FUNCTIONAL INTERDEPENDANCE AND PRODUCT SIMILARITY BASED ON CUSTOMER NEEDS *

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Abstract

In this paper, related product functions are determined for a group of approximately 70 consumer products. Using customer need data, a new matrix approach is introduced to identify these relationships. Techniques are then created for determining product similarity. These techniques are clarified and validated through three case studies, including beverage brewers and material-removal products. The results of these case studies are argued to have significant impact on design-by-analogy procedures, benchmarking methods, mass customization strategies, and modular design. The paper concludes with a discussion of applications and related procedures for product development.

1 Introduction

A quality product meets or exceeds customer needs. Current design methodologies, which focus on achieving customer needs, favor decomposing the overall function of a product into sub-functions[1] [7, 10, 11, 1]. To consistently achieve customer satisfaction, the relationship between

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[1]From here forward, the word “function” will be used interchangeably to mean overall product function and sub-function.

customer needs and sub-functions needs to be understood. In this paper, this relationship is investigated using empirical data from many consumer products. Because multiple products are studied, this research work impacts design-by-analogy procedures, benchmarking techniques, mass customization strategies, and modular design.

Although functional analysis is a common topic of research, functional interrelationships have a limited treatment in the literature. Suh [8] promotes the decoupling of function requirements in design. The independence of functional requirements allows design parameters to have a controllable effect on a specific functional requirement and minimal negative impact on other functional requirements. Suh does not, however, explore the relationship between sub-functions that are used to achieve an overall functional requirement. Johannesson [2] extends Suh's axiomatic approach to functional coupling in machine design. Johannesson defines functional coupling to be the negative interaction between two sub-system solutions in achieving a functional requirement. His work is largely concerned with the impact of a given function solution on other functional requirements, or solutions and not the specific function interdependency.

The sub-function relationships existing in 68 products are explored in this paper. The products investigated cover a wide range of consumer applications, customer needs, and overall product function. The products are mainly consumer oriented, mechanical or electro-mechanical devices including toys, small kitchen appliances, small construction tools, and other small household appliances. This set of products represents over one hundred person years of work in reverse engineering and redesign. The redesigns and case studies are taken from course work and research at The University of Texas at Austin as well as product development in industry.

The following section presents a procedure for functional analysis. This technique is extended to group products into logical subsets. Then, two product subsets are analyzed and the results discussed. The paper concludes with a general discussion of the results and potential applications of the procedure.

2 Procedure of Investigation

The procedure used to investigate function interrelationships is an extension of the methodology developed by Little et al. [4]. In this section, a summary of the procedure, which creates a function-product matrix using normalized customer needs, is presented. It is then extended to determine related functions, or *function chains*, for a group of products.

2.1 Creating the Product-Function Matrix

Our functional analysis approach assumes that a number of products are being studied. It also assumes that a functional description, a function structure[2] [7, 10, 11, 1], and a list of rated customer needs exists for each product. The first step in our approach is then to transform each product functional description into a common set of basic functions and flows. The formal terminology for these functions and flows, and a detailed example of a function structure transformation, is presented in [4]. The second step is to ensure that each of the function structures is at a similar level of complexity. For the data set of 68 products analyzed here, the product complexity required approximately 20 functions for a complete functional description.

After transforming the functional descriptions to a common basis, customer-need ratings are translated to a scale of 1 ("optional") to 5 ("must have"), using an appropriate method [6]. The transform to this scale is completed prior to correlation of customer needs with functions. To correlate the functions to customer needs, a two stage process is used. First, material, energy, and signal flows are assigned to customer needs. Then, by following the flows through the function structure, functions are related to flows, and in turn to customer needs. A function is assigned the customer need rank for every customer need that depends on that function. The customer need ranks assigned to a function are then summed to determine the total customer need for that function.

Determining function importance for a domain of products requires arithmetic manipulation of the customer need weighted functions for each product. To simplify this numerical analysis, functions that a product does not have are assigned a value of zero. In turn, each function that does not directly relate to a customer need, termed a *supporting function*, is assigned a value of 1. To maintain the 5 point resolution of the customer need scale, a value of 1 is added to the summed total of the remaining functions, termed *carrier functions*. As a result, the function importance scale is now a 1 to 6 scale. A value of 1 indicates a supporting function, a value of 6 or higher

[2] A *function structure* is simply a graphical mapping of input material, energy, or signal flows to desired product output flows.

indicates an essential, or highly important, function. Values greater than 6 can occur when one function relates to several customer needs.

A mxn (m total different functions, n products) product-function matrix, $\mathbf{\Phi}$, is assembled by considering each product as a vector of function importance weights in a vector space of design functions. Each element ϕ_{ij} is the cumulative customer-need importance for the ith function for the jth product. Different detail, and customer enthusiasm, will affect the magnitude of the ϕ_{ij}'s for each product. To compensate for differing levels of detail, $\mathbf{\Phi}$ is normalized to validate comparisons between products with different complexities. $\mathbf{\Phi}$ matrices for two subsets of products are shown in the appendix. The techniqes used to select these subsets from the entire product set are presented later in this paper.

The philosophy used to normalize the function-product matrix consists of two complimentary aspects:

1. all products are of equal importance (to compare products), and
2. products with more functions are more complex; thus the customer-need rankings must be normalized to compensate for varying complexity.

First, to equalize products, the customer-need value of each function is scaled so that the sum of a given product's importance level is equal to the average sum of the customer need importance for all products. Second, to represent varying levels of product complexity, each product function is scaled by the ratio of the number of functions in that product to the average number of functions per product.

Implementing these steps precisely, the elements of the normalized version of $\mathbf{\Phi}$, $\mathbf{N}$, are

$$\nu_{ij} = \phi_{ij}(\frac{\overline{\eta}}{\eta_j})(\frac{\mu_j}{\overline{\mu}}), \tag{1}$$

where the average customer need is

$$\overline{\eta} = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\phi_{ij}, \tag{2}$$

the total customer need for the jth product is

$$\eta_j = \sum_{i=1}^{m}\phi_{ij}, \tag{3}$$

the number of functions in the jth product is

$$\mu_j = \sum_{i=1}^{m} H(\phi_{ij}), \tag{4}$$

and the average number of functions is

$$\overline{\mu} = \frac{1}{n} \sum_{i=1}^{m} \sum_{j=1}^{n} H(\phi_{ij}). \tag{5}$$

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

2.2 Selecting Data Sets for Investigation

Before determining function relationships and importance across a group of products, we present two techniques for reducing the product domain to a subset of products. By so doing, we will be able to identify potential product families. First we present a product hierarchy based on the primary flow of energy, and energy conversions, through the product system. The second technique uses customer weighted sub-function similarity to create product subsets.

Figure 1 shows a product hierarchy based on the energy conversion technique. The primary energy input is followed through the product until it leaves. A hierarchical distinction is made at each energy conversion. A bottom level in the hierarchy represents products with common energy conversions. For example, in Figure 1, the primary energy input chosen is electricity. The products underlined in Figure 1 are those investigated in this study. In Section 3, function relationships are investigated for the *electricity→heat→material* group.

An alternative approach for identifying product domains is to determine sub-function similarity across a set of products. We use the function vector-space representation, **N**, to calculate this similarity. The product vectors from Eq. 1 are renormalized so that their norm is 1. We then calculate the inner product of the normalized product vectors for each combination of products. Forming the inner product between a product a and a product b, $a \circ b$, gives the projection of product a on product b. Forming the inner product of a product with itself (the completely similar product) gives a value of 1; forming the inner product of a product with one that shares no common functions yields a result of zero.

A matrix of these projections is

$$\mathbf{\Lambda} = \mathcal{N}^T \mathcal{N}. \tag{6}$$

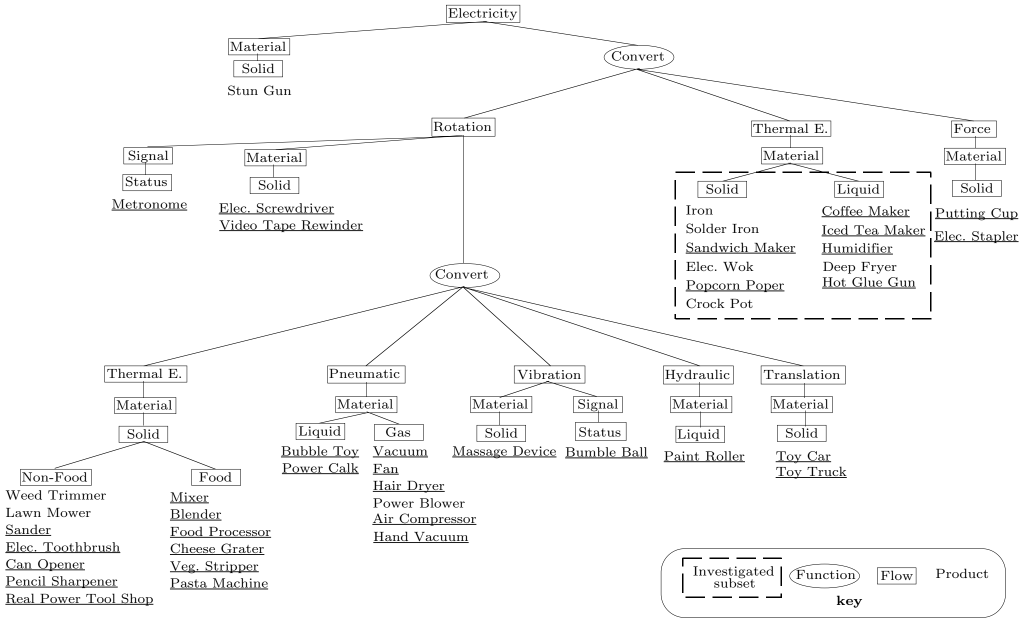


Figure 1: Product hierarchy for products with electricity as a primary input flow.

$\mathcal{N}$ is the matrix of unity normalized product vectors, similar to $\mathbf{N}$. Each element of $\mathbf{\Lambda}$, λ_{ij}, is the projection of the *ith* product on the *jth* product. $\mathbf{\Lambda}$ is the product similarity matrix. Using matrix multiplication to form the product similarity matrix Λ, and coupled function importance matrix $\mathcal{S}$ (introduced below), is similar to a technique Taylor [9] used to determine topics and frequencies of discussion on internet newsgoup communication in student design teams.

Table 1 is a subset of products generated using the functional similarity method. The subset-*generating* product is a hand held palm sander. The products in Table 1 are those, of all 68 reviewed in this study, with the 12 largest projections onto the hand sander. Inspection of the Table 1 shows the results are consistent with intuition.

For any set of products, a *conglomerate* product can be constructed. The conglomerate product is defined as a vector in the sub-function space, where each scalar component of the vector is

$$p'_i = \sum_{j=1}^{n} \nu_{ij} \tag{7}$$

The vector p' is then unity normalized giving the conglomerate product vector p. The conglomerate product represents the customer need weighted functionality of the entire product domain. An application for the conglomerate product is discussed in section 4.

Product	Projection
palm sander	1.000000
fruit & vegetable peeler	0.808
power screwdriver	0.797
oscillating sander	0.791
electric knife	0.753
hand vacuum	0.752
mini pro hair dryer	0.730
electric can opener	0.718
electric polisher	0.708
hand blender	0.688
toy fishing reel	0.673
electric pencil sharpener	0.668

Table 1: Product subset based on customer weighted functional similarity to the palm sander.

2.3 Creating the Function-Function Matrix and Solving for Function Chains

To determine product function relationships throughout a domain, repeatedly occurring function groups with a high customer need are found. These function chains are then categorized according to their common energy, material, or signal flow.

The first step in determining function dependencies is to form the function-function matrix, $\mathcal{S}$. The construction begins with the formation of the unscaled function importance matrix $\mathcal{S}'$. Let

$$\mathcal{S}' = NN^T. \tag{8}$$

Each element of $\mathcal{S}'$ is

$$s'_{ij} = \sum_{p=1}^{n} \nu_{ip}\nu_{jp}, \tag{9}$$

where n is the number of products. Note that the indices of the second term are jp (as opposed to pj) as a result of multiplication by the transpose of $\mathbf{N}$. Therefore, each term in the sum of Eq.(9) is the multiplicative product of the ith function and the jth function for the pth product. The function chain customer importance, s_{ij} clearly relies on the existence of both functions in a product. For a product to make a non-zero contribution to s_{ij}, both functions must appear in that product.

To maintain the customer need scale magnitude of 6, the square root of the multiplicative product $\nu_{ip}\nu_{jp}$ is taken. The sum is divided by the number of products, n. Equation (9) now becomes,

$$s_{ij} = \frac{1}{n}\sum_{p=1}^{n} \sqrt{\nu_{ip}\nu_{jp}}. \tag{10}$$

Let $\mathcal{S}$ be a mxm matrix with elements s_{ij}. $\mathcal{S}$ is the coupled function, or two function chain, importance matrix. Each s_{ij} is the customer importance of the combination of the ith function and the jth function in a domain of products. The measure of s is on a 6 point scale, where 6 is must have, and 1 is a supporting function combination. For example, if s_{37} has a value of 6, the combination of the functions 3 and 7 is, on average, a "must" for all products analyzed.

Equation (10) extends easily to more than two functions. To determine the three function chains Eq.(10), becomes

$$s_{ijk} = \frac{1}{n} \sum_{p=1}^{n} \sqrt[3]{\nu_{ip} \nu_{jp} \nu_{kp}}. \tag{11}$$

The interpretation of this relationship is similar to the two function case. Here, each element of the tensor, s_{ijk}, is the product of the i, j and kth functions customer need rank, summed over all products. If a product does not contain all three functions, the contribution to s_{ijk} is zero.

2.3.1 The Resolution of s_{ij}

The initial customer importance ranking has a resolution of 1, on an integer 6 point scale. The arithmetic manipulation in Eqs.(1) through (10) leads to s values that are not integers. Initially, discernible customer needs have a resolution of 1. The question arises: How does changing a customer need rank in $\mathbf{\Phi}$ by one point of resolution (1) affect a value of $\mathcal{S}$? In this section the resolution of s is determined. The results of this analysis are used in both the numerical presentation and the customer need rank data presented in the following sections.

Defining the resolution as

$$\varepsilon_{ijpq} = \frac{\partial s_{ij}}{\partial \phi_{pq}}. \tag{12}$$

where s_{ij} and ϕ_{pq} are arbitrary, the derivation is straight forward.

For brevity, the complete derivation is not presented here. Two function are defined to express the resolution compactly. The first is defined as

$$f[a, b, c, d] = \begin{cases} 1, & \text{when a = b and c = d} \\ 0, & \text{otherwise} \end{cases} . \tag{13}$$

The second is

$$g[a, b] = \begin{cases} 1, & \text{when a = b} \\ 0, & \text{otherwise} \end{cases} . \tag{14}$$

function combination	s	ε
import human force+convert electricity to rotation	2.464211	0.038523
dissipate sound+convert electricity to rotation	1.949093	0.030458
dissipate translation+convert electricity to rotation	1.892236	0.029581
convert electricity to rotation+actuate electricity	1.800231	0.028466
import solid+import human force	1.797064	0.028230
import human hand+import human force	1.789280	0.027945
import human force+dissipate translation	1.769951	0.027721
convert electricity to rotation+change rotation	1.763166	0.027557
import human force+change rotation	1.731498	0.027121
secure solid+import human force	1.665674	0.026137

Table 2: Sensitivity of s to customer need ranking for function coupling.

Using these two functions, the resultion is expressed as

$$\varepsilon_{ijpq} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{2}\frac{1}{\sqrt{\nu_{ik}\nu_{jk}}}(\frac{\mu_k\overline{\eta}}{\overline{\mu}\eta_k}) \quad (15)$$

$$\{(f[i,p,k,q]+\phi_{ik}(\frac{1}{\overline{\eta}}-\frac{1}{\eta_k}g[k,q]))\nu_{jk}+ \quad (16)$$

$$\nu_{ik}(f[j,p,k,q]+\phi_{jk}(\frac{1}{\overline{\eta}}-\frac{1}{\eta_k}g[k,q]))\} \quad (17)$$

Equation (17) is the change in s_{ij} with a 1 point change in ϕ_{pq}.

For each of the $\begin{pmatrix} m \\ 2 \end{pmatrix}$ combinations of ε, there will be mn different values. To simplify interpretation and communication of the resolution, an average ε_{ij} is used. Table 2 lists the top 10 function pairs, the s value, and the associated average sensitivity. The ε's indicate that a variation in customer need of 1, for a single function on a single product, will change s_{ij} in the second decimal place. In all the following tables the s values are listed to two decimal places. Also, the specific resolution values are used to distinguish between different groups of function chains. Function chain values indistinguishable within their repsective resolutions are considered equivalent with respect to customer importance.

3 Analysis and Example Case Studies

In this section the linked function relationships for two product domains: an energy conversion hierarchy group and a device similarity group are analyzed and discussed. To verify the functional interdependence procedure, specific case studies are examined for the two product subsets. The first case involves an apples to apples comparison (same product, different manufacturer), the second case is more of an apples to crab apples comparison (similar product, slightly different material flow), the last is akin to an apples to oranges comparison (different products, same family). The three case studies identify actual modules that agree with the results of the functional interdependence method, providing validation of the method as a tool for module identification. Furthermore, it demonstrates that while module creation in product design may not have a formal framework, it is used at various stages in industry.

The case study procedure looks at actual products from the 68 product function database. The four steps of the procedure are;

1. generate the function dependency chains for a product family,
2. disassemble the product (from the product family in step 1) and document its components,
3. identify actual modules in the product and,
4. compare with the predicted modules from step 1.

Before discussing the specific groups and case studies, some terminology is introduced to simplify the discussion and categorization of the results.

Common flow function chains are those in which each function operates on a common basic flow. Distinctions between the order of the function in the chains are not made. Common flow function chains with a high customer importance are those most suitable for function sharing, modularity, function solution optimization, and function interaction analysis.

Flow independent, causally linked function chains 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. The flow independent, causal function chains motivate redesign efforts on the causal function. In general, determining which function chains are causally linked requires some knowledge of the product group.

Independent flow, non-causal function chains share no common flow, operate separately from each other, and often result from distinct customer needs. These function chains are not chains in the sense of the previous two function groupings. In fact, combinations in this chain indicate functions that should not be grouped together into modules. Nevertheless, identification of customer important function chains have implications for mass customization. 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 [3], similar to the fashion in which automobile manufactures handle option cutouts on a dashboard. Here, a single housing could provide the interface for different modules. Likewise, independent flow, non-causal function chains with high occurrence present a starting point for design for recycle-ability analysis [5] including materials selection and potential clumping options.

The results of the analysis are presented in Tables 3 through 7, each of which is organized in the following manner. Column one lists the function chain. Column two lists the function-chain customer need importance index s. Column three is the occurrence of the function chain as a percentage of the total possible (the total number of products analyzed in the group or subset). Within the table, the function chains are broken down into three sub-groups: the first is common flow functions; the second flow independent, causally linked functions; and the last is flow independent, causal independent functions. Within the sub-groups, the function chains are listed in descending order of customer importance, s. The 25 function chains listed are those with the highest ranking customer-need values.

3.1 The Energy Conversion Hierarchy Subset

The first set of products analyzed is the *electricity→heat→material* subset of the total 68 products. Table 3 presents the two function chains, Table 4 the three function chains. The products in this group (Figure 1) are a sandwich maker, a popcorn popper, a coffee maker, an iced tea maker, a hot glue gun, and a humidifier.

The common flow functions for the two function chains are, predictably, those which manipulate the electricity, the heat (thermal energy), and the solid. The independent flow, causally linked function chains are those that manipulate electricity and thermal energy. In the function chain *transmit thermal energy+regulate electricity*, the electricity is regulated to determine how much thermal energy is transmitted. The *transmit thermal energy+regulate electricity* function chain may be used to connect modules from the common flow functions, creating a larger module. Similarly, *import electricity+transmit thermal energy* may be used to join the common thermal energy and common electricity function chains to create larger modules.

Function Combination	s	%
Common Flow		
transmit heat+convert electricity to heat	6.61	100
secure solid+import solid	3.29	67
import electricity+convert electricity to heat	2.98	100
transmit heat+stop heat	2.58	67
Flow Independent, Causally Linked		
transmit heat+import electricity	3.34	100
transmit heat+regulate electricity	2.48	50
import solid+import human force	3.82	67
store solid+import human force	3.13	83
store liquid+import human force	2.90	50
Flow Independent, Non-Causal		
transmit heat+import human force	6.34	83
transmit heat+import solid	5.23	83
import human force+convert electricity to heat	5.14	83
import solid+convert electricity to heat	4.40	83
transmit heat+store liquid	4.21	67
store liquid+convert electricity to heat	4.18	67
transmit heat+store solid	3.78	83
store solid+convert electricity to heat	3.40	83
transmit heat+secure solid	3.27	67
import solid+import electricity	3.00	83
store liquid+import solid	2.98	50
transmit heat+clean product	2.90	50
secure solid+convert electricity to heat	2.74	67
convert electricity to heat+clean product	2.56	50
regulate electricity+import human force	2.51	50
import human force+clean product	2.50	50
import solid+guide liquid	2.41	50

Table 3: Customer need index and % occurrence for two function chains in the *electricity*→*heat*→*material* products.

Function Combination	s	%
Common Flow		
convert electricity to heat+stop heat+transmit heat	2.86	67
Flow Independent, Causal		
convert electricity to heat+import electricity+transmit heat	3.88	100
Flow Independent, Non-Causal		
convert electricity to heat+import human force+transmit heat	5.73	83
convert electricity to heat+import solid+transmit heat	4.67	83
convert electricity to heat+store liquid+transmit heat	4.34	67
import human force+import solid+transmit heat	4.25	67
convert electricity to heat+store solid+transmit heat	4.22	83
import human force+store solid+transmit heat	4.10	83
convert electricity to heat+import human force+store solid	3.70	83
convert electricity to heat+import human force+import solid	3.59	67
import electricity+import solid+transmit heat	3.43	83
import electricity+import human force+transmit heat	3.29	83
import human force+store liquid+transmit heat	3.28	50
import solid+secure solid+transmit heat	3.25	67
convert electricity to heat+import human force+store liquid	3.23	50
clean product+convert electricity to heat+transmit heat	3.19	50
clean product+import human force+transmit heat	3.13	50
convert electricity to heat+import electricity+import solid	3.12	83
convert electricity to heat+secure solid+transmit heat	3.03	67
import human force+regulate electricity+transmit heat	3.01	50
convert electricity to heat+import solid+secure solid	3.00	67
import solid+store liquid+transmit heat	2.97	50
import solid+store solid+transmit heat	2.90	67
convert electricity to heat+import electricity+import human force	2.89	83
clean product+convert electricity to heat+import human force	2.88	50
import human force+stop heat+transmit heat	2.85	67

Table 4: Customer need index and % occurrence for three function chains in the *electricity*→*heat*→*material* products.

Identified module Description	Brand A	Brand B	Assoc. Fig.
electricity to thermal energy Imports electricity, actuates electricity, regulates electricity, converts electricity to thermal energy, transmits thermal energy, measures thermal energy, stops thermal energy, transports liquid	exists	exists	2
ice containment imports human force, imports solid, stores solid, secure solid	exists	exists	3
filter, tea containment imports human force, imports solid, stores solid, secure solid	exists	does not exist as a module	4
liquid containment imports human force, imports liquid, stores liquid	exists	exists	3

Table 5: Identified modules in Brand A and Brand B iced tea brewers.

Table 4 contains only one common flow function chain, *convert electricity to thermal energy+stop thermal energy+transmit thermal energy* for the set of products. This result is clearly consistent with the technique used to generate the product subset. The highest ranking flow independent, non-causel three function chain is *convert electricity to thermal energy+import human force+transmit thermal energy.* This function chain is represented in 5 of the 6 functional descriptions for this product subset and is a customer "must." Any domain redesign, or reorganization, efforts need to consider the function chain interaction, or interference, constraints of these functions.

3.1.1 Case 1: Apples vs. Apples - Iced tea makers

In the apples vs. apples comparison of the electricity-heat-material family, we look at two iced tea brewers from different makers, Brand A and Brand B. The conjecture is that for two functionally similar products, the better product should make use of more modules.

The function chains for this product family are listed in Tables 3 and 4. Modules found upon disassembly of the two iced tea brewers are listed in Table 5. Both products shared many of the same modules, with the Brand A iced tea brewer exhibiting a greater number of modules.

The common flow function combinations listed in Table 3 all appear in the iced tea brewers as all or part of a module. The electricity to thermal energy module in Figure 2 contains 3 of the 4 common flow function chains as submodules: *transmit thermal energy+convert electricity to thermal energy*, *transmit thermal energy+stop thermal energy*, and *import electricity+convert electricity to thermal energy.* The fourth function chain, *secure solid+import solid*, manifests itself as the pitcher and lid (for holding the ice) for both products in Figure 3. Additionally, in Figure 4,

Figure 2: The convert electricity to thermal energy module for both tea brewers.

Mr. Coffee has a module for importing the filter and tea which is another manifestation of *secure solid+import solid* which the Brand B lacks.

The flow independent, causally linked function chains also represent modules found within both products. They are again subsets of the identified modules discussed above, with the addition of the liquid containment module identified by the *store liquid+import human force* combination. This module is shown in Figure 3.

In both the common flow and flow independent, causally linked chains, the combinations of functions form all, or part, of assembly modules. Assembly modules are components, or groups of components, that solve related functions and are assembled in stages to increase assembly ease.

The three function dependency shown in Table 4 reveals only two possible modules in the common flow and flow independent, causally linked chains. This fact compares favorably with the results in Table 3. The two, three function combinations are both subsets of the assembly module electricity to thermal energy shown in Figure 2, which is described by 3 out of 4 of the two function dependency combinations.

As expected, no modules are found which embody the combinations of the flow independent, non-causal category. In fact, this category is interpreted as functions that should not be combined as modules.

Figure 3: The *secure solid+import solid* and *import force+store liquid* for both tea brewers.

Figure 4: The *import human force+import solid* and *store solid+secure solid* for the Brand A tea brewer.

Figure 5: The *convert electricity to thermal energy module* for the Brand A tea brewer and the Brand A coffee maker.

3.1.2 Case 2: Apples vs. Crab Apples - Coffee maker vs. iced tea maker

Continuing analysis of the electricity-heat-material product family, we look at two different products (coffee maker vs. iced tea maker) by the same company, Brand A. The functional interdependence procedure suggests that these different, but related, products share the same modules in solution concept, if not in actual parts.

The function dependency combinations for this product family are listed in Tables 3 and 4. Three shared modules were found in the coffee maker and iced tea maker: the electricity to thermal energy module (that was common to both tea makers in case 1); a liquid containment module; and a *transport liquid+stop liquid flow* module.

The electricity to thermal energy assembly module appears as a sizable, or scalable, module and is shown in Figure 5. Here we define a sizable module as one which is physically identical to another module except for the its scale. In both products, the electricity to thermal energy module is made from the same extruded tubing as evidenced in Figure 5. The actuate energy function solution is slightly different, due to the automatic shut-off feature of the tea maker. Recall that both the two and three function dependency chains predict subsets of this module.

The second module, predicted by the two function dependency combination *store liquid+import human force*, is a conceptual module. Here, a conceptual module uses the same solution principle

(a) Coffee maker. (b) Tea Brewer.

Figure 6: The *transport liquid+stop liquid flow* solution for the coffee maker and the tea brewer.

in both products, but the physical incarnation is different. Compared to the tea brewer's plastic, essentially cylindrical liquid containment module, the coffee maker's is glass, and more spherical in shape.

The third module identified, *transport liquid+stop liquid flow*, is shown in Figure 6. This module is an exact module. Exact modules are those in which the same part is used in both products. This module is not identified in either Table 3 or 4. However, this is not a short comming of the functional interdependence method. Both *transport liquid* and *stop liquid flow* are supporting functions and, thus, only have a relative customer need rank of one. The normalization procedure of the function-function matrix will never rank this combination above that of a supporting function (i.e., a value of 1). The combinations shown in the tables are only those with a customer need rank greater than one.

To sum up case 2, three modules were found to exist between the Brand A coffee maker and iced tea maker: one sizable, one conceptual, and the last exact in both products. Opportunities exist for further modularity. For example, the iced tea maker has a tea and filter containment module. The coffee maker could incorporate a sizable or exact containment module for coffee and filter. This case shows that, within product families, the functional interdependence method provides a framework for module sharing between different products.

Function Combination	s	%
Common Flow		
secure solid+remove solid	5.09	67
convert electricity to rotation+actuate electricity	3.79	100
import electricity+convert electricity to rotation	3.27	100
convert rotation to pneumatics+convert electricity to rotation	3.08	50
secure solid+position solid	2.87	50
Flow Independent, Causal		
import human hand+import human force	6.46	100
import human hand+actuate electricity	4.24	100
import human hand+dissipate vibrations	3.12	50
secure solid+import human hand	5.68	83
remove solid+import human hand	4.87	67
secure solid+import human force	4.86	83
remove solid+import human force	4.50	67
remove solid+dissipate vibrations	3.12	50
position solid+import human hand	2.83	50
Flow Independent, Non-Causal		
import human hand+convert electricity to rotation	6.57	100
import human force+convert electricity to rotation	5.73	100
secure solid+convert electricity to rotation	4.87	83
remove solid+convert electricity to rotation	4.34	67
import human force+actuate electricity	3.63	100
import human hand+import electricity	3.60	100
import human force+import electricity	3.29	100
secure solid+actuate electricity	3.21	83
separate solid+import human hand	3.18	67
remove solid+import electricity	3.09	67
import human hand+convert rotation to pneumatics	3.08	50
secure solid+import electricity	3.07	83

Table 6: Coupled functions ranked by s and % occurrence for products similar to the palm sander. Those products are a fruit and vegetable stripper, a power screwdriver, an oscillating sander an electric knife, and a hand vacuum.

3.2 The Functional Similarity Subset

A second subset of 6 products, selected based on sub-functional similarity, is analyzed in this section. The products are the first 6 appearing in Table 1. Table 6 contains the two function chains, and Table 7 contains the three function chains for these 6 products. For this product subset, the common flow two function chains are those which manipulate solids and electricity. Within this subset, there are three flow independent, causally linked function chains of importance. The first is the *remove solid* function causing a need to *dissipate vibrations*. The second, existing in half of these products, is *import human hand* used to *position a solid*. All products require *import human hand* to *actuate electricity*, the third important function chain.

Function Combination	s	%
Flow Independent, Causal		
import human force+import human hand+secure solid	5.22	83
import human hand+remove solid+secure solid	4.82	67
actuate electricity+convert electricity to rotation+import human hand	4.65	100
actuate electricity+import human force+import human hand	4.57	100
import human force+remove solid+secure solid	4.52	67
import human force+import human hand+remove solid	4.47	67
Flow Independent, Non-Causal		
convert electricity to rotation+import human force+import human hand	6.19	100
convert electricity to rotation+import human hand+secure solid	5.20	83
convert electricity to rotation+import human force+secure solid	4.67	83
convert electricity to rotation+remove solid+secure solid	4.44	67
convert electricity to rotation+import human hand+remove solid	4.33	67
actuate electricity+convert electricity to rotation+import human force	4.22	100
import electricity+import human force+import human hand	4.17	100
convert electricity to rotation+import electricity+import human hand	4.15	100
convert electricity to rotation+import human force+remove solid	4.07	67
actuate electricity+import human hand+secure solid	3.99	83
convert electricity to rotation+import electricity+import human force	3.87	100
import electricity+import human hand+secure solid	3.69	83
actuate electricity+convert electricity to rotation+secure solid	3.63	83
actuate electricity+import human force+secure solid	3.58	83
import electricity+remove solid+secure solid	3.47	67
import electricity+import human force+secure solid	3.42	83
convert electricity to rotation+import electricity+secure solid	3.37	83
import electricity+import human hand+remove solid	3.35	67
convert electricity to rotation+import human hand+separate solid	3.35	67
import human force+import human hand+separate solid	3.26	67

Table 7: Three function dependency for products similar to the hand sander. Those products are a fruit and vegetable stripper, a power screwdriver, an oscillating sander, an electric knife, and a hand vacuum.

3.2.1 Case 3: Apples vs. Oranges - Palm Grip Sander vs. Fruit Peeler

Considering a wider product family than the previous two cases, two different products from the palm sander similarity subset are examined, the palm sander itself and a fruit and vegetable peeler. As in case 2, the functional interdependence method predicts modules across the product family. Tables 6 and 7 list the two and three function dependency combinations for the family. The two function common flow chain deals with manipulating the solid and electricity. In the two function flow independent, causally linked combinations, two types of chains exist. The first type shows that remove solid necessitates a need to dissipate vibrations. The second type of chain deals with importing human force to manipulate solids and energies. The three function flow independent, causally linked combinations mimic the two function combinations, with the exception of the dissipate vibrations chain.

Upon disassembly of the two products, no exact or sizable modules are found. However, conceptual modules are located. In particular, the manipulate solid modules predicted by the two and three function common flow and flow independent, causally linked combinations exist and are shown in Figure 7. On first review, their embodiment appears different, though they each solve the same functions of *secure solid*, *remove solid*, and *position solid*. However, the peeler and the sander use similar means of securing the solid. Note in Figure 7 (b) that the peeler has a spring loaded arm to hold the blade next to the solid for peeling. The sander, in Figure 7 (c) uses spring arms to secure the sand paper on its block. As an additional means of securing the sand paper, the sander could incorporate piercing prongs as the peeler does in Figure 7 (a).

Another conceptual module of *import electricity+convert electricity to rotation* is found in both the sander and peeler. These modules are shown in Figure 8. An opportunity for part sharing of motors exists between the two if the output can be geared down for the peeler or, conversely, if a smaller motor can be geared up and maintain adequate torque for the sander.

This case study purposely sought a device family with a wider scope (devices that are not intuitively similar) and devices made by different manufacturers. Since modules are found under these circumstances, the functional interdependence method has passed a rigorous test. Although no exact or sizable modules are located in these devices, opportunities for such modules exist. Specific examples are the use of a piercing method to hold sandpaper and the use of a common motor. This module information could provide a company with a means of identifying a new device

(a) Fruit and vegetable peeler. (b) Fruit and vegetable peeler. (c) Sander.

Figure 7: Manipulate solid solutions for the hand sander and the fruit and vegetable peeler.

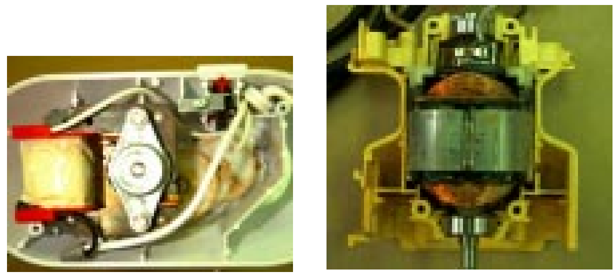
to manufacture that can draw on its current line of components and expertise. This is the power of identifying conceptual modules - they provide a first step toward greater use of exact or sizable modules and the associated cost savings.

4 A Project Planning Application

Three case studies have shown the utility of the functional interdependence method for identifying modules and opportunities for modular architecture. The procedure, used to determine and rank related functions, has applications other then modular design. It is clearly useful as part of a designer's toolkit. The function coupling analysis technique can be applied to product planning. A sample application is outlined here.

Organizations involved with product design and manufacture can use function dependency and product functional similarity knowledge to determine new products for development. This method depends on an existing knowledge of product need. This method is useful for predicting a company's success in delivering a quality, and thus successful, product based on their existing design and manufacturing knowledge.

To begin, it is necessary to collect and organize information about the company's existing product line. To do this, all the existing products are reverse engineered. Then, a product-function matrix for the company's product line, or specific subset is created. With the existing product information well organized, design begins on the proposed new products. The conceptual design,



(a) Fruit and vegetable peeler.

(b) Hand Sander.

Figure 8: The *convert electricity to rotation* solution for the hand sander and the fruit and vegetable peeler.

through the generation of a function structure, is completed for each of these products. The proposed products can now be compared to the company's existing, customer weighted (satisfied), design and manufacturing expertise. This is done by inserting the potential product's sub-function vector into $\mathbf{\Phi}$ and creating $\mathbf{N}$. Then, the new product is compared to the companies existing design and manufacturing expertise by calculating the inner product of the proposed new product's sub-function vector and the conglomerate product, p, yielding a measure of product similarity. This procedure is repeated for each of the potential products. The product which scores the highest, i.e. has the most sub-function similarity, is the product which will draw largely on the company's existing knowledge, and requires a minimum of new pre-prototype testing and analysis.

Once a product is chosen for development, the design and implementation team can be chosen using the product similarity technique. Product development teams that have worked on a functionally similar product have the most knowledge of the atomic functional operation of the new product and thus are most suited for a successful continuation of the project through detail design, manufacturing, and testing.

5 Conclusion

In this paper, a novel procedure for determining functional interdependence based on customer-need data is presented. The procedure is used to investigate the importance of function chains in specific and general sets of products. A result of this analysis is a quantitative framework for identifying sub-functions that can be grouped into assembly modules. Case studies performed on specific subsets of products show that modules are present in current devices, specifically within device families and competing manufacturers of the same device. Among manufacturers that have several devices in one device family, exact and sizable modules exist, with opportunities for more exact module incorporation. An application of the functional interdependence procedure for product development is briefly presented.

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Appendix

Functional analysis of a large set of products is simplified be representing products as a vector of function importance weights in a vector space of design functions. Function-product matrices, $\mathbf{\Phi}$ for the two product subsets used as examples in this paper are shown in this appendix.

Function	popcorn popper	sandwich maker	coffee maker	humidifier	iced tea maker (B)	hot glue gun
actuate electricity	0	4	1	4	1	0
change friction	0	14	0	0	0	0
change pneumatics	0	0	0	6	0	0
change translation	0	15	0	0	0	1
clean product	5	0	0	4	3	0
convert electricity to rotation	1	0	0	0	0	0
convert electricity to heat	6	3	3	19	6	3
convert rotation to sound	3	0	0	0	0	0
convert rotation to pneumatics	6	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	1
dissipate sound	0	0	0	6	0	0
dissipate translation	0	0	0	1	0	0
distribute gas	0	0	0	10	0	0
distribute liquid	0	0	1	0	0	0
export gas	0	0	1	0	0	0
export liquid	0	0	1	0	1	2
export solid	3	6	0	0	1	0
form solid	0	1	0	0	0	0
guide electricity	0	0	0	0	0	3
guide gas	10	0	4	1	0	0
guide human force	0	0	0	0	4	0
guide liquid	0	0	2	0	1	2
import electricity	1	1	1	1	1	3
import gas	1	0	0	0	0	0
import human force	6	15	10	10	10	1
import human hand	0	5	5	0	0	2
import liquid	0	0	1	6	1	0
import solid	9	1	3	0	7	7
indicate status	0	0	0	0	1	0
indicate temperature	0	0	0	0	0	1
measure displacement	0	0	0	1	0	0
measure pressure	0	0	1	0	0	0
measure temperature	0	9	1	0	1	0
mix liquid and gas	0	0	8	2	0	0
mix liquid and solid	0	0	6	0	6	0
mix solid	5	0	0	0	0	0
refine liquid	0	0	1	0	1	0
regulate electricity	0	9	0	3	1	0
regulate hydraulics	0	0	0	0	0	2
secure solid	0	5	1	0	1	6
stabilize translation	0	5	0	5	0	0
stop chemical energy	0	0	0	1	0	0
stop gas	0	0	0	0	2	0
stop liquid	0	0	0	5	1	0
stop heat	2	3	0	1	0	2
store liquid	0	0	7	11	5	2
store product	3	1	0	0	3	0
store solids	4	1	0	9	1	1
store translation	0	0	0	0	0	1
transmit electricity	0	1	0	0	0	0
transmit rotation	1	0	0	0	0	0
transmit heat	11	12	9	15	9	3
transmit translation	0	1	0	0	0	1
transport solid	0	0	0	0	0	1

a)

Function	palm sander	fruit & vegetable stripper	power screwdriver	hand vacuum	oscillating sander	electric can opener	electric polisher	electric knife	toy fishing reel	electric pencil sharpener	mini pro hair dryer	hand blender
actuate electricity	3	1	5	1	5	1	1	1	0	1	1	5
allow DOF of solid	0	0	1	0	0	0	0	0	6	0	0	0
assemble product	0	0	0	1	0	0	0	0	4	0	0	0
change electricity	0	0	0	0	0	0	0	0	0	0	0	1
change friction	0	0	0	0	1	0	0	0	0	5	0	0
change rotation	0	4	6	0	0	12	0	1	2	3	0	10
change translation	0	1	0	0	0	9	0	0	0	0	0	0
clean product	0	3	0	0	0	0	0	2	0	0	0	4
convert electricity to rotation	9	4	6	12	11	9	12	1	0	7	15	7
convert electricity to heat	0	0	0	0	0	0	0	0	0	0	3	0
convert rotation to pneumatics	9	0	0	9	1	0	0	0	0	0	4	0
convert rotation to translation	0	1	0	0	11	0	0	0	1	0	0	0
convert rotation to vibration	0	0	0	0	0	0	0	1	0	0	0	0
convert translation to rotation	0	0	0	0	0	0	0	0	6	0	0	0
couple solid	0	0	1	0	0	0	1	0	0	0	0	0
dissipate sound	4	0	0	0	4	4	5	3	0	2	6	3
dissipate heat	6	0	0	3	1	0	0	0	0	0	0	0
dissipate translation	0	0	2	3	0	1	5	1	4	0	5	6
dissipate vibrations	4	0	0	4	5	0	5	6	0	0	0	4
distribute gas	0	0	0	0	0	0	0	0	0	0	5	0
distribute rotation	0	1	0	0	0	0	0	0	0	0	0	0
export solid	1	1	0	4	2	1	0	0	0	2	0	0
guide gas	6	0	0	1	1	0	0	0	0	0	5	0
guide rotation	0	4	0	0	0	0	0	0	0	0	0	0
guide solid	0	1	0	0	0	4	0	0	0	2	0	0
import electricity	1	4	1	0	1	1	1	1	0	1	1	1
import gas	0	0	0	0	0	0	0	0	0	0	1	0
import human force	7	6	5	6	6	5	1	3	14	5	4	9
import human hand	15	6	10	6	6	5	1	3	7	0	6	9
import solid	1	4	0	5	1	8	1	1	4	2	0	0
indicate status	1	0	0	4	0	0	1	0	0	0	0	0
maintain device	0	0	0	0	5	4	0	0	0	0	0	3
position product	0	0	0	0	4	0	10	0	0	0	1	2
position solid	8	4	0	0	1	0	5	1	0	0	0	0
refine gas	0	0	0	1	0	0	0	0	0	0	1	0
regulate electricity	1	1	1	1	0	0	1	0	0	0	5	4
regulate human force	0	0	0	0	1	0	0	0	1	0	0	0
regulate rotation	0	0	1	0	0	0	0	0	0	0	0	0
regulate translation	0	0	1	0	0	0	0	0	0	0	0	0
remove solid	6	11	0	0	13	14	8	3	0	8	0	0
rotate solid	0	2	1	0	0	4	0	0	0	0	0	0
secure rotation	0	0	3	0	0	0	0	0	0	1	0	0
secure solid	13	12	3	0	7	13	7	1	6	3	0	0
sense control	0	0	0	0	0	0	0	0	0	0	5	4
sense status	0	4	0	0	0	0	0	0	0	0	0	0
separate solid	6	0	2	2	4	0	1	3	0	0	0	0
stabilize translation	0	0	0	0	0	0	0	0	0	1	0	0
stop chemical energy	0	0	0	1	0	5	0	0	0	0	0	0
stop gas	0	0	0	1	0	0	0	0	0	0	0	0
stop solid	0	1	0	0	0	0	0	1	4	1	1	0
stop heat	0	0	0	0	0	0	0	0	0	0	1	0
store electricity	0	0	0	12	0	0	0	0	0	0	0	0
store mechanical energy	0	0	0	0	0	0	0	0	1	0	0	0
store product	0	0	0	3	0	0	0	0	0	0	1	1
store solids	3	0	1	1	0	0	0	0	0	8	0	0
supply electricity	0	0	0	1	0	0	0	0	0	0	0	0
supply mechanical energy	0	0	0	0	0	0	0	0	1	0	0	0
transmit electricity	0	0	0	0	0	0	1	0	0	2	0	0
transmit human force	7	0	0	0	7	0	0	0	0	0	0	0
transmit rotation	0	0	1	0	0	0	1	0	2	0	0	1
transmit heat	0	0	0	0	0	0	0	0	0	0	1	0
transmit translation	0	0	0	0	0	1	1	0	2	0	0	0
transport solid	3	0	0	0	0	0	0	3	3	0	0	0

b)

Figure A.1: Phi matrices for both subsets of products investigated.