a module compiler assumes that a standard set of modules can be identified for a class of devices. For instance, the class of hand held power tools has an associated set of modules, ***H***, from which all devices can be described. The modules making up ***H*** are also sets, where each set consists of actual components which embody the module concept. Innovative and new power tools are constructed conceptually from the set of modules. The module compiler then combines compatible components to produce physical variants based on input specifications.

7.3.4 Checklist for Modular vs. Integral Design

How do you answer the question, “When is a modular design better than a integral design?” The quantitative method presented in Chapter 4 shows how combinations of sub-functions meet multiple customer needs, but sometimes data is not available for a domain of devices, as that method requires. A simple checklist or decision matrix for modularity is proposed for such cases. As an example, Table 7.1 shows a binary checklist for modularity. The nine questions are answered yes, no or not applicable and the answers are assigned values of +1, -1 and 0, respectively. The first column lists the questions. The remaining three columns show the answers for three devices: the SKIL power screwdriver, the clinker clearer of Chapter 6 and a hand held vegetable peeler. The values for each device are summed. If the sum is negative, then integral design is recommended. If the sum is in the range [0,2], a modular design should be strongly considered since, at worst, the device is neutral to the modularity questions. For sums greater than 2, then the device is screaming for a modular design.

Table 7.1 Sample checklist for modularity. A SKIL power screwdriver, clinker clearer and hand held vegetable peeler are compared.

Checklist item	SKIL power screw.	Clink. clearer	Hand veggie peeler
Will device be upgradeable?	-1	1	-1
Are elements consumed?	1	1	1
Will there be add-on elements?	1	1	-1
Use in different environments?	1	-1	-1
Are multiple models planned?	1	-1	-1
Do other devices you produce use standardized components?	1	1	-1
Are any compatible with new device?	1	1	-1
Is a similar device on the market?	1	-1	1
Are adaptability and function more important than performance?	-1	1	-1
Sum	5	3	-5

7.3.5 A True Functional Basis and Flow Cues

A final area of future work that is not confined to modular design concerns the functional base set. The functional base set is a basis set in spirit, but lacks a mathematical proof. It would be interesting to see if such a mathematical formulation could be applied to the base set.

Another area related to the functional base set is the creation of flow cues. Flow cues are a list of characteristics of the functional basis flows which serve as cues to match flows with customer need statements. This customer need to flow correlation was the first part of the formation of the device-function matrix presented in Chapter 4 and was noted to require engineering judgment. Flow cues could make that correlation more systematic. As an example, consider the flow *pneumatic energy*. A list of cues for *pneumatic energy* is: quick response, generates large magnitude forces, noise emission, inherent cooling. The cues could be used to associate the customer needs of *generate ample force* and *quick recoil* with the flow pneumatic energy. Note that the customer statements contain elements of the cues for pneumatic energy.

7.3.6 Other Open Questions

Finally, I close with a few open questions resulting from this work. Comments are included where necessary.

1) Can elegance of design be combined with modularity in design? Integral designs often are perceived as more elegant and, therefore, command a premium price. For example, consider the Braun line of coffee makers versus Mr. Coffee products. Braun is the more expensive, often more integral, brand.

2) How can industry save money by using this methodology? Modular design was cited as the driving force behind savings for industry examples Xerox and Arrow Automotive Industries (Congress, 1992). Now we need to study the economic benefits of this particular modular design methodology.

3) How can this theory of modular design lead to rational approaches to developing product architectures? This ties in with the work by Kishnan et al. (1996) concerning device platforms. One such issue is how a

company can develop similar modular devices based on a common platform without cannibalizing the existing device's market share.

4) What does it take to make this theory a usable tool for practicing engineers? Specifically, we are interested in a computer-based implementation that adds the modular design methodology to the designer's tool kit.

As I noted at the beginning of this chapter, no body of research is ever really complete. But good research topics always lead to more questions. The questions mentioned here will form the basis for my future research in design issues. Hopefully, it will do the same for others.

APPENDIX A

FLOW DEFINITIONS

Matter and energy receive equal stature in the theory of relativity. Humans comprehend these concepts only with reference to time. Thus, we understand matter and energy based on how it changes with time, or, how it flows.

Energy, matter and information are considered basic concepts in any design problem (Pahl & Beitz, 1988). It is the flow of these three concepts that concerns designers. Matter is better represented as material. Information is more concretely expressed as a signal. Signals, in actuality are either flows of material or energy, but receive a special classification because their function is to carry information.

All design problems deal with these three basic flows, but it seldom advances the design solution to deal with flows at this highest level. How do we specify these flows more accurately? The flow categories in Table 2.3 of Chapter 2 provide a greater specification of flows; however, ambiguity still exists in their use. Definitions of flows are provided here to eliminate this ambiguity and make function structure decomposition a repeatable exercise. For materials, basic physics provides suitable definitions. The energy class is specified further by a bond graph approach of effort and flows (Karnopp et al., 1990; Karnopp, 1990; Breedveld et al., 1991; Tipler, 1978). Most of the energy categories are well studied in bond graph literature, but literature on the solar and optical energy categories is scarce. The effort and flow *analogies* used do not all have power as their product. However, they may all be scaled to produce power as their product, with the exception of the thermal energy basic category. In this category, a pseudo bond graph approach is used to provide a more practical set of flows for designers to work with. Signals are defined from a human factors standpoint (U.S. Department of Transportation, 1996).

The set of flows that follows is part of the functional base set described in Chapter 2. A flow from this list is selected to fill the object position of the verb-object functional description. Flows in the functional base set are more abstract representations of the actual problem's flows. The given definitions make the transformation from actual flow to base set flow more methodical and repeatable. An example of the flow usage follows each definition.

1. Material
    (a) **Solid**. Any object with mass having a definite, firm shape. Example: The flow of sand paper into a hand sander is transformed into a *solid* entering the sander.
    (b) **Liquid**. A readily flowing fluid, specifically having its molecules moving freely with respect to each other, but because of cohesive forces, not expanding indefinitely. Example: The flow of water through a coffee maker is a *liquid*.
    (c) **Gas**. Any collection of molecules which are characterized by random motion and the absence of bonds between the molecules.

Example: An oscillating fan moves air by rotating blades. The air is transformed as *gas* flow.

(d) **Human**. All or part of a person who crosses the device boundary. Example: Most coffee makers require the flow of a *human hand* to actuate (or start) the electricity and thus heat the water.

2. Energy

(a) **Human**. Work performed by a person on the device. Example: An automobile requires the flow of *human energy* to steer and accelerate the vehicle.

i. **Force**. The activity which requires effort into the system while not requiring significant motion. Example: *Human force* is needed to actuate the trigger of a toy gun.

ii. **Motion**. The activity of moving all or part of the body through a prescribed path. Example: The trackpad on a PowerBook receives the flow of *human motion* to control the cursor.

(b) **Acoustic**. Work performed in the production and transmission of sound. Example: The motor of a power drill generates a flow of *acoustic energy* in addition to the torque.

i. **Pressure**. Energy utilized is the pressure field of the sound waves. Example: A condenser microphone has a diaphragm which vibrates in response to *acoustic pressure*. This vibration changes the capacitance of the diaphragm, thus superimposing an alternating voltage on the direct voltage applied to the circuit.

ii. **Particle velocity**. The speed at which sound waves travel through a conducting medium. Example: Sonar devices rely on the flow of *acoustic particle velocity* to determine the range of an object.

(c) **Biological**. Work produced by or connected with plants or animals. Example: In poultry houses, the *biological energy* produced by thousands of chickens (in the form of heat) is an important flow in determining cooling requirements for the house.

i. **Pressure**. Energy utilized is the pressure field exerted by a compressed biological fluid. Example: The high concentration of sugars and salts inside a cell causes the entry, via osmosis, of water into the vacuole, which in turn expands the vacuole and generates a hydrostatic *biological pressure*, called turgor, that presses the cell membrane against the cell wall. Turgor is the cause of rigidity in living plant tissue.

ii. **Volumetric flow**. Energy utilized is the kinetic energy of molecules in a biological fluid flow. Example: Increased metabolic activity of tissues such as muscles or the intestine automatically induces increased *volumetric flow* of blood through the dilated vessels.

(d) **Chemical**. Work resulting from the reactions by which substances are produced from or converted into other substances. Example: A battery converts the flow of *chemical energy* into electrical energy.

   i. **Affinity**. The force with which atoms are held together in chemical bonds. Affinity is proportional to the chemical potential of a compound's constituent species. Example: An internal combustion engine transforms the *chemical affinity* of the gas into a mechanical force.

   ii. **Reaction rate**. The speed or velocity at which chemical reactants produce products. Reaction rate is proportional to the mole rate of the constituent species Example: Special coatings on automobile panels stop the *chemical reaction rate* of the metal with the environment.

(e) **Electrical**. Work resulting from the flow of electrons from a negative to a positive source. Example: A power belt sander imports a flow of *electricity* from a wall outlet and transforms it into a rotation.

   i. **Electromotive force**. Potential difference across the positive and negative sources. Example: Household electrical receptacles provide a flow of *electromotive force* of 110 V.

   ii. **Current**. The flow or rate of flow of electric charge in a conductor or medium between two points having a difference in potential. Example: Circuit breakers trip when the *current* exceeds a specified limit.

(f) **Electromagnetic**. Energy that is propagated through free space or through a material medium in the form of electromagnetic waves (Britannica Online, 1997). It has both wave and particle-like properties. Example: Solar panels convert the flow *electromagnetic energy* into electricity.

  i **Optical**. Work associated with the nature and properties of light and vision. Example: A car visor refines the flow of *optical energy* that its passengers receive.

    (a) **Intensity**. The amount of optical energy per unit area. Example: Tinted windows reduce the *optical intensity* of the light entering.

    (b) **Velocity**. The speed of light in its conducting medium. Example: NASA developed and tested a trajectory control sensor (TCS) for the space shuttle to calculate the distance between the payload bay and a satellite. It relied on the constancy of the *optical velocity* flow to calculate distance from time of flight measurements of a reflected laser.

  ii **Solar**. Work produced by or coming from the sun. Example: Solar panels collect the flow of *solar energy* and transform it into electricity.

    (a) **Intensity**. The amount of solar energy per unit area. Example: A cloudy day reduces the *solar* *intensity* available to solar panels for conversion to electricity.

(b) **Velocity**. The speed of light in free space. Example: Unlike most energy flows, *solar velocity* is a well known constant.

(g) **Hydraulic**. Work that results from the movement and force of a liquid, including hydrostatic forces. Example: Hydroelectric dams generate electricity by harnessing the *hydraulic energy* in the water that passes through the turbines.

i. **Pressure**. Energy utilized is the pressure field exerted by a compressed liquid. Example: A hydraulic jack uses the flow *hydraulic pressure* to lift heavy objects.

ii. **Volumetric flow**. Energy utilized is the kinetic energy of molecules in a fluid flow. Example: A water meter measures the *volumetric flow* of water without a significant pressure drop in the line.

(h) **Magnetic**. Work resulting from materials that have the property of attracting other like materials, whether that quality is naturally occurring or electrically induced. Example: The *magnetic energy* of a magnetic lock is the flow that keeps it secured to the iron based structure.

i. **Magnetomotive force**. The driving force which sets up the magnetic flux inside of a core. Magnetomotive force is directly proportional to the current in the coil surrounding the core. Example: In a magnetic door lock, a change in *magnetomotive force* (brought about by a change in electrical current) allows the lock to disengage and the door to open.

ii. **Time rate of change of magnetic flux**. Flux is the magnetic displacement variable in a core induced by the flow of current through a coil. The magnetic flow variable is the time rate of change of the flux. The voltage across a magnetic coil is directly proportional to the time rate of change of magnetic flux. Example: A magnetic relay is a transducer that senses the *time rate of change of magnetic flux* when the relay arm moves.

(i) **Mechanical**. Work provided by moving parts of a machine. Example: An elevator converts electrical or hydraulic energy into *mechanical energy*.

i. **Rotational energy**. Energy that results from a rotation or an attempted rotation. Example:

(a) **Torque**. Pertaining to the moment that produces or tends to produce rotation. Example: In a power screwdriver, electricity is converted into the flow *torque*. The relevant flow is *torque* since the primary customer need is to insert screws easily, not quickly.

(b) **Angular velocity**. Pertaining to the orientation or the magnitude of the time rate of change of angular position about a specified axis. Example: A centrifuge is used to separate out liquids of different densities from a mixture. The primary flow it produces is that of *angular velocity*, since the rate of rotation about an axis is the main concern.

ii. **Translational energy**. Energy that results from a translation or an attempted translation. Example:

    (a) **Force**. The action that produces or attempts to produce a translation. Example: In a tensile testing machine, the primary flow is that of a *force* which produces a stress in the test specimen. Although there is translation associated with the machine, it is a result of the force.

    (b) **Linear velocity**. Motion that can be described by three component directions. Example: An elevator car receives a flow of *linear velocity* to move between floors.

iii. **Vibrational energy**. Oscillating translational or rotational energy that is characterized by an amplitude and frequency. In the rotational case, motion does not complete a 360° cycle. Example: In many block sanders, the sanding surface receives a flow of *vibration* to remove the wood surface. *Vibration* is produced by an off-center mass on the motor shaft.

        (a) **Amplitude**. Energy is characterized by the magnitude of the generalized force or displacement. Example: In fatigue testing, the *vibrational amplitude* of the tensile stress is more important than the speed of each loading cycle.

        (b) **Frequency**. Energy is characterized by the speed of the oscillation. Example. Human exposure to vibration can induce sickness at certain *vibrational frequencies.*

(j) **Pneumatic**. Work resulting from a compressed gas flow or pressure source. Example: A B-B gun relies on the flow of *pneumatic energy* (from compressed air) to propel the projectile (B-B).

    i. **Pressure**. Energy utilized is the pressure field exerted by a compressed gas. Example: Certain cylinders rely on the flow of *pneumatic pressure* to move a piston or support a force.

    ii. **Mass flow**. Energy utilized is the kinetic energy of molecules in a gas flow. Example: The *mass flow* of air is the flow that transmits the thermal energy of a hair dryer to damp hair.

(k) **Radioactive**. Work resulting from or produced by particles or rays, such as alpha, beta and gamma rays, by the spontaneous disintegration of atomic nuclei. Example: Nuclear reactors produce a flow of *radioactive energy* which heats water into steam and then drives electricity generating turbines.

i. **Intensity**. The amount of radioactive particles per unit area. Example: Concrete is an effective radioactive shielding material, reducing the *radioactive intensity* in proportion to its thickness.

ii. **Decay rate**. The rate of emission of radioactive particles from a substance. Example: The *decay rate* of carbon provides a method to date pre-historic objects.

(l) **Thermal**. A form of energy that is transferred between bodies as a result of their temperature difference. Example: A coffee maker converts the flow of electricity into the flow of *thermal energy* which it transmits to the water.

Note: A pseudo bond graph approach is used here. The true effort and flow variables are temperature and the time rate of change of entropy. However, a more practical pseudo-flow of heat is chosen here.

i. **Temperature**. The degree of heat of a body. Example: A coffee maker brings the *temperature* of the water to boiling in order to siphon the water from the holding tank to the filter basket.

ii. **Heat flow**. (Note: this is a pseudo-flow) The time rate of change of heat energy of a body. Example: Fins on a motor casing take *heat flow* away from the motor by conduction (through the fin), convection (to the air) and radiation (to the environment).

3. Signal
   - (a) **Status**. A condition of some system, as in information about the state of the system. Example: Automobiles often measure the engine water temperature and send a *status signal* to the driver via a temperature gage.
     - i. **Auditory**. A condition of some system as displayed by a sound. Example: Pilots receive an *auditory status*, often the words "pull up," when their aircraft reaches a dangerously low altitude.
     - ii. **Olfactory**. A condition of some system as related by the sense of smell or particulate count. Example: Carbon monoxide detectors receive an *olfactory status signal* from the environment and monitor it for high levels of CO.
     - iii. **Tactile**. A condition of some system as perceived by touch or direct contact. Example: Temperature, pressure and roughness measurements are examples of *tactile status signals*.
     - iv. **Taste**. A condition of some dissolved substance as perceived by the sense of taste. Example: In an electric wok, the *taste status signal* from the human chef is used to determine when to turn off the wok.

  v. **Visual**. A condition of some system as displayed by some image. Example: A power screwdriver provides a *visual status* of its direction through the display of arrows on the switch.

(b) **Control**. A command sent to an instrument or apparatus to regulate a mechanism. Example: An airplane pilot sends a *control signal* to the elevators through movement of the yoke. The yoke movement is transformed into an electrical signal, sent through wiring to the elevator, and then transformed back into a physical elevator deflection.

APPENDIX B

FUNCTION DEFINITIONS

The function classes are introduced in Chapter 2. Definitions for each class and basic function are presented below. Examples are given for the basic functions. These definitions first appeared in work by Little et al. (1997). Used with the flow definitions of Appendix A, the function definitions complete the functional base set which improves repeatability of function structure development and provides a standard level of detail at which the decomposition process stops.

1. **Channel**
   - (a) **Import**. To bring in an energy or material from outside the system boundary. Example: A physical opening at the top of a blender pitcher *imports* a solid (food) into the system. Also, a handle on the blender pitcher *imports* a human hand. The blender system *imports* electricity via an electric plug.
   - (b) **Export**. To send an energy or material outside the system boundary. Example: Pouring blended food out of a standard blender pitcher is *exporting* liquid from the system. The opening at the top of the blender is a solution to the *export* sub-function.
   - (c) **Transfer**. To shift, or convey, a flow from one place to another.

    i. **Transport**. To move a *material* from one place to another. Example: A coffee maker *transports* liquid (water) from its reservoir through its heating chamber and then to the filter basket.

    ii. **Transmit**. To move an *energy* from one place to another. Example: In a hand held power sander, human force is *transmitted* from the human to the object being sanded through the housing of the sander.

(d) **Guide**. To direct the course of an energy or material along a specific path. Example: In a domestic HVAC system, gas (air) is *guided* around the house to the correct locations via a set of ducts.

    i. **Translate**. To fix the movement of a *material* into one linear direction. Example: In an assembly line, partially completed products are *translated* straight from one assembly station to another by a conveyor belt.

    ii. **Rotate**. To fix the movement of a *material* around one axis. Example: In a computer disk drive, the magnetic disks *rotate* around an axis so that data can be read by the head.

    iii. **Allow degree of freedom**. To control the movement of a *material* into one or more directions. Example: To provide easy trunk access and close appropriately, trunk lids need to move along a specific degree of freedom. A four bar linkage might give the trunk lid this degree of freedom.

2. **Support**. To firmly fix a material into a defined location, or secure an energy into a specific course.
    - (a) **Stop**. To cease, or prevent, the transfer of a material or energy. Example: The transmission of UV radiation through a window is *stopped* by applying a reflective coating to the window.
    - (b) **Stabilize**. To prevent a material or energy from changing course or location. Example: Auto shock absorbers *stabilize* the vehicle by preventing the axle from changing its course from that of the car.
    - (c) **Secure**. To firmly fix a material or energy path. Example: On a bicycling glove, a velcro strap is used to secure the human hand in the correct place.
    - (d) **Position**. To place a material or energy into a specific location or orientation. Example: The coin slot on a soda machine is used to *position* the coin to begin the coin evaluation and transportation procedure.
3. **Connect**. To bring two or more energies or materials together.
    - (a) **Couple**. To join or bring together energies or materials such that the members are still distinguishable from each other. Example: On a standard pencil, an eraser is *coupled* to the shaft. The coupling is performed using a metal sleeve that is crimped to the eraser and the shaft.
    - (b) **Mix**. To combine two materials into a single, uniform homogeneous mass. Paint is *mixed* before application. Its base and dyes are *mixed* to form an homogeneous liquid.

4. **Branch**. To cause an material or energy to no longer be joined or mixed.
    (a) **Separate**. To isolate a material or energy into distinct components. The separated components are distinct from the flow before separation, as well as each other. Example: Light is *separated* into different wavelength components to produce a rainbow. A glass prism performs this separation.
        i. **Remove**. To take away a part of a *material* from its prefixed place. Example: Small pieces of the surface of wood are *removed* by a sander to smooth the wood.
    (b) **Refine**. To reduce a material or energy such that only the desired elements remain. Example: Coffee grounds are *refined* by passing a hot liquid (water) through the grounds. A filter retains the *refined* coffee grounds and allows the new liquid (coffee) to pass through.
    (c) **Distribute**. To cause a material or energy to break up. The individual bits are similar to each other and the undistributed flow. Example: Hair-styling liquids are *distributed* over the head to hold the hair in the desired style. An atomizer is used to *distribute*, or spray, the liquid.
    (d) **Dissipate**. To break up and drive away or dispel. Example: The steel safety cage of an automobile *dissipates* impact energy to prevent injury to its passengers. The energy is *dissipated* by the steel members bending and twisting during impact.
5. **Provide**. To accumulate or provide material or energy.

    - (a) **Store**. To accumulate material or energy. Example: Energy is stored in a flashlight. A DC electrical battery is used to *store* the energy.
    - (b) **Supply**. To provide material or energy from storage. Example: In a flashlight, energy is *supplied* to the bulb by the battery.
    - (c) **Extract**. To draw, or forcibly pull out, a material or energy. Example: Mechanical kinetic energy is *extracted* from the wind in a windmill. The *extraction* is performed by the airfoil (windmill blades).

6. **Control Magnitude**. To alter or govern the size or amplitude of material or energy.
    - (a) **Actuate**. To commence the flow of energy or material in response to an imported control signal. Example: *Actuating* the flow of electrical energy turns on a light bulb. The *actuation* is performed using a circuit switch.
    - (b) **Regulate**. To adjust the flow of energy or material in response to a control signal, such as a characteristic of a flow. Example: The liquid flowing from a faucet is *regulated* to allow different flow rates.
    - (c) **Change**. To adjust the flow of energy or material in a predetermined and fixed manner. In a hand held drill, the electrical energy flow to the motor is *changed* thus changing the speed the drill turns. This *change* is accomplished by a variable resistor.

        i. **Form**. To mold or shape a material. Example: In the auto industry, sheet metal is *formed* into contoured surfaces that become fenders, hoods and trunks. These parts are *formed* by large presses.

        ii. **Condition**. To render an energy appropriate for the desired use. Example: To prevent damage to electrical equipment, electrical energy is conditioned by excluding spikes and noise from the energy path.

7. **Convert**. To change from one form of energy or material to another. For completeness, any type of flow conversion is valid. In practice, conversions such as *convert electricity to torque* will be more common than *convert solid to optical energy*. Example: An electrical motor *converts* electricity to rotational energy.

8. **Signal**. To provide information.

    (a) **Sense**. To perceive, or become aware, of a signal. Example: An audio cassette machine *senses* if the end of the tape has been reached. A spring *senses* an increase in tension when the tape ends.

    (b) **Indicate**. To make something known to the user. Example: A coffee maker *indicates* the level of water in the machine. A small window into the water container *indicates* the level to the user.

    (c) **Display**. To show a visual effect. Example: The face and needle of an air pressure gage *display* the status of the pressure vessel.

(d) **Measure**. To determine the magnitude of a material or energy flow. Example: A thermostat *measures* temperature. A bimetallic strip is used to measure the temperature.

APPENDIX C

FUNCTION STRUCTURES IN FUNCTIONAL BASE SET FORM

The function structures, in functional base set form, for the 18 devices examined in Section 3.4 are presented here. The module heuristics were applied to this set of devices and the results appear in Table 3.3. Two types of similar devices were included, iced tea brewers and power screwdrivers. For each type, two competing devices were examined. The competing devices, for a given type of device, were functionally equivalent. Therefore, two of the function structures each represent two devices. This is noted on the function structure.

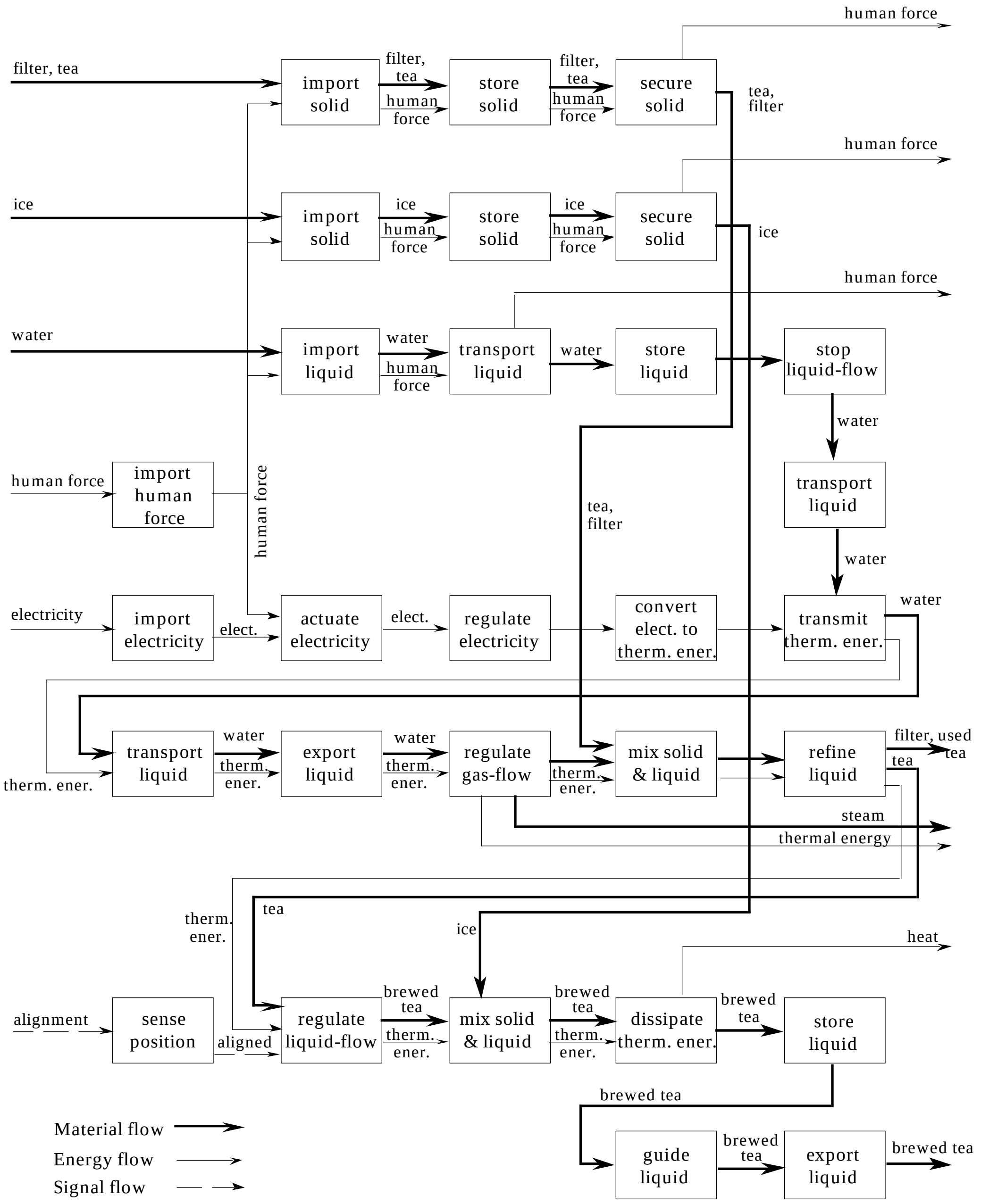


Figure C.1 Function structure, in functional base set form, for a Mr. Coffee and West Bend iced tea / coffee brewer.

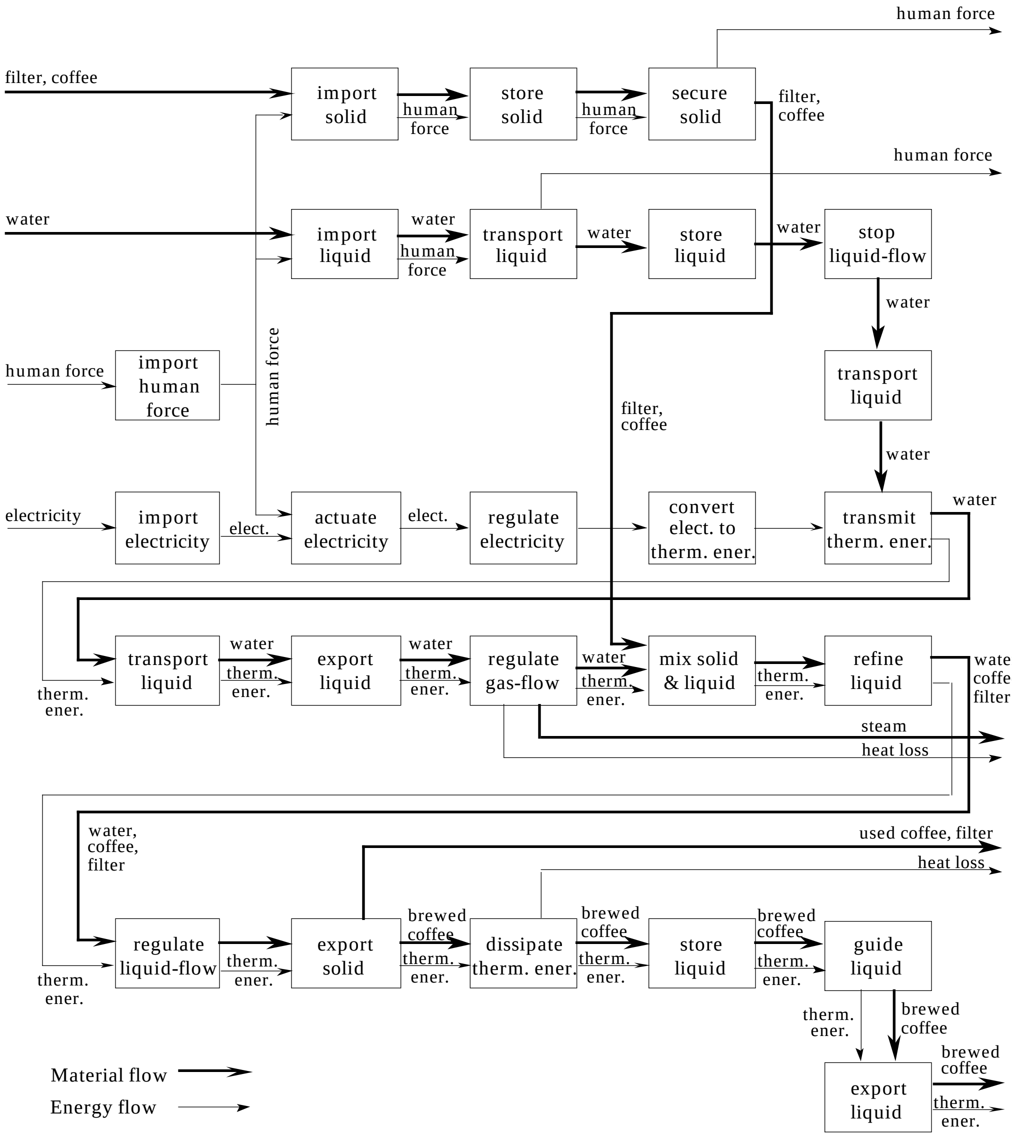


Figure C.2 Function structure, in functional base set form, for a Mr. Coffee coffee maker.

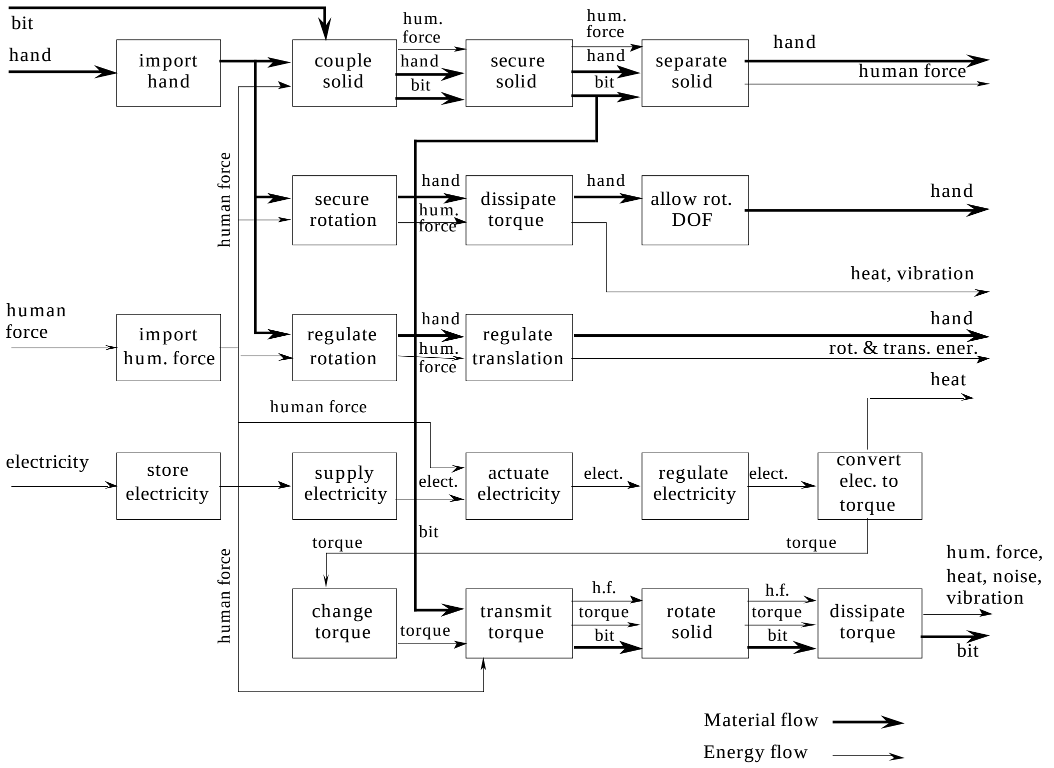


Figure C.3 Function structure, in functional base set form, for a SKIL and Black and Decker power screwdriver.

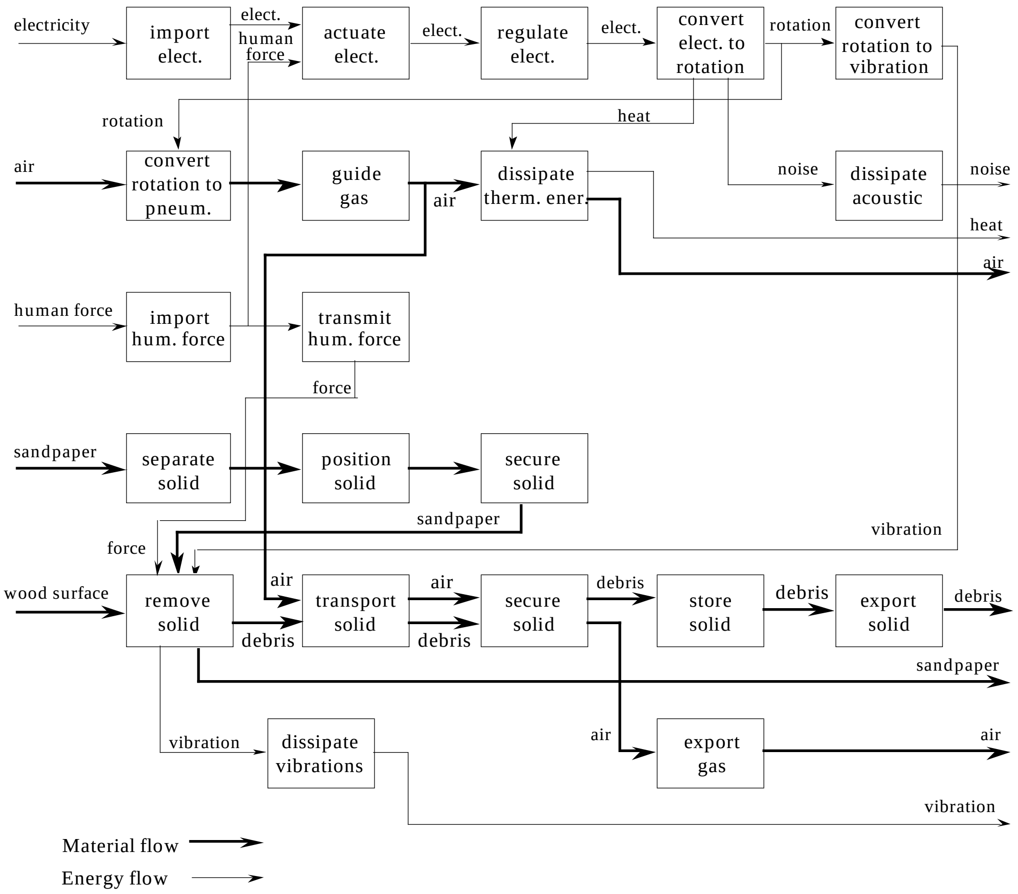


Figure C.4 Function structure, in functional base set form, for a DeWalt palm grip sander with debris bag.

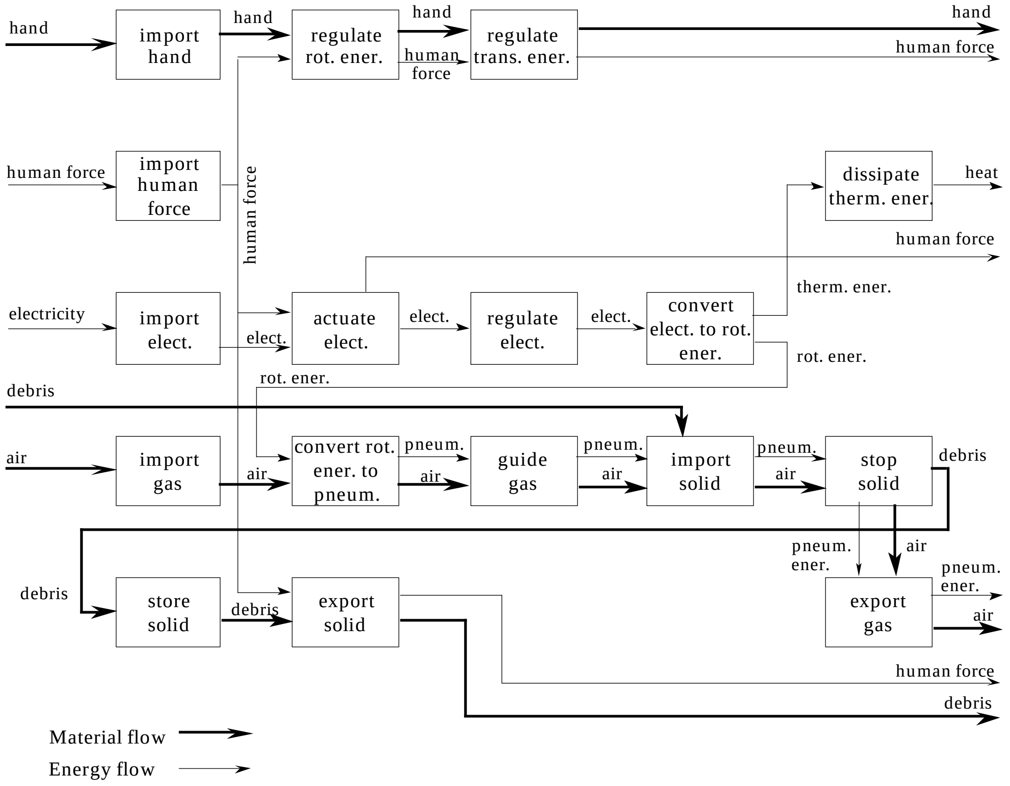


Figure C.5 Function structure, in functional base set form, for a Bissel hand vacuum.

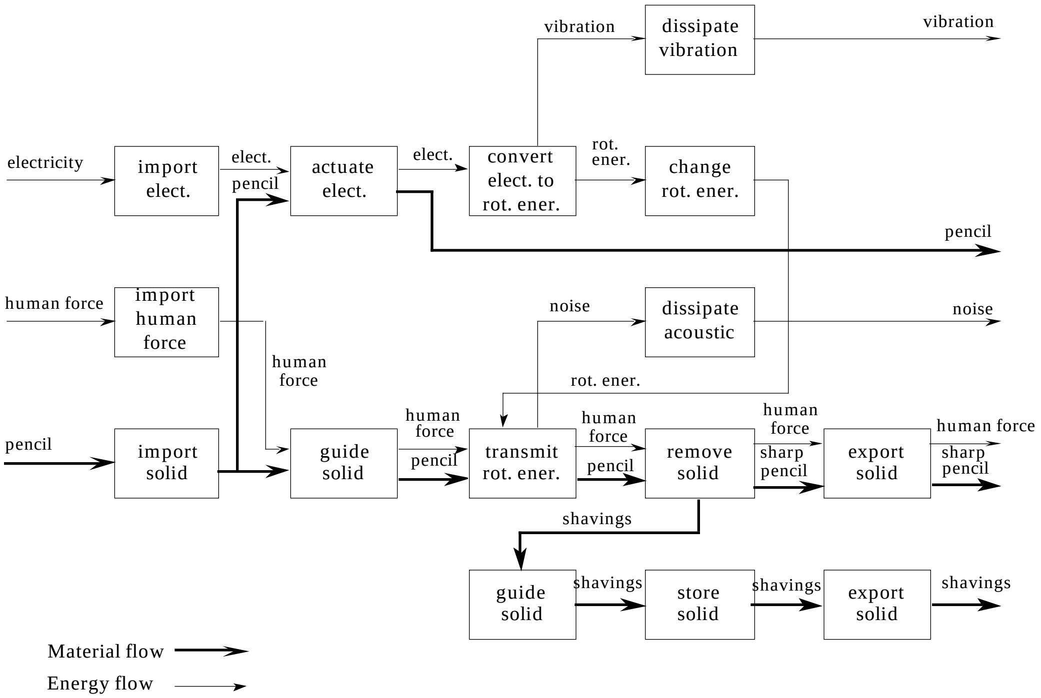


Figure C.6 Function structure, in functional base set form, for a an electric penscil sharpener.

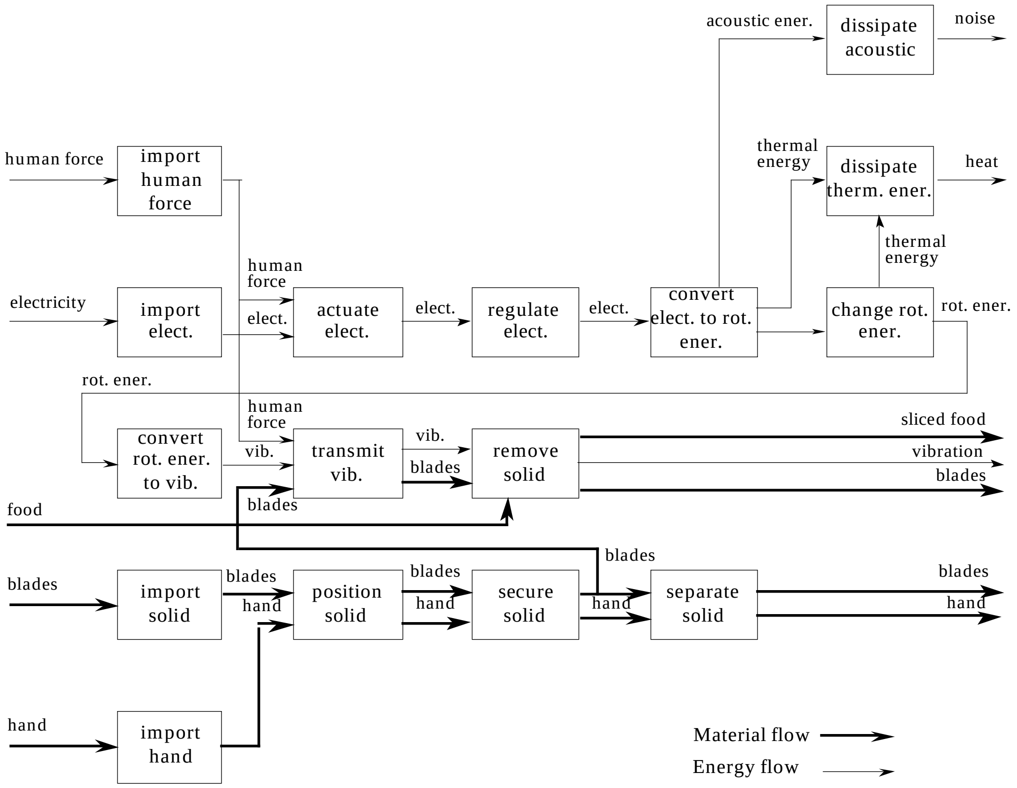


Figure C.7 Function structure, in functional base set form, for a Black and Decker electric knife.

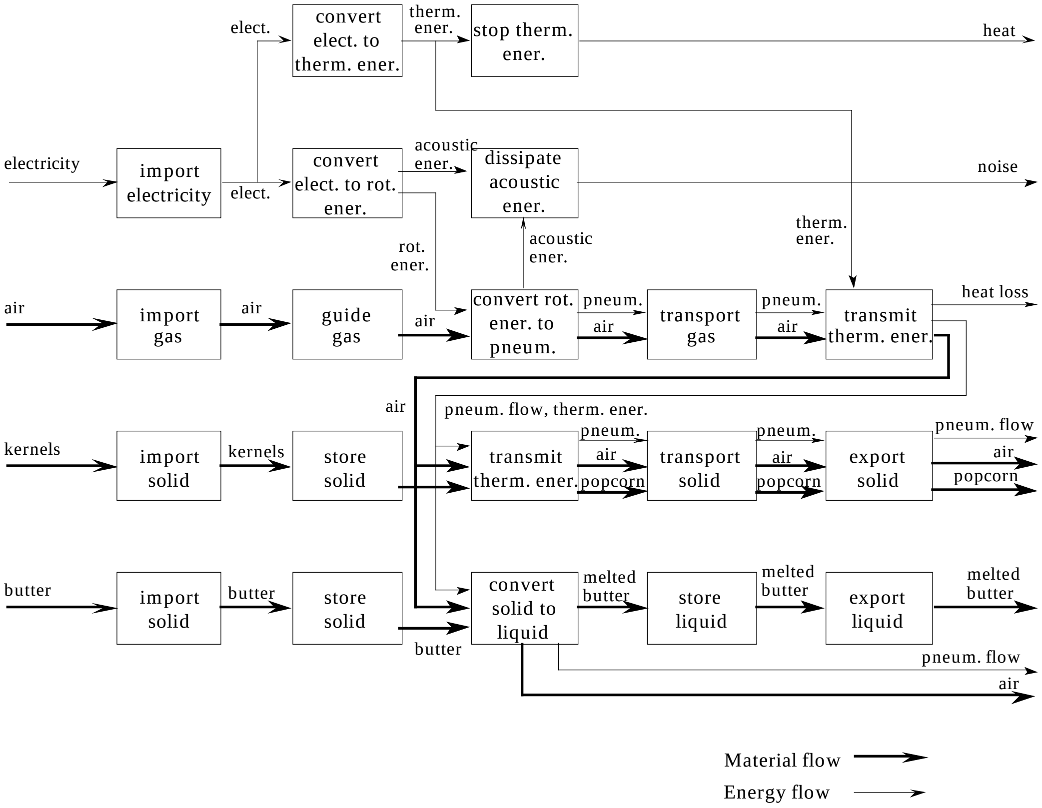


Figure C.8 Function structure, in functional base set form, for a Presto hot air popcorn popper.

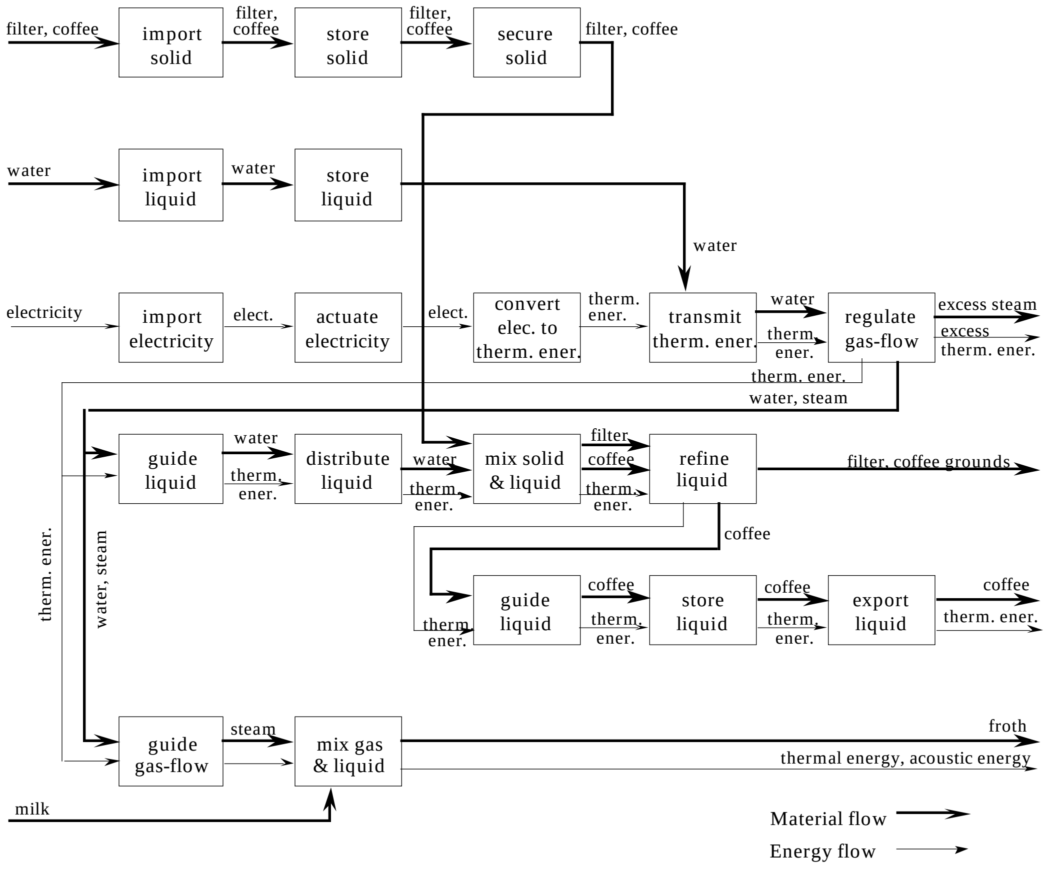


Figure C.9 Function structure, in functional base set form, for a Krups café trio (coffee / expresso maker).

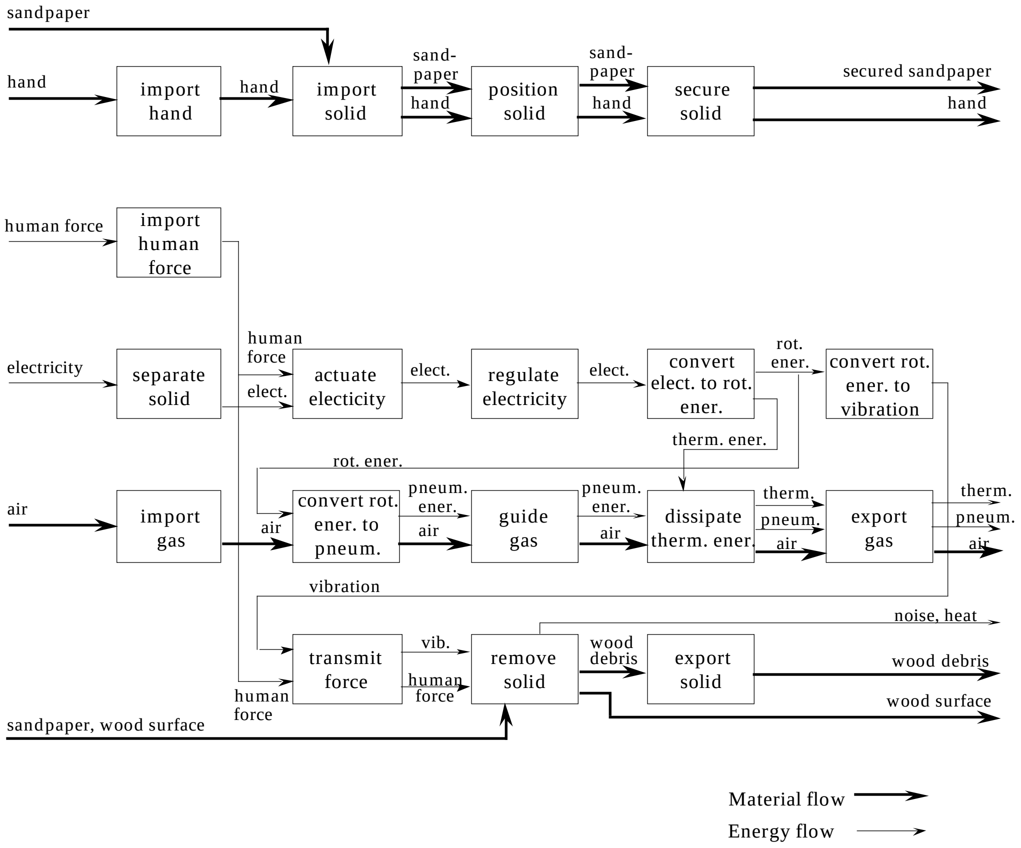


Figure C.10 Function structure, in functional base set form, for a Black and Decker power block sander.

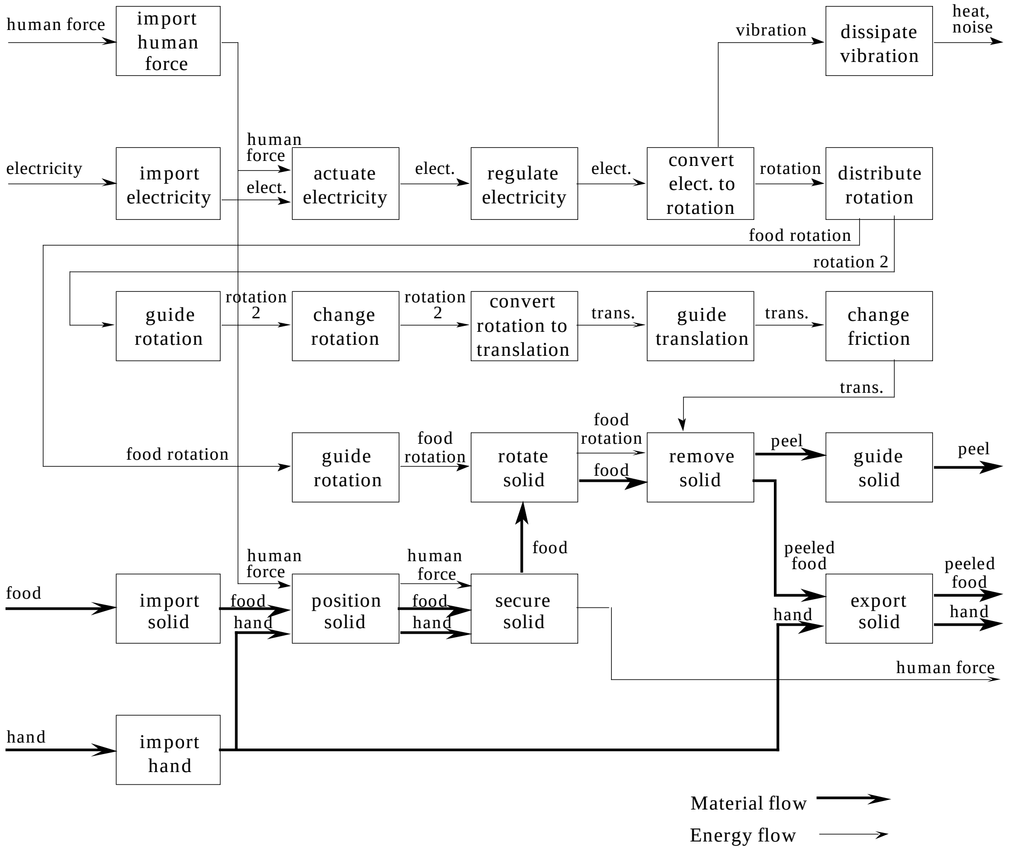


Figure C.11 Function structure, in functional base set form, for a Dazey fruit / veggie peeler.

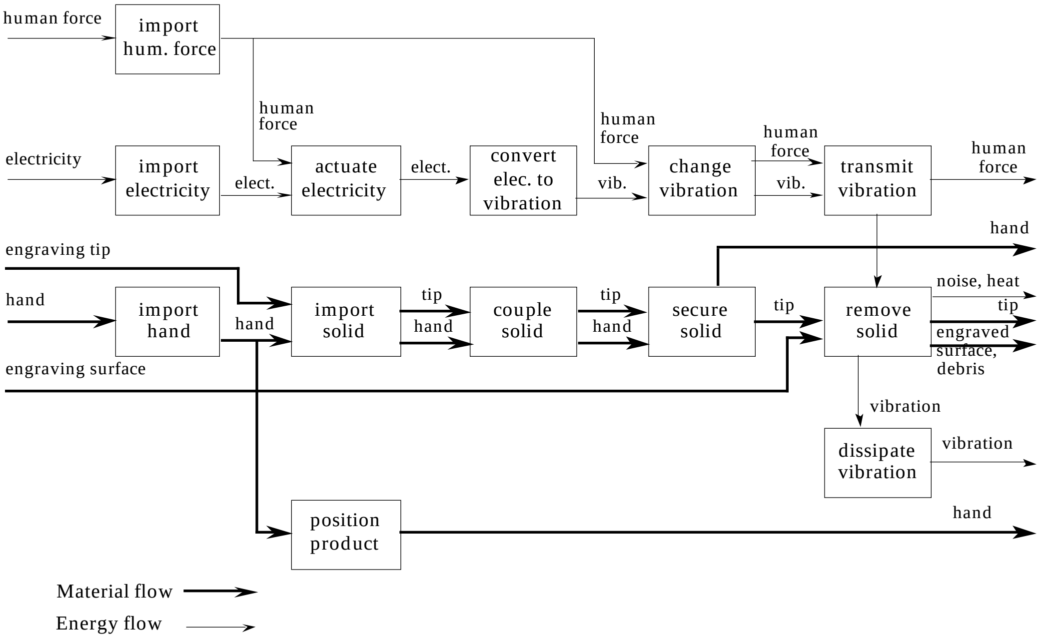


Figure C.12 Function structure, in functional base set form, for a Dremel engraver.

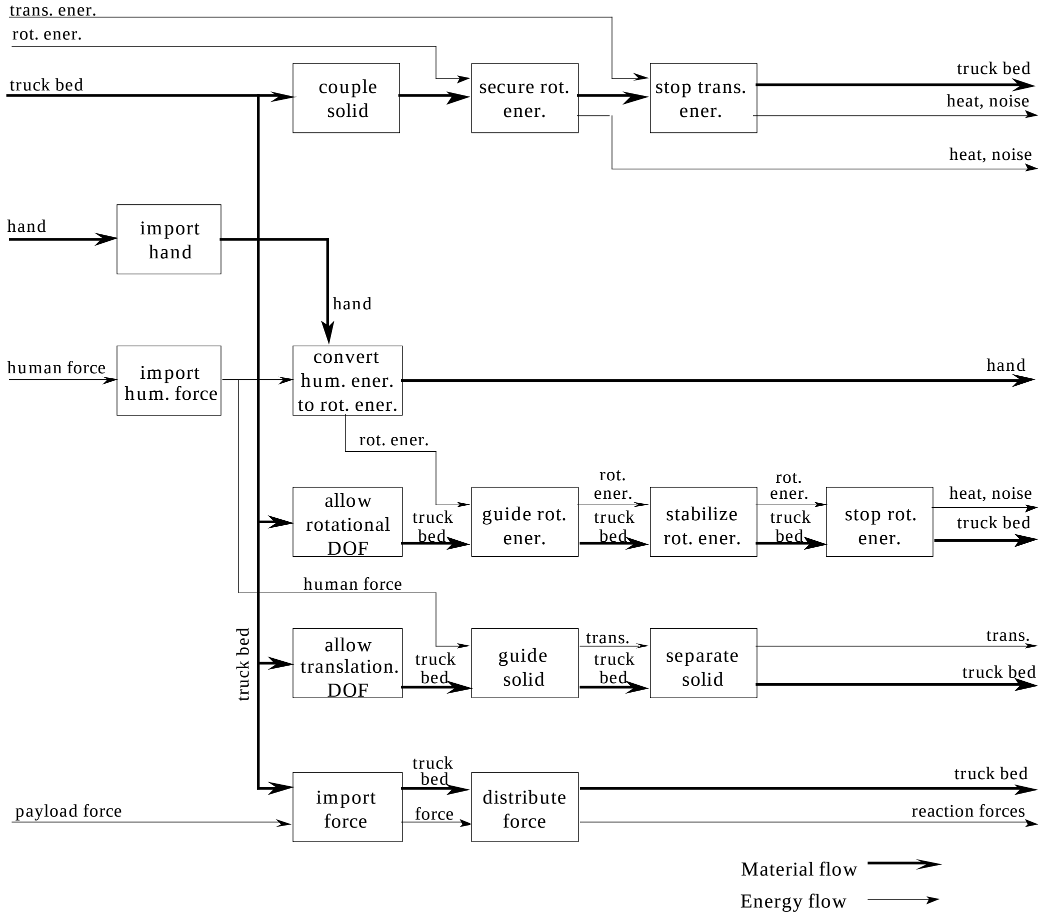


Figure C.13 Function structure, in functional base set form, for a 1974 Chevrolet tailgate.

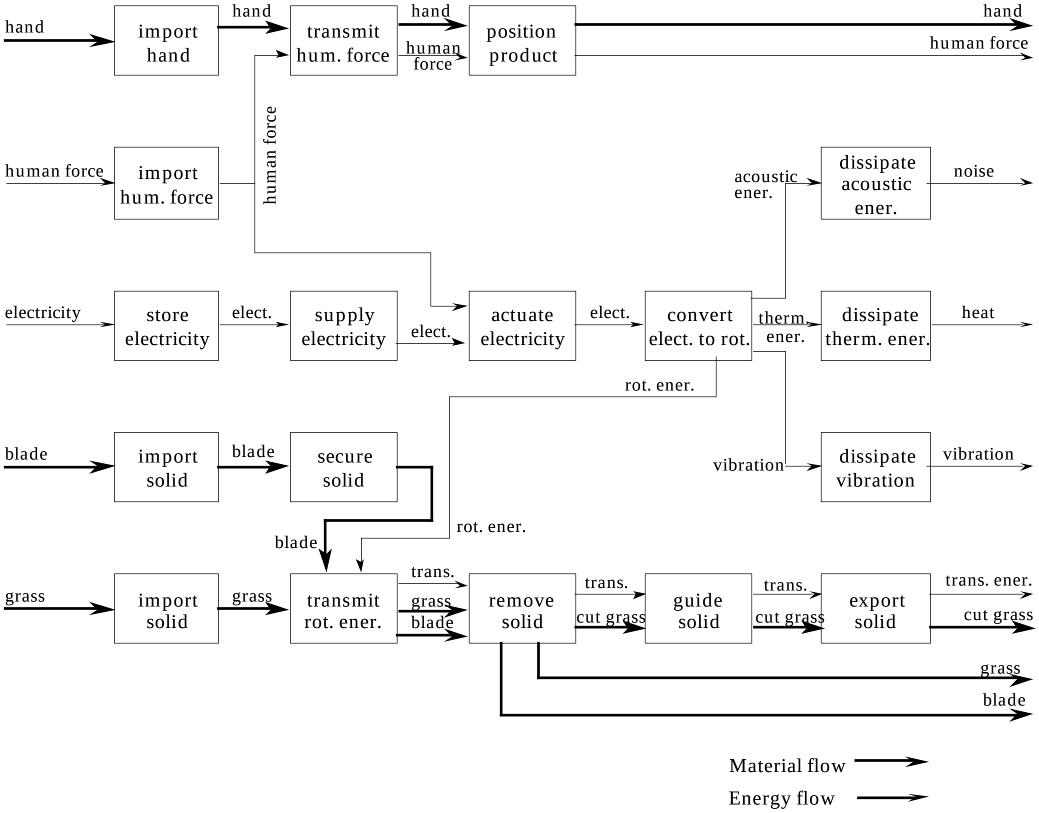


Figure C.14 Function structure, in functional base set form, for a Black and Decker VersaPak weed trimmer.

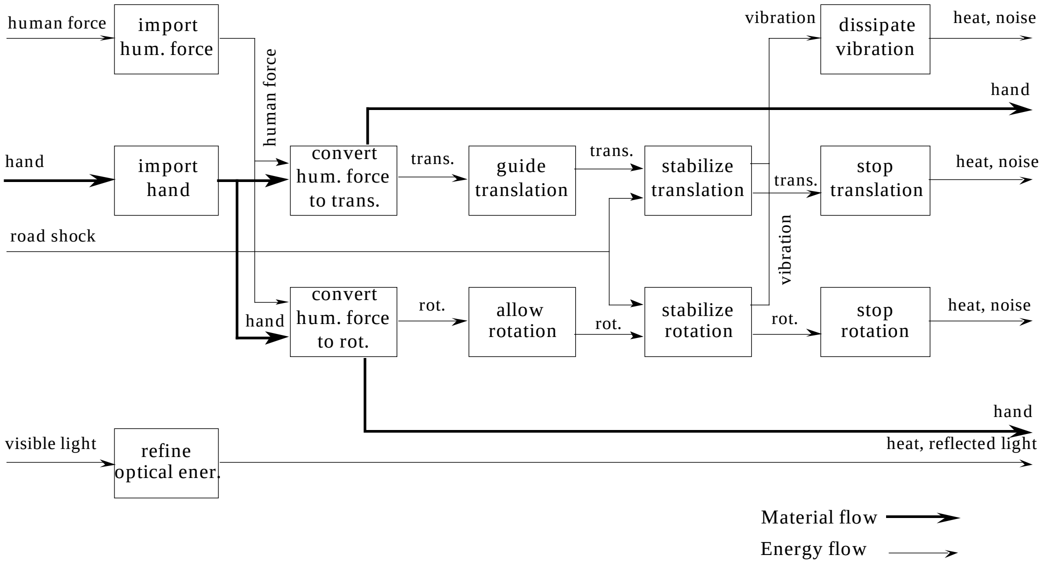


Figure C.15 Function structure, in functional base set form, for a Cadillac visor.

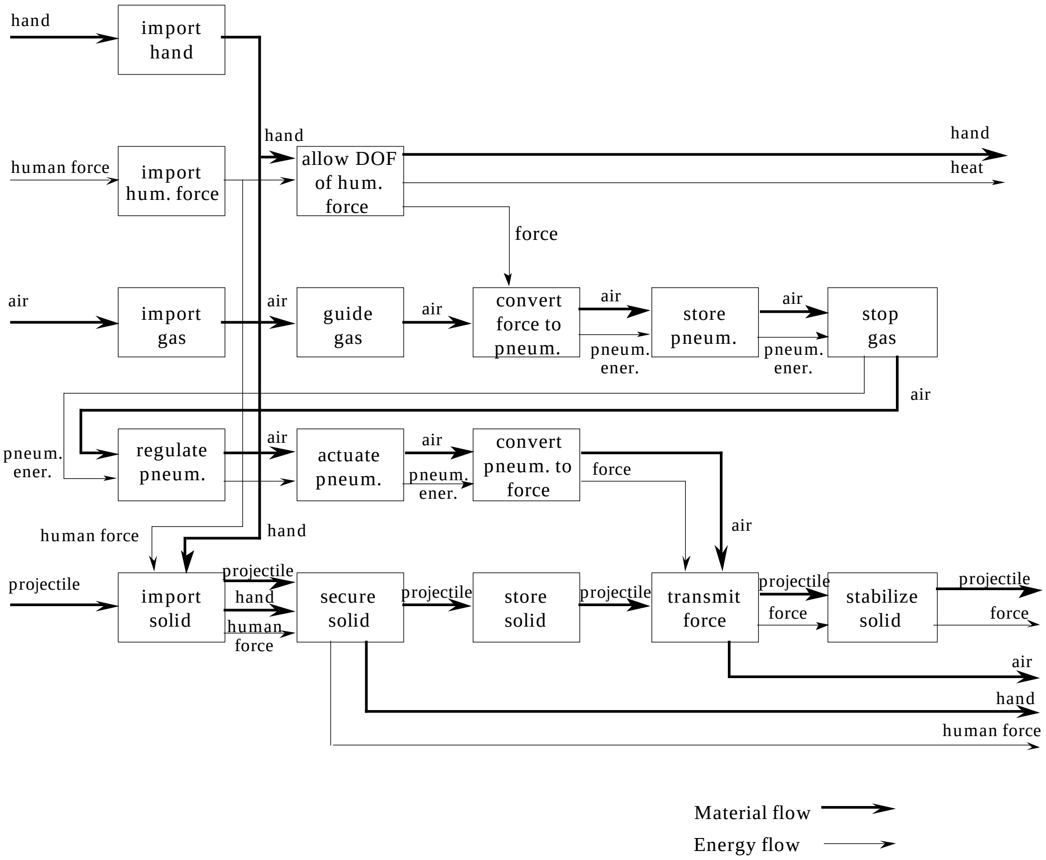


Figure C.16 Function structure, in functional basis form, for a Super Maxx ball shooter.

APPENDIX D

SUPPORTING MATRICES FOR QUANTITATIVE METHOD

The matrices referred to in Chapter 4 are presented here. The matrices are all quite large and require several pages for display. The Φ and $\mathbf{N}$ matrices are each 174 (functions) x 70 (devices). The similarity matrix Λ is a 70 (device) x 70 (device) matrix. The function-function matrix $\boldsymbol{S}$ is a 56 x 56 matrix for the power screwdriver subset considered in the Chapter 4 example.

Sub-function \ Device	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet / Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS	Durabuilt Hand Vacuum
actuate electricity	3	4	0	0	4	1	1	0	1	3	0	0	1	1	1	0	0	8	1
actuate pneumatics	0	0	6	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	1	0
assemble product	0	4	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	1
change sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	14	0	0	0	0	0	7	0	0	0	0	0	0	0	0
change human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0
change rotation	0	0	16	0	0	4	4	0	0	1	4	6	0	0	0	0	0	6	0
change translation	0	0	0	0	15	0	1	0	0	0	0	0	0	0	0	0	0	0	0
clean product	0	0	0	5	0	6	3	0	2	4	0	0	0	4	2	0	0	0	0
condition electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
connect solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to rotation	9	8	0	1	0	14	4	0	6	4	6	0	7	19	0	0	0	14	12
convert electricity to heat	0	0	0	6	3	0	0	0	10	0	0	0	4	0	0	0	0	0	0
convert electricity to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
convert pneumatics to rotation	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	9	0	0	6	0	0	0	0	5	0	0	0	1	22	0	0	0	0	9
convert rotation to translation	0	0	0	0	0	0	1	0	0	0	1	6	0	0	1	0	0	0	0
convert rotation to vibration	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to pneumatics	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
convert translation to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert vibration to rotation	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
disassemble product	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
display status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dissipate sound	4	0	0	0	0	3	0	0	4	8	4	0	4	0	0	0	0	0	0
dissipate heat	6	0	0	0	0	0	0	0	0	3	0	0	0	1	0	0	0	0	3
dissipate translation	0	0	6	0	0	0	0	0	3	6	0	4	0	6	10	0	0	2	3
dissipate vibrations	4	0	0	0	0	0	0	0	0	0	0	0	4	0	4	0	5	0	4
distribute gas	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0
distribute liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute rotation	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
distribute translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export gas	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
export liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export solid	1	0	0	3	6	7	1	0	0	1	0	0	0	1	0	0	0	0	4
export translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
export vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
extract solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide gas	6	0	0	10	0	0	0	1	1	0	0	0	1	0	0	0	0	0	1
guide human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide human hand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet / Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS	Durabuilt Hand Vacuum
guide liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide rotation	0	0	1	0	0	0	4	0	1	0	0	0	0	0	0	1	3	0	0
guide solid	0	0	0	0	0	10	1	0	0	0	0	5	0	0	7	1	9	0	0
guide translation	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
import control signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import electricity	1	0	0	1	1	0	4	0	1	1	0	0	3	0	0	0	0	0	0
import gas	0	0	6	1	0	0	0	1	1	0	0	0	1	4	0	0	0	0	0
import human energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import human force	7	0	13	6	15	13	6	9	4	5	0	7	4	5	6	2	5	9	6
import human hand	15	0	0	0	5	6	6	6	4	0	0	7	4	0	0	2	5	10	6
import liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import pneumatics	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import solar energy	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
import solid	1	0	0	9	1	1	4	4	0	1	0	1	0	1	7	0	0	0	5
import translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
indicate status	1	0	3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	4
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
maintain device	0	0	0	0	0	2	0	0	0	0	0	0	3	0	0	0	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure pressure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	9	0	0	0	3	0	0	0	6	0	0	0	0	0	0
mix liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix solid	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
position product	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
position solid	8	1	0	0	0	6	4	0	0	1	0	0	0	0	0	0	0	0	0
position translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
refine gas	0	0	6	0	0	0	0	0	0	0	0	0	4	5	0	0	0	0	1
refine liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0
refine solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	1	0	0	0	9	0	1	0	8	0	0	0	2	0	0	0	0	4	1
regulate human force	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
regulate hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate pneumatics	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
regulate rotation	0	0	11	0	0	0	0	0	5	0	0	0	6	0	0	0	0	3	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
remove solid	6	9	0	0	0	14	11	0	0	4	0	0	0	0	0	0	0	0	0
resist corrosion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rotate solid	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0
secure liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
secure rotation	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	3	0	5	0
secure solid	13	2	6	0	5	6	12	1	0	5	0	0	0	0	7	0	0	5	0
secure translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	0	0	1	0	0	0	0	0	7	0	0	0	20	0	0	0	0	0	0
sense status	0	0	0	0	0	0	4	0	0	6	0	0	0	0	0	0	0	0	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
separate solid	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	9	0	0
stabilize solid	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
stabilize translation	0	0	0	0	5	0	0	0	0	5	1	0	0	0	0	0	9	0	0
stop chemical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
stop electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop gas	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	1
stop human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet / Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS	Durabuilt Hand Vacuum
stop liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0
stop solid	0	6	0	0	0	0	1	0	0	0	1	0	1	5	0	0	0	0	0
stop heat	0	0	0	2	3	0	0	0	4	0	0	0	4	0	0	0	0	0	0
stop translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0
store electricity	0	0	0	0	0	10	0	0	0	0	0	0	0	21	0	0	0	7	12
store energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0
store mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
store pneumatics	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
store product	0	2	0	3	1	0	0	0	0	0	0	0	0	0	2	0	0	0	3
store solids	3	0	0	4	1	1	0	2	0	3	0	0	0	5	0	0	0	1	1
store translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electricity	0	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1
supply liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply mechanical energy	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
supply rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit electricity	0	0	0	0	1	1	0	0	0	0	1	0	0	1	0	0	0	0	0
transmit energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit human force	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	0	1	3	1	0	0	0	0	0	1	1	3	1	0	0	0	0	1	0
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit heat	0	0	0	11	12	0	0	0	1	0	0	0	4	0	0	0	0	0	0
transmit translation	0	0	0	0	1	0	0	2	0	0	0	4	0	0	6	0	0	0	0
transmit vibrations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transport liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transport solid	3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car	Ertl Bumble Ball	Fisher Price Bubble Mower
actuate electricity	0	10	1	1	1	4	0	1	5	1	1	1	4	5	1	0	1	1	0
actuate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	4	0	0	0	0	1	0	0	0	0	0	0	0	0	0
assemble product	0	0	6	0	0	0	0	0	0	0	0	0	5	0	0	4	0	0	0
change sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	4	0	0	0	0	0	0	0	0	1	0	0	5	0	5
change human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change rotation	0	0	1	4	4	6	0	1	1	19	4	0	5	0	4	0	7	0	0
change translation	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
clean product	0	0	6	2	0	0	0	4	0	0	6	0	4	0	0	0	0	0	2
condition electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
connect solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to rotation	0	11	1	1	3	2	0	4	3	16	11	1	5	11	8	0	4	10	0
convert electricity to heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
convert rotation to hydraulics	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	0	0	0	0	0	0	5	0	0	0	0	9	0	1	0	0	0	0	6
convert rotation to translation	0	0	1	0	0	7	0	0	0	0	0	0	0	11	0	0	4	0	0
convert rotation to vibration	0	0	0	0	0	0	0	11	7	0	0	0	0	0	0	0	0	10	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to hydraulics	0	0	7	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to pneumatics	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to rotation	0	0	1	0	0	0	6	0	0	0	0	0	0	0	0	0	1	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert vibration to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0
disassemble product	0	0	6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
display status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dissipate sound	0	0	0	2	3	0	3	5	0	0	6	4	4	4	3	0	3	0	0
dissipate heat	0	0	0	0	0	0	0	4	0	1	1	0	0	1	0	0	0	1	0
dissipate translation	0	2	5	3	0	5	0	0	11	3	0	0	0	0	0	6	5	6	3
dissipate vibrations	0	0	0	0	2	0	0	5	0	1	0	0	0	5	2	1	1	0	0
distribute gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
distribute translation	0	0	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	5
export gas	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export liquid	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
export solid	0	1	0	0	0	0	1	0	0	0	0	0	2	2	1	6	0	0	0
export translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export vibration	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	4	0
extract solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form liquid	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide gas	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
guide human force	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
guide human hand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car	Ertl Bumble Ball	Fisher Price Bubble Mower
guide liquid	0	0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
guide rotation	0	0	0	0	0	0	0	1	4	0	0	0	0	0	0	0	0	0	0
guide solid	7	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
guide translation	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
import control signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import electricity	0	0	0	0	0	1	0	1	0	0	1	1	2	1	1	3	0	0	0
import gas	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
import human energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import human force	1	6	5	5	0	0	8	5	0	4	1	6	0	6	5	0	1	0	5
import human hand	0	0	0	0	0	0	0	0	0	4	0	0	0	6	0	0	0	0	0
import liquid	0	0	5	0	0	0	10	0	0	0	6	0	0	0	0	0	0	0	1
import pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
import solar energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import solid	1	1	0	1	0	0	0	5	0	0	1	6	3	1	4	5	0	0	0
import translation	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
indicate status	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
maintain device	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	3	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure pressure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid	0	0	0	1	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix solid	0	0	0	0	0	0	0	0	0	0	1	0	0	0	7	0	0	0	0
position product	0	9	0	6	0	4	0	0	0	0	0	5	0	4	0	0	0	0	0
position solid	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
position translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine gas	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
refine liquid	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	0	0	0	1	1	0	0	0	0	1	6	0	0	0	0	1	0	1	0
regulate human force	0	0	0	0	0	0	0	0	5	0	0	0	0	1	0	0	0	0	0
regulate hydraulics	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate rotation	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	14	1	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
remove solid	0	6	0	0	0	0	0	6	0	0	6	0	2	13	0	0	0	0	0
resist corrosion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rotate solid	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
secure liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
secure rotation	0	0	0	0	0	0	0	0	1	4	0	0	0	0	0	0	0	1	0
secure solid	1	1	0	1	0	0	0	1	0	5	0	0	3	7	0	0	0	0	0
secure translation	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	0	0	0	6	2	0	0	0	0	0	2	0	0	0	4	6	1	0	0
sense status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
separate solid	1	0	0	0	0	0	0	5	0	3	0	0	0	4	0	0	0	3	0
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize translation	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
stop chemical energy	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
stop electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	1	0	0	0
stop gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car	Ertl Bumble Ball	Fisher Price Bubble Mower
stop liquid	0	0	2	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0
stop rotation	0	0	0	0	1	0	0	0	0	5	0	0	0	0	0	0	0	0	0
stop solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
store electricity	0	6	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0
store energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store liquid	0	0	4	0	0	0	6	0	0	0	0	0	6	0	0	0	0	0	3
store mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store pneumatics	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store product	0	0	0	1	0	0	0	0	0	0	6	1	4	0	0	0	0	0	0
store solids	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
store translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electricity	0	0	0	0	0	5	0	0	1	2	0	0	0	0	0	0	4	3	0
supply liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply mechanical energy	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit electricity	0	0	0	0	2	0	0	1	0	0	0	0	0	0	1	1	0	0	0
transmit energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit human force	0	1	1	0	0	0	0	0	0	0	0	0	0	7	0	0	1	0	0
transmit hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	0	6	0	3	6	5	0	1	0	2	1	1	0	0	1	0	10	0	6
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
transmit heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit translation	2	0	1	3	0	0	0	1	0	0	0	0	0	0	0	14	0	0	0
transmit vibrations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
transport liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transport solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck
actuate electricity	1	1	0	1	0	1	1	0	1	0	1	0	4	1	1	1	1	2	3
actuate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
assemble product	0	0	3	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
change sound	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
change electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	0	0	0	0	0	0	0	3	0	5	0	0	0	0	0
change human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change pneumatics	0	0	1	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0
change rotation	12	0	1	0	1	1	0	2	0	0	8	6	0	3	0	0	0	0	16
change translation	9	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
clean product	0	2	1	0	0	2	0	0	0	0	1	0	4	0	0	3	0	4	0
condition electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
connect solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to rotation	9	5	0	12	0	1	0	0	0	0	9	0	0	7	15	0	0	0	19
convert electricity to heat	0	0	0	0	0	0	3	0	0	0	0	0	19	0	3	6	3	5	0
convert electricity to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0
convert rotation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	0	5	6	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
convert rotation to translation	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
convert rotation to vibration	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to rotation	0	0	1	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert vibration to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
disassemble product	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
display status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dissipate sound	4	6	0	5	0	3	0	0	0	0	3	0	6	2	6	0	0	0	0
dissipate heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	3	0
dissipate translation	1	0	5	5	0	1	0	4	0	0	5	1	1	0	5	0	0	0	5
dissipate vibrations	0	6	0	5	0	6	0	0	1	0	3	0	0	0	0	0	0	0	10
distribute gas	0	4	0	0	0	0	0	0	0	0	0	0	10	0	5	0	0	0	0
distribute liquid	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	1	0
distribute rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export gas	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
export liquid	0	0	0	0	0	0	1	0	0	4	0	0	0	0	0	1	1	1	0
export solid	1	0	0	0	0	0	1	0	0	0	0	0	0	2	0	1	0	1	0
export translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
extract solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form liquid	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide gas	0	0	2	0	0	0	4	0	0	0	0	0	1	0	5	0	0	0	0
guide human force	0	4	0	0	0	0	0	0	0	5	0	0	0	0	0	4	0	0	0
guide human hand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck
guide liquid	0	0	0	0	0	0	2	0	0	4	0	0	0	0	0	1	1	1	0
guide rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide solid	4	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0
guide translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
import control signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import electricity	1	1	0	1	0	1	1	0	1	0	0	0	1	1	1	1	1	1	0
import gas	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
import human energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import human force	5	0	6	1	1	3	10	14	6	6	11	2	10	5	4	10	12	11	5
import human hand	5	0	0	1	1	3	5	7	3	6	5	0	0	0	6	0	0	0	0
import liquid	0	0	3	0	0	0	1	0	0	2	1	0	6	0	0	1	9	2	0
import pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
import solar energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import solid	8	0	0	1	1	1	3	4	1	0	1	0	0	2	0	7	16	3	6
import translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
indicate status	0	1	0	1	0	0	1	0	0	0	0	3	0	0	0	1	1	1	0
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
maintain device	4	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
measure pressure	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0
mix liquid	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	8	0	0	0	0	0	2	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	6	8	8	1
mix solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
position product	0	0	0	10	0	0	0	0	0	0	4	0	0	0	1	0	0	0	0
position solid	0	0	1	5	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
position translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine gas	0	6	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
refine liquid	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	6	6	5	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine solid	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	0	0	0	1	0	0	0	0	0	0	0	0	3	0	5	1	1	1	2
regulate human force	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
regulate hydraulics	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	7	0	0
regulate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	1	0
regulate rotation	0	0	0	0	0	0	0	0	0	0	5	13	0	0	0	0	0	0	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
remove solid	14	0	0	8	0	3	0	0	6	0	11	0	0	8	0	0	0	0	0
resist corrosion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rotate solid	4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
secure liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
secure rotation	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
secure solid	13	0	0	7	0	1	1	6	1	0	0	0	0	3	0	1	6	1	1
secure translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	0	8	0	0	0	0	0	0	0	11	5	5	0	0	5	0	0	0	0
sense status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
separate solid	0	0	0	1	0	3	0	0	5	0	0	0	0	0	0	0	0	0	0
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize translation	0	3	0	0	0	0	0	0	0	0	0	0	5	1	0	0	0	0	0
stop chemical energy	5	0	3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
stop electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck
stop liquid	0	0	0	0	0	0	0	0	0	0	10	0	5	0	0	1	1	1	0
stop rotation	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
stop solid	0	0	0	0	0	1	0	4	0	0	0	0	0	1	1	0	0	0	0
stop heat	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
stop translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store liquid	0	0	2	0	0	0	7	0	0	0	0	0	11	0	0	5	14	6	0
store mechanical energy	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
store pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store product	0	4	0	0	0	0	0	0	0	0	0	1	0	0	1	3	0	0	0
store solids	0	0	0	0	1	0	0	0	0	0	0	0	9	8	0	1	12	1	0
store translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electricity	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
supply liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply mechanical energy	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
supply rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit electricity	0	0	0	1	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0
transmit energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	0	0	1	1	1	0	0	2	0	0	1	4	0	0	0	0	0	0	0
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit heat	0	0	0	0	0	0	9	0	0	0	0	0	15	0	1	9	6	8	0
transmit translation	1	0	0	1	2	0	0	2	1	0	0	0	0	0	0	0	0	0	0
transmit vibrations	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
transport liquid	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	4	1	0
transport solid	0	0	0	0	2	3	0	3	0	0	0	0	0	0	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
actuate electricity	5	0	1	0	1	0	0	1	0	0	0	0	0
actuate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	0	0	0	0	0	0	0	0	0
assemble product	0	7	0	0	0	0	0	0	0	0	0	0	0
change sound	0	0	0	0	0	0	0	0	0	0	0	0	0
change electricity	1	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	0	0	0	0	0	0	0	0	0
change human force	0	0	0	0	0	0	0	0	0	0	5	0	0
change pneumatics	0	0	0	0	13	0	0	0	0	0	0	0	0
change rotation	10	0	0	0	0	0	4	0	0	0	0	0	0
change translation	0	0	0	0	0	0	0	0	0	1	5	0	1
clean product	4	9	1	0	0	0	0	0	0	0	0	0	0
condition electricity	0	0	0	0	0	0	0	0	0	0	0	1	0
connect solid	0	0	0	0	7	0	0	0	0	0	4	0	0
convert electricity to rotation	7	16	8	0	6	0	0	0	0	0	0	5	0
convert electricity to heat	0	0	0	0	0	0	0	0	0	0	0	0	3
convert electricity to translation	0	0	0	0	0	0	0	6	9	0	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	2	0
convert pneumatics to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	0	0	4	0	0	0	0	0	0	0
convert rotation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	0	0	9	0	0	0	0	0	0	0	0	0	0
convert rotation to translation	0	10	0	0	0	0	0	0	1	0	0	0	0
convert rotation to vibration	0	0	0	0	6	0	0	0	0	0	0	0	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	1
convert translation to hydraulics	0	16	0	0	0	0	0	0	2	0	0	0	0
convert translation to pneumatics	0	0	0	0	0	0	0	6	5	0	0	0	0
convert translation to rotation	0	0	0	0	0	0	4	0	0	1	0	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	1	0
convert vibration to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	0	0	0	0	0	0	5	0	0	0
disassemble product	0	6	0	0	0	0	0	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0
display status	0	0	0	4	0	0	0	0	0	7	0	0	0
dissipate sound	3	0	0	0	2	0	0	2	0	0	0	4	0
dissipate heat	0	1	0	0	0	0	0	0	0	0	0	0	0
dissipate translation	6	4	0	0	4	4	5	0	0	0	0	14	0
dissipate vibrations	4	0	0	0	5	0	0	0	0	0	0	0	0
distribute gas	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute liquid	0	6	0	0	0	0	0	0	0	0	0	0	0
distribute rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute translation	0	0	0	0	0	0	0	0	0	0	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0
export gas	0	0	0	0	1	0	0	1	0	0	0	0	0
export liquid	0	0	0	0	0	0	0	0	0	0	0	0	2
export solid	0	0	6	1	2	0	0	4	8	0	0	0	0
export translation	0	0	0	0	0	0	0	0	0	0	8	0	0
export vibration	0	0	0	0	0	0	0	0	0	0	0	0	0
extract solid	0	0	0	0	0	0	0	6	0	0	0	0	0
form liquid	0	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	0	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	3
guide gas	0	0	1	0	1	0	0	0	0	0	0	0	0
guide human force	0	0	6	6	0	0	6	4	0	0	0	4	0
guide human hand	0	0	0	0	0	0	0	4	0	0	0	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
guide liquid	0	15	0	0	0	0	0	3	0	5	0	0	2
guide rotation	0	0	0	0	0	1	0	0	0	0	0	0	0
guide solid	0	0	1	0	0	0	0	6	0	4	0	4	0
guide translation	0	0	0	6	4	4	0	0	6	0	1	0	0
import control signal	0	0	0	0	0	0	0	0	5	0	0	0	0
import electricity	1	1	1	0	1	0	0	4	0	0	0	0	3
import gas	0	0	4	0	1	0	0	0	0	0	0	0	0
import human energy	0	0	0	6	0	0	0	0	0	0	0	0	0
import human force	9	5	6	6	0	1	4	0	0	0	0	0	1
import human hand	9	0	6	0	0	4	4	3	5	0	0	0	2
import liquid	0	1	0	0	0	0	0	0	3	4	0	0	0
import pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0
import solar energy	0	0	0	0	0	0	0	0	0	0	0	0	0
import solid	0	0	0	6	2	1	0	6	2	5	4	4	7
import translation	0	0	0	0	0	0	0	0	0	0	0	0	0
indicate status	0	0	1	0	0	0	0	2	0	0	0	0	0
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	1
maintain device	3	0	0	0	0	0	0	0	0	0	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	0
measure pressure	0	1	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	0	0	0	0	0	0	0
mix solid	0	0	0	0	0	0	0	0	0	0	0	0	0
position product	2	0	0	0	0	0	0	0	0	0	0	0	0
position solid	0	0	0	0	0	0	0	0	0	0	1	0	0
position translation	0	0	0	0	0	0	0	4	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0
refine gas	0	0	1	0	0	0	0	2	0	0	0	0	0
refine liquid	0	6	0	0	0	0	0	0	0	0	0	0	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
refine solid	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	4	0	0	0	0	0	0	0	9	0	0	0	0
regulate human force	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate hydraulics	0	2	0	0	0	0	0	0	0	0	0	0	2
regulate pneumatics	0	0	0	0	1	0	0	0	0	0	0	0	0
regulate rotation	0	0	0	0	0	2	0	0	0	0	0	0	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	1	0	0	0	0	0	0
remove solid	0	0	0	0	0	0	0	0	0	0	0	0	0
resist corrosion	0	0	0	5	0	0	0	0	3	0	0	0	0
rotate solid	0	0	0	0	0	0	0	0	0	0	0	0	0
secure liquid	0	0	0	0	0	0	0	0	0	5	0	0	0
secure rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
secure solid	0	0	0	6	0	1	0	0	1	8	1	1	6
secure translation	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	4	1	0	0	0	0	0	0	0	0	0	0	0
sense status	0	0	0	0	0	1	0	0	0	0	0	1	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0
separate solid	0	0	0	0	0	0	0	0	0	5	0	0	0
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0	1	0	0
stabilize translation	0	0	0	0	0	0	0	0	0	0	4	0	0
stop chemical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
stop electricity	0	1	0	0	0	0	0	0	0	0	0	0	0
stop gas	0	0	0	0	0	0	0	0	0	0	0	0	0
stop human force	0	0	0	0	0	0	0	0	0	0	8	0	0

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
stop liquid	0	7	0	0	0	0	0	3	0	0	0	0	0
stop rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
stop solid	0	0	0	0	0	0	0	0	0	0	1	0	0
stop heat	0	0	0	0	0	0	0	0	0	0	0	0	2
stop translation	0	0	0	1	0	0	6	0	0	0	0	0	0
store electricity	0	0	0	0	0	0	0	0	1	0	0	0	0
store energy	0	0	0	0	0	11	4	0	0	0	0	0	0
store liquid	0	9	0	0	0	0	0	0	0	1	0	0	2
store mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
store pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0
store product	1	0	2	0	0	0	0	0	0	0	0	0	0
store solids	0	0	2	0	6	1	0	8	0	1	0	0	1
store translation	0	0	0	0	0	0	0	0	0	0	0	0	1
supply electricity	0	0	0	0	0	0	0	0	3	0	0	0	0
supply liquid	0	0	0	0	0	0	0	0	0	5	0	0	0
supply mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
supply rotation	0	0	0	0	1	5	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	1	0
transmit electricity	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit energy	0	0	0	1	0	0	0	0	0	0	0	0	0
transmit human force	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit hydraulics	0	1	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	1	0	0	0	1	5	4	0	0	0	0	3	0
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit heat	0	0	0	0	0	0	0	1	0	0	0	0	3
transmit translation	0	0	0	0	0	6	8	0	5	0	5	5	1
transmit vibrations	0	0	0	0	0	0	0	0	0	0	0	0	0
transport liquid	0	0	0	0	0	0	0	0	0	0	0	0	0
transport solid	0	0	0	0	0	0	0	0	0	8	0	0	1

Figure D.1 Phi matrix for the 70 device database.

Sub-function \ Device	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet/Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS	Durabuilt Hand Vacuum
actuate electricity	2.17	4.39	0	0	2.81	0.69	1.09	0	1.05	3.39	0	0	0.98	0.69	0.94	0	0	7.2	1.05
actuate pneumatics	0	0	3.71	0	0	0	0	3.61	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	2.71	0	0	0	0	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.5	2.16	0.9	0
assemble product	0	4.39	0	0	0	0	0	0	0	4.52	5.38	0	0	0	0	0	0	0	1.05
change sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	9.82	0	0	0	0	0	9.41	0	0	0	0	0	0	0	0
change human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	3.93	0	0	0	0	0	0
change rotation	0	0	9.9	0	0	2.77	4.34	0	0	1.13	5.38	6.02	0	0	0	0	0	5.4	0
change translation	0	0	0	0	10.5	0	1.09	0	0	0	0	0	0	0	0	0	0	0	0
clean product	0	0	0	4.34	0	4.15	3.26	0	2.1	4.52	0	0	0	2.77	1.87	0	0	0	0
condition electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
connect solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to rotation	6.51	8.77	0	0.87	0	9.68	4.34	0	6.31	4.52	8.07	0	6.88	13.1	0	0	0	12.6	12.7
convert electricity to heat	0	0	0	5.21	2.11	0	0	0	10.5	0	0	0	3.93	0	0	0	0	0	0
convert electricity to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.55	0	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.5	0	0	0
convert pneumatics to rotation	0	0	9.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	0	0	0	0	0	0	0	6.32	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	2.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	6.51	0	0	5.21	0	0	0	0	5.26	0	0	0	0.98	15.2	0	0	0	0	9.49
convert rotation to translation	0	0	0	0	0	0	1.09	0	0	0	1.34	6.02	0	0	0.94	0	0	0	0
convert rotation to vibration	0	0	3.71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	8.07	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to pneumatics	0	0	0	0	0	0	0	9.03	0	0	0	0	0	0	0	0	0	0	0
convert translation to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert vibration to rotation	0	0	3.71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0
disassemble product	0	0	0	0	0	1.38	0	0	0	0	0	2.01	0	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
display status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dissipate sound	2.9	0	0	0	0	2.07	0	0	4.21	9.05	5.38	0	3.93	0	0	0	0	0	0
dissipate heat	4.34	0	0	0	0	0	0	0	0	3.39	0	0	0	0.69	0	0	0	0	3.16
dissipate translation	0	0	3.71	0	0	0	0	0	3.15	6.79	0	4.01	0	4.15	9.36	0	0	1.8	3.16
dissipate vibrations	2.9	0	0	0	0	0	0	0	0	0	0	0	3.93	0	3.74	0	3.6	0	4.22
distribute gas	0	0	0	0	0	0	0	0	0	0	0	0	3.93	0	0	0	0	0	0
distribute liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute rotation	0	0	0	0	0	0	1.09	0	0	0	0	0	0	0	0	0	0	0	0
distribute translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0.69	0	0	0	0	0
export liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export solid	0.72	0	0	2.6	4.21	4.84	1.09	0	0	1.13	0	0	0	0.69	0	0	0	0	4.22
export translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75	0	0	0
export vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
extract solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide gas	4.34	0	0	8.68	0	0	0	0.9	1.05	0	0	0	0.98	0	0	0	0	0	1.05
guide human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide human hand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet / Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS	Durabuilt Hand Vacuum
guide liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide rotation	0	0	0.62	0	0	0	4.34	0	1.05	0	0	0	0	0	0	2.75	2.16	0	0
guide solid	0	0	0	0	0	6.91	1.09	0	0	0	0	5.02	0	0	6.55	2.75	6.48	0	0
guide translation	0	0	0	0	0	0	0	0	0	0	0	0	0.98	0	0	0	0	0	0
import control signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import electricity	0.72	0	0	0.87	0.7	0	4.34	0	1.05	1.13	0	0	2.95	0	0	0	0	0	0
import gas	0	0	3.71	0.87	0	0	0	0.9	1.05	0	0	0	0.98	2.77	0	0	0	0	0
import human energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import human force	5.07	0	8.04	5.21	10.5	8.99	6.51	8.12	4.21	5.66	0	7.02	3.93	3.46	5.61	5.5	3.6	8.1	6.33
import human hand	10.9	0	0	0	3.51	4.15	6.51	5.42	4.21	0	0	7.02	3.93	0	0	5.5	3.6	8.99	6.33
import liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import pneumatics	0	0	0.62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import solar energy	0	0	0	0	0	0	0	0	0	0	1.34	0	0	0	0	0	0	0	0
import solid	0.72	0	0	7.81	0.7	0.69	4.34	3.61	0	1.13	0	1	0	0.69	6.55	0	0	0	5.27
import translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75	0	0	0
indicate status	0.72	0	1.86	0	0	0	0	1.81	0	0	0	0	0	0	0	0	0	0	4.22
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
maintain device	0	0	0	0	0	1.38	0	0	0	0	0	0	2.95	0	0	0	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure pressure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	6.32	0	0	0	3.15	0	0	0	5.89	0	0	0	0	0	0
mix liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix solid	0	0	0	4.34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
position product	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
position solid	5.79	1.1	0	0	0	4.15	4.34	0	0	1.13	0	0	0	0	0	0	0	0	0
position translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.94	0	0	0	0
refine gas	0	0	3.71	0	0	0	0	0	0	0	0	0	3.93	3.46	0	0	0	0	1.05
refine liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.32	0	0
refine solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	0.72	0	0	0	6.32	0	1.09	0	8.41	0	0	0	1.96	0	0	0	0	3.6	1.05
regulate human force	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0.94	0	0	0	0
regulate hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate pneumatics	0	0	0	0	0	0	0	8.12	0	0	0	0	0	0	0	0	0	0	0
regulate rotation	0	0	6.8	0	0	0	0	0	5.26	0	0	0	5.89	0	0	0	0	2.7	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	5.89	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.7	0
remove solid	4.34	9.87	0	0	0	9.68	11.9	0	0	4.52	0	0	0	0	0	0	0	0	0
resist corrosion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rotate solid	0	0	0	0	0	0	2.17	0	0	0	0	0	0	0	0	0	0	0.9	0
secure liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
secure rotation	0	0	0.62	0	0	0	0	0	0	0	1.34	0	0	0	0	8.25	0	4.5	0
secure solid	9.41	2.19	3.71	0	3.51	4.15	13	0.9	0	5.66	0	0	0	0	6.55	0	0	4.5	0
secure translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	0	0	0.62	0	0	0	0	0	7.36	0	0	0	19.6	0	0	0	0	0	0
sense status	0	0	0	0	0	0	4.34	0	0	6.79	0	0	0	0	0	0	0	0	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
separate solid	4.34	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75	0	0.9	2.11
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75	6.48	0	0
stabilize solid	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0
stabilize translation	0	0	0	0	3.51	0	0	0	0	5.66	1.34	0	0	0	0	0	6.48	0	0
stop chemical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0.69	0	0	0	0	1.05
stop electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop gas	0	0	0	0	0	0	0	5.42	0	0	0	0	0	0	0	0	0	0	1.05
stop human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet / Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS	Durabuilt Hand Vacuum
stop liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75	2.16	0	0
stop solid	0	6.58	0	0	0	0	1.09	0	0	0	1.34	0	0.98	3.46	0	0	0	0	0
stop heat	0	0	0	1.74	2.11	0	0	0	4.21	0	0	0	3.93	0	0	0	0	0	0
stop translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75	2.16	0	0
store electricity	0	0	0	0	0	6.91	0	0	0	0	0	0	0	14.5	0	0	0	6.3	12.7
store energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	2.77	0	0	0	0	0
store mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.94	0	0	0	0
store pneumatics	0	0	0	0	0	0	0	5.42	0	0	0	0	0	0	0	0	0	0	0
store product	0	2.19	0	2.6	0.7	0	0	0	0	0	0	0	0	0	1.87	0	0	0	3.16
store solids	2.17	0	0	3.47	0.7	0.69	0	1.81	0	3.39	0	0	0	3.46	0	0	0	0.9	1.05
store translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electricity	0	4.39	0	0	0	0.69	0	0	0	0	0	0	0	0	0	0	0	0.9	1.05
supply liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply mechanical energy	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
supply rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit electricity	0	0	0	0	0.7	0.69	0	0	0	0	1.34	0	0	0.69	0	0	0	0	0
transmit energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit human force	5.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	0	1.1	1.86	0.87	0	0	0	0	0	1.13	1.34	3.01	0.98	0	0	0	0	0.9	0
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit heat	0	0	0	9.54	8.42	0	0	0	1.05	0	0	0	3.93	0	0	0	0	0	0
transmit translation	0	0	0	0	0.7	0	0	1.81	0	0	0	4.01	0	0	5.61	0	0	0	0
transmit vibrations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transport liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transport solid	2.17	0	0	0	0	0	0	0	0	0	0	0	0	0.69	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car	Ertl Bumble Ball	Fisher Price Bubble Mower
actuate electricity	0	8.24	1.24	1.59	1.43	4.15	0	1.25	4.81	0.88	1.02	1.19	4.62	4.41	1.23	0	1.09	1.06	0
actuate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	0	0	0	0	1.19	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	5.72	0	0	0	0	0.88	0	0	0	0	0	0	0	0	0
assemble product	0	0	7.47	0	0	0	0	0	0	0	0	0	5.78	0	0	3.27	0	0	0
change sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	5.72	0	0	0	0	0	0	0	0	0.88	0	0	5.44	0	4.91
change human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change rotation	0	0	1.24	6.36	5.72	6.23	0	1.25	0.96	16.7	4.09	0	5.78	0	4.93	0	7.62	0	0
change translation	11.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
clean product	0	0	7.47	3.18	0	0	0	5	0	0	6.14	0	4.62	0	0	0	0	0	1.96
condition electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
connect solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to rotation	0	9.06	1.24	1.59	4.29	2.08	0	5	2.89	14	11.2	1.19	5.78	9.7	9.86	0	4.35	10.6	0
convert electricity to heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15.6	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	1.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.91
convert rotation to hydraulics	0	0	0	0	0	0	1.03	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	0	0	0	0	0	0	5.17	0	0	0	0	10.7	0	0.88	0	0	0	0	5.89
convert rotation to translation	0	0	1.24	0	0	7.27	0	0	0	0	0	0	0	9.7	0	0	4.35	0	0
convert rotation to vibration	0	0	0	0	0	0	0	13.8	6.74	0	0	0	0	0	0	0	0	10.6	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to hydraulics	0	0	8.71	0	0	7.27	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to pneumatics	11.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to rotation	0	0	1.24	0	0	0	6.2	0	0	0	0	0	0	0	0	0	1.09	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert vibration to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	0	0	0	0	0	0	5.27	0	0	0	0	0	0	0	0	0
disassemble product	0	0	7.47	0	0	0	0	0	0	0	0	0	1.16	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.89
display status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dissipate sound	0	0	0	3.18	4.29	0	3.1	6.25	0	0	6.14	4.75	4.62	3.53	3.7	0	3.26	0	0
dissipate heat	0	0	0	0	0	0	0	5	0	0.88	1.02	0	0	0.88	0	0	0	1.06	0
dissipate translation	0	1.65	6.22	4.77	0	5.19	0	0	10.6	2.63	0	0	0	0	0	4.91	5.44	6.39	2.95
dissipate vibrations	0	0	0	0	2.86	0	0	6.25	0	0.88	0	0	0	4.41	2.47	0.82	1.09	0	0
distribute gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.98
distribute translation	0	0	0	1.59	0	0	0	0	2.89	0	0	0	0	0	0	0	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.39	4.91
export gas	1.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export liquid	0	0	0	0	0	0	1.03	0	0	0	0	0	0	0	0	0	0	0	0
export solid	0	0.82	0	0	0	0	1.03	0	0	0	0	0	2.31	1.76	1.23	4.91	0	0	0
export translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export vibration	0	0	0	0	0	0	0	0	6.74	0	0	0	0	0	0	0	0	4.26	0
extract solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form liquid	0	0	0	0	0	0	11.4	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	0	0	0	0	0	0	6.14	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide gas	1.91	0	0	0	0	0	1.03	0	0	0	0	0	0	0.88	0	0	0	0	0
guide human force	0	0	0	0	0	4.15	0	0	0	0	0	0	0	0	0	0	0	0	0
guide human hand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car	Ertl Bumble Ball	Fisher Price Bubble Mower
guide liquid	0	0	2.49	0	0	0	1.03	0	0	0	0	0	0	0	0	0	0	0	0
guide rotation	0	0	0	0	0	0	0	1.25	3.85	0	0	0	0	0	0	0	0	0	0
guide solid	13.3	1.65	0	0	0	0	0	1.25	0	0	0	0	0	0	0	0	0	0	0
guide translation	0	0	0	0	0	0	0	1.25	0	0	0	0	0	0	0	0	0	0	0
import control signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import electricity	0	0	0	0	0	1.04	0	1.25	0	0	1.02	1.19	2.31	0.88	1.23	2.46	0	0	0
import gas	1.91	0	0	0	0	0	1.03	0	0	0	0	0	0	0	0	0	0	0	0
import human energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import human force	1.91	4.94	6.22	7.95	0	0	8.27	6.25	0	3.51	1.02	7.13	0	5.29	6.16	0	1.09	0	4.91
import human hand	0	0	0	0	0	0	0	0	0	3.51	0	0	0	5.29	0	0	0	0	0
import liquid	0	0	6.22	0	0	0	10.3	0	0	0	6.14	0	0	0	0	0	0	0	0.98
import pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.09	0	0
import solar energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import solid	1.91	0.82	0	1.59	0	0	0	6.25	0	0	1.02	7.13	3.47	0.88	4.93	4.09	0	0	0
import translation	0	0	0	0	0	1.04	0	0	0	0	0	0	0	0	0	0	0	0	0
indicate status	0	0	0	0	0	0	0	0	0	0	1.02	0	1.16	0	1.23	0	0	0	0
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
maintain device	0	0	0	0	0	0	0	0	0	0	0	0	0	4.41	0	2.46	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure pressure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid	0	0	0	1.59	0	0	0	0	0	0	6.14	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	1.03	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mix solid	0	0	0	0	0	0	0	0	0	0	1.02	0	0	0	8.63	0	0	0	0
position product	0	7.42	0	9.54	0	4.15	0	0	0	0	0	5.94	0	3.53	0	0	0	0	0
position solid	1.91	0	0	0	0	0	0	0	0	0	0	0	0	0.88	0	0	0	0	0
position translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine gas	0	0	0	0	0	0	0	0	0	0	0	4.75	0	0	0	0	0	0	0
refine liquid	0	0	1.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	0	0	0	1.59	1.43	0	0	0	0	0.88	6.14	0	0	0	0	0.82	0	1.06	0
regulate human force	0	0	0	0	0	0	0	0	4.81	0	0	0	0	0.88	0	0	0	0	0
regulate hydraulics	0	0	4.98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate rotation	0	0	0	0	0	0	0	0	0	0.88	0	0	0	0	2.47	0	15.2	1.06	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	0	0	0	0.88	0	0	0	0	0	0	0	0	0
remove solid	0	4.94	0	0	0	0	0	7.5	0	0	6.14	0	2.31	11.5	0	0	0	0	0
resist corrosion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rotate solid	0	0	0	0	0	0	0	0	0	0.88	0	0	0	0	0	0	0	0	0
secure liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
secure rotation	0	0	0	0	0	0	0	0	0.96	3.51	0	0	0	0	0	0	0	1.06	0
secure solid	1.91	0.82	0	1.59	0	0	0	1.25	0	4.39	0	0	3.47	6.17	0	0	0	0	0
secure translation	1.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	0	0	0	9.54	2.86	0	0	0	0	0	2.05	0	0	0	4.93	4.91	1.09	0	0
sense status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.09	0	0
separate solid	1.91	0	0	0	0	0	0	6.25	0	2.63	0	0	0	3.53	0	0	0	3.19	0
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize translation	0	0	0	0	0	0	0	0	0.96	0	0	0	0	0	0	0	0	0	0
stop chemical energy	0	0	0	0	0	1.04	1.03	0	0	0	0	0	0	0	0	0	0	0	0
stop electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.4	0.82	0	0	0
stop gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car	Ertl Bumble Ball	Fisher Price Bubble Mower
stop liquid	0	0	2.49	0	0	1.04	0	2.5	0	0	0	0	0	0	0	0	0	0	0
stop rotation	0	0	0	0	1.43	0	0	0	0	4.39	0	0	0	0	0	0	0	0	0
stop solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.82	0	0	0
store electricity	0	4.94	0	0	0	0	0	0	0	11.4	0	0	0	0	0	0	0	0	0
store energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store liquid	0	0	4.98	0	0	0	6.2	0	0	0	0	0	6.93	0	0	0	0	0	2.95
store mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store pneumatics	1.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store product	0	0	0	1.59	0	0	0	0	0	0	6.14	1.19	4.62	0	0	0	0	0	0
store solids	0	0	0	0	0	0	0	0	0	0	0	3.56	0	0	0	0	0	0	0
store translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electricity	0	0	0	0	0	5.19	0	0	0.96	1.76	0	0	0	0	0	0	4.35	3.19	0
supply liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply mechanical energy	1.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit electricity	0	0	0	0	2.86	0	0	1.25	0	0	0	0	0	0	1.23	0.82	0	0	0
transmit energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit human force	0	0.82	1.24	0	0	0	0	0	0	0	0	0	0	6.17	0	0	1.09	0	0
transmit hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	0	4.94	0	4.77	8.57	5.19	0	1.25	0	1.76	1.02	1.19	0	0	1.23	0	10.9	0	5.89
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.09	0	0
transmit heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit translation	3.81	0	1.24	4.77	0	0	0	1.25	0	0	0	0	0	0	0	11.5	0	0	0
transmit vibrations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.06	0
transport liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transport solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.82	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck
actuate electricity	0.7	1.16	0	1.14	0	1.96	1.29	0	1.41	0	0.94	0	2.73	1.24	1.09	1.29	0.77	2.81	1.78
actuate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	0	0	0	5.89	0	0	0	0	0	0	0	0	0	0	0
assemble product	0	0	4.78	0	0	0	0	3.93	0	0	0	0	0	0	0	0	0	0	0
change sound	0	0	0	0	0	0	0	0	0	0	0	8.87	0	0	0	0	0	0	0
change electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	0	0	0	0	0	0	0	2.66	0	6.19	0	0	0	0	0
change human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change pneumatics	0	0	1.59	0	0	0	0	0	0	0	0	0	4.09	0	0	0	0	0	0
change rotation	8.4	0	1.59	0	3.37	1.96	0	1.96	0	0	7.52	5.32	0	3.71	0	0	0	0	9.5
change translation	6.3	0	0	0	0	0	0	0	2.82	0	0	0	0	0	0	0	0	0	0
clean product	0	2.32	1.59	0	0	3.93	0	0	0	0	0.94	0	2.73	0	0	3.88	0	5.61	0
condition electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
connect solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to rotation	6.3	5.8	0	13.7	0	1.96	0	0	0	0	8.46	0	0	8.66	16.4	0	0	0	11.3
convert electricity to heat	0	0	0	0	0	0	3.87	0	0	0	0	0	13	0	3.27	7.76	2.32	7.02	0
convert electricity to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	5.64	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	0	0	0	0	0	0	0	0	9.76	0	0	0	0	0	0	0
convert rotation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	0	5.8	9.56	0	0	0	0	0	0	0	0	0	0	0	4.37	0	0	0	0
convert rotation to translation	0	0	0	0	3.37	0	0	0.98	0	0	0	0	0	0	0	0	0	0	0
convert rotation to vibration	0	0	0	0	0	1.96	0	0	0	0	0.94	0	0	0	0	0	0	0	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert translation to rotation	0	0	1.59	0	0	0	0	5.89	0	0	0	0	0	0	0	0	0	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
convert vibration to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	1.14	0	0	0	0	1.41	0	0	0	0	0	0	0	0	0	0
disassemble product	0	2.32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
display status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dissipate sound	2.8	6.96	0	5.69	0	5.89	0	0	0	0	2.82	0	4.09	2.47	6.55	0	0	0	0
dissipate heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.88	3.09	4.21	0
dissipate translation	0.7	0	7.96	5.69	0	1.96	0	3.93	0	0	4.7	0.89	0.68	0	5.46	0	0	0	2.97
dissipate vibrations	0	6.96	0	5.69	0	11.8	0	0	1.41	0	2.82	0	0	0	0	0	0	0	5.94
distribute gas	0	4.64	0	0	0	0	0	0	0	0	0	0	6.82	0	5.46	0	0	0	0
distribute liquid	0	0	0	0	0	0	1.29	0	0	0	0	0	0	0	0	2.59	0	1.4	0
distribute rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export gas	0	1.16	0	0	0	0	1.29	0	0	0	0	0	0	0	0	0	0	0	0
export liquid	0	0	0	0	0	0	1.29	0	0	2.83	0	0	0	0	0	1.29	0.77	1.4	0
export solid	0.7	0	0	0	0	0	1.29	0	0	0	0	0	0	2.47	0	1.29	0	1.4	0
export translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
extract solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form liquid	0	0	1.59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide gas	0	0	3.19	0	0	0	5.16	0	0	0	0	0	0.68	0	5.46	0	0	0	0
guide human force	0	4.64	0	0	0	0	0	0	0	3.54	0	0	0	0	0	5.17	0	0	0
guide human hand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck
guide liquid	0	0	0	0	0	0	2.58	0	0	2.83	0	0	0	0	0	1.29	0.77	1.4	0
guide rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide solid	2.8	0	0	0	3.37	0	0	0	0	0	0	0	0	2.47	0	0	0	0	0
guide translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.13
import control signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import electricity	0.7	1.16	0	1.14	0	1.96	1.29	0	1.41	0	0	0	0.68	1.24	1.09	1.29	0.77	1.4	0
import gas	0	1.16	0	0	0	0	0	0	0	0	0	0	0	0	1.09	0	0	0	0
import human energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import human force	3.5	0	9.56	1.14	3.37	5.89	12.9	13.8	8.46	4.24	10.3	1.77	6.82	6.19	4.37	12.9	9.28	15.4	2.97
import human hand	3.5	0	0	1.14	3.37	5.89	6.46	6.88	4.23	4.24	4.7	0	0	0	6.55	0	0	0	0
import liquid	0	0	4.78	0	0	0	1.29	0	0	1.41	0.94	0	4.09	0	0	1.29	6.96	2.81	0
import pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.97
import solar energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
import solid	5.6	0	0	1.14	3.37	1.96	3.87	3.93	1.41	0	0.94	0	0	2.47	0	9.05	12.4	4.21	3.56
import translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
indicate status	0	1.16	0	1.14	0	0	1.29	0	0	0	0	2.66	0	0	0	1.29	0.77	1.4	0
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
maintain device	2.8	0	0	0	0	0	0	0	0	0	3.76	0	0	0	0	0	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	0.68	0	0	0	0	0	0
measure pressure	0	0	0	0	0	0	1.29	0	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	0	0	1.29	0	0	0	0	0	0	0	0	1.29	0.77	1.4	0
mix liquid	0	0	0	0	0	0	0	0	0	0.71	0	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	10.3	0	0	0	0	0	1.36	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	7.75	0	0	0	0	0	0	0	0	7.76	6.18	11.2	0.59
mix solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
position product	0	0	0	11.4	0	0	0	0	0	0	3.76	0	0	0	1.09	0	0	0	0
position solid	0	0	1.59	5.69	3.37	1.96	0	0	0	0	0	0	0	0	0	0	0	0	0
position translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine gas	0	6.96	0	0	0	0	0	0	0	0	0	0	0	0	1.09	0	0	0	0
refine liquid	0	0	0	0	0	0	1.29	0	0	0	0	0	0	0	0	7.76	4.64	7.02	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
refine solid	0	1.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	0	0	0	1.14	0	0	0	0	0	0	0	0	2.05	0	5.46	1.29	0.77	1.4	1.19
regulate human force	0	0	0	0	0	0	0	0.98	0	0	0	0	0	0	0	0	0	0	0
regulate hydraulics	0	0	0	0	0	0	0	0	0	7.78	0	0	0	0	0	0	5.41	0	0
regulate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.59	4.64	1.4	0
regulate rotation	0	0	0	0	0	0	0	0	0	0	4.7	11.5	0	0	0	0	0	0	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
remove solid	9.8	0	0	9.11	0	5.89	0	0	8.46	0	10.3	0	0	9.9	0	0	0	0	0
resist corrosion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rotate solid	2.8	0	0	0	0	0	0	0	0	0	0.94	0	0	0	0	0	0	0	0
secure liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
secure rotation	0	0	0	0	0	0	0	0	0	0	0	0.89	0	1.24	0	0	0	0	0
secure solid	9.1	0	0	7.97	0	1.96	1.29	5.89	1.41	0	0	0	0	3.71	0	1.29	4.64	1.4	0.59
secure translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	0	9.28	0	0	0	0	0	0	0	7.78	4.7	4.44	0	0	5.46	0	0	0	0
sense status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.77	0	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.59
separate solid	0	0	0	1.14	0	5.89	0	0	7.05	0	0	0	0	0	0	0	0	0	0
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize translation	0	3.48	0	0	0	0	0	0	0	0	0	0	3.41	1.24	0	0	0	0	0
stop chemical energy	3.5	0	4.78	0	0	0	0	0	0	0	0	0	0.68	0	0	0	0	0	0
stop electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stop human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck
stop liquid	0	0	0	0	0	0	0	0	0	0	9.4	0	3.41	0	0	1.29	0.77	1.4	0
stop rotation	0	0	0	0	0	0	0	0	0	0	0	0.89	0	0	0	0	0	0	0
stop solid	0	0	0	0	0	1.96	0	3.93	0	0	0	0	0	1.24	1.09	0	0	0	0
stop heat	0	0	0	0	0	0	0	0	0	0	0	0	0.68	0	1.09	0	0	0	0
stop translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store liquid	0	0	3.19	0	0	0	9.04	0	0	0	0	0	7.5	0	0	6.47	10.8	8.42	0
store mechanical energy	0	0	0	0	0	0	0	0.98	0	0	0	0.89	0	0	0	0	0	0	0
store pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
store product	0	4.64	0	0	0	0	0	0	0	0	0	0.89	0	0	1.09	3.88	0	0	0
store solids	0	0	0	0	3.37	0	0	0	0	0	0	0	6.14	9.9	0	1.29	9.28	1.4	0
store translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electricity	0	0	0	0	3.37	0	0	0	0	0	0.94	0	0	0	0	0	0	0	0
supply liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply mechanical energy	0	0	0	0	0	0	0	0.98	0	0	0	0	0	0	0	0	0	0	0
supply rotation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit electricity	0	0	0	1.14	0	0	0	0	0	0	0.94	0	0	2.47	0	0	0	0	0
transmit energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit human force	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	0	0	1.59	1.14	3.37	0	0	1.96	0	0	0.94	3.55	0	0	0	0	0	0	0
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit heat	0	0	0	0	0	0	11.6	0	0	0	0	0	10.2	0	1.09	11.6	4.64	11.2	0
transmit translation	0.7	0	0	1.14	6.74	0	0	1.96	1.41	0	0	0	0	0	0	0	0	0	0
transmit vibrations	0	0	0	0	0	0	0	0	8.46	0	0	0	0	0	0	0	0	0	0
transport liquid	0	0	0	0	0	0	1.29	0	0	0	0	0	0	0	0	1.29	3.09	1.4	0
transport solid	0	0	0	0	6.74	5.89	0	2.95	0	0	0	0	0	0	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
actuate electricity	4.51	0	1.12	0	1.15	0	0	1.03	0	0	0	0	0
actuate pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of human force	0	0	0	0	0	0	0	0	0	0	0	0	0
allow DOF of solid	0	0	0	0	0	0	0	0	0	0	0	0	0
assemble product	0	4.62	0	0	0	0	0	0	0	0	0	0	0
change sound	0	0	0	0	0	0	0	0	0	0	0	0	0
change electricity	0.9	0	0	0	0	0	0	0	0	0	0	0	0
change friction	0	0	0	0	0	0	0	0	0	0	0	0	0
change human force	0	0	0	0	0	0	0	0	0	0	5.32	0	0
change pneumatics	0	0	0	0	14.9	0	0	0	0	0	0	0	0
change rotation	9.03	0	0	0	0	0	3.46	0	0	0	0	0	0
change translation	0	0	0	0	0	0	0	0	0	0.91	5.32	0	1.75
clean product	3.61	5.94	1.12	0	0	0	0	0	0	0	0	0	0
condition electricity	0	0	0	0	0	0	0	0	0	0	0	1.1	0
connect solid	0	0	0	0	8.04	0	0	0	0	0	4.26	0	0
convert electricity to rotation	6.32	10.6	8.98	0	6.89	0	0	0	0	0	0	5.5	0
convert electricity to heat	0	0	0	0	0	0	0	0	0	0	0	0	5.24
convert electricity to translation	0	0	0	0	0	0	0	6.2	8.32	0	0	0	0
convert electricity to vibration	0	0	0	0	0	0	0	0	0	0	0	0	0
convert human en. to translation	0	0	0	0	0	0	0	0	0	0	0	2.2	0
convert pneumatics to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
convert pneumatics to translation	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to sound	0	0	0	0	0	4.62	0	0	0	0	0	0	0
convert rotation to hydraulics	0	0	0	0	0	0	0	0	0	0	0	0	0
convert rotation to pneumatics	0	0	10.1	0	0	0	0	0	0	0	0	0	0
convert rotation to translation	0	6.6	0	0	0	0	0	0	0.92	0	0	0	0
convert rotation to vibration	0	0	0	0	6.89	0	0	0	0	0	0	0	0
convert solar energy to electricity	0	0	0	0	0	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0	0	0	0	0	1.75
convert translation to hydraulics	0	10.6	0	0	0	0	0	0	1.85	0	0	0	0
convert translation to pneumatics	0	0	0	0	0	0	0	6.2	4.62	0	0	0	0
convert translation to rotation	0	0	0	0	0	0	3.46	0	0	0.91	0	0	0
convert translation to signal	0	0	0	0	0	0	0	0	0	0	0	1.1	0
convert vibration to rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
couple solid	0	0	0	0	0	0	0	0	0	4.53	0	0	0
disassemble product	0	3.96	0	0	0	0	0	0	0	0	0	0	0
display signal	0	0	0	0	0	0	0	0	0	0	0	0	0
display status	0	0	0	3.6	0	0	0	0	0	6.35	0	0	0
dissipate sound	2.71	0	0	0	2.3	0	0	2.07	0	0	0	4.4	0
dissipate heat	0	0.66	0	0	0	0	0	0	0	0	0	0	0
dissipate translation	5.42	2.64	0	0	4.59	4.62	4.32	0	0	0	0	15.4	0
dissipate vibrations	3.61	0	0	0	5.74	0	0	0	0	0	0	0	0
distribute gas	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute liquid	0	3.96	0	0	0	0	0	0	0	0	0	0	0
distribute rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
distribute translation	0	0	0	0	0	0	0	0	0	0	0	0	0
export sound	0	0	0	0	0	0	0	0	0	0	0	0	0
export gas	0	0	0	0	1.15	0	0	1.03	0	0	0	0	0
export liquid	0	0	0	0	0	0	0	0	0	0	0	0	3.49
export solid	0	0	6.74	0.9	2.3	0	0	4.14	7.4	0	0	0	0
export translation	0	0	0	0	0	0	0	0	0	0	8.51	0	0
export vibration	0	0	0	0	0	0	0	0	0	0	0	0	0
extract solid	0	0	0	0	0	0	0	6.2	0	0	0	0	0
form liquid	0	0	0	0	0	0	0	0	0	0	0	0	0
form solid	0	0	0	0	0	0	0	0	0	0	0	0	0
guide electricity	0	0	0	0	0	0	0	0	0	0	0	0	5.24
guide gas	0	0	1.12	0	1.15	0	0	0	0	0	0	0	0
guide human force	0	0	6.74	5.4	0	0	5.19	4.14	0	0	0	4.4	0
guide human hand	0	0	0	0	0	0	0	4.14	0	0	0	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
guide liquid	0	9.9	0	0	0	0	0	3.1	0	4.53	0	0	3.49
guide rotation	0	0	0	0	0	1.16	0	0	0	0	0	0	0
guide solid	0	0	1.12	0	0	0	0	6.2	0	3.63	0	4.4	0
guide translation	0	0	0	5.4	4.59	4.62	0	0	5.55	0	1.06	0	0
import control signal	0	0	0	0	0	0	0	0	4.62	0	0	0	0
import electricity	0.9	0.66	1.12	0	1.15	0	0	4.14	0	0	0	0	5.24
import gas	0	0	4.49	0	1.15	0	0	0	0	0	0	0	0
import human energy	0	0	0	5.4	0	0	0	0	0	0	0	0	0
import human force	8.12	3.3	6.74	5.4	0	1.16	3.46	0	0	0	0	0	1.75
import human hand	8.12	0	6.74	0	0	4.62	3.46	3.1	4.62	0	0	0	3.49
import liquid	0	0.66	0	0	0	0	0	0	2.77	3.63	0	0	0
import pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0
import signal	0	0	0	0	0	0	0	0	0	0	0	0	0
import solar energy	0	0	0	0	0	0	0	0	0	0	0	0	0
import solid	0	0	0	5.4	2.3	1.16	0	6.2	1.85	4.53	4.26	4.4	12.2
import translation	0	0	0	0	0	0	0	0	0	0	0	0	0
indicate status	0	0	1.12	0	0	0	0	2.07	0	0	0	0	0
indicate temperature	0	0	0	0	0	0	0	0	0	0	0	0	1.75
maintain device	2.71	0	0	0	0	0	0	0	0	0	0	0	0
measure displacement	0	0	0	0	0	0	0	0	0	0	0	0	0
measure pressure	0	0.66	0	0	0	0	0	0	0	0	0	0	0
measure temperature	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and gas	0	0	0	0	0	0	0	0	0	0	0	0	0
mix liquid and solid	0	0	0	0	0	0	0	0	0	0	0	0	0
mix solid	0	0	0	0	0	0	0	0	0	0	0	0	0
position product	1.81	0	0	0	0	0	0	0	0	0	0	0	0
position solid	0	0	0	0	0	0	0	0	0	0	1.06	0	0
position translation	0	0	0	0	0	0	0	4.14	0	0	0	0	0
refine electricity	0	0	0	0	0	0	0	0	0	0	0	0	0
refine gas	0	0	1.12	0	0	0	0	2.07	0	0	0	0	0
refine liquid	0	3.96	0	0	0	0	0	0	0	0	0	0	0
refine optical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
refine solid	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate electricity	3.61	0	0	0	0	0	0	0	8.32	0	0	0	0
regulate human force	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate hydraulics	0	1.32	0	0	0	0	0	0	0	0	0	0	3.49
regulate pneumatics	0	0	0	0	1.15	0	0	0	0	0	0	0	0
regulate rotation	0	0	0	0	0	2.31	0	0	0	0	0	0	0
regulate heat	0	0	0	0	0	0	0	0	0	0	0	0	0
regulate translation	0	0	0	0	0	0	0.86	0	0	0	0	0	0
remove solid	0	0	0	0	0	0	0	0	0	0	0	0	0
resist corrosion	0	0	0	4.5	0	0	0	0	2.77	0	0	0	0
rotate solid	0	0	0	0	0	0	0	0	0	0	0	0	0
secure liquid	0	0	0	0	0	0	0	0	0	4.53	0	0	0
secure rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
secure solid	0	0	0	5.4	0	1.16	0	0	0.92	7.25	1.06	1.1	10.5
secure translation	0	0	0	0	0	0	0	0	0	0	0	0	0
sense control	3.61	0.66	0	0	0	0	0	0	0	0	0	0	0
sense status	0	0	0	0	0	1.16	0	0	0	0	0	1.1	0
separate signal	0	0	0	0	0	0	0	0	0	0	0	0	0
separate solid	0	0	0	0	0	0	0	0	0	4.53	0	0	0
stabilize rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0	1.06	0	0
stabilize translation	0	0	0	0	0	0	0	0	0	0	4.26	0	0
stop chemical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
stop electricity	0	0.66	0	0	0	0	0	0	0	0	0	0	0
stop gas	0	0	0	0	0	0	0	0	0	0	0	0	0
stop human force	0	0	0	0	0	0	0	0	0	0	8.51	0	0

Figure D.2 The **N** matrix for the 70 device database.

Sub-function \ Device	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
stop liquid	0	4.62	0	0	0	0	0	3.1	0	0	0	0	0
stop rotation	0	0	0	0	0	0	0	0	0	0	0	0	0
stop solid	0	0	0	0	0	0	0	0	0	0	1.06	0	0
stop heat	0	0	0	0	0	0	0	0	0	0	0	0	3.49
stop translation	0	0	0	0.9	0	0	5.19	0	0	0	0	0	0
store electricity	0	0	0	0	0	0	0	0	0.92	0	0	0	0
store energy	0	0	0	0	0	12.7	3.46	0	0	0	0	0	0
store liquid	0	5.94	0	0	0	0	0	0	0	0.91	0	0	3.49
store mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
store pneumatics	0	0	0	0	0	0	0	0	0	0	0	0	0
store product	0.9	0	2.25	0	0	0	0	0	0	0	0	0	0
store solids	0	0	2.25	0	6.89	1.16	0	8.27	0	0.91	0	0	1.75
store translation	0	0	0	0	0	0	0	0	0	0	0	0	1.75
supply electricity	0	0	0	0	0	0	0	0	2.77	0	0	0	0
supply liquid	0	0	0	0	0	0	0	0	0	4.53	0	0	0
supply mechanical energy	0	0	0	0	0	0	0	0	0	0	0	0	0
supply rotation	0	0	0	0	1.15	5.78	0	0	0	0	0	0	0
supply translation	0	0	0	0	0	0	0	0	0	0	0	1.1	0
transmit electricity	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit energy	0	0	0	0.9	0	0	0	0	0	0	0	0	0
transmit human force	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit hydraulics	0	0.66	0	0	0	0	0	0	0	0	0	0	0
transmit rotation	0.9	0	0	0	1.15	5.78	3.46	0	0	0	0	3.3	0
transmit signal	0	0	0	0	0	0	0	0	0	0	0	0	0
transmit heat	0	0	0	0	0	0	0	1.03	0	0	0	0	5.24
transmit translation	0	0	0	0	0	6.93	6.92	0	4.62	0	5.32	5.5	1.75
transmit vibrations	0	0	0	0	0	0	0	0	0	0	0	0	0
transport liquid	0	0	0	0	0	0	0	0	0	0	0	0	0
transport solid	0	0	0	0	0	0	0	0	0	7.25	0	0	1.75

Figure D.2 The **N** matrix for the 70 device database.

Similarity matrix	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet / Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS
De walt sander	1	0.377	0.172	0.276	0.274	0.567	0.659	0.277	0.367	0.448	0.173	0.327	0.248	0.37	0.262	0.282	0.216	0.582
Real Power Tool Shop	0.377	1	0.029	0.043	0.054	0.54	0.502	0.006	0.169	0.396	0.345	0.012	0.158	0.312	0.071	0.011	0	0.414
Pneumatic Air Ratchet	0.172	0.029	1	0.117	0.206	0.26	0.307	0.222	0.214	0.261	0.156	0.43	0.191	0.123	0.275	0.157	0.105	0.362
Presto Popcorn Popper	0.276	0.043	0.117	1	0.374	0.219	0.2	0.221	0.36	0.202	0.023	0.153	0.207	0.273	0.255	0.091	0.067	0.13
Salton Sandwich Maker	0.274	0.054	0.206	0.374	1	0.29	0.308	0.246	0.362	0.254	0.236	0.28	0.255	0.072	0.218	0.206	0.221	0.337
Krups Cheese Grater	0.567	0.54	0.26	0.219	0.29	1	0.697	0.24	0.297	0.505	0.27	0.432	0.224	0.479	0.335	0.261	0.297	0.646
Dazey Fruit & Veg. Stripper-RBS	0.659	0.502	0.307	0.2	0.308	0.697	1	0.249	0.222	0.541	0.146	0.364	0.155	0.155	0.377	0.229	0.189	0.496
Super Maxx Ball Shooter-RBS	0.277	0.006	0.222	0.221	0.246	0.24	0.249	1	0.144	0.157	0	0.344	0.104	0.075	0.232	0.236	0.174	0.272
Salon Series 795 Hair Dryer	0.367	0.169	0.214	0.36	0.362	0.297	0.222	0.144	1	0.305	0.198	0.221	0.676	0.362	0.15	0.147	0.11	0.448
Presto Salad Shooter	0.448	0.396	0.261	0.202	0.254	0.505	0.541	0.157	0.305	1	0.352	0.252	0.181	0.261	0.409	0.098	0.202	0.393
Toy Solar Car	0.173	0.345	0.156	0.023	0.236	0.27	0.146	0	0.198	0.352	1	0.16	0.166	0.235	0.004	0.039	0.034	0.345
Small Projectile Toy	0.327	0.012	0.43	0.153	0.28	0.432	0.364	0.344	0.221	0.252	0.16	1	0.139	0.1	0.499	0.363	0.374	0.463
Hair Dryer	0.248	0.158	0.191	0.207	0.255	0.224	0.155	0.104	0.676	0.181	0.166	0.139	1	0.195	0.075	0.1	0.111	0.307
Wet / Dry Vacuum	0.37	0.312	0.123	0.273	0.072	0.479	0.155	0.075	0.362	0.261	0.235	0.1	0.195	1	0.138	0.045	0.033	0.504
Stanley Electric Stapler	0.262	0.071	0.275	0.255	0.218	0.335	0.377	0.232	0.15	0.409	0.004	0.499	0.075	0.138	1	0.164	0.287	0.236
74 Chevy Tailgate Support-RBS	0.282	0.011	0.157	0.091	0.206	0.261	0.229	0.236	0.147	0.098	0.039	0.363	0.1	0.045	0.164	1	0.46	0.385
Cadillac Slide-Out Visor-RBS	0.216	0	0.105	0.067	0.221	0.297	0.189	0.174	0.11	0.202	0.034	0.374	0.111	0.033	0.287	0.46	1	0.199
SKIL Power Screwdriver-RBS	0.582	0.414	0.362	0.13	0.337	0.646	0.496	0.272	0.448	0.393	0.345	0.463	0.307	0.504	0.236	0.385	0.199	1
Durabuilt Hand Vacuum	0.549	0.317	0.148	0.342	0.212	0.591	0.286	0.247	0.395	0.3	0.243	0.275	0.257	0.829	0.264	0.189	0.172	0.662
Tactical Nerf Toy Gun	0.115	0.022	0.065	0.098	0.291	0.26	0.154	0.364	0.026	0.058	0	0.285	0.019	0.024	0.347	0.147	0.294	0.051
B&D Weed Trimmer	0.352	0.599	0.162	0.134	0.2	0.623	0.377	0.126	0.25	0.407	0.254	0.237	0.2	0.473	0.22	0.112	0.114	0.647
Wagner Paint Roller	0.106	0.139	0.202	0.161	0.144	0.25	0.16	0.129	0.163	0.378	0.158	0.318	0.061	0.179	0.3	0.102	0.076	0.199
Hamilton Elec. Mixer	0.184	0.129	0.41	0.198	0.236	0.308	0.273	0.206	0.397	0.397	0.199	0.478	0.472	0.15	0.398	0.151	0.101	0.35
OverRider Toy Car	0.155	0.202	0.237	0.037	0.198	0.205	0.128	0	0.248	0.258	0.571	0.249	0.305	0.144	0.042	0.143	0.117	0.326
Horseman Swimming Toy	0.063	0.241	0.264	0.022	0.031	0.119	0.133	0	0.099	0.217	0.222	0.445	0.058	0.117	0.188	0.011	0	0.286
Mattel Bubble Extinguisher	0.197	0	0.168	0.204	0.19	0.191	0.113	0.17	0.18	0.185	0.045	0.18	0.093	0.234	0.121	0.137	0.101	0.145
Regal Ware Electric Knife	0.395	0.34	0.258	0.241	0.149	0.464	0.423	0.168	0.205	0.458	0.203	0.201	0.186	0.18	0.308	0.157	0.169	0.273
Bumble Ball Toy	0.079	0.176	0.224	0.008	0.043	0.094	0.097	0	0.173	0.322	0.103	0.201	0.054	0.19	0.344	0.098	0.061	0.266
B&D Cordless Screwdriver	0.35	0.323	0.419	0.06	0.115	0.554	0.376	0.096	0.247	0.284	0.434	0.39	0.188	0.52	0.153	0.211	0.103	0.765
Takka-1000 Pasta Machine	0.289	0.49	0.124	0.171	0.125	0.491	0.364	0.033	0.411	0.431	0.386	0.107	0.284	0.3	0.091	0.016	0.012	0.422
Upright Vacuum Cleaner	0.366	0.086	0.213	0.478	0.211	0.241	0.212	0.266	0.314	0.327	0.116	0.218	0.188	0.501	0.271	0.137	0.101	0.214
WestBend Food Processor	0.301	0.484	0.214	0.221	0.109	0.43	0.436	0.054	0.211	0.535	0.451	0.156	0.155	0.26	0.216	0	0	0.41
Black & Decker Sander	0.684	0.597	0.137	0.131	0.228	0.641	0.643	0.175	0.268	0.46	0.282	0.364	0.254	0.262	0.242	0.179	0.161	0.52
West Bend Mixer	0.288	0.284	0.314	0.322	0.175	0.436	0.295	0.184	0.388	0.346	0.376	0.27	0.451	0.306	0.215	0.11	0.113	0.502
Green Eagle Putting Cup	0.027	0.038	0.047	0.108	0.076	0.063	0.067	0.081	0.133	0.139	0.047	0.202	0.195	0.047	0.587	0.006	0.015	0.024
F.Price Remote Control Car	0.106	0.186	0.483	0.041	0.125	0.164	0.118	0.019	0.313	0.252	0.397	0.367	0.278	0.136	0.152	0.016	0.024	0.338
Ertl Bumble Ball	0.22	0.361	0.186	0.025	0.022	0.259	0.11	0	0.263	0.265	0.26	0.087	0.164	0.336	0.173	0.058	0	0.404
Fisher Price Bubble Mower	0.192	0.025	0.202	0.282	0.287	0.161	0.112	0.135	0.209	0.213	0.203	0.274	0.077	0.333	0.211	0.113	0.083	0.15
Electric Can Opener	0.524	0.495	0.351	0.172	0.325	0.663	0.798	0.189	0.196	0.471	0.3	0.385	0.167	0.19	0.376	0.139	0.147	0.504
Portable Fan	0.275	0.196	0.094	0.152	0.042	0.195	0.084	0.008	0.42	0.316	0.251	0.015	0.627	0.378	0.108	0	0.169	0.183
Bubble Machine	0.323	0.076	0.328	0.368	0.23	0.253	0.184	0.218	0.313	0.382	0.109	0.386	0.115	0.457	0.375	0.175	0.129	0.242
B&D Elec. Polisher	0.549	0.604	0.128	0.059	0.1	0.57	0.558	0.063	0.292	0.529	0.327	0.124	0.235	0.319	0.322	0.04	0.082	0.458
Crossfire Game	0.31	0.091	0.23	0.209	0.17	0.314	0.283	0.27	0.095	0.161	0.107	0.65	0.078	0.08	0.39	0.202	0.227	0.265
Black & Decker Elec. Knife	0.586	0.322	0.218	0.169	0.21	0.473	0.493	0.225	0.253	0.453	0.17	0.333	0.258	0.148	0.349	0.252	0.298	0.374
KRUPS Café Trio	0.312	0.019	0.21	0.544	0.478	0.279	0.275	0.316	0.271	0.178	0	0.344	0.222	0.108	0.222	0.255	0.188	0.305
Good Times Fishing Reel	0.46	0.165	0.406	0.257	0.402	0.411	0.498	0.423	0.231	0.401	0.111	0.613	0.157	0.15	0.499	0.44	0.296	0.485
Dremel Electric Engraver-RBS	0.442	0.322	0.197	0.157	0.34	0.459	0.507	0.279	0.148	0.281	0	0.336	0.124	0.064	0.236	0.303	0.195	0.318
Moen Kitchen Water Faucet	0.224	0	0.14	0.082	0.186	0.187	0.171	0.213	0.326	0.088	0	0.278	0.506	0.04	0.093	0.212	0.157	0.236
Battery Op. Toothbrush	0.423	0.466	0.444	0.157	0.232	0.64	0.535	0.24	0.414	0.462	0.297	0.464	0.425	0.269	0.273	0.216	0.189	0.567
Metronome	0.025	0.017	0.409	0.103	0.099	0.071	0.075	0.049	0.253	0.067	0.17	0.19	0.313	0.019	0.056	0.062	0.03	0.188
Humidifier	0.136	0.03	0.12	0.522	0.407	0.17	0.111	0.144	0.459	0.305	0.063	0.137	0.298	0.125	0.119	0.099	0.139	0.168
Electric Pencil Sharpener	0.45	0.565	0.245	0.253	0.355	0.692	0.595	0.201	0.222	0.541	0.468	0.254	0.183	0.332	0.244	0.157	0.16	0.481
Mini Pro Hair Dryer	0.532	0.394	0.139	0.303	0.229	0.463	0.278	0.165	0.715	0.425	0.399	0.266	0.57	0.524	0.178	0.158	0.117	0.635
West Bend Iced Tea Maker-RBS	0.188	0.037	0.205	0.621	0.468	0.261	0.259	0.313	0.313	0.251	0	0.239	0.198	0.125	0.313	0.166	0.123	0.21
Mr. Coffee Iced Tea Maker-RBS	0.239	0.031	0.177	0.46	0.306	0.209	0.299	0.352	0.146	0.278	0	0.191	0.105	0.153	0.339	0.123	0.09	0.194
Mr. Coffee Coffee Maker-RBS	0.206	0.033	0.235	0.535	0.485	0.299	0.257	0.29	0.318	0.286	0	0.26	0.202	0.144	0.264	0.191	0.141	0.254
Radio Controlled Truck	0.289	0.34	0.346	0.145	0.111	0.414	0.31	0.102	0.27	0.303	0.427	0.32	0.247	0.352	0.275	0.055	0.121	0.58
Braun Hand Blender	0.472	0.243	0.454	0.177	0.333	0.521	0.431	0.288	0.513	0.467	0.333	0.636	0.434	0.284	0.339	0.287	0.259	0.743
Paint Sprayer	0.172	0.283	0.077	0.115	0.065	0.318	0.176	0.058	0.22	0.291	0.285	0.223	0.16	0.313	0.139	0.048	0.036	0.314
Bissel Hand Vacuum	0.566	0.259	0.189	0.371	0.278	0.509	0.307	0.259	0.424	0.261	0.202	0.319	0.258	0.614	0.14	0.24	0.195	0.529
Drill and Nail Extractor 11	0.259	0.048	0.216	0.255	0.246	0.25	0.38	0.239	0.075	0.237	0	0.191	0.068	0.06	0.374	0.138	0.104	0.209
Air Compressor 22	0.187	0.17	0.105	0.148	0.037	0.179	0.09	0.071	0.151	0.258	0.169	0.067	0.243	0.231	0.188	0	0.063	0.214
Chainsaw Toy Truck 18	0.165	0.027	0.147	0.095	0.086	0.085	0.149	0.142	0.13	0.167	0.022	0.348	0.09	0.054	0.287	0.113	0.085	0.177

Figure D.3 The similarity matrix for the 70 device database.

Similarity matrix	De walt sander	Real Power Tool Shop	Pneumatic Air Ratchet	Presto Popcorn Popper	Salton Sandwich Maker	Krups Cheese Grater	Dazey Fruit & Veg. Stripper-RBS	Super Maxx Ball Shooter-RBS	Salon Series 795 Hair Dryer	Presto Salad Shooter	Toy Solar Car	Small Projectile Toy	Hair Dryer	Wet / Dry Vacuum	Stanley Electric Stapler	74 Chevy Tailgate Support-RBS	Cadillac Slide-Out Visor-RBS	SKIL Power Screwdriver-RBS
Push-n-Go Train 13	0.18	0.016	0.3	0.077	0.165	0.182	0.184	0.217	0.148	0.206	0.094	0.575	0.082	0.081	0.381	0.235	0.183	0.292
Corvette Vac 23	0.165	0.013	0.029	0.261	0.115	0.211	0.166	0.292	0.069	0.17	0.032	0.191	0.086	0.084	0.333	0.108	0.183	0.096
Power Caulk 20	0.176	0.045	0.009	0.093	0.25	0.17	0.157	0.227	0.233	0.043	0.004	0.202	0.081	0.04	0.289	0.086	0.063	0.203
Stamp Machine 17	0.286	0.071	0.077	0.114	0.096	0.157	0.293	0.072	0	0.144	0	0.084	0	0.03	0.313	0.081	0.096	0.107
bicycle brake 18	0.051	0.036	0.011	0.1	0.205	0.032	0.11	0.08	0	0.107	0.024	0.096	0.005	0.015	0.204	0.086	0.114	0.013
Tape Rewinder 22	0.142	0.16	0.167	0.107	0.023	0.231	0.143	0.068	0.246	0.485	0.204	0.386	0.109	0.263	0.646	0.076	0.101	0.235
Hot Glue Gun 21	0.348	0.062	0.121	0.469	0.324	0.177	0.489	0.219	0.229	0.221	0	0.166	0.157	0.055	0.418	0.083	0.061	0.195

Figure D.3 The similarity matrix for the 70 device database.

Similarity matrix	Durabuilt Hand Vacuum	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car
De walt sander	0.549	0.115	0.352	0.106	0.184	0.155	0.063	0.197	0.395	0.079	0.35	0.289	0.366	0.301	0.684	0.288	0.027	0.106
Real Power Tool Shop	0.317	0.022	0.599	0.139	0.129	0.202	0.241	0	0.34	0.176	0.323	0.49	0.086	0.484	0.597	0.284	0.038	0.186
Pneumatic Air Ratchet	0.148	0.065	0.162	0.202	0.41	0.237	0.264	0.168	0.258	0.224	0.419	0.124	0.213	0.214	0.137	0.314	0.047	0.483
Presto Popcorn Popper	0.342	0.098	0.134	0.161	0.198	0.037	0.022	0.204	0.241	0.008	0.06	0.171	0.478	0.221	0.131	0.322	0.108	0.041
Salton Sandwich Maker	0.212	0.291	0.2	0.144	0.236	0.198	0.031	0.19	0.149	0.043	0.115	0.125	0.211	0.109	0.228	0.175	0.076	0.125
Krups Cheese Grater	0.591	0.26	0.623	0.25	0.308	0.205	0.119	0.191	0.464	0.094	0.554	0.491	0.241	0.43	0.641	0.436	0.063	0.164
Dazey Fruit & Veg. Stripper-RBS	0.286	0.154	0.377	0.16	0.273	0.128	0.133	0.113	0.423	0.097	0.376	0.364	0.212	0.436	0.643	0.295	0.067	0.118
Super Maxx Ball Shooter-RBS	0.247	0.364	0.126	0.129	0.206	0	0	0.17	0.168	0	0.096	0.033	0.266	0.054	0.175	0.184	0.081	0.019
Salon Series 795 Hair Dryer	0.395	0.026	0.25	0.163	0.397	0.248	0.099	0.18	0.205	0.173	0.247	0.411	0.314	0.211	0.268	0.388	0.133	0.313
Presto Salad Shooter	0.3	0.058	0.407	0.378	0.397	0.258	0.217	0.185	0.458	0.322	0.284	0.431	0.327	0.535	0.46	0.346	0.139	0.252
Toy Solar Car	0.243	0	0.254	0.158	0.199	0.571	0.222	0.045	0.203	0.103	0.434	0.386	0.116	0.451	0.282	0.376	0.047	0.397
Small Projectile Toy	0.275	0.285	0.237	0.318	0.478	0.249	0.445	0.18	0.201	0.201	0.39	0.107	0.218	0.156	0.364	0.27	0.202	0.367
Hair Dryer	0.257	0.019	0.2	0.061	0.472	0.305	0.058	0.093	0.186	0.054	0.188	0.284	0.188	0.155	0.254	0.451	0.195	0.278
Wet / Dry Vacuum	0.829	0.024	0.473	0.179	0.15	0.144	0.117	0.234	0.18	0.19	0.52	0.3	0.501	0.26	0.262	0.306	0.047	0.136
Stanley Electric Stapler	0.264	0.347	0.22	0.3	0.398	0.042	0.188	0.121	0.308	0.344	0.153	0.091	0.271	0.216	0.242	0.215	0.587	0.152
74 Chevy Tailgate Support-RBS	0.189	0.147	0.112	0.102	0.151	0.143	0.011	0.137	0.157	0.098	0.211	0.016	0.137	0	0.179	0.11	0.006	0.016
Cadillac Slide-Out Visor-RBS	0.172	0.294	0.114	0.076	0.101	0.117	0	0.101	0.169	0.061	0.103	0.012	0.101	0	0.161	0.113	0.015	0.024
SKIL Power Screwdriver-RBS	0.662	0.051	0.647	0.199	0.35	0.326	0.286	0.145	0.273	0.266	0.765	0.422	0.214	0.41	0.52	0.502	0.024	0.338
Durabuilt Hand Vacuum	1	0.051	0.526	0.162	0.207	0.181	0.128	0.211	0.334	0.182	0.58	0.356	0.482	0.319	0.418	0.442	0.12	0.154
Tactical Nerf Toy Gun	0.051	1	0.088	0.036	0.089	0	0	0.043	0.115	0	0.033	0.008	0.068	0.036	0.064	0.049	0.104	0.004
B&D Weed Trimmer	0.526	0.088	1	0.173	0.49	0.341	0.396	0.115	0.338	0.28	0.47	0.402	0.355	0.373	0.59	0.415	0.04	0.285
Wagner Paint Roller	0.162	0.036	0.173	1	0.292	0.044	0.349	0.365	0.193	0.218	0.137	0.249	0.127	0.407	0.143	0.145	0.15	0.134
Hamilton Elec. Mixer	0.207	0.089	0.49	0.292	1	0.422	0.413	0.184	0.276	0.219	0.347	0.349	0.427	0.306	0.257	0.445	0.302	0.354
OverRider Toy Car	0.181	0	0.341	0.044	0.422	1	0.363	0.042	0.249	0.095	0.446	0.371	0.136	0.328	0.221	0.413	0.058	0.577
Horseman Swimming Toy	0.128	0	0.396	0.349	0.413	0.363	1	0.003	0.086	0.323	0.368	0.165	0.131	0.248	0.312	0.196	0.075	0.506
Mattel Bubble Extinguisher	0.211	0.043	0.115	0.365	0.184	0.042	0.003	1	0.148	0	0.052	0.206	0.35	0.174	0.127	0.16	0.011	0.054
Regal Ware Electric Knife	0.334	0.115	0.338	0.193	0.276	0.249	0.086	0.148	1	0.305	0.236	0.4	0.313	0.364	0.482	0.379	0.096	0.148
Bumble Ball Toy	0.182	0	0.28	0.218	0.219	0.095	0.323	0	0.305	1	0.205	0.115	0.03	0.159	0.134	0.12	0.139	0.221
B&D Cordless Screwdriver	0.58	0.033	0.47	0.137	0.347	0.446	0.368	0.052	0.236	0.205	1	0.412	0.093	0.437	0.341	0.478	0.024	0.392
Takka-1000 Pasta Machine	0.356	0.008	0.402	0.249	0.349	0.371	0.165	0.206	0.4	0.115	0.412	1	0.179	0.562	0.424	0.458	0.046	0.232
Upright Vacuum Cleaner	0.482	0.068	0.355	0.127	0.427	0.136	0.131	0.35	0.313	0.03	0.093	0.179	1	0.227	0.259	0.328	0.081	0.102
WestBend Food Processor	0.319	0.036	0.373	0.407	0.306	0.328	0.248	0.174	0.364	0.159	0.437	0.562	0.227	1	0.382	0.413	0.136	0.23
Black & Decker Sander	0.418	0.064	0.59	0.143	0.257	0.221	0.312	0.127	0.482	0.134	0.341	0.424	0.259	0.382	1	0.363	0.055	0.223
West Bend Mixer	0.442	0.049	0.415	0.145	0.445	0.413	0.196	0.16	0.379	0.12	0.478	0.458	0.328	0.413	0.363	1	0.147	0.354
Green Eagle Putting Cup	0.12	0.104	0.04	0.15	0.302	0.058	0.075	0.011	0.096	0.139	0.024	0.046	0.081	0.136	0.055	0.147	1	0.064
F.Price Remote Control Car	0.154	0.004	0.285	0.134	0.354	0.577	0.506	0.054	0.148	0.221	0.392	0.232	0.102	0.23	0.223	0.354	0.064	1
Ertl Bumble Ball	0.366	0.015	0.349	0.139	0.136	0.167	0.24	0	0.519	0.656	0.368	0.32	0.042	0.212	0.271	0.3	0.078	0.256
Fisher Price Bubble Mower	0.259	0.028	0.221	0.271	0.294	0.34	0.181	0.322	0.138	0.124	0.087	0.091	0.394	0.119	0.101	0.13	0.044	0.321
Electric Can Opener	0.317	0.317	0.402	0.107	0.319	0.274	0.218	0.098	0.431	0.106	0.53	0.436	0.236	0.516	0.61	0.414	0.101	0.225
Portable Fan	0.377	0.01	0.177	0.105	0.346	0.335	0.111	0.129	0.283	0.077	0.165	0.408	0.405	0.333	0.262	0.392	0.123	0.144
Bubble Machine	0.407	0.065	0.206	0.527	0.367	0.078	0.203	0.603	0.165	0.271	0.165	0.142	0.515	0.212	0.143	0.19	0.132	0.194
B&D Elec. Polisher	0.4	0.067	0.669	0.121	0.436	0.303	0.281	0.053	0.431	0.253	0.401	0.49	0.299	0.408	0.687	0.398	0.101	0.226
Crossfire Game	0.19	0.282	0.165	0.127	0.359	0.218	0.333	0.094	0.191	0.027	0.237	0.079	0.251	0.131	0.22	0.211	0.305	0.285
Black & Decker Elec. Knife	0.362	0.075	0.279	0.205	0.283	0.263	0.108	0.162	0.661	0.151	0.264	0.324	0.255	0.327	0.568	0.338	0.083	0.16
KRUPS Café Trio	0.249	0.081	0.174	0.264	0.219	0.005	0.015	0.368	0.182	0.014	0.106	0.052	0.265	0.217	0.208	0.209	0.044	0.025
Good Times Fishing Reel	0.327	0.118	0.253	0.355	0.427	0.193	0.143	0.352	0.262	0.138	0.268	0.064	0.349	0.198	0.327	0.292	0.16	0.173
Dremel Electric Engraver-RBS	0.242	0.177	0.302	0.147	0.222	0.021	0.024	0.185	0.435	0.022	0.159	0.166	0.226	0.128	0.492	0.187	0.065	0.029
Moen Kitchen Water Faucet	0.158	0.026	0.087	0.284	0.401	0.105	0.063	0.196	0.083	0	0.08	0.113	0.124	0	0.139	0.244	0.126	0.041
Battery Op. Toothbrush	0.398	0.04	0.541	0.303	0.561	0.338	0.317	0.211	0.505	0.231	0.496	0.472	0.302	0.356	0.598	0.53	0.118	0.421
Metronome	0.057	0.008	0.08	0.056	0.288	0.295	0.169	0.036	0.049	0.046	0.226	0.105	0.051	0.116	0.025	0.25	0.06	0.61
Humidifier	0.099	0.027	0.138	0.288	0.185	0.067	0.05	0.33	0.173	0.059	0.047	0.178	0.224	0.249	0.114	0.135	0.013	0.05
Electric Pencil Sharpener	0.365	0.125	0.5	0.131	0.263	0.36	0.138	0.146	0.436	0.108	0.412	0.46	0.337	0.419	0.585	0.439	0.061	0.244
Mini Pro Hair Dryer	0.598	0.039	0.469	0.168	0.387	0.336	0.181	0.175	0.278	0.276	0.449	0.557	0.341	0.349	0.461	0.529	0.116	0.242
West Bend Iced Tea Maker-RBS	0.255	0.074	0.179	0.301	0.267	0.009	0.065	0.298	0.297	0.014	0.078	0.164	0.355	0.293	0.154	0.254	0.081	0.025
Mr. Coffee Iced Tea Maker-RBS	0.23	0.086	0.145	0.356	0.2	0.006	0.011	0.405	0.266	0.008	0.081	0.135	0.409	0.325	0.156	0.242	0.093	0.018
Mr. Coffee Coffee Maker-RBS	0.219	0.065	0.215	0.375	0.284	0.014	0.031	0.373	0.284	0.029	0.09	0.153	0.304	0.271	0.174	0.233	0.047	0.031
Radio Controlled Truck	0.47	0.033	0.425	0.167	0.344	0.429	0.334	0.064	0.365	0.26	0.683	0.455	0.187	0.46	0.377	0.585	0.085	0.351
Braun Hand Blender	0.47	0.036	0.472	0.336	0.644	0.434	0.394	0.189	0.354	0.324	0.613	0.474	0.282	0.449	0.462	0.538	0.138	0.366
Paint Sprayer	0.292	0.012	0.282	0.698	0.174	0.13	0.419	0.168	0.219	0.148	0.264	0.331	0.088	0.418	0.335	0.296	0.065	0.171
Bissel Hand Vacuum	0.684	0.086	0.371	0.15	0.192	0.129	0.155	0.291	0.208	0.093	0.32	0.308	0.518	0.276	0.393	0.368	0.081	0.102
Drill and Nail Extractor 11	0.184	0.095	0.142	0.111	0.209	0	0.091	0.152	0.241	0	0.108	0.036	0.298	0.164	0.199	0.218	0.085	0.017
Air Compressor 22	0.275	0.021	0.219	0.08	0.112	0.189	0.129	0.025	0.381	0.31	0.187	0.198	0.156	0.187	0.209	0.245	0.1	0.153
Chainsaw Toy Truck 18	0.122	0.076	0.128	0.111	0.248	0.165	0.165	0.024	0.087	0.163	0.095	0.02	0.08	0.025	0.085	0.069	0.249	0.275

Figure D.3 The similarity matrix for the 70 device database.

Similarity matrix	Durabuilt Hand Vacuum	Tactical Nerf Toy Gun	B&D Weed Trimmer	Wagner Paint Roller	Hamilton Elec. Mixer	OverRider Toy Car	Horseman Swimming Toy	Mattel Bubble Extinguisher	Regal Ware Electric Knife	Bumble Ball Toy	B&D Cordless Screwdriver	Takka-1000 Pasta Machine	Upright Vacuum Cleaner	WestBend Food Processor	Black & Decker Sander	West Bend Mixer	Green Eagle Putting Cup	F.Price Remote Control Car
Push-n-Go Train 13	0.167	0.106	0.169	0.227	0.434	0.23	0.356	0.175	0.121	0.21	0.266	0.071	0.116	0.087	0.112	0.159	0.341	0.293
Corvette Vac 23	0.184	0.38	0.078	0.041	0.046	0.034	0.087	0.034	0.161	0.015	0.022	0.063	0.282	0.174	0.096	0.137	0.348	0.017
Power Caulk 20	0.204	0.184	0.04	0.105	0.108	0.042	0.111	0.095	0.059	0.009	0.086	0.177	0.04	0.087	0.123	0.051	0.57	0.037
Stamp Machine 17	0.08	0.233	0.052	0.11	0.055	0	0	0.15	0.175	0	0.144	0.073	0.115	0.164	0.159	0.067	0.064	0.002
bicycle brake 18	0.053	0.246	0.015	0.019	0.1	0	0	0	0.091	0.014	0.01	0.012	0.1	0.065	0.028	0.064	0.208	0
Tape Rewinder 22	0.286	0.203	0.294	0.264	0.371	0.23	0.376	0.033	0.217	0.533	0.238	0.227	0.177	0.215	0.169	0.25	0.356	0.339
Hot Glue Gun 21	0.185	0.152	0.072	0.126	0.136	0	0.015	0.097	0.218	0	0.11	0.043	0.291	0.32	0.211	0.186	0.177	0.004

Figure D.3 The similarity matrix for the 70 device database.

Similarity matrix	Ertl Bumble Ball	Fisher Price Bubble Mower	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS
De walt sander	0.22	0.192	0.524	0.275	0.323	0.549	0.31	0.586	0.312	0.46	0.442	0.224	0.423	0.025	0.136	0.45	0.532	0.188
Real Power Tool Shop	0.361	0.025	0.495	0.196	0.076	0.604	0.091	0.322	0.019	0.165	0.322	0	0.466	0.017	0.03	0.565	0.394	0.037
Pneumatic Air Ratchet	0.186	0.202	0.351	0.094	0.328	0.128	0.23	0.218	0.21	0.406	0.197	0.14	0.444	0.409	0.12	0.245	0.139	0.205
Presto Popcorn Popper	0.025	0.282	0.172	0.152	0.368	0.059	0.209	0.169	0.544	0.257	0.157	0.082	0.157	0.103	0.522	0.253	0.303	0.621
Salton Sandwich Maker	0.022	0.287	0.325	0.042	0.23	0.1	0.17	0.21	0.478	0.402	0.34	0.186	0.232	0.099	0.407	0.355	0.229	0.468
Krups Cheese Grater	0.259	0.161	0.663	0.195	0.253	0.57	0.314	0.473	0.279	0.411	0.459	0.187	0.64	0.071	0.17	0.692	0.463	0.261
Dazey Fruit & Veg. Stripper-RBS	0.11	0.112	0.798	0.084	0.184	0.558	0.283	0.493	0.275	0.498	0.507	0.171	0.535	0.075	0.111	0.595	0.278	0.259
Super Maxx Ball Shooter-RBS	0	0.135	0.189	0.008	0.218	0.063	0.27	0.225	0.316	0.423	0.279	0.213	0.24	0.049	0.144	0.201	0.165	0.313
Salon Series 795 Hair Dryer	0.263	0.209	0.196	0.42	0.313	0.292	0.095	0.253	0.271	0.231	0.148	0.326	0.414	0.253	0.459	0.222	0.715	0.313
Presto Salad Shooter	0.265	0.213	0.471	0.316	0.382	0.529	0.161	0.453	0.178	0.401	0.281	0.088	0.462	0.067	0.305	0.541	0.425	0.251
Toy Solar Car	0.26	0.203	0.3	0.251	0.109	0.327	0.107	0.17	0	0.111	0	0	0.297	0.17	0.063	0.468	0.399	0
Small Projectile Toy	0.087	0.274	0.385	0.015	0.386	0.124	0.65	0.333	0.344	0.613	0.336	0.278	0.464	0.19	0.137	0.254	0.266	0.239
Hair Dryer	0.164	0.077	0.167	0.627	0.115	0.235	0.078	0.258	0.222	0.157	0.124	0.506	0.425	0.313	0.298	0.183	0.57	0.198
Wet/Dry Vacuum	0.336	0.333	0.19	0.378	0.457	0.319	0.08	0.148	0.108	0.15	0.064	0.04	0.269	0.019	0.125	0.332	0.524	0.125
Stanley Electric Stapler	0.173	0.211	0.376	0.108	0.375	0.322	0.39	0.349	0.222	0.499	0.236	0.093	0.273	0.056	0.119	0.244	0.178	0.313
74 Chevy Tailgate Support-RBS	0.058	0.113	0.139	0	0.175	0.04	0.202	0.252	0.255	0.44	0.303	0.212	0.216	0.062	0.099	0.157	0.158	0.166
Cadillac Slide-Out Visor-RBS	0	0.083	0.147	0.169	0.129	0.082	0.227	0.298	0.188	0.296	0.195	0.157	0.189	0.03	0.139	0.16	0.117	0.123
SKIL Power Screwdriver-RBS	0.404	0.15	0.504	0.183	0.242	0.458	0.265	0.374	0.305	0.485	0.318	0.236	0.567	0.188	0.168	0.481	0.635	0.21
Durabuilt Hand Vacuum	0.366	0.259	0.317	0.377	0.407	0.4	0.19	0.362	0.249	0.327	0.242	0.158	0.398	0.057	0.099	0.365	0.598	0.255
Tactical Nerf Toy Gun	0.015	0.028	0.317	0.01	0.065	0.067	0.282	0.075	0.081	0.118	0.177	0.026	0.04	0.008	0.027	0.125	0.039	0.074
B&D Weed Trimmer	0.349	0.221	0.402	0.177	0.206	0.669	0.165	0.279	0.174	0.253	0.302	0.087	0.541	0.08	0.138	0.5	0.469	0.179
Wagner Paint Roller	0.139	0.271	0.107	0.105	0.527	0.121	0.127	0.205	0.264	0.355	0.147	0.284	0.303	0.056	0.288	0.131	0.168	0.301
Hamilton Elec. Mixer	0.136	0.294	0.319	0.346	0.367	0.436	0.359	0.283	0.219	0.427	0.222	0.401	0.561	0.288	0.185	0.263	0.387	0.267
OverRider Toy Car	0.167	0.34	0.274	0.335	0.078	0.303	0.218	0.263	0.005	0.193	0.021	0.105	0.338	0.295	0.067	0.36	0.336	0.009
Horseman Swimming Toy	0.24	0.181	0.218	0.111	0.203	0.281	0.333	0.108	0.015	0.143	0.024	0.063	0.317	0.169	0.05	0.138	0.181	0.065
Mattel Bubble Extinguisher	0	0.322	0.098	0.129	0.603	0.053	0.094	0.162	0.368	0.352	0.185	0.196	0.211	0.036	0.33	0.146	0.175	0.298
Regal Ware Electric Knife	0.519	0.138	0.431	0.283	0.165	0.431	0.191	0.661	0.182	0.262	0.435	0.083	0.505	0.049	0.173	0.436	0.278	0.297
Bumble Ball Toy	0.656	0.124	0.106	0.077	0.271	0.253	0.027	0.151	0.014	0.138	0.022	0	0.231	0.046	0.059	0.108	0.276	0.014
B&D Cordless Screwdriver	0.368	0.087	0.53	0.165	0.165	0.401	0.237	0.264	0.106	0.268	0.159	0.08	0.496	0.226	0.047	0.412	0.449	0.078
Takka-1000 Pasta Machine	0.32	0.091	0.436	0.408	0.142	0.49	0.079	0.324	0.052	0.064	0.166	0.113	0.472	0.105	0.178	0.46	0.557	0.164
Upright Vacuum Cleaner	0.042	0.394	0.236	0.405	0.515	0.299	0.251	0.255	0.265	0.349	0.226	0.124	0.302	0.051	0.224	0.337	0.341	0.355
WestBend Food Processor	0.212	0.119	0.516	0.333	0.212	0.408	0.131	0.327	0.217	0.198	0.128	0	0.356	0.116	0.249	0.419	0.349	0.293
Black & Decker Sander	0.271	0.101	0.61	0.262	0.143	0.687	0.22	0.568	0.208	0.327	0.492	0.139	0.598	0.025	0.114	0.585	0.461	0.154
West Bend Mixer	0.3	0.13	0.414	0.392	0.19	0.398	0.211	0.338	0.209	0.292	0.187	0.244	0.53	0.25	0.135	0.439	0.529	0.254
Green Eagle Putting Cup	0.078	0.044	0.101	0.123	0.132	0.101	0.305	0.083	0.044	0.16	0.065	0.126	0.118	0.06	0.013	0.061	0.116	0.081
F.Price Remote Control Car	0.256	0.321	0.225	0.144	0.194	0.226	0.285	0.16	0.025	0.173	0.029	0.041	0.421	0.61	0.05	0.244	0.242	0.025
Ertl Bumble Ball	1	0.178	0.185	0.169	0.144	0.405	0.04	0.2	0.003	0.065	0.096	0	0.31	0.051	0.021	0.248	0.485	0.014
Fisher Price Bubble Mower	0.178	1	0.062	0.13	0.546	0.079	0.17	0.142	0.235	0.294	0.152	0.108	0.204	0.316	0.19	0.2	0.178	0.229
Electric Can Opener	0.185	0.062	1	0.14	0.177	0.556	0.286	0.427	0.193	0.393	0.444	0.104	0.606	0.126	0.083	0.638	0.335	0.199
Portable Fan	0.169	0.13	0.14	1	0.159	0.332	0	0.372	0.012	0	0.036	0.325	0.285	0.124	0.176	0.185	0.549	0.105
Bubble Machine	0.144	0.546	0.177	0.159	1	0.145	0.18	0.225	0.358	0.508	0.235	0.184	0.347	0.103	0.294	0.17	0.324	0.312
B&D Elec. Polisher	0.405	0.079	0.556	0.332	0.145	1	0.12	0.498	0.064	0.2	0.281	0.029	0.565	0.029	0.071	0.534	0.557	0.063
Crossfire Game	0.04	0.17	0.286	0	0.18	0.12	1	0.347	0.211	0.448	0.218	0.146	0.25	0.127	0.129	0.287	0.108	0.205
Black & Decker Elec. Knife	0.2	0.142	0.427	0.372	0.225	0.498	0.347	1	0.248	0.429	0.528	0.182	0.521	0.057	0.176	0.376	0.32	0.218
KRUPS Café Trio	0.003	0.235	0.193	0.012	0.358	0.064	0.211	0.248	1	0.456	0.309	0.266	0.273	0.051	0.574	0.19	0.251	0.745
Good Times Fishing Reel	0.065	0.294	0.393	0	0.508	0.2	0.448	0.429	0.456	1	0.428	0.309	0.432	0.113	0.198	0.307	0.267	0.401
Dremel Electric Engraver-RBS	0.096	0.152	0.444	0.036	0.235	0.281	0.218	0.528	0.309	0.428	1	0.214	0.46	0.042	0.145	0.398	0.156	0.261
Moen Kitchen Water Faucet	0	0.108	0.104	0.325	0.184	0.029	0.146	0.182	0.266	0.309	0.214	1	0.31	0.155	0.107	0.094	0.273	0.225
Battery Op. Toothbrush	0.31	0.204	0.606	0.285	0.347	0.565	0.25	0.521	0.273	0.432	0.46	0.31	1	0.299	0.224	0.577	0.511	0.251
Metronome	0.051	0.316	0.126	0.124	0.103	0.029	0.127	0.057	0.051	0.113	0.042	0.155	0.299	1	0.027	0.12	0.081	0.057
Humidifier	0.021	0.19	0.083	0.176	0.294	0.071	0.129	0.176	0.574	0.198	0.145	0.107	0.224	0.027	1	0.253	0.305	0.621
Electric Pencil Sharpener	0.248	0.2	0.638	0.185	0.17	0.534	0.287	0.376	0.19	0.307	0.398	0.094	0.577	0.12	0.253	1	0.392	0.233
Mini Pro Hair Dryer	0.485	0.178	0.335	0.549	0.324	0.557	0.108	0.32	0.251	0.267	0.156	0.273	0.511	0.081	0.305	0.392	1	0.172
West Bend Iced Tea Maker-RBS	0.014	0.229	0.199	0.105	0.312	0.063	0.205	0.218	0.745	0.401	0.261	0.225	0.251	0.057	0.621	0.233	0.172	1
Mr. Coffee Iced Tea Maker-RBS	0.01	0.217	0.269	0.005	0.321	0.102	0.281	0.175	0.604	0.38	0.22	0.269	0.197	0.036	0.513	0.377	0.096	0.751
Mr. Coffee Coffee Maker-RBS	0.017	0.276	0.164	0.035	0.378	0.061	0.179	0.238	0.792	0.414	0.284	0.204	0.283	0.057	0.651	0.237	0.175	0.934
Radio Controlled Truck	0.405	0.084	0.49	0.294	0.192	0.479	0.202	0.39	0.123	0.23	0.122	0.049	0.523	0.159	0.067	0.434	0.502	0.16
Braun Hand Blender	0.303	0.235	0.485	0.345	0.391	0.425	0.318	0.566	0.326	0.52	0.326	0.365	0.71	0.228	0.219	0.385	0.625	0.259
Paint Sprayer	0.295	0.154	0.166	0.196	0.242	0.284	0.1	0.149	0.221	0.166	0.067	0.182	0.337	0.024	0.188	0.237	0.371	0.269
Bissel Hand Vacuum	0.256	0.316	0.272	0.431	0.441	0.287	0.198	0.263	0.286	0.335	0.241	0.294	0.374	0.043	0.142	0.401	0.592	0.281
Drill and Nail Extractor 11	0	0.122	0.328	0.087	0.189	0.155	0.175	0.182	0.262	0.425	0.229	0.211	0.176	0.033	0.108	0.234	0.069	0.399
Air Compressor 22	0.409	0.059	0.144	0.221	0.152	0.304	0.106	0.274	0.037	0.062	0.034	0	0.206	0.018	0.222	0.315	0.298	0.063
Chainsaw Toy Truck 18	0.088	0.262	0.113	0	0.157	0.121	0.337	0.123	0.101	0.255	0.119	0.092	0.157	0.258	0.04	0.065	0.132	0.055

Figure D.3 The similarity matrix for the 70 device database.

Similarity matrix	Ertl Bumble Ball	Fisher Price Bubble Mower	Electric Can Opener	Portable Fan	Bubble Machine	B&D Elec. Polisher	Crossfire Game	Black & Decker Elec. Knife	KRUPS Café Trio	Good Times Fishing Reel	Dremel Electric Engraver-RBS	Moen Kitchen Water Faucet	Battery Op. Toothbrush	Metronome	Humidifier	Electric Pencil Sharpener	Mini Pro Hair Dryer	West Bend Iced Tea Maker-RBS
Push-n-Go Train 13	0.106	0.241	0.212	0.087	0.322	0.129	0.47	0.201	0.185	0.474	0.211	0.25	0.306	0.148	0.081	0.121	0.186	0.193
Corvette Vac 23	0.003	0	0.183	0.147	0	0.063	0.283	0.133	0.156	0.112	0.08	0.135	0.119	0.014	0.184	0.334	0.091	0.233
Power Caulk 20	0.051	0.01	0.113	0	0.038	0.065	0.247	0.088	0.107	0.143	0.088	0.093	0.065	0	0.065	0.07	0.173	0.085
Stamp Machine 17	0.045	0.024	0.299	0	0.067	0.172	0.322	0.268	0.115	0.245	0.182	0.076	0.019	0	0.067	0.16	0	0.147
bicycle brake 18	0	0	0.2	0.044	0.005	0.061	0.221	0.043	0.04	0.107	0.096	0	0.01	0	0.036	0.061	0.003	0.088
Tape Rewinder 22	0.419	0.218	0.263	0.21	0.342	0.431	0.273	0.195	0.036	0.247	0.042	0.057	0.291	0.065	0.061	0.208	0.43	0.12
Hot Glue Gun 21	0	0.058	0.442	0.014	0.069	0.209	0.286	0.222	0.425	0.373	0.193	0.233	0.089	0.007	0.346	0.236	0.123	0.501

Figure D.3 The similarity matrix for the 70 device database.

Similarity matrix	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
De walt sander	0.239	0.206	0.289	0.472	0.172	0.566	0.259	0.187	0.165	0.18	0.165	0.176	0.286	0.051	0.142	0.348
Real Power Tool Shop	0.031	0.033	0.34	0.243	0.283	0.259	0.048	0.17	0.027	0.016	0.013	0.045	0.071	0.036	0.16	0.062
Pneumatic Air Ratchet	0.177	0.235	0.346	0.454	0.077	0.189	0.216	0.105	0.147	0.3	0.029	0.009	0.077	0.011	0.167	0.121
Presto Popcorn Popper	0.46	0.535	0.145	0.177	0.115	0.371	0.255	0.148	0.095	0.077	0.261	0.093	0.114	0.1	0.107	0.469
Salton Sandwich Maker	0.306	0.485	0.111	0.333	0.065	0.278	0.246	0.037	0.086	0.165	0.115	0.25	0.096	0.205	0.023	0.324
Krups Cheese Grater	0.209	0.299	0.414	0.521	0.318	0.509	0.25	0.179	0.085	0.182	0.211	0.17	0.157	0.032	0.231	0.177
Dazey Fruit & Veg. Stripper-RBS	0.299	0.257	0.31	0.431	0.176	0.307	0.38	0.09	0.149	0.184	0.166	0.157	0.293	0.11	0.143	0.489
Super Maxx Ball Shooter-RBS	0.352	0.29	0.102	0.288	0.058	0.259	0.239	0.071	0.142	0.217	0.292	0.227	0.072	0.08	0.068	0.219
Salon Series 795 Hair Dryer	0.146	0.318	0.27	0.513	0.22	0.424	0.075	0.151	0.13	0.148	0.069	0.233	0	0	0.246	0.229
Presto Salad Shooter	0.278	0.286	0.303	0.467	0.291	0.261	0.237	0.258	0.167	0.206	0.17	0.043	0.144	0.107	0.485	0.221
Toy Solar Car	0	0	0.427	0.333	0.285	0.202	0	0.169	0.022	0.094	0.032	0.004	0	0.024	0.204	0
Small Projectile Toy	0.191	0.26	0.32	0.636	0.223	0.319	0.191	0.067	0.348	0.575	0.191	0.202	0.084	0.096	0.386	0.166
Hair Dryer	0.105	0.202	0.247	0.434	0.16	0.258	0.068	0.243	0.09	0.082	0.086	0.081	0	0.005	0.109	0.157
Wet / Dry Vacuum	0.153	0.144	0.352	0.284	0.313	0.614	0.06	0.231	0.054	0.081	0.084	0.04	0.03	0.015	0.263	0.055
Stanley Electric Stapler	0.339	0.264	0.275	0.339	0.139	0.14	0.374	0.188	0.287	0.381	0.333	0.289	0.313	0.204	0.646	0.418
74 Chevy Tailgate Support-RBS	0.123	0.191	0.055	0.287	0.048	0.24	0.138	0	0.113	0.235	0.108	0.086	0.081	0.086	0.076	0.083
Cadillac Slide-Out Visor-RBS	0.09	0.141	0.121	0.259	0.036	0.195	0.104	0.063	0.085	0.183	0.183	0.063	0.096	0.114	0.101	0.061
SKIL Power Screwdriver-RBS	0.194	0.254	0.58	0.743	0.314	0.529	0.209	0.214	0.177	0.292	0.096	0.203	0.107	0.013	0.235	0.195
Durabuilt Hand Vacuum	0.23	0.219	0.47	0.47	0.292	0.684	0.184	0.275	0.122	0.167	0.184	0.204	0.08	0.053	0.286	0.185
Tactical Nerf Toy Gun	0.086	0.065	0.033	0.036	0.012	0.086	0.095	0.021	0.076	0.106	0.38	0.184	0.233	0.246	0.203	0.152
B&D Weed Trimmer	0.145	0.215	0.425	0.472	0.282	0.371	0.142	0.219	0.128	0.169	0.078	0.04	0.052	0.015	0.294	0.072
Wagner Paint Roller	0.356	0.375	0.167	0.336	0.698	0.15	0.111	0.08	0.111	0.227	0.041	0.105	0.11	0.019	0.264	0.126
Hamilton Elec. Mixer	0.2	0.284	0.344	0.644	0.174	0.192	0.209	0.112	0.248	0.434	0.046	0.108	0.055	0.1	0.371	0.136
OverRider Toy Car	0.006	0.014	0.429	0.434	0.13	0.129	0	0.189	0.165	0.23	0.034	0.042	0	0	0.23	0
Horseman Swimming Toy	0.011	0.031	0.334	0.394	0.419	0.155	0.091	0.129	0.165	0.356	0.087	0.111	0	0	0.376	0.015
Mattel Bubble Extinguisher	0.405	0.373	0.064	0.189	0.168	0.291	0.152	0.025	0.024	0.175	0.034	0.095	0.15	0	0.033	0.097
Regal Ware Electric Knife	0.266	0.284	0.365	0.354	0.219	0.208	0.241	0.381	0.087	0.121	0.161	0.059	0.175	0.091	0.217	0.218
Bumble Ball Toy	0.008	0.029	0.26	0.324	0.148	0.093	0	0.31	0.163	0.21	0.015	0.009	0	0.014	0.533	0
B&D Cordless Screwdriver	0.081	0.09	0.683	0.613	0.264	0.32	0.108	0.187	0.095	0.266	0.022	0.086	0.144	0.01	0.238	0.11
Takka-1000 Pasta Machine	0.135	0.153	0.455	0.474	0.331	0.308	0.036	0.198	0.02	0.071	0.063	0.177	0.073	0.012	0.227	0.043
Upright Vacuum Cleaner	0.409	0.304	0.187	0.282	0.088	0.518	0.298	0.156	0.08	0.116	0.282	0.04	0.115	0.1	0.177	0.291
WestBend Food Processor	0.325	0.271	0.46	0.449	0.418	0.276	0.164	0.187	0.025	0.087	0.174	0.087	0.164	0.065	0.215	0.32
Black & Decker Sander	0.156	0.174	0.377	0.462	0.335	0.393	0.199	0.209	0.085	0.112	0.096	0.123	0.159	0.028	0.169	0.211
West Bend Mixer	0.242	0.233	0.585	0.538	0.296	0.368	0.218	0.245	0.069	0.159	0.137	0.051	0.067	0.064	0.25	0.186
Green Eagle Putting Cup	0.093	0.047	0.085	0.138	0.065	0.081	0.085	0.1	0.249	0.341	0.348	0.57	0.064	0.208	0.356	0.177
F.Price Remote Control Car	0.018	0.031	0.351	0.366	0.171	0.102	0.017	0.153	0.275	0.293	0.017	0.037	0.002	0	0.339	0.004
Ertl Bumble Ball	0.01	0.017	0.405	0.303	0.295	0.256	0	0.409	0.088	0.106	0.003	0.051	0.045	0	0.419	0
Fisher Price Bubble Mower	0.217	0.276	0.084	0.235	0.154	0.316	0.122	0.059	0.262	0.241	0	0.01	0.024	0	0.218	0.058
Electric Can Opener	0.269	0.164	0.49	0.485	0.166	0.272	0.328	0.144	0.113	0.212	0.183	0.113	0.299	0.2	0.263	0.442
Portable Fan	0.005	0.035	0.294	0.345	0.196	0.431	0.087	0.221	0	0.087	0.147	0	0	0.044	0.21	0.014
Bubble Machine	0.321	0.378	0.192	0.391	0.242	0.441	0.189	0.152	0.157	0.322	0	0.038	0.067	0.005	0.342	0.069
B&D Elec. Polisher	0.102	0.061	0.479	0.425	0.284	0.287	0.155	0.304	0.121	0.129	0.063	0.065	0.172	0.061	0.431	0.209
Crossfire Game	0.281	0.179	0.202	0.318	0.1	0.198	0.175	0.106	0.337	0.47	0.283	0.247	0.322	0.221	0.273	0.286
Black & Decker Elec. Knife	0.175	0.238	0.39	0.566	0.149	0.263	0.182	0.274	0.123	0.201	0.133	0.088	0.268	0.043	0.195	0.222
KRUPS Café Trio	0.604	0.792	0.123	0.326	0.221	0.286	0.262	0.037	0.101	0.185	0.156	0.107	0.115	0.04	0.036	0.425
Good Times Fishing Reel	0.38	0.414	0.23	0.52	0.166	0.335	0.425	0.062	0.255	0.474	0.112	0.143	0.245	0.107	0.247	0.373
Dremel Electric Engraver-RBS	0.22	0.284	0.122	0.326	0.067	0.241	0.229	0.034	0.119	0.211	0.08	0.088	0.182	0.096	0.042	0.193
Moen Kitchen Water Faucet	0.269	0.204	0.049	0.365	0.182	0.294	0.211	0	0.092	0.25	0.135	0.093	0.076	0	0.057	0.233
Battery Op. Toothbrush	0.197	0.283	0.523	0.71	0.337	0.374	0.176	0.206	0.157	0.306	0.119	0.065	0.019	0.01	0.291	0.089
Metronome	0.036	0.057	0.159	0.228	0.024	0.043	0.033	0.018	0.258	0.148	0.014	0	0	0	0.065	0.007
Humidifier	0.513	0.651	0.067	0.219	0.188	0.142	0.108	0.222	0.04	0.081	0.184	0.065	0.067	0.036	0.061	0.346
Electric Pencil Sharpener	0.377	0.237	0.434	0.385	0.237	0.401	0.234	0.315	0.065	0.121	0.334	0.07	0.16	0.061	0.208	0.236
Mini Pro Hair Dryer	0.096	0.175	0.502	0.625	0.371	0.592	0.069	0.298	0.132	0.186	0.091	0.173	0	0.003	0.43	0.123
West Bend Iced Tea Maker-RBS	0.751	0.934	0.16	0.259	0.269	0.281	0.399	0.063	0.055	0.193	0.233	0.085	0.147	0.088	0.12	0.501
Mr. Coffee Iced Tea Maker-RBS	1	0.736	0.166	0.163	0.228	0.165	0.377	0.166	0.083	0.089	0.328	0.11	0.305	0.13	0.117	0.597
Mr. Coffee Coffee Maker-RBS	0.736	1	0.145	0.306	0.299	0.232	0.286	0.045	0.048	0.139	0.138	0.076	0.114	0.041	0.036	0.397
Radio Controlled Truck	0.166	0.145	1	0.638	0.313	0.329	0.284	0.391	0.152	0.216	0.065	0.164	0.063	0.074	0.334	0.136
Braun Hand Blender	0.163	0.306	0.638	1	0.291	0.458	0.156	0.229	0.205	0.423	0.102	0.188	0	0	0.344	0.113
Paint Sprayer	0.228	0.299	0.313	0.291	1	0.265	0.052	0.159	0.035	0.07	0.103	0.063	0.13	0	0.212	0.137
Bissel Hand Vacuum	0.165	0.232	0.329	0.458	0.265	1	0.27	0.22	0.107	0.292	0.283	0.218	0.018	0	0.21	0.104
Drill and Nail Extractor 11	0.377	0.286	0.284	0.156	0.052	0.27	1	0.117	0.155	0.255	0.207	0.239	0.345	0.14	0.185	0.421
Air Compressor 22	0.166	0.045	0.391	0.229	0.159	0.22	0.117	1	0.149	0.074	0.203	0.11	0.042	0.125	0.289	0.093
Chainsaw Toy Truck 18	0.083	0.048	0.152	0.205	0.035	0.107	0.155	0.149	1	0.565	0.081	0.23	0.044	0.145	0.352	0.14

Figure D.3 The similarity matrix for the 70 device database.

Similarity matrix	Mr. Coffee Iced Tea Maker-RBS	Mr. Coffee Coffee Maker-RBS	Radio Controlled Truck	Braun Hand Blender	Paint Sprayer	Bissel Hand Vacuum	Drill and Nail Extractor 11	Air Compressor 22	Chainsaw Toy Truck 18	Push-n-Go Train 13	Corvette Vac 23	Power Caulk 20	Stamp Machine 17	bicycle brake 18	Tape Rewinder 22	Hot Glue Gun 21
Push-n-Go Train 13	0.089	0.139	0.216	0.423	0.07	0.292	0.255	0.074	0.565	1	0.117	0.187	0.013	0.156	0.502	0.101
Corvette Vac 23	0.328	0.138	0.065	0.102	0.103	0.283	0.207	0.203	0.081	0.117	1	0.374	0.211	0.078	0.208	0.325
Power Caulk 20	0.11	0.076	0.164	0.188	0.063	0.218	0.239	0.11	0.23	0.187	0.374	1	0.079	0.125	0.094	0.141
Stamp Machine 17	0.305	0.114	0.063	0	0.13	0.018	0.345	0.042	0.044	0.013	0.211	0.079	1	0.108	0.128	0.446
bicycle brake 18	0.13	0.041	0.074	0	0	0	0.14	0.125	0.145	0.156	0.078	0.125	0.108	1	0.145	0.222
Tape Rewinder 22	0.117	0.036	0.334	0.344	0.212	0.21	0.185	0.289	0.352	0.502	0.208	0.094	0.128	0.145	1	0.174
Hot Glue Gun 21	0.597	0.397	0.136	0.113	0.137	0.104	0.421	0.093	0.14	0.101	0.325	0.141	0.446	0.222	0.174	1

Figure D.3 The similarity matrix for the 70 device database.

Function \ Function	actuate electricity	allow DOF of solid	assemble product	change electricity	change rotation	clean product	convert electricity to rotation	convert rotation to pneumatics	convert rotation to translation	convert rotation to vibration	convert translation to rotation	couple solid	disassemble product	dissipate sound	dissipate heat
actuate electricity	2.761	0.412	0.117	0.225	2.356	0.742	4.143	0.77	0	0.105	0	0.554	0.109	0.982	0.642
allow DOF of solid	0.412	0.894	0.535	0	1.149	0	0.735	0	0.268	0	0.656	0.38	0	0	0.098
assemble product	0.117	0.535	0.554	0	0.309	0	0.406	0.352	0.219	0	0.535	0	0	0	0.203
change electricity	0.225	0	0	0.1	0.318	0.201	0.266	0	0	0	0	0	0	0.174	0
change rotation	2.356	1.149	0.309	0.318	5.737	1.308	4.85	0	0.824	0.296	0.379	1.388	0.604	1.329	0.426
clean product	0.742	0	0	0.201	1.308	0.968	1.55	0	0	0.105	0	0	0.266	0.855	0
convert electricity to rotation	4.143	0.735	0.406	0.266	4.85	1.55	8.268	1.944	0	0.314	0	1.302	0.407	1.985	1.686
convert rotation to pneumatics	0.77	0	0.352	0	0	0	1.944	1.78	0	0	0	0	0	0.483	1.201
convert rotation to translation	0	0.268	0.219	0	0.824	0	0	0	0.779	0	0.268	0	0.387	0	0
convert rotation to vibration	0.105	0	0	0	0.296	0.105	0.314	0	0	0.105	0	0	0	0.181	0
convert translation to rotation	0	0.656	0.535	0	0.379	0	0	0	0.268	0	0.656	0	0	0	0
couple solid	0.554	0.38	0	0	1.388	0	1.302	0	0	0	0	0.727	0	0	0.239
disassemble product	0.109	0	0	0	0.604	0.266	0.407	0	0.387	0	0	0	0.377	0.188	0
dissipate sound	0.982	0	0	0.174	1.329	0.855	1.985	0.483	0	0.181	0	0	0.188	1.168	0.395
dissipate heat	0.642	0.098	0.203	0	0.426	0	1.686	1.201	0	0	0	0.239	0	0.395	0.933
dissipate translation	2.011	0.904	0.64	0.246	3.52	0.726	3.65	0.609	0.765	0.234	0.535	0.613	0.316	0.831	0.521
dissipate vibrations	1.241	0.098	0.235	0.201	1.573	0.583	2.761	1.187	0	0.181	0	0.239	0	0.984	0.898
export solid	0.867	0	0.235	0	0.407	0.498	2.12	0.945	0	0	0	0	0.288	0.513	0.604
guide gas	0.459	0	0.117	0	0	0	0.998	0.944	0	0	0	0	0	0.395	0.686
guide solid	0.653	0	0	0	1.098	0.596	1.34	0	0.611	0	0	0	0.697	0.421	0
import electricity	0.364	0	0	0.1	0.318	0.201	0.507	0.242	0	0	0	0	0	0.335	0.197
import human force	3.563	1.512	1.105	0.301	5.412	1.629	6.806	1.501	1.132	0.347	1.002	0.793	0.81	2.029	1.215
import human hand	3.114	1.349	0.866	0.301	5.065	1.298	6.006	1.798	1.013	0.234	0.708	0.924	0.684	1.877	1.457
import liquid	0.105	0	0	0	0.296	0.105	0.314	0	0	0.105	0	0	0	0.181	0
import solid	0.873	0.535	0.699	0	1.032	0.293	2.055	1.028	0.492	0.105	0.535	0	0.267	0.475	0.652
indicate status	0.374	0	0.235	0	0	0	1.054	0.945	0	0	0	0	0	0.161	0.604
maintain device	0.707	0	0	0.174	1.359	0.823	1.494	0	0	0.209	0	0	0.154	0.852	0
position product	1.396	0	0	0.142	1.04	0.493	1.915	0	0	0.209	0	0	0	0.608	0
position solid	0.583	0	0	0	0.377	0.461	1.388	0.683	0	0	0	0	0.266	0.782	0.558
refine gas	0.117	0	0.117	0	0	0	0.406	0.352	0	0	0	0	0	0	0.203
regulate electricity	1.118	0.238	0.117	0.201	1.406	0.402	1.915	0.593	0	0	0	0.38	0	0.509	0.498
regulate human force	0	0.268	0.219	0	0.428	0	0	0	0.383	0	0.268	0	0.158	0	0
regulate rotation	0.646	0.238	0	0	1.432	0.234	1.437	0	0	0.234	0	0.38	0	0.405	0.098
regulate translation	0.412	0.238	0	0	0.771	0	0.735	0	0	0	0	0.38	0	0	0.098
remove solid	1.686	0	0	0	1.556	1.052	3.453	0.592	0	0.347	0	0	0.407	1.493	0.483
rotate solid	0.517	0.238	0	0	1.066	0.105	1.049	0	0	0.105	0	0.38	0	0.181	0.098
secure rotation	0.741	0.439	0	0	1.449	0	1.379	0	0	0	0	0.722	0	0	0.195
secure solid	1.745	1.118	0.535	0	2.305	0.461	3.351	0.871	0.268	0	0.656	0.779	0.266	0.907	0.93
sense control	0.683	0	0	0.201	1.296	0.635	1.233	0	0	0.234	0	0	0	0.753	0
separate solid	1.122	0.368	0.166	0	1.225	0	2.331	1.089	0	0	0	0.613	0	0.395	0.94
stop chemical energy	0.117	0	0.117	0	0	0	0.406	0.352	0	0	0	0	0	0	0.203
stop gas	0.117	0	0.117	0	0	0	0.406	0.352	0	0	0	0	0	0	0.203
stop liquid	0.331	0	0	0	0.935	0.331	0.992	0	0	0.331	0	0	0	0.573	0
stop rotation	0.218	0.218	0	0	0.952	0	0.874	0	0	0	0	0.535	0	0	0.218
stop solid	0	0.535	0.437	0	0.309	0	0	0	0.219	0	0.535	0	0	0	0
store electricity	2.545	0.725	0.406	0	2.934	0.596	5.383	1.219	0	0	0	1.235	0.344	0.421	1.056
store mechanical energy	0	0.268	0.219	0	0.155	0	0	0	0.109	0	0.268	0	0	0	0
store product	0.428	0	0.203	0.1	0.318	0.201	0.969	0.609	0	0	0	0	0	0.174	0.352
store solids	0.751	0.141	0.117	0	0.499	0.188	1.457	0.77	0	0	0	0.141	0.109	0.412	0.545
supply electricity	0.882	0.337	0.117	0	1.539	0.293	2.048	0.352	0	0.105	0	0.537	0.109	0.314	0.341
supply mechanical energy	0	0.268	0.219	0	0.428	0	0	0	0.383	0	0.268	0	0.158	0	0
transmit electricity	0.181	0	0	0	0.449	0.293	0.601	0	0	0.105	0	0	0.109	0.314	0
transmit human force	0.659	0	0	0	0	0	0.943	0.639	0	0	0	0	0	0.426	0.522
transmit rotation	1.492	0.657	0.309	0.1	2.252	0.305	2.221	0	0.628	0.105	0.379	0.479	0.273	0.355	0.138
transmit translation	0	0.379	0.309	0	0.765	0	0	0	0.701	0	0.379	0	0.316	0	0
transport solid	0.242	0.464	0.379	0	0.268	0	0.418	0.418	0.189	0	0.464	0	0	0.279	0.342

Figure D.4 The $\boldsymbol{S}$ matrix for the power screwdriver subset.

Function \ Function	dissipate translation	dissipate vibrations	export solid	guide gas	guide solid	import electricity	import human force	import human hand	import liquid	import solid	indicate status	maintain device	position product	position solid	refine gas
actuate electricity	2.011	1.241	0.867	0.459	0.653	0.364	3.563	3.114	0.105	0.873	0.374	0.707	1.396	0.583	0.117
allow DOF of solid	0.904	0.098	0	0	0	0	1.512	1.349	0	0.535	0	0	0	0	0
assemble product	0.64	0.235	0.235	0.117	0	0	1.105	0.866	0	0.699	0.235	0	0	0	0.117
change electricity	0.246	0.201	0	0	0	0.1	0.301	0.301	0	0	0	0.174	0.142	0	0
change rotation	3.52	1.573	0.407	0	1.098	0.318	5.412	5.065	0.296	1.032	0	1.359	1.04	0.377	0
clean product	0.726	0.583	0.498	0	0.596	0.201	1.629	1.298	0.105	0.293	0	0.823	0.493	0.461	0
convert electricity to rotation	3.65	2.761	2.12	0.998	1.34	0.507	6.806	6.006	0.314	2.055	1.054	1.494	1.915	1.388	0.406
convert rotation to pneumatics	0.609	1.187	0.945	0.944	0	0.242	1.501	1.798	0	1.028	0.945	0	0	0.683	0.352
convert rotation to translation	0.765	0	0	0	0.611	0	1.132	1.013	0	0.492	0	0	0	0	0
convert rotation to vibration	0.234	0.181	0	0	0	0	0.347	0.234	0.105	0.105	0	0.209	0.209	0	0
convert translation to rotation	0.535	0	0	0	0	0	1.002	0.708	0	0.535	0	0	0	0	0
couple solid	0.613	0.239	0	0	0	0	0.793	0.924	0	0	0	0	0	0	0
disassemble product	0.316	0	0.288	0	0.697	0	0.81	0.684	0	0.267	0	0.154	0	0.266	0
dissipate sound	0.831	0.984	0.513	0.395	0.421	0.335	2.029	1.877	0.181	0.475	0.161	0.852	0.608	0.782	0
dissipate heat	0.521	0.898	0.604	0.686	0	0.197	1.215	1.457	0	0.652	0.604	0	0	0.558	0.203
dissipate translation	3.119	1.472	0.536	0.203	0.682	0.246	4.52	3.895	0.234	1.478	0.406	0.894	1.204	0	0.203
dissipate vibrations	1.472	1.604	0.63	0.629	0	0.362	2.399	2.401	0.181	0.867	0.63	0.71	0.646	0.456	0.235
export solid	0.536	0.63	1.18	0.432	0.773	0.081	1.746	1.385	0	0.9	0.55	0.288	0.275	0.726	0.235
guide gas	0.203	0.629	0.432	0.6	0	0.197	0.809	1.051	0	0.46	0.432	0	0	0.558	0.117
guide solid	0.682	0	0.773	0	1.51	0	1.855	1.256	0	0.622	0	0.344	0.389	0.596	0
import electricity	0.246	0.362	0.081	0.197	0	0.181	0.514	0.613	0	0.081	0.081	0.174	0.142	0.228	0
import human force	4.52	2.399	1.746	0.809	1.855	0.514	8.277	7.137	0.347	2.817	0.788	1.607	1.793	1.282	0.287
import human hand	3.895	2.401	1.385	1.051	1.256	0.613	7.137	7.144	0.234	2.25	0.886	1.256	0.894	1.344	0.287
import liquid	0.234	0.181	0	0	0	0	0.347	0.234	0.105	0.105	0	0.209	0.209	0	0
import solid	1.478	0.867	0.9	0.46	0.622	0.081	2.817	2.25	0.105	1.489	0.605	0.318	0.484	0.416	0.262
indicate status	0.406	0.63	0.55	0.432	0	0.081	0.788	0.886	0	0.605	0.55	0	0	0.228	0.235
maintain device	0.894	0.71	0.288	0	0.344	0.174	1.607	1.256	0.209	0.318	0	0.873	0.664	0.266	0
position product	1.204	0.646	0.275	0	0.389	0.142	1.793	0.894	0.209	0.484	0	0.664	1.444	0	0
position solid	0	0.456	0.726	0.558	0.596	0.228	1.282	1.344	0	0.416	0.228	0.266	0	1.106	0
refine gas	0.203	0.235	0.235	0.117	0	0	0.287	0.287	0	0.262	0.235	0	0	0	0.117
regulate electricity	1.063	0.895	0.315	0.315	0	0.281	1.613	1.842	0	0.343	0.315	0.348	0.284	0.228	0.117
regulate human force	0.442	0	0	0	0.25	0	0.704	0.584	0	0.33	0	0	0	0	0
regulate rotation	0.891	0.503	0	0	0	0	1.285	1.163	0.234	0.234	0	0.468	0.468	0	0
regulate translation	0.368	0.098	0	0	0	0	0.51	0.641	0	0	0	0	0	0	0
remove solid	1.093	0.995	1.183	0.483	1.228	0.197	3.259	2.244	0.347	1.056	0.197	1.1	1.367	1.263	0
rotate solid	0.602	0.279	0	0	0	0	0.857	0.874	0.105	0.105	0	0.209	0.209	0	0
secure rotation	0.683	0.195	0	0	0	0	0.936	1.162	0	0	0	0	0	0	0
secure solid	1.388	0.799	0.88	0.711	0.725	0.29	3.656	3.502	0	1.106	0.29	0.266	0.275	1.283	0
sense control	1.015	0.807	0	0	0	0.201	1.378	1.125	0.234	0.234	0	0.815	0.752	0	0
separate solid	0.862	0.895	0.529	0.649	0	0.197	1.712	2.138	0	0.568	0.529	0	0	0.558	0.166
stop chemical energy	0.203	0.235	0.235	0.117	0	0	0.287	0.287	0	0.262	0.235	0	0	0	0.117
stop gas	0.203	0.235	0.235	0.117	0	0	0.287	0.287	0	0.262	0.235	0	0	0	0.117
stop liquid	0.739	0.573	0	0	0	0	1.096	0.739	0.331	0.331	0	0.661	0.661	0	0
stop rotation	0.378	0.218	0	0	0	0	0.437	0.437	0	0	0	0	0	0	0
stop solid	0.437	0	0	0	0	0	0.818	0.578	0	0.437	0	0	0	0	0
store electricity	2.158	1.165	1.681	0.406	1.087	0	3.959	3.473	0	1.376	0.813	0.344	0.674	0.596	0.406
store mechanical energy	0.219	0	0	0	0	0	0.409	0.289	0	0.219	0	0	0	0	0
store product	0.598	0.607	0.406	0.203	0	0.1	0.799	0.799	0	0.454	0.406	0.174	0.142	0	0.203
store solids	0.402	0.514	0.578	0.459	0.243	0.139	1.248	1.461	0	0.479	0.374	0.109	0	0.583	0.117
supply electricity	0.958	0.554	0.438	0.117	0.243	0	1.633	1.615	0.105	0.444	0.235	0.318	0.209	0.188	0.117
supply mechanical energy	0.442	0	0	0	0.25	0	0.704	0.584	0	0.33	0	0	0	0	0
transmit electricity	0.234	0.181	0.203	0	0.243	0	0.624	0.422	0.105	0.181	0	0.318	0.209	0.188	0
transmit human force	0.13	0.426	0.305	0.522	0.13	0.213	0.788	0.825	0	0.305	0.213	0	0.275	0.603	0
transmit rotation	1.931	0.52	0.225	0	0.75	0.1	2.879	2.177	0.105	0.832	0	0.383	1.025	0	0
transmit translation	0.756	0	0	0	0.499	0	1.169	1	0	0.532	0	0	0	0	0
transport solid	0.379	0.279	0.139	0.342	0	0.139	1.077	1.041	0	0.518	0.139	0	0	0.395	0

Figure D.4 The ***S*** matrix for the power screwdriver subset.

Function \ Function	regulate electricity	regulate human force	regulate rotation	regulate translation	remove solid	rotate solid	secure rotation	secure solid	sense control	separate solid	stop chemical energy	stop gas	stop liquid	stop rotation	stop solid
actuate electricity	1.118	0	0.646	0.412	1.686	0.517	0.741	1.745	0.683	1.122	0.117	0.117	0.331	0.218	0
allow DOF of solid	0.238	0.268	0.238	0.238	0	0.238	0.439	1.118	0	0.368	0	0	0	0.218	0.535
assemble product	0.117	0.219	0	0	0	0	0	0.535	0	0.166	0.117	0.117	0	0	0.437
change electricity	0.201	0	0	0	0	0	0	0	0.201	0	0	0	0	0	0
change rotation	1.406	0.428	1.432	0.771	1.556	1.066	1.449	2.305	1.296	1.225	0	0	0.935	0.952	0.309
clean product	0.402	0	0.234	0	1.052	0.105	0	0.461	0.635	0	0	0	0.331	0	0
convert electricity to rotation	1.915	0	1.437	0.735	3.453	1.049	1.379	3.351	1.233	2.331	0.406	0.406	0.992	0.874	0
convert rotation to pneumatics	0.593	0	0	0	0.592	0	0	0.871	0	1.089	0.352	0.352	0	0	0
convert rotation to translation	0	0.383	0	0	0	0	0	0.268	0	0	0	0	0	0	0.219
convert rotation to vibration	0	0	0.234	0	0.347	0.105	0	0	0.234	0	0	0	0.331	0	0
convert translation to rotation	0	0.268	0	0	0	0	0	0.656	0	0	0	0	0	0	0.535
couple solid	0.38	0	0.38	0.38	0	0.38	0.722	0.779	0	0.613	0	0	0	0.535	0
disassemble product	0	0.158	0	0	0.407	0	0	0.266	0	0	0	0	0	0	0
dissipate sound	0.509	0	0.405	0	1.493	0.181	0	0.907	0.753	0.395	0	0	0.573	0	0
dissipate heat	0.498	0	0.098	0.098	0.483	0.098	0.195	0.93	0	0.94	0.203	0.203	0	0.218	0
dissipate translation	1.063	0.442	0.891	0.368	1.093	0.602	0.683	1.388	1.015	0.862	0.203	0.203	0.739	0.378	0.437
dissipate vibrations	0.895	0	0.503	0.098	0.995	0.279	0.195	0.799	0.807	0.895	0.235	0.235	0.573	0.218	0
export solid	0.315	0	0	0	1.183	0	0	0.88	0	0.529	0.235	0.235	0	0	0
guide gas	0.315	0	0	0	0.483	0	0	0.711	0	0.649	0.117	0.117	0	0	0
guide solid	0	0.25	0	0	1.228	0	0	0.725	0	0	0	0	0	0	0
import electricity	0.281	0	0	0	0.197	0	0	0.29	0.201	0.197	0	0	0	0	0
import human force	1.613	0.704	1.285	0.51	3.259	0.857	0.936	3.656	1.378	1.712	0.287	0.287	1.096	0.437	0.818
import human hand	1.842	0.584	1.163	0.641	2.244	0.874	1.162	3.502	1.125	2.138	0.287	0.287	0.739	0.437	0.578
import liquid	0	0	0.234	0	0.347	0.105	0	0	0.234	0	0	0	0.331	0	0
import solid	0.343	0.33	0.234	0	1.056	0.105	0	1.106	0.234	0.568	0.262	0.262	0.331	0	0.437
indicate status	0.315	0	0	0	0.197	0	0	0.29	0	0.529	0.235	0.235	0	0	0
maintain device	0.348	0	0.468	0	1.1	0.209	0	0.266	0.815	0	0	0	0.661	0	0
position product	0.284	0	0.468	0	1.367	0.209	0	0.275	0.752	0	0	0	0.661	0	0
position solid	0.228	0	0	0	1.263	0	0	1.283	0	0.558	0	0	0	0	0
refine gas	0.117	0	0	0	0	0	0	0	0	0.166	0.117	0.117	0	0	0
regulate electricity	0.838	0	0.238	0.238	0.197	0.238	0.439	0.753	0.402	0.731	0.117	0.117	0	0.218	0
regulate human force	0	0.221	0	0	0	0	0	0.268	0	0	0	0	0	0	0.219
regulate rotation	0.238	0	0.761	0.238	0.775	0.472	0.439	0.462	0.523	0.368	0	0	0.739	0.218	0
regulate translation	0.238	0	0.238	0.238	0	0.238	0.439	0.462	0	0.368	0	0	0	0.218	0
remove solid	0.197	0	0.775	0	3.26	0.347	0	1.641	0.775	0.483	0	0	1.096	0	0
rotate solid	0.238	0	0.472	0.238	0.347	0.343	0.439	0.462	0.234	0.368	0	0	0.331	0.218	0
secure rotation	0.439	0	0.439	0.439	0	0.439	0.813	0.859	0	0.683	0	0	0	0.437	0
secure solid	0.753	0.268	0.462	0.462	1.641	0.462	0.859	3.166	0	1.434	0	0	0	0.488	0.535
sense control	0.402	0	0.523	0	0.775	0.234	0	0	0.924	0	0	0	0.739	0	0
separate solid	0.731	0	0.368	0.368	0.483	0.368	0.683	1.434	0	1.292	0.166	0.166	0	0.378	0
stop chemical energy	0.117	0	0	0	0	0	0	0	0	0.166	0.117	0.117	0	0	0
stop gas	0.117	0	0	0	0	0	0	0	0	0.166	0.117	0.117	0	0	0
stop liquid	0	0	0.739	0	1.096	0.331	0	0	0.739	0	0	0	1.045	0	0
stop rotation	0.218	0	0.218	0.218	0	0.218	0.437	0.488	0	0.378	0	0	0	0.488	0
stop solid	0	0.219	0	0	0	0	0	0.535	0	0	0	0	0	0	0.437
store electricity	1.131	0	0.725	0.725	1.46	0.725	1.349	2.253	0	1.711	0.406	0.406	0	0.787	0
store mechanical energy	0	0.109	0	0	0	0	0	0.268	0	0	0	0	0	0	0.219
store product	0.404	0	0	0	0	0	0	0	0.201	0.287	0.203	0.203	0	0	0
store solids	0.398	0	0.141	0.141	0.629	0.141	0.244	0.935	0	0.707	0.117	0.117	0	0	0
supply electricity	0.454	0	0.571	0.337	0.634	0.442	0.621	0.842	0.234	0.687	0.117	0.117	0.331	0.309	0
supply mechanical energy	0	0.221	0	0	0	0	0	0.268	0	0	0	0	0	0	0.219
transmit electricity	0	0	0.234	0	0.634	0.105	0	0.188	0.234	0	0	0	0.331	0	0
transmit human force	0.213	0	0	0	0.746	0	0	0.86	0	0.522	0	0	0	0	0
transmit rotation	0.48	0.348	0.513	0.279	0.897	0.383	0.52	1.156	0.435	0.438	0	0	0.331	0.309	0.309
transmit translation	0	0.378	0	0	0	0	0	0.379	0	0	0	0	0	0	0.309
transport solid	0.139	0.189	0	0	0.342	0	0	0.967	0	0.342	0	0	0	0	0.379

Figure D.4 The **S** matrix for the power screwdriver subset.

Function \ Function	store electricity	store mechanical energy	store product	store solids	supply electricity	supply mechanical energy	transmit electricity	transmit human force	transmit rotation	transmit translation	transport solid
actuate electricity	2.545	0	0.428	0.751	0.882	0	0.181	0.659	1.492	0	0.242
allow DOF of solid	0.725	0.268	0	0.141	0.337	0.268	0	0	0.657	0.379	0.464
assemble product	0.406	0.219	0.203	0.117	0.117	0.219	0	0	0.309	0.309	0.379
change electricity	0	0	0.1	0	0	0	0	0	0.1	0	0
change rotation	2.934	0.155	0.318	0.499	1.539	0.428	0.449	0	2.252	0.765	0.268
clean product	0.596	0	0.201	0.188	0.293	0	0.293	0	0.305	0	0
convert electricity to rotation	5.383	0	0.969	1.457	2.048	0	0.601	0.943	2.221	0	0.418
convert rotation to pneumatics	1.219	0	0.609	0.77	0.352	0	0	0.639	0	0	0.418
convert rotation to translation	0	0.109	0	0	0	0.383	0	0	0.628	0.701	0.189
convert rotation to vibration	0	0	0	0	0.105	0	0.105	0	0.105	0	0
convert translation to rotation	0	0.268	0	0	0	0.268	0	0	0.379	0.379	0.464
couple solid	1.235	0	0	0.141	0.537	0	0	0	0.479	0	0
disassemble product	0.344	0	0	0.109	0.109	0.158	0.109	0	0.273	0.316	0
dissipate sound	0.421	0	0.174	0.412	0.314	0	0.314	0.426	0.355	0	0.279
dissipate heat	1.056	0	0.352	0.545	0.341	0	0	0.522	0.138	0	0.342
dissipate translation	2.158	0.219	0.598	0.402	0.958	0.442	0.234	0.13	1.931	0.756	0.379
dissipate vibrations	1.165	0	0.607	0.514	0.554	0	0.181	0.426	0.52	0	0.279
export solid	1.681	0	0.406	0.578	0.438	0	0.203	0.305	0.225	0	0.139
guide gas	0.406	0	0.203	0.459	0.117	0	0	0.522	0	0	0.342
guide solid	1.087	0	0	0.243	0.243	0.25	0.243	0.13	0.75	0.499	0
import electricity	0	0	0.1	0.139	0	0	0	0.213	0.1	0	0.139
import human force	3.959	0.409	0.799	1.248	1.633	0.704	0.624	0.788	2.879	1.169	1.077
import human hand	3.473	0.289	0.799	1.461	1.615	0.584	0.422	0.825	2.177	1	1.041
import liquid	0	0	0	0	0.105	0	0.105	0	0.105	0	0
import solid	1.376	0.219	0.454	0.479	0.444	0.33	0.181	0.305	0.832	0.532	0.518
indicate status	0.813	0	0.406	0.374	0.235	0	0	0.213	0	0	0.139
maintain device	0.344	0	0.174	0.109	0.318	0	0.318	0	0.383	0	0
position product	0.674	0	0.142	0	0.209	0	0.209	0.275	1.025	0	0
position solid	0.596	0	0	0.583	0.188	0	0.188	0.603	0	0	0.395
refine gas	0.406	0	0.203	0.117	0.117	0	0	0	0	0	0
regulate electricity	1.131	0	0.404	0.398	0.454	0	0	0.213	0.48	0	0.139
regulate human force	0	0.109	0	0	0	0.221	0	0	0.348	0.378	0.189
regulate rotation	0.725	0	0	0.141	0.571	0	0.234	0	0.513	0	0
regulate translation	0.725	0	0	0.141	0.337	0	0	0	0.279	0	0
remove solid	1.46	0	0	0.629	0.634	0	0.634	0.746	0.897	0	0.342
rotate solid	0.725	0	0	0.141	0.442	0	0.105	0	0.383	0	0
secure rotation	1.349	0	0	0.244	0.621	0	0	0	0.52	0	0
secure solid	2.253	0.268	0	0.935	0.842	0.268	0.188	0.86	1.156	0.379	0.967
sense control	0	0	0.201	0	0.234	0	0.234	0	0.435	0	0
separate solid	1.711	0	0.287	0.707	0.687	0	0	0.522	0.438	0	0.342
stop chemical energy	0.406	0	0.203	0.117	0.117	0	0	0	0	0	0
stop gas	0.406	0	0.203	0.117	0.117	0	0	0	0	0	0
stop liquid	0	0	0	0	0.331	0	0.331	0	0.331	0	0
stop rotation	0.787	0	0	0	0.309	0	0	0	0.309	0	0
stop solid	0	0.219	0	0	0	0.219	0	0	0.309	0.309	0.379
store electricity	4.982	0	0.704	1.022	1.674	0	0.243	0.225	1.42	0	0
store mechanical energy	0	0.109	0	0	0	0.109	0	0	0.155	0.155	0.189
store product	0.704	0	0.452	0.203	0.203	0	0	0	0.1	0	0
store solids	1.022	0	0.203	0.577	0.393	0	0.077	0.369	0.141	0	0.242
supply electricity	1.674	0	0.203	0.393	0.776	0	0.181	0	0.499	0	0
supply mechanical energy	0	0.109	0	0	0	0.221	0	0	0.348	0.378	0.189
transmit electricity	0.243	0	0	0.077	0.181	0	0.181	0	0.105	0	0
transmit human force	0.225	0	0	0.369	0	0	0	0.655	0.225	0	0.369
transmit rotation	1.42	0.155	0.1	0.141	0.499	0.348	0.105	0.225	1.644	0.605	0.268
transmit translation	0	0.155	0	0	0	0.378	0	0	0.605	0.665	0.268
transport solid	0	0.189	0	0.242	0	0.189	0	0.369	0.268	0.268	0.569

Figure D.4 The ***S*** matrix for the power screwdriver subset.

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