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Developing design templates for product platform focused design

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Product platforms, product families, and modular design are an evolving research area. Many of the theories and concepts proposed serve as powerful tools to industry in reducing the number of specialized components in products, reducing assembly time and accelerating the conceptual and embodiment design stages. In this paper, a structured approach to the modular design of electro-mechanical consumer products is proposed based on a study of the module structure of products. The approach is based on developing product family design templates. These templates are based on prior product design knowledge and the flow and conversion of energy through a product. The templates also carry potential embodiment solution information. Design templates for two product classes, *electricity to thermal energy* and *electricity to rotational energy*, have been developed and can be used by designers to undertake design or re-design efforts on products. A group of 16 consumer products from two product families has been used in this study. A clarifying design example is presented.

1. Introduction

Modular product architecture offers many advantages to manufacturers and consumers. Modular product architectures can reduce the number of parts in a product, reduce the time to manufacture and assemble the product, and streamline and simplify the conceptual design and embodiment design phases through the re-use of previous parts or ideas. On the whole, significant reductions in both design and production time can be achieved through utilization of modular product architectures. Although there has been significant research activity into modular design, designers still have little in the way of guidelines, principles, methods, or theories of modular design that they can use to develop useful and intelligent modular product architectures. This article builds upon and extends previous modular product architecture research to contribute to the available methods by which a designer may design a modular product architecture.

The research reported in this article focuses on a key advantage of modular product architectures: common conceptual and physical platforms can be used in different products that share a common module. This approach reduces the need to develop unique parts for each new product and potentially reduces part count for a family of products. Here, an approach for developing common product platform is developed.

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2. Background and related work

The product architecture design approach developed in this article builds upon the construction of a product functional model and the identification of potential modules from analysis of the functional model. Construction of functional models and related prior work is presented in this section. Also discussed is other relevant work in the area of product architecture, product platforms, and modular design methods.

2.1. Functional modeling

At a high and abstract level, a product can be represented by a single overall function. This overall function is generally referred to as a black box function. Shown in figure 1 is a black box function for some product that is to heat and/or process food. To completely describe product functionality, the overall production is decomposed into a set of subfunctions. These subfunctions provide a detailed description of what a product most *do* rather than what it *is*. For example, a required product subfunction could be to store energy. The form or component that provides this function could be a compressed helical coil spring.

Returning to the black box model of figure 1, a chain of simpler tasks or subfunctions solves the objective *heat or process food*. Relationships between these subfunctions are established on the basis of energy, material and signal interactions. The flow of energy, material and signal through the different subfunctions of a product is traced, and the graphical representation of these interactions is called a *function structure* or *function model*, as shown in figure 2.

Research in value engineering establishes the description of a subfunction as a verb–object pair (Miles 1972). Subfunctions are later described by a set of five valid functions and three flow types (Pahl and Beitz 1988). More recent work by Stone and Wood (2000) has resulted in a formal *functional basis*, which is a method to derive functional models for products from a standard set of functions and flows capable of describing the mechanical design space. Hirtz *et al.* (2002) have reported more work

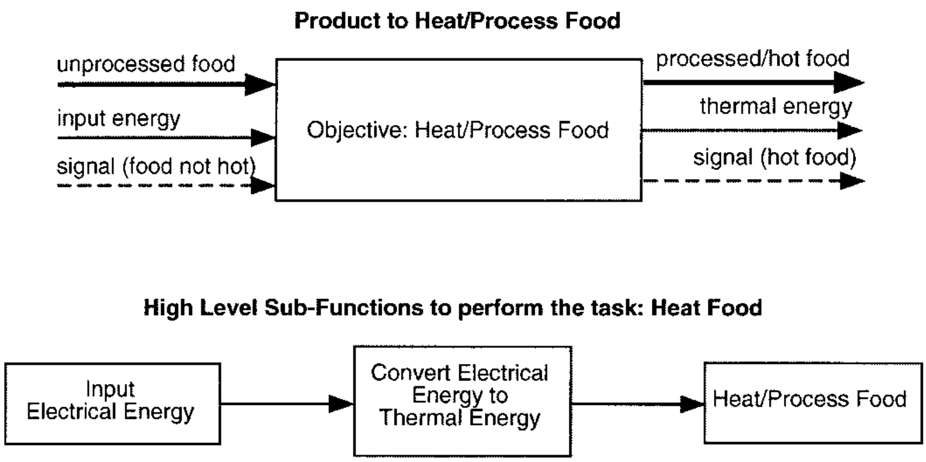

Figure 1. Application 'heat food'.

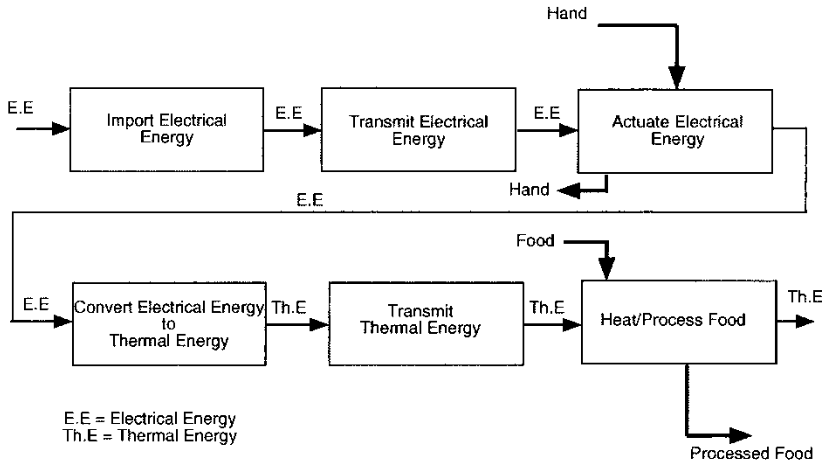

Figure 2. A fragment of function structure for the application 'heat food'.

on the evolution of functional basis. In this article, we use the functional basis from Hirtz *et al.* as the most recent and preferred terminology for describing product function.

2.2. Product architecture

The development of a framework to collect, classify and share information on products and their components has been discussed by Pahng *et al.* (1997). In their work, they have delineated a framework for Object-based Modeling and Evaluation (OME) of product design problems. Otto and Wood (1998) have proposed a 10-step reverse engineering and re-design methodology for improving design of existing products. Marshal *et al.* (1999) have discussed the benefits of design modularization. Their emphasis is that variety can be offered efficiently through a standard set of modules, and the re-use of related modules. Ulrich (1995) has defined product architecture as the mapping from function to form. Huang and Kusiak (1996) have also discussed types of modularity. Two main categories of product architectures are identified; namely, integral and modular.

An integral architecture is one in which the different subfunctions have a complex mapping relationship with the components of the product. In this case, replacement or re-design of a singular component is not a direct task. Systems in which the components have a large number of interactions with many components, for example the automobile cruise control system, fall into this category.

In products that are grouped into modular architecture, there is a one-to-one correspondence between subfunction sets and the components. This renders the opportunity to improve or re-design a single component or a subsystem without affecting the working of the overall system. It is not uncommon to see that a set of products performing similar tasks is composed of similar modules with little or no changes in part composition. This results because re-using parts and subassemblies is a key advantage to developing modular designs. Companies take advantage of this to augment product performance through improvements in subassemblies, and to successfully launch a platform of products in which each product targets different customer populations.

2.3. Product platforms

Meyer and Lehnerd (1997) define a product platform as a set of parts, subsystems, interfaces and manufacturing processes that are shared among a set of products, thus allowing the development of derivative products with cost and time savings. The development of product platforms with extensive information on the part sets, subsystems, interfaces, and the manufacturing processes is assumed to benefit companies. The product platform approach is a major step towards meeting inexpensive product variants, mass customization, shrinking of the design cycle, and a medium for information sharing by engineers and designers. Although product platforms offer many advantages, as products become more complex, product platforms become more complex. The design and embodiment information associated with the product platform becomes both large and complex.

The development of product platforms is discussed by Otto *et al.* (1998). Specific applications to interplanetary missions and consumer products are explored. Regardless of the application, extending tools for modular product design and product platform design remains a critical design need. Frameworks are needed that allow designers to reason about various modules, interfaces, interaction information and embodiment information.

2.4. Modular design

Modularity is viewed by Ulrich and Tung (1991) as: (i) similarity between the physical and the functional architecture, and (ii) minimization of incidental interactions between physical components. McAdams *et al.* (1999) have described analytical methods to study the percentage occurrence of function chains in products and their interactions. Sets of subfunctions that are grouped based on a logic pattern are called modules. Stone *et al.* (1998, 2000) have formulated a set of heuristics to group functions to form a module. These modules in effect are a collection of related subfunctions that perform one of the many tasks accomplished by the final product. We will use the heuristics here to identify modules from functional models.

Kayyalethekkal (2000) has performed experimental studies on part count reduction in products and developed a product architecture based conceptual design for assembly technique. In this work, the author recommends a heuristic that if the number of functional modules recognized by Stone's heuristics is less than the number of assembly module identified by disassembly, then part count reduction is possible by reducing the number of elements that take part in modular interaction.

2.4.1. Types of modularity. Modularity in the basic sense means the handling of common units among products to create product variants. Ulrich and Tung (1991) have formulated a basic generalization of types of modularity: *Component Swapping*, *Component Sharing*, and *Bus Modularity*. While bus modularity is evident in computer memory chip fabrication, the prominent types of modules present in consumer products are component swapping and component sharing.

Component swapping can occur either external or internal to a product. Changing bit types in a screwdriver or changing bulbs in a table lamp is an example of external component swapping. In some consumer products the electrical module is responsible for providing power to thermal and rotational modules. This exemplifies internal component swapping. In such cases, some components of the electrical module are shared by the thermal and rotational modules. Component swapping can be considered as a means improve the versatility of a product by enabling different levels of performance and/or different applications. Examples of component swapping include mixers with different mixing paddles and hand-held drills with different bits. Component sharing is the primary type of modularity seen when products are developed on a common platform. This type of modularity is largely the focus of this article. The goal is to develop tools to allow designers to develop better product platforms and utilize existing platforms more efficiently.

2.5. Product platforms and modular design

Finally, we end this literature review with a discussion of some recent and pertinent work on modular products. Otto *et al.* (2000) have formulated a framework for architecting a family of products that share inter-changeable modules. They define a modularity matrix for one family of products from a manufacturer. This matrix lists the subfunctions as rows and products as columns. The matrix allows commonalties to be easily identified. Otto *et al.* (2000) discuss the design of products that are in common classes of energy conversion, for example the conversion of electrical energy to rotational energy, or an *electricity to rotation* class.

The interchangeability and reusability of modules for one energy conversion class of products from one manufacturer has been investigated by Otto *et al.* (2000). We extend on this approach here by considering multiple energy flow issues in single products and then extend that to product platforms.

3. Developing a foundation for product platform design templates

Before proposing a product platform design template, a fundamental understanding of the common and differentiating structure of products is needed. What modules occur repeatedly? What modules often occur together? What modules differentiate products and thus serve poorly as a foundation for a product platform design template? An empirical research approach is employed to explore these issues.

In brief, the research followed three broad phases: (1) identification of modules in an electromechanical product and mapping of function to module for a set of 16 products; (2) examination of the identified modules for frequency of occurrence; and (3) cataloging of module–function–form design knowledge.

3.1. Phase 1: empirical study data collection

Phase one consists of disassembling and cataloging electromechanical products to develop a classification scheme for the types of modules in a system. For the work presented here, 16 products were disassembled. A functional model was developed for each product. The functional basis is used to develop the functional models (Hirtz *et al.* 2000, Kurfman *et al.* 2001). The module heuristics are used to classify and recognize modules (Stone *et al.* 1998, 2000).

3.2. Phase 2: exploring modular frequency

The next step is to identify the modules that repeat in many products as well as chains of modules appearing frequently in a product function structure. The approach here is to explore the occurrence of modules. The identification of module chains is as follows.

1. Apply the module heuristics to the functional model of each product to identify the various modules in product set.
2. Develop a Product–Module matrix and record the presence of a module in a particular product with an 'X' in the corresponding matrix element. The Product–Module matrix developed for a set of 16 consumer products is presented in table 1.
3. Re-arrange the columns without disturbing the rows to group together the types of modules of interest. Here, the modules of interest are those that operate on energy. The result of rearranging the columns of modules that operate on energy is presented in table 2, where energy related modules are shown shaded. Additionally, the modules that operate on material and signal flows may be grouped together.
4. Rearrange the rows such that the clusters of 'X' marks are diagonalized for the modules that operate on energy flows.

The fourth step groups products based on repeated modules. The presence of repeated or common modules indicates a large similarity between the products that can be enhanced by formally developing a common platform of some kind for this product family. The results of step 4 as applied to this product set are presented in table 3. We note that we have neglected five energy-related modules (vibration, magnetic, mechanical, lock and support) for two contrasting reasons. The first four are scarcely seen in the product set. The final support module is pervasive throughout the product set and will be considered for any product.

The results presented in this article are intended to benefit individual designers, product family planners, and product developers focusing on mass customization. Tables 1–3 represent a wide and diverse group of product information. Product family planners and other designers working on developing large-scale design initiatives can use product information such as that in tables 1–3. In the case where a single company or designer may not have access to this volume of information, design catalogues and standardized parts can be developed to enable product design using templates similar to those developed in this article.

3.2.1. Developing module classifications. Once the row–column rearrangement is complete, it is apparent that different modules arrange themselves in three ways. Modules like *electrical module*, *thermal module*, *rotational module*, and so on, are found in thick clusters and in large numbers, which means many of these modules are present in most of the products. These modules deal with importing, manipulating, converting, and expending energy forms like electrical energy, thermal energy, pneumatic energy, and so on. These modules are classified as *primary energy flow modules.*

Modules like *air module*, *liquid module*, *water module*, and so on, are arranged in thinly populated clusters, as presented in table 3. These modules are present where there is a need to carry or transmit energy through a material with some measurable momentum. For example, consider the interaction between the *steam module*, thermal module, and *electrical module* in a coffee maker. In this case thermal energy is transported physically from one module to the other through resistance coils. There is no significant momentum. In contrast, the energy transmitted between the steam module and thermal module is through hot water. The movement of water has a measurable

Product to Module Relationship-1	MODULES																												
PRODUCTS	Air	Bit	Blade	Butter	Cloth	Coffee	Corn	Debris	Electrical	Food	Froth	Liquid	Lock	Magnetic	Mechanical	Pencil	Powder	Rotational	Rot Control	Sandpaper	Steam	Support	Tea	Tea Bag	Temp Control	Thermal	Tip	Vibration	Water
B&D Power Sander	X							X	X									X		X								X	
Bissel Hand Vacuum	X							X	X									X				X							
Mr.Coffee Coffee maker						X			X								X					X			X	X			X
SKIl Cordless screwdriver		X							X				X					X	X			X							
Dewalt Palm Sander								X	X									X		X		X						X	
Electric Pencil Sharpener								X	X							X		X											
West Bend Electric Wok									X	X		X										X			X	X			
Con Air Hair Dryer	X								X									X				X			X	X			
Heavy Duty Stapler		X											X				X										X		
Mr.Coffee Iced Tea Maker									X													X	X	X	X	X			X
Proctor-Silex Iron Box					X				X			X									X	X			X	X			
Krups Café Trio						X			X		X						X				X					X			X
Presto Popcorn Popper	X			X			X		X									X				X			X	X			
Spatula Mixer	X								X									X	X			X							
Proctor-Silex Electric Toaster									X	X				X	X							X			X	X			
Weed trimmer			X																										

Table 1. Product-module relationship: step 1.

Product to Module Relationship-2	MODULES																											
PRODUCTS	Bit	Blade	Butter	Cloth	Coffee	Corn	Food	Pencil	Powder	Tea	Tea Bag	Tip	Sand Paper	Air	Debris	Froth	Liquid	Steam	Water	Electrical	Rotational	Rot Control	Temp Control	Thermal	Vibration	Magnetic	Mechanical	Lock	Support
B&D Power Sander													X	X	X					X	X				X				
Bissel Hand Vacuum														X	X					X	X								X
Mr.Coffee Coffee maker					X				X										X	X				X					X
SKII Cordless screwdriver	X																			X	X	X						X	X
Dewalt Palm Sander													X		X					X	X				X				X
Electric Pencil Sharpener								X				X			X					X	X								
West Bend Electric Wok							X										X			X			X	X					X
Con Air Hair Dryer														X						X	X		X	X					X
Heavy Duty Stapler	X																				X								
Mr.Coffee Iced Tea Maker										X	X								X	X				X					X
Proctor-Silex Iron Box				X													X	X		X			X	X					X
Krups Café Trio					X				X							X		X	X	X			X	X					
Presto Popcorn Popper			X			X								X						X	X			X					X
Spatula Mixer							X							X						X	X	X	X						X
Proctor-Silex Electric Toaster																				X				X		X	X		X
Weed trimmer		X																		X			X						

Table 2. Product-module matrix: step 2.

		MODULES																												
	Product to Module Relationship-3	Bit	Blade	Butter	Cloth	Coffee	Corn	Food	Pencil	Powder	Tea	Tea Bag	Tip	Sand Paper	Air	Debris	Froth	Liquid	Steam	Water	Temp Control	Thermal	Electrical	Rotation	Rot Control	Vibration	Magnetic	Mechanical	Lock	Support
PRODUCTS	West Bend Electric Wok							X										X			X	X	X							X
	Proctor-Silex Electric Iron				X													X	X		X	X	X							X
	Krups Café Trio					X				X							X		X	X	X	X	X							X
	Proctor-Silex Electric Toaster							X								X					X	X	X				X	X		X
	Con Air Hair Dryer														X						X	X	X	X						X
	Presto Popcorn Popper			X			X								X							X	X	X						X
	Mr.Coffee Coffee Maker					X				X										X		X	X							X
	Mr.Coffee Iced Tea Maker										X	X								X		X	X							X
	B&D Power Sander													X	X	X							X	X		X				
	Bissel hand Vacuum														X	X							X	X						X
	DeWalt palm sander													X		X							X	X		X				X
	Electric Pencil Sharpener								X				X			X							X	X						
	Weed Trimmer		X													X							X	X						X
	SKIL Cordless screwdriver	X																					X	X	X				X	X
	Spatula Mix																						X	X	X					
	Heavy Duty Stapler	X																						X						

Table 3. Product-module matrix: classification of modules.

momentum that is large compared with any other measurable momentum in the system. Thus, these modules are classified as *material momentum modules.*

Modules like *corn module* (popcorn popper) and *bit module* (Screwdriver) are scarcely distributed across products as presented in table 3. For instance, the corn and butter module is found only in the popcorn popper. The sandpaper module is found only in the sanders. These modules are unique to a product and, while satisfying certain customer needs, tend to define the size and shape of the final product. Thus, we classify these modules as *form defining modules.*

In summary, the modules classify neatly into three groups, the primary energy flow modules, the material momentum modules, and the form defining modules. These classifications are now used to develop a template for designing products from the product platform perspective.

3.3. Phase 3: cataloguing module–function–form knowledge

An automated or semi-automated design template would enable the quick progression from module to function to component descriptions of a product. To enable such a progression, the existing knowledge can be stored using a module–function–component hierarchy.

A module consists of several functions. Each of these functions is solved by some component or components. Presented in table 4 is the module–function–component breakdown for a hot air popcorn popper. Presented in table 5 is a similar decomposition for the primary energy modules of all 16 products reviewed for this study. All the components used to solve a particular function from this product group are included in the table. These databases allow a quick progression from abstract modular product representations to components that constitute the product.

4. Developing product platform design templates

Here, we present the step-by-step process required to develop a product platform design template. Based on the research presented in section 3, our philosophy is to consider the flow of energy as the driving factor in the development of a product platform. The product platform is derived from the main energy conversion subfunction in the product. Because of the occurrence and recurrence of primary energy flow modules, this extends naturally to a useful design template for the product platform. Also, the primary energy flow modules contain the primary energy conversion subfunction. Thus, the primary energy flow modules and how these interact with the material momentum and form defining modules constitute the backbone of the design template.

The four-step design template develop process is as follows.

1. Identify an existing set of products to serve as a knowledge base. Select a group of products that share a common primary energy conversion subfunction. From this group of products, create a module pool of energy flow modules using the module heuristics.
2. Establish module dependency. Module dependency is used to distinguish primary and secondary energy flow modules. Energy flow modules that are dependent on other energy flow modules are secondary modules. Energy control modules are also considered secondary modules.

Module	Subfunctions	Form elements/embodiment solutions
Corn module	Import solid	Transparent plastic guide
	Store solid	Heavy plastic popping chamber lid
	Transmit thermal energy	Hollow aluminium cylinder
	Guide solid	Flanged base
	Export solid	Flanged base
Air module	Import gas	External plastic cover
	Convert mechanical energy to pneumatic energy	Fan
	Transmit thermal energy	Fan
	Transport gas	Heavy plastic popping chamber lid
Thermal module	Convert electrical energy to thermal energy	Big heating element, small heating element
	Stop thermal energy	Big mica sheet, small mica sheet
Rotational module	Convert electrical energy to rotational energy	DC motor
	Transmit rotational energy	Shaft on motor
Temperature control module	Measure thermal energy	Thermostat, bimetallic strip, thermostat support
Butter module	Import solid	Butter cup
	Store solid	Butter cup
	Convert solid to liquid	(Hot air)/air medium
	Store liquid	Butter cup
	Export liquid	Butter cup
Electrical module	Import electrical energy	Plug, electric cord
	Separate electrical energy	Wires and wire connections
	Transmit electrical energy	Metal contacts, solders
	Regulate electrical energy	(Bimetallic strip)
Support module	Import weight	Plastic casing
	Distribute weight	Bottom metal plate
	Stabilize weight	Fan and motor holder, screws

Table 4. Module to form feature relationship for a hot air popcorn popper.

3. Construct the product family design template using the following rules:
   - Develop a central horizontal block. The central horizontal block of the template contains the critical energy flow through the product. This block includes the primary energy flow modules, the material momentum modules, and the form defining modules
   - Secondary modules branch off from the flow chain vertically.
4. Complete the design template by expanding the modules in the template to include the subfunctions that constitute the modules.

With the subfunctions integrated into the modules, the design template is complete. In short, the template represents the complete functionality of the product platform grouped by modules. Note that the particular component or form solution used to solve the functions in the template can be linked to the template and thus provide a knowledge base for accessing prior design solution knowledge.

Module	Subfunctions	Possible form solutions at the conceptual level
Electrical module	Import electrical energy	Plug, cord
	Store electrical energy	Battery, cells
	Supply electrical energy	Leads, contacts, solders, wires
	Activate electrical energy	Switches, contacts
	Separate electrical energy	Wires, solders
	Transmit electrical energy	Wires
	Regulate electrical energy	Potentiometers, resistance, coils
Thermal module	Convert electrical energy to thermal energy	Resistances, heating coils
	Transmit thermal energy	Heating elements, heating plate, heating tubes, medium (air/water)
	Stop thermal energy	Insulator pads, mica sheets, thermocouple, thermostat
Rotation module	Convert electrical energy to rotational energy	DC/AC motors
	Transmit rotational energy	Motor shaft, armature
Pneumatic module	Convert electrical energy to pneumatic module	Fan, external case for air intake
	Transmit pneumatic energy	Fan, external case for air intake
Temperature control module	Measure thermal energy	Thermostat, resistance coils, bimetallic strips
	Stop thermal energy	Bimetallic strips
Rotation control module	Change rotational energy (direction)	Direction-reversing DC circuit
	Change rotational energy (speed/torque)	Potentiometers, resistances
	Arrest degree of fredom (lock)	Push buttons, slot and bit, cam and lock
	Stop rotation	Switches, contacts

Table 5. Aggregate list of possible form solutions to modules at the conceptual level.

To clarify the procedure, an example is presented here for a set of products that have convert electricity to thermal energy subfunctions producing electricity to thermal energy product platforms. This set of products consists of eight of the 16 products studied for this research.

Step 1: *create primary energy flow module pool.* The energy flow modules in the electricity to thermal energy product group are the *electrical module*, the *thermal module*, the *temperature control module* and the *rotation module.* These modules are identified from table 6, a fragment of the overall product-module matrix showing the frequently occurring energy flow modules.

Step 2: *establish module dependency.* In this group of products, the presence of the temperature control module is necessitated by the presence of the thermal module in a product. In the context of developing product family design template, this relationship could occur in multiple products in the family. Thus,

PRODUCTS	Diagnolised Product-Operational Module matrix	Temp Control	Thermal	Electrical	Rotation	Rot Control	
	West Bend Electric Wok	X	X	X			Electricity to Thermal with Temperature Control
	Proctor-Silex Electric Iron	X	X	X			
	Krups café Trio	X	X	X			
	Proctor-Silex Electric Toaster	X	X	X			
	Con Air Hair Dryer	X	X	X	X		Electricity to Thermal, Rotation
	Presto Popcorn Popper		X	X	X		
	Mr.Coffee Coffee maker		X	X			Electricity to Thermal
	Mr.Coffee Iced team maker		X	X			
	B&D Power Sander			X	X		Electricity to Rotation
	Bissel Hand vacuum			X	X		
	DeWalt Palm Sander			X	X		
	Electric pencil sharpener			X	X		
	Weed trimmer			X	X		
	SKIL Cordless screw driver			X	X	X	Electricity to Rotation with rotational control
	Spatula Mix			X	X	X	
	Heavy duty stapler				X		

Table 6. Diagonalized product-primary energy flow module matrix.

it is important to account for this in the template. Also, the dependency relationship identifies which modules in the module pool are primary energy flow modules and which are secondary modules.

For the products under study, electrical energy is the input energy to the products. The input energy module is treated as a primary energy flow module. From study of the products in the group, the thermal module is a primary energy flow module. The remaining modules, the temperature control module and the rotation module, are considered as dependent or secondary modules. These modules existence is dependent on the existence of the primary energy flow modules.

Step 3: *construct the product family design template.* Once the primary and secondary energy flow modules are identified, a general product family design template is constructed. Following the rules already presented, the graphical template evolves as shown in figures 3–5. Initially, the electrical module and the thermal module are positioned on the horizontal block (figure 3). Next, the secondary energy flow modules for control and rotation are added above and below the primary energy flow modules (figure 4). Next, the material momentum and form definition modules are added at the right of the central block (figure 5).

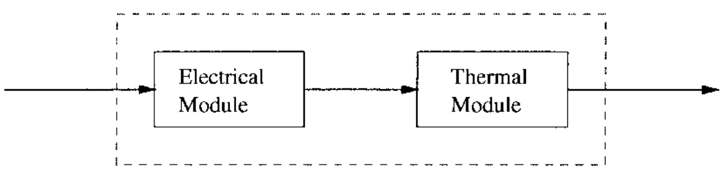

Figure 3. Adding the primary energy flow modules to the design template.

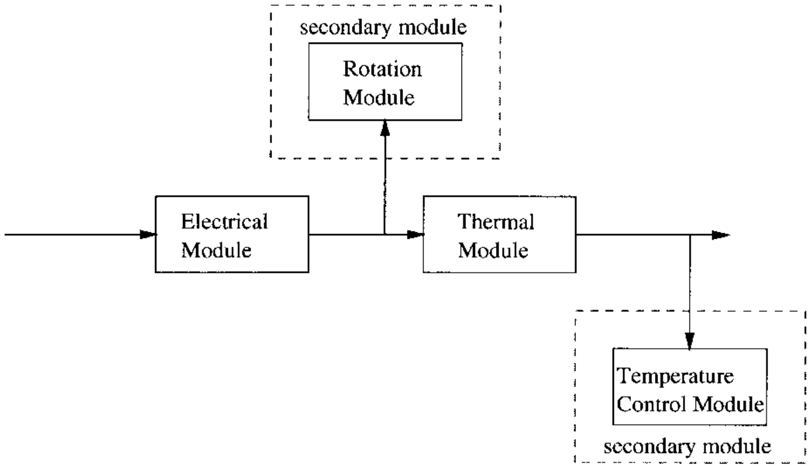

Figure 4. Adding the secondary modules to the design template.

Step 4: *expand the module representations.* The final step is to expand the product platform design template to include the subfunctions in each of the modules. As the template is expanded, conversion functions are included in the template. For the secondary energy flow modules, the conversion functions are included in the same way as for the primary energy flow modules. The primary and secondary energy flow modules contain a functional similarity: the function chains are connected by a conversion function. The critical difference is that the secondary energy flow module does not make a good candidate for a product platform design template since its functions are dependent on the existence of the primary energy flow functions.

Also included in the final expansion are the interface modules. These modules may not always be needed when designing a single product with integral architecture. However, when developing products on a product platform, these functions are needed to allow different modules to be plugged in and out of the basic product platform.

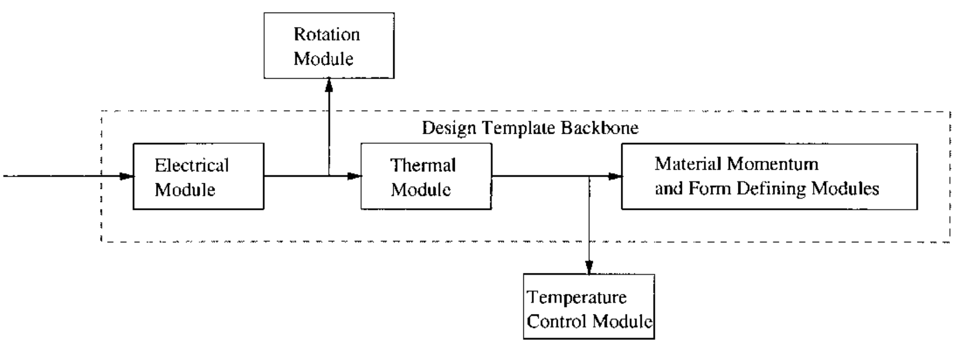

Figure 5. Adding the form defining modules to the design template.

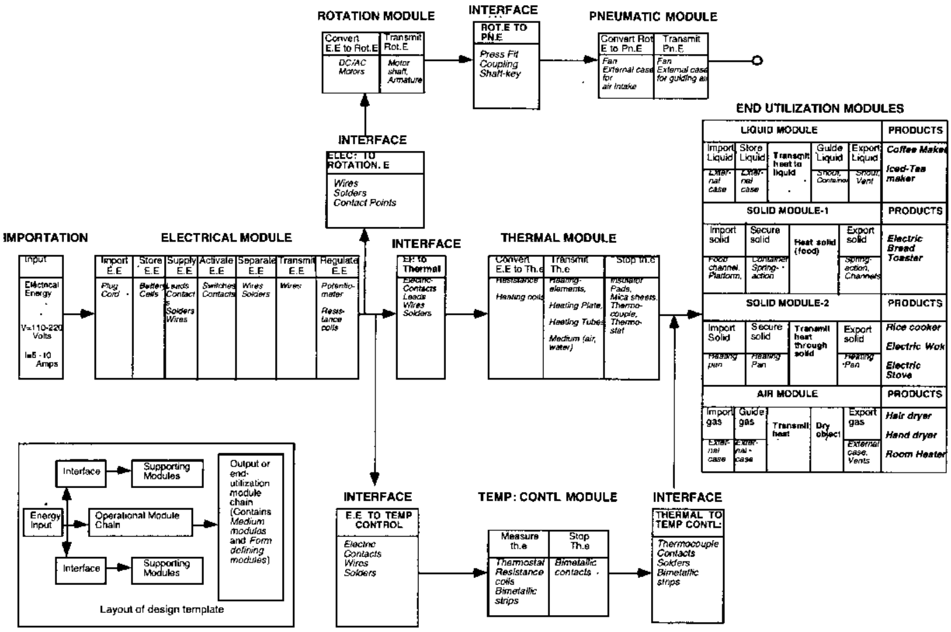

Figure 6. Generic design template for the electrical to thermal energy product class.

The final product platform design template is shown in figure 6 for the convert electricity to thermal energy product platform. A similar process is used to form the convert electricity to rotational energy product platform shown in figure 7.

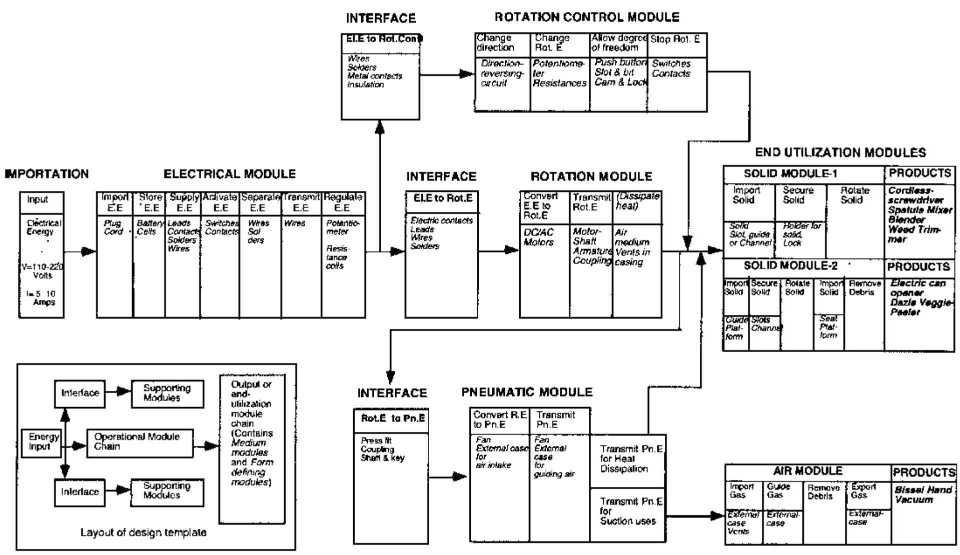

Figure 7. Generic design template for the electricity to rotational energy product class.

The product family design templates developed above provide a design framework to enable the synthesis of products designs within the framework of an existing or desired product platform. The templates focus on the key aspects of energy conversion, utilization, and control. Specifically, the templates identify the primary energy flow and the dependent functions that define a product family. Of critical importance to developing modular products and modular product families, the templates gives a generalized layout of the primary energy flow modules specific to that product family domain. Included in the template are constituent subfunctions of the individual modules.

5. Example: developing a product from a product platform design template

In this section, the previously developed design templates are used to explore a new product within the framework of an existing product platform. In addition, design knowledge about component solutions is used to generate a preliminary bill of materials and potential subfunction solutions very early in the design stage. Of key importance is that this bill of materials supports modular product architecture early in the design stage when a minimum number of decisions have been made about the rest of the product's architecture and embodiment.

A product that performs the function of both the coffee mill and the coffee brewer is relatively new to the consumer market. Here we show how this product could be developed as part of an existing product family using the design templates developed earlier. Some initial design decisions lead to the following observations. Electrical energy will be used as the primary energy input to the system. Thermal energy will be needed to brew the coffee. Also, a decision is made to use a rotational motion to grind the coffee. Based on these decisions, the coffee grinder and brewer could be developed using the template for either of the product platforms convert electricity to thermal energy or convert electricity to rotational energy. Here, we will explore developing the coffee grinder and brewer on the electricity to thermal energy product platform.

First, a functional model for the proposed coffee grinder and brewer is developed. This functional model is shown in figure 8. The functional model is developed using a method stated in Kurfman *et al.* (2001). Although abstract, the fundamental representation as shown in the Functional models as shown in figure 8 have been used to improve the development of new products and re-designs (Pahl and Beitz 1988). With a functional model, integrating the coffee grinder and brewer into an existing product platform can be explored.

Shown in figure 9 is the functional model of the coffee grinder and brewer rearranged to conform to the design template format as developed earlier. Comparison of figure 9 with the template in figure 6 leads to the following conclusions. The coffee grinder and brewer share many common functions with the electricity to thermal energy product platform. The overlap of functions includes import electrical energy, activate electrical energy, separate electrical energy, transmit electrical energy, convert electricity to thermal energy, transmit thermal energy, convert electrical energy to rotational energy, transmit rotational energy, import liquid, store liquid, guide liquid, export liquid, import solid, and export solid. Based on the number of common functions, the coffee brewer and grinder could utilize modules from the product platform thus minimizing the 'new' design required on the part of the development firm. Also of

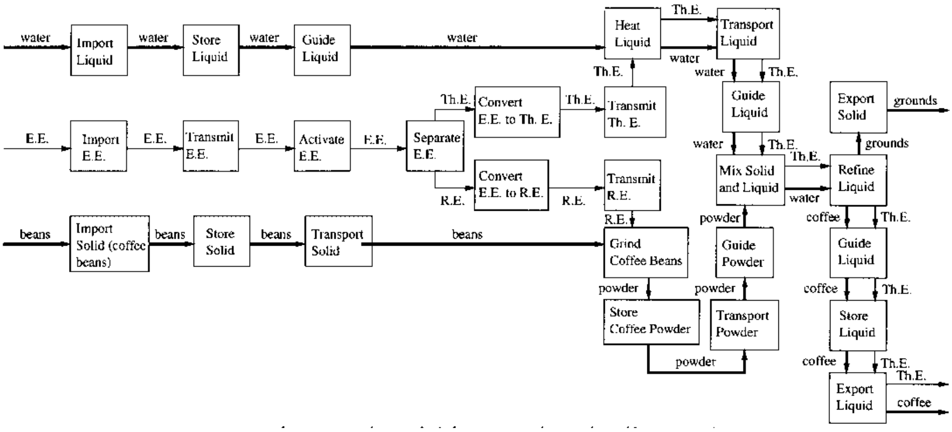

Figure 8. A functional model for a combined coffee grinder and brewer.

interest is that the form defining functions are also very similar to the form defining and material momentum functions in the electricity to thermal energy product platform. In the case of the material momentum functions, some components could also probably be re-used to reduce the development and production cost of this new product.

Another important impact of using the product platform design template is recognition of the need to include interface functions and to include the corresponding solution. In the original functional model for the coffee grinder and brewer, there was no inclusion of functionality to accommodate product platform integration. By formatting the coffee grinder and brewer into the design template, it is clear that the integration of interface functions is required.

Another beneficial result of using the product platform design template is the ability to re-use prior design knowledge. Recall that the design templates store both abstract functional and modular knowledge as well as embodiment knowledge about the components used to solve particular functions in modular products. Here we use this design knowledge to develop a preliminary bill of materials as presented in table 7. This preliminary bill of materials gives the designer an initial indication of the ability to use standard catalogue parts and materials requirements for the product.

Using design templates, two important design objectives have been achieved early in the design stage. First, a modular based functional model is developed for the

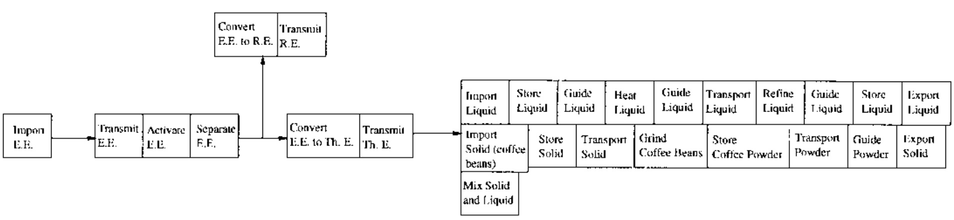

Figure 9. The coffee grinder and brewer functional model rearranged as a design to integrate with a design template.

Electrical module	Electric plug, electric cord and switch
Thermal module	Heating coil, heating coil case and hollow aluminium tube
Temperature control module	Bimetallic strip, thermostat and metal wires
Powder module	Powder compartment and holder
Coffee refining module	Heating plate, powder compartment and glass pot
Water module	External cover, water compartment lid, U-shaped rubber tubing
Rotation module	DC/AC motor, contacts and motor shaft
Coffee bean module	Grinding blade, grinding compartment and cover

Table 7. A preliminary bill of materials for an integrated coffee grinder and brewer product.

product. As the functional model is modular in nature, developing complete embodied modular designs will flow naturally. The second important objective is the re-use of prior design knowledge. The preliminary bill of materials in table 7 is quickly produced based on the components used in similar products.

6. Conclusions and future work

In this work, a modular focused design template is proposed. A specific methodology for developing design templates is presented. This template is based on the critical flows of energy through a product. The template utilizes design knowledge both in the form of modular architectures and specific component solutions. It is shown that by grouping primary energy into module chains and creating a generic design template, conceptual design and embodiment design can be performed as a simultaneous process with a natural focus on modular design. The case of an integrated coffee grinder and brewer is presented as an example. The design template provides functional and component information of all the products in a product family. The current work has been carried out over a set of 16 consumer products belonging to the two classes.

What this work provides for the practicing product development community is the ability to organize current design knowledge and extend that knowledge into new products. By using these product family design templates, these new products will share significant components with existing products. Thus, company time and money can be focused on those issues that are specific to the new product; those issues that will set the product as unique and different. Specifically, the designers may focus on the particular solutions for the form defining modules.

Critical immediate extensions to this work include increasing the scope of products in the knowledge base and the automation with which design knowledge is accessed though this knowledge base. With the work presented here, 16 products are included in the knowledge base. With the current knowledge base, the templates are limited to products that are electro-mechanical in nature. The amount of recorded empirical design knowledge needs to be increased both with the current electro-mechanical focus and to a wider range of product variety. As the empirical knowledge is increased, the basic theory in the article will be extended to handle products that are not electro-mechanical in nature. As a result, different templates will be produced. Also, the knowledge recorded in this article is currently accessed manually. A computer application needs to be generated to automate the access of the design knowledge to improve the speed and ease of access. Once this is done, a design template could be used to automatically present a designer with candidate designs.

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