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Functional Interdependence 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.*

Keywords: Design-by-analogy; Functional analysis; Mass customization; Modular design

1. Introduction

It is demonstrated in the literature (Hubker and Ernst Eder 1988; Ulrich 1995; Pahl and Beitz 1996; Ullman 1997) that customer-need-based, functionally-descriptive design methodologies are valid and effective. In this paper, we build on this philosophical background. We develop a method to determine the occurrence and importance of interdependent design functions[1] in groups of products. Interdependent functions are those that, throughout a set of products, occur in groups and have a significant impact on customer needs.

1.1. Motivation: The Niche of the Research

To understand the motivation for this research, consider the following questions: Why analyze products at a functional level? Such an approach allows fundamental explorations in design to be performed independent of and prior to the existence of form or structure. It also allows us to make a clear connection between customer needs, function, and form. Such connections are often implicit during product development; we wish to make them explicit and measurable. Why investigate interdependent functions; what impact can such methods have on practical design and design research? The identification of important interdependent functions in a group of products impacts product architecture, design by analogy, benchmarking, modularity, mass customization and product planning.

With the tools developed in this paper, specific architectural and form solutions for interdependent functions can be reviewed in a large class of products. Thus, design-by-analogy approaches may extend beyond singular functional comparisons, yet remain at a fundamental functional level. A designer's current design-by-analogy vocabulary can be extended beyond their immediate experience, providing access and contributions to new domains by discovering different products with common significant interdependent functions.

For redesign and product benchmarking efforts, the method developed here presents a quantitative measure of product similarity. This measure allows a designer to locate products for benchmarking whose similarity, or comparability, is not initially clear.

Identifying important interdependent functions in a group of products locates avenues for modularity that have an impact beyond a single product. Recognition of such information enables development and manufacturing on larger, more efficient, economies of scale. In addition, modules incorporating overlapping interdependent functions may be used to develop product architectures that enable, or simplify, mass customization and bus modularity (Rosenau et al. 1996).

Developing and evaluating modularity at a functional level has key advantages over structurally-based modularity. Modules developed post structure

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

are fully dependent on the form of the product, and thus only the solution parameters can be changed. If modularity is approached at a functional level, the module itself becomes a design parameter. Different modules and module embodiments can be combined with distinct product architectures and evaluated during conceptual design.

Also presented in this paper are tools that assist in product planning and resource allocation. Determining functional interdependence provides a solid foundation for companies to explore the development of new products using their existing, though perhaps not readily evident, expertise in functionally similar products. By measuring the impact of customer needs, companies may understand their competitive advantage and allocate resources for improvements along critical paths.

1.2. Related Work

Although functional analysis is a common topic of research, functional interrelationships have a limited treatment in the literature. Suh (1990) 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 (1996) 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.

1.3. Overview

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. Using this functional analysis, a technique is presented to group products into logical subsets. Using this grouping method, the analysis and discussion of two product subsets follows. The specifics of function interdependency and modularity are explored in detail through case studies in this section. These case studies also provide validation of the functional interdependence method. The paper concludes with a general discussion of the results and potential applications of the procedure.

2. Procedure of Investigation

The goal of this section is to develop a numerical measure of the importance of interdependent functions for a domain of products. Such a goal presents two problems. First, a domain comparable measure of single function importance is needed. Secondly, interdependent functions need to be identified. With these two problems solved, the single function importance measure may then be used to assigned a meaningful importance measure on the interdependent functions.

To determine the importance of a single function, we use the methodology developed by Little et al. (1997). We then extend the methodology to identify which functions occur together and assign a customer need related importance index. Also presented in this section are methods to select a set of products for analysis and the determination of the resolution of the interdependent function importance. We present the entire procedure in sufficient detail so that it may be repeated. Figure 1 shows the procedure in terms of the inputs, steps, and output of the overall process.

2.1. Organizing the Functional Product Data

In this subsection, we detail the steps required to organize the product-function data. To begin, customer need data and functional descriptions, or function structures[2], are needed for each product in the group (Hubker and Ernst Eder 1988; Ulrich 1995; Pahl and Beitz 1996; Ullman 1997). The first step in the procedure is to transform the product function structures into a common terminology of *basic* functions and flows. This transformation enables

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

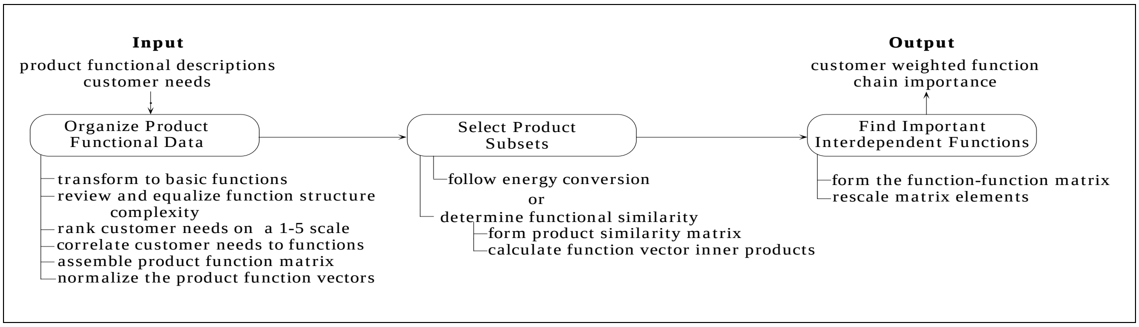


Fig. 1. The steps for determining the product interdependent functions.

comparison and identification of the same function in different products. These *basic* functions and flows are a basis set: a function structure for a large class or products can be generated from this finite set of functions and flows. Appendix A contains definitions for the *class* functions as well as tables of basic functions, basic flows, and the corresponding synonyms. The complete formal definitions for these functions and flows, and a detailed example of a function structure transformation, are presented in Little et al. (1997).

With product functionality described using a consistent terminology, the function structures are now reviewed and revised in the next step. The function structures are updated to express an equal level of complexity and detail in the functional model. For the data set of 68 products analyzed in this paper, the product complexity required approximately 20 functions for a complete functional description. The products can now be accurately compared at a purely functional level as they are expressed with a common terminology and an equal level of functional detail in representation.

Customer need weights are used to determine the functional importance. Before relating customer needs to functions, customer-need ratings for each product are translated to a scale of 1 (‘optional’) to 5 (‘must have’), using an appropriate method (Otto 1996). Recapping the procedure thus far, all the function structures are represented using a common terminology and all the customer need weights are ranked on a common scale. Next, functions are related to customer needs and assigned a numerical importance.

To determine the importance of a function, the impact of a function on a customer need is evaluated. If a function affects a specific customer need, then the weight of that customer need is assigned to the importance value of that function. Proceeding through each customer need, the assigned customer need weights are summed to determine the function importance.

It is important that the designer accurately assesses the relationship between customer needs and functions so that functions are appropriately weighted. To assure that the function importance value is accurate and repeatable, a two stage process is used. First, the material, energy, and signal flows from the function structure are assigned to the appropriate customer needs. For example, a customer need for ‘quiet operation’ is related to the flow of acoustic energy. After the customer need flow assignment, flows are related to functions by following the path of the flow through the function structure. In this manner, functions are related to flows, and in turn to customer needs.

A summary of the process so far is most easily expressed by recognizing the similarity of the current product-function representation with a vector space. At this point, each product is representable in a simple manner as a vector. Each element of this function vector is the importance measure of that function. Similarly, the function vectors naturally assemble into a product-function matrix. This matrix representation provides a clear and compact way of reviewing the data. Also, this approach to data organization facilitates computations on the importance measures.

Before assembling the vectors into a product-function matrix, we add the value of one (1) to each of the function importance values. This shift is performed so that the product vectors may be assembled into a matrix. In the product-function matrix, the functions that a product does not have are represented by a zero. The function importance scale is now a 1 to 6 point scale. Functions with an importance of 1 – those not directly related to a customer need – are supporting functions. A function importance value of 6 or higher indicates an essential, or highly important, function. Values greater than 6 can occur when one function relates to several customer needs.

The product-function matrix, $\mathbf{\Phi}$, is a mxn (m total different functions, n products) matrix. Each element ϕ_{ij} is the cumulative customer-need importance of the

ith function for the jth product. $\mathbf{\Phi}$ matrices for two subsets of products are shown in Appendix B as examples of the result of the procedure thus far[3].

Different product complexity and customer enthusiasm (during the customer need acquisition process) will affect the magnitude of the ϕ_{ij}'s for each product. To compensate for these differences, $\mathbf{\Phi}$ is normalized to validate comparisons between products. 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. Secondly, 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 $\mathbf{N}$, the normalized version of $\mathbf{\Phi}$, are

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

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.

[3]The techniques used to select these subsets from the entire product set are presented later in this paper.

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 product sub-function similarity to create product subsets.

Figure 2 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 Fig. 2, the primary energy input chosen is electricity. In Section 4, 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, $\mathbf{N}$, 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

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

$\mathcal{N}$ is the matrix of unity normalized product vectors, similar to $\mathbf{N}$. Each element, 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 $\mathbf{\Lambda}$, and coupled function importance matrix $\mathcal{S}$ (presented below), is similar to a technique Taylor (1996) used to determine topics and frequencies of discussion on internet newsgroup communication in student design teams.

Table 1 is a subset of products generated using the functional similarity method. The subset-*generating* product is a Dewalt 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.

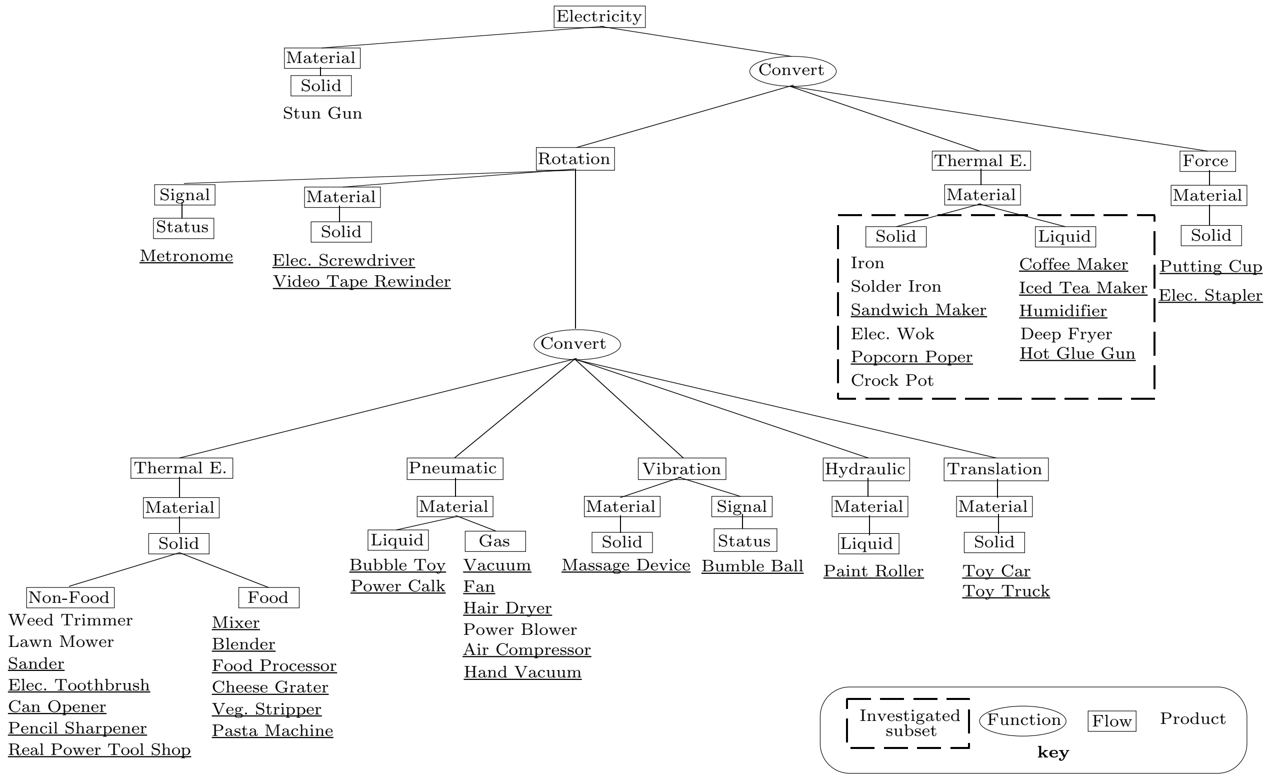


Fig. 2. Product hierarchy for products with electricity as a primary input flow. Underlined products are investigated in this study.

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

Product	Projection
palm sander	1.000000
fruit & veggie 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

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

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

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.

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

In this subsection, we present the final portion of the process: the computations for finding the important function groups are introduced. 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 based on common flows in the group of functions.

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

$$\mathcal{S}' = NN^T \quad (8)$$

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, a 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 in $\mathcal{S}$? 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 straightforward.

For brevity, the complete derivation is not presented here. Two functions 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

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

Using these two functions, the resolution is expressed as

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

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

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

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

For each of the $\binom{m}{2}$ 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.

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

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 rotations	1.763166	0.027557
import human force+change rotation	1.731498	0.027121
secure solid+import human force	1.665674	0.026137

3. Analysis and Example Case Studies

In this section, the linked function relationships for 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. 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. For example, in a small electrical palm sander, the functions *convert electricity to rotation* and *actuate electricity* operate on the common flow of electricity, thus these two functions form a common flow function chain. Distinctions between the sequence of the functions 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. The function *import human hand* may be a causal function for a *dissipate vibrations* function. The customer needs in this case are comfort issues. The presence of the hand in the system causes the need to prevent vibrations from causing hand discomfort. In other causally linked cases, the functions may be linked by control or prevention relationships. In the hot glue gun (from the functional similarity product subset), *transmit heat* and *regulate electricity* are considered causally linked because the *regulate electricity* function controls the amount of heat transmitted. In general, determining which function chains are causally linked requires some knowledge of the product group. Finding flow independent, causal function chains has a key application in redesign. Changing (improving) the causal function to eliminate the need for the caused function simplifies and improves an entire domain of products.

Independent flow, non-causal function chains share no common flow, operate separately from each other, and often result from distinct customer needs. In practice, these function chains are identified by removing one of the functions from the proposed chain. If eliminating a function allows the removal of another function in the chain (from the function structure) while still meeting all customer needs, these functions are not independent – some causal

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

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		
import solid+import human force	3.82	67
transmit heat+import electricity	3.34	100
store solid+import human force	3.13	83
store liquid+import human force	2.90	50
transmit heat+regulate electricity	2.48	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

relationship exists. Independent flow, non-causal function chains are not interdependent 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. These chains, however, do have an important impact on modular design.

Identification of important independent flow non-causal chains has implications for mass customization and product architecture. 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 manufactures handle option cutouts on a dashboard (Rosenau et al. 1996). 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 including materials selection and potential clumping options (Marks et al 1993).

The results of the analysis presented in this section are shown 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, non-causal 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 (Fig. 2) 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 flow independent, causally linked function chains are those that manipulate electricity and thermal energy. In the function chain *transmit heat+regulate electricity*, the electricity is regulated to determine how much thermal energy is transmitted. The *transmit heat+regulate electricity* function chain may be used to connect modules from the common flow functions, creating a larger module. Similarly, *transmit heat +import electricity* may be used to join the common thermal energy and common electricity function chains to create larger modules.

Table 4 contains only one common flow function chain, *convert electricity to heat+stop heat+transmit heat* 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-causal three function chain is *convert electricity*

Table 4. Customer need index and % occurrence for three 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+tramsit 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+tramsit 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+import 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+requlate 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 5. Identified modules in Brand A and Brand B iced tea brewers

Identified module Description	Brand A	Brand B	Assoc. Fig.
electricity to heat, imports electricity, actuates electricity, regulates electricity, converts electricity to heat, transmits heat, measures heat, stops heat, transports liquid	exists	exists	3
ice containment imports human force, imports solid, stores solid, secure solid	exists	exists	4
filter, tea containment imports human force, imports solid, stores solid, secure solid	exists	does not exist as a module	5
liquid containment imports human force, imports liquid, stores liquid	exists	exists	4

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

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 electricity to pneumatics+convert electricity to rotation	3.08	50
secure solid+position solid	2.87	50
Flow independent, causal		
import human hand+actuate electricity	4.24	100
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 hand+import human force	6.46	100
import human force+convert electricity to rotation	5.73	100
secure solid+import human hand	5.68	83
secure solid+convert electricity to rotation	4.87	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+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
import human hand+dissipate vibrations	3.12	50
remove solid+import electricity	3.09	67
import human hand+convert electricity to pneumatics	3.08	50
secure solid+import electricity	3.07	83

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, reorganization, or modularity 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 Fig. 3 contains three of the four common flow function chains as submodules: *transmit heat+convert electricity to heat*, *transmit heat+stop heat*, and *import electricity+convert electricity to heat*. The fourth function chain, *secure solid+import solid*, manifests itself as the pitcher and lid (for holding the ice) for

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

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

Fig. 3. The convert electricity to thermal energy module for both tea brewers.

Fig. 4. The *secure solid+import solid* and *import force+store liquid* for both tea brewers.

Fig. 5. The *import human force+import solid* and *store solid+secure solid* solution for the Brand A tea brewer.

both products in Fig. 4. Additionally, in Fig. 5, Brand A has a module for importing the filter and tea which is another manifestation of *secure solid+import solid* which the Brand B coffee brewer 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 Fig. 4.

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 clearly distinct 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 Fig. 3, which is described by three out of four 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.

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 embodied solution principle, 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 Fig. 6. 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 Fig. 6. 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. A module similar in concept, or a conceptual module, is one in which different products exhibit a module for the same function chains and the physical principle of solutions is the same. Details of embodiment, such as choice of materials, specific geometries, scales, and etc. are different. Here, a conceptual module uses the same solution principle 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.

Fig. 6. The *convert electricity to thermal energy* module for the Brand A tea brewer (left) and the Brand A coffee maker (right).

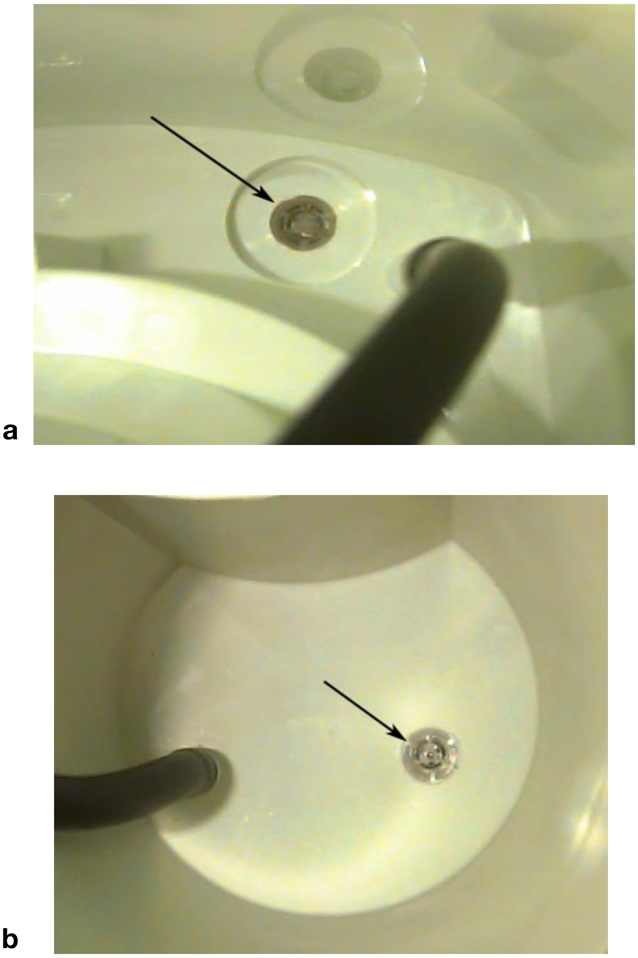


Fig. 7. The *transport liquid+stop liquid flow* solution for the coffee maker and the tea brewer. (a) Coffee maker, (b) tea brewer.

The third module identified, *transport liquid+stop liquid flow*, is shown in Fig. 7. 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 shortcoming 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.

3.2. The Functional Similarity Subset

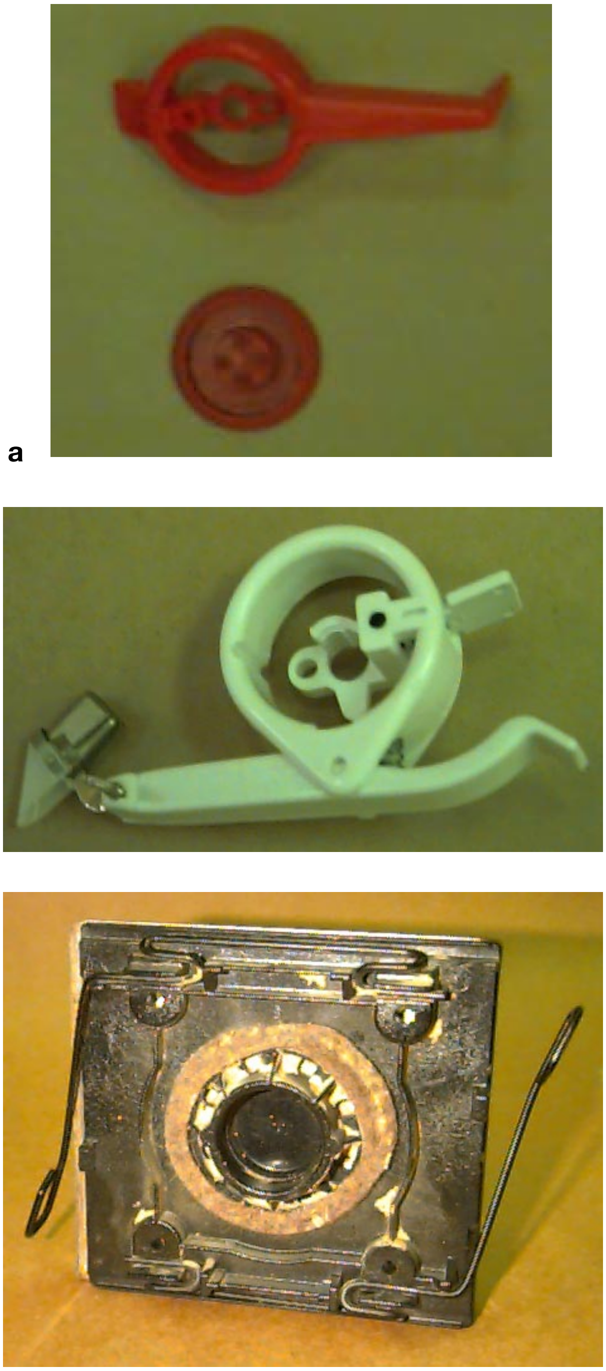
A second subset of six products, selected based on sub-functional similarity, is analyzed in this section. The products are the first six appearing in Table 1 Table 6 contains the two function chains, and Table 7 contains the three function chains for these six products. For this product subset, the 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 that all products require *import human hand to actuate electricity*. The second, existing in half of these products, is the *remove solid* function causing a need to *dissipate vibrations*. Also, half the products require *import human hand* which is causal to *position a solid* creating the third important function chain.

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



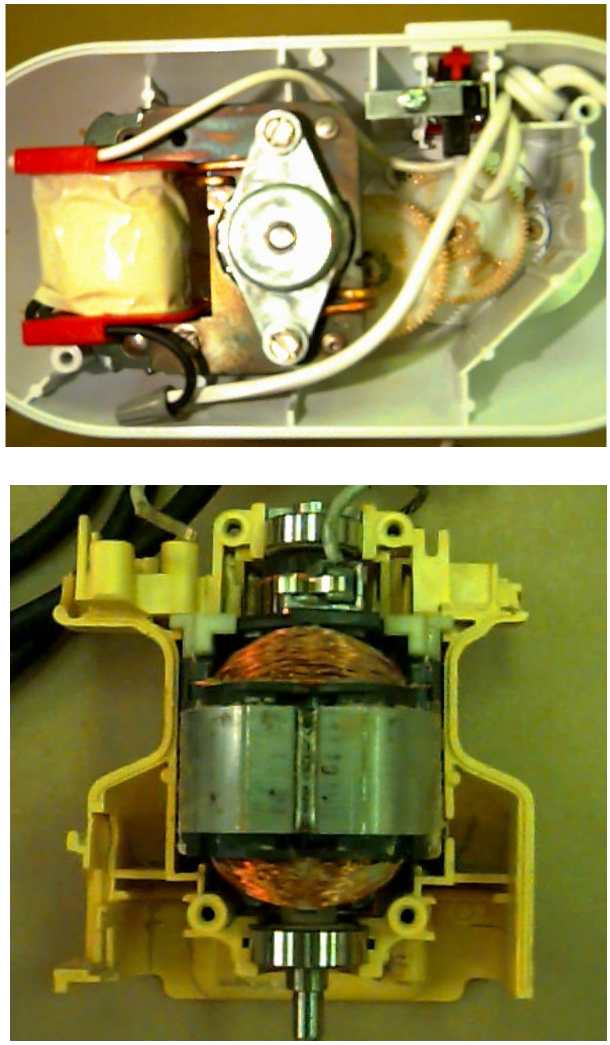
a

b

c

Fig. 8. Manipulate solid solutions for the fruit and vegetable peeler (a and b) and the hand sander (c).

combinations exist and are shown in Fig. 8. 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 Fig. 8(b) that the peeler has a spring loaded arm to hold the blade next to the solid for peeling. The



a

b

Fig. 9. The *convert electricity to rotation* solution for the hand sander and the fruit and vegetable peeler. (a) Fruit and vegetable peeler, (b) hand sander

sander, in Fig. 8(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 Fig. 8(a).

Another conceptual module of *import electricity*+-*convert electricity to rotation* is found in both the sander and peeler. These modules are shown in Fig. 9. 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 obviously 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 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 than 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 select new products for development. This method depends on an existing knowledge of product need. Also, this method allows a company to predict their 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, 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 product subsets 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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References

Hubka V, Ernst Eder W (1998) Theory of technical systems. Springer-Verlag, Berlin

Johannesson HL (1996) On the nature and consequences of functional couplings in axiomatic machine design. Proceedings of the 1996 DETC, 96-DETC/DTM-1528, Irvine, CA, August 18–22

Little AD, Wood KL, McAdams DA (1997) Functional analysis: A fundamental empirical study for reverse engineering, benchmarking and redesign. Proceedings of the 1997 ASME DETC, 97-DETC/DTM-3879, Sacramento, CA, September 14-17
Marks MD, Eubanks CF, Ishii K (1993) Life-cycle clumping of product designs for ownership and retirement. Design Theory and Methodology Proceedings, Volume 53, ASME, September 1993, pp 83–90
Nam P Suh (1990) The principles of design. Oxford University Press, New York
Otto, K (1996) Forming product design specifications. Proceedings of the 1996 ASME Design Theory and Methodology Conference, 96-DETC/DTM-1517, Irvine, CA
Pahl G, Beitz W (1996) Engineering design: a systematic approach. Springer, New York
Rosenau MD Jr et al. (editors) (1996) The PDMA handbook of new product development, Chapter 16, Wiley, pp 216–235
Taylor D (1996) Process metrics for asynchronous concurrent engineering. Proceedings of the 1996 DETC, 96-DECT/DTM-1500, Irvine, CA, August 18–22
Ullman D (1997) The mechanical design process. McGraw-Hill, New York
Ulrich KT, Eppinger S (1995) Product design and development. McGraw-Hill, NY

Appendix A: Functions and Flows

In this section, flows from Table A1 are clarified and class functions from Table A2 are defined. We have attempted to make the definitions consistent with engineering terminology and standard English definitions. However, some definitions used are not the common primary definition. Also, the meaning of a word is often restricted. Our object here is not complete linguistic accuracy, but operational classification. The goal is to present a terminology for research and discussion.

Flows. Flows are first distinguished by class *materials*, *energy*, and *signals* (Pahl and Beitz 1996), then by basic flows and, if desired, into compliment flows, as shown in Table A1.

Human energy and human material are both basic flows. This inclusion is a result of the importance of human-product interaction and generally improves functional descriptions and design solutions. It is often known early in a product design that certain energy and material inputs are going to be a person's interaction with the product.

The *compliment* subdivision of flows allows for a more concrete description of the flow to be used. The compliment flow terminology should only be used when it is required by the operational constraints, or customer needs, of the product. Using the basic flow, or class flow, terminology allows a broader and less solution-associated functional description.

Signals are a separate flow class, even though signals are either material or energy. The relevant

Table A1. Basic flows

Class	Basic	
Material	Solid	
	Liquid	
	Human	
	Gas	
Energy	Human	Motion, Force
	Biological	
	Mechanical	Translation, Force, Rotation, Torque, Random motion, Vibration, Rotational energy, Translational energy
	Electrical	Voltage, Current
	Hydraulic	Pressure, Volumetric Flow
	Thermal	Conduction, Convection
	Pneumatic	Pressure, Volumetric Flow
	Chemical	
	Radioactive	
	Acoustic	
	Optical	
	Solar	
	Magnetic	Magnetomotive Force, Flux Rate
Signal	Status	Pressure, Temperature, Position, Displacement
	Control	

Table A2. Function classes, basic functions and synonyms. Italics indicate a repeated synonym

Function class	Basic function	Flow restricted	Synonyms
Channel	Import		Input, Receive, *Allow*, Form Entrance, *Capture*
	Export		Discharge, Eject, Dispose, Remove
	Transfer		
		Transport	Lift, Move
		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, Value
		Remove	Cut, Polish, Sand, Drill, Lathe
	Refine		Purify, Strain, Filter, Percolate, Clear
	Distribute		Diverge, Scatter, Disperse, *Diffuse*, Resist
	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 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, Verify
	Indicate		Mark
	Display		
	Measure		Calculate

feature of a signal flow is the information it carries. The specifics of how that information is carried, including embodiment as energy or materials, is a solution for that signal manipulation.

Specific definitions for the flows listed in Table A1 are not given here. The definitions we used for the flows are consistent with those commonly used. Discerning between basic flows may not always be clear. For example, is asphalt best characterized a liquid or a solid? Is dust a gas or a solid? The answer to these questions is a technical one, and not one of categorical philosophy.

Functions. The same philosophy used to categorize flows is used to categorize the functions. Definitions are given for each function class.

- *Channel:* To control the motion, or path, of a material or energy flow.
- *Support:* To firmly fix a material into a defined location, or secure an energy into a specific course.
- *Connect:* To bring two or more energies or materials together.
- *Branch:* To cause a material or energy to no longer be joined or mixed.

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

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

Fig. B1. Phi matrices for both subsets of products investigated.

- *Provision:* To accumulate or provide material or energy.
- *Control Magnitude:* To alter or govern the size or amplitude of material or energy.
- *Convert:* To change from one form of energy or material to another.
- *Signal:* To provide information.

Appendix B: Function-Product Matrices

Functional analysis of a large set of products is simplified by representing products as a vector of function importance weights in a vector space of design functions. Function-product matrices, $\boldsymbol{\Phi}$ for the two product subsets used as examples in this paper are shown in Fig. B1.