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A FUNCTION BASED APPROACH FOR PRODUCT INTEGRATION

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ABSTRACT
Reconfigurable and multifunctional products are breeds of products that cater to the increased diversification of customer needs. Unlike single-state static products which can perform only one primary function, these products cater to different customer needs by performing more than one function with or without changing their configuration. However, there is a lack of systematic methods to support the conceptual task of combining two existing single-state products into an integrated product that provides multiple functions. In this paper, a function based approach is proposed which provides more rigorous support to assess the feasibility of integrating two products. The function structures of the existing products are combined to obtain the overall function structure of the reconfigurable product. Function sharing, based on quantified functional similarity, is proposed and applied to identify functions that can be shared by the same component. The information obtained from the function structure is then mapped to the components of two existing products to analyze their roles in the final reconfigurable product architecture. A case study illustrates the proposed approach by analyzing the integration of a power drill and a dust buster.

1.0 INTRODUCTION
With the diversification of customer needs, the drawbacks of single-state static systems are more evident. Their ability to perform only one primary function has led to the emergence of product types that perform multiple primary functions, including reconfigurable systems and multifunction products.. Reconfigurable products have a broader functional repertoire than the traditional single-state products [1]. They are designed to perform a variety of functions, enhance performance or execute the same function under different operating conditions by changing its configuration. A reconfigurable aircraft shown in Figure 1(a) can be converted into a car based on the customer use. This product has two states and performs two different functions under two operating conditions and can be configured to any one of the states based on the requirements. An important characteristic of reconfigurable products is that they cannot perform more than one function simultaneously. On the other hand multi-functional products are able to perform multiple functions concurrently. Figure 1(b) shows an example of a multifunctional product which is able perform the function of both a coffee maker and a microwave oven at the same time.

(a) (b)

Figure 1. (a) Reconfigurable [2] (b) Multifunctional [3] Products

As the proliferation of reconfigurable and multifunction products continues, it becomes increasingly important that methods are developed to support the design of these new breeds of systems. One important task in the design of these kinds of systems is assessing the feasibility of combining two given single-state products into an integrated product. After such an integration it is reasonable to assume that some of the components from the original products may be common, some may be variant or similar, and some may be unique. For example, the wheels of the system in Figure 1(a) perform common functions in both the aircraft and ground vehicle while the wing of the aircraft needed to be redesigned to fold in order to support the system in ground vehicle mode. The relative levels of common, similar, and dissimilar components will dictate the final integrated product architecture and its operation. Therefore, in this paper, we present a function-based method to evaluate and quantify the level of similarity between two products. Then based on this evaluation, designers can develop various concept architectures of the single integrated product. Thus far, a systematic approach to evaluate the integration of two products has been missing from the design literature.

In Section 2, related work on reconfigurable systems, functional modeling, and function sharing is discussed along with the fundamental background for the proposed approach. In Section 3, we present the three phases of the approach and in Section 4, the approach is applied to the integration of a power drill and dust buster into a single product. Insights, conclusions, limitations, and future work are discussed in Section 5.

2 BACKGROUND

With consumer preferences gaining the upper hand over mass production, product proliferation is a new paradigm adopted when designing a product [4]. With the large homogeneous market shifting towards an increasingly heterogeneous market, demand is being fragmented and the power is shifting to the consumer [5]. This can be effectively addressed by providing variety and customization in products through flexibility and quick responsiveness.

2.1 Reconfigurable Products

Reconfigurable products incorporate functionally different products into a single product by allowing the customer to configure the product to achieve the current desired functionality. Reconfigurable manufacturing systems (RMS) are predecessors of reconfigurable products which are manufacturing systems that can be configured for different operations for a given family of components [6]. In [7], four primary aspects of changeable/reconfigurable systems are presented: adaptability, flexibility, robustness and agility. In [8], the use of flexibility is further delineated and quantified as an engineering attribute in various fields. In [9], reconfigurable systems are classified into multi-ability, evolution and survivability based on their function, future capabilities, and design and performance space requirements. These classifications could be used to categorize possible outcomes of the method presented in this paper.

Other research has looked at how the system can physically reconfigure. An important part of the research in reconfigurable systems that has emerged is the concept of transformation principles [1, 10-11]. These principles were developed by analyzing existing patents and reconfiguring systems, both natural and manmade, to identify the primary methods that systems transform from one form to another. The different types of form transformations are called *principles*, which are shown in Figure 2. These principles are made possible by various *facilitators*, such common core, enclosure, fan, fold, function sharing, etc. These principles and facilitators together provide a transformer theory to support the development of reconfigurable systems. These transformational principles have been expanded [12], applied to a morphing wing concept [13], studied empirically [14], and used to enhance concept generation [15]. In [15], the Concept Opportunity Diagram, a visualization technique based on these principles and facilitators to enable the designer to generate several concepts of multifunctional products, was developed. While these principles and facilitators are useful in the top-down design of new reconfigurable systems, they do not address the bottom-up integration of existing products into a single reconfigurable system.

Expose / Collapse Expose/ Cover Fuse / Divide

Figure 2. Principles and Facilitators - Transformers Design [1]

Other methods have focused more on the detailed design of reconfigurable systems. A linear state feedback model was developed to determine the path taken by and stability of the design variables during transition from one state to another [16]. Decision based design and conjoint analysis have been used to analyze the dimensional flexibility of a reconfiguring system based on the overall utility of the system [17]. In [18-19], Markov models and control theory are used to model off-line and on-line system reconfiguration processes. Variable segregation mapping functions were developed in [20] to determine the optimal set of adaptive and fixed design variables based on a penalty function and performance sensitivity of each variable. A multi-objective optimization formulation was used to identify an optimal modular reconfigurable architecture [21].

While each of these methods provides some effective support for the detailed design of reconfigurable systems, there is a lack of methods to support the re-design and integration of multiple existing single-state systems into a new reconfigurable system. In this paper, we attempt to begin to fill this gap by providing an approach to support the development of product architectures of these integrated systems. Before presenting the approach, relevant background on product architecture and functional analysis is provided in the next sections.

2.2 Product Architecture

Product architecture is the arrangement of functional elements into physical “chunks” that constitute the building blocks for a product or family of products [22]. The three constituents necessary for a product architecture are as follows [23]: 1) the arrangement of functional elements into chunks, 2) the mapping from functional elements to physical components, and 3) the specification of the interfaces among interacting physical components. This research work focuses on the first two constituents of product architecture for reconfigurable systems. In the next two subsections some of the tools that aid in product architecture development are discussed. In the last subsection, function sharing, a niche design streamlining technique to reduce component usage is discussed.

2.2.1 Function modeling

Function structures are systematic means of representing the interrelationship between functions and flows involved in the product. Functions have three elements as shown in Figure 3: an input flow descriptor, a function descriptor, and an output flow descriptor.

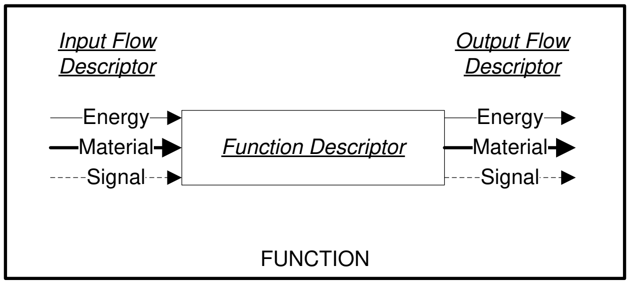


Figure 3. Elements of a function

A number of methodologies have been proposed for effective functional modeling [22, 24-25]. In order to achieve a single universal language to represent products, the reconciled function flow set was developed by combining two previous independent research efforts of the NIST design repository and functional basis [26]. The reconciled function flow set consists of two basic descriptors namely, flow descriptors and function descriptors. The levels of abstraction in the reconciled function flow set are shown in Figure 4.

Increase in level of specificity

Class (Primary)	Secondary	Tertiary	Correspondents
Branch	Separate		isolate, sever, disjoin
		Divide	detach, isolate, release, sort, split, disconnect, subtract
		Extract	refine, filter, purify, percolate, strain, clear
		Remove	cut, drill, lathe, polish, sand

(a)

Class (Primary)	Secondary	Tertiary	Correspondents
Material	Human		hand, foot, head
	Gas		homogeneous
	Liquid		incompressible, compressible, homogeneous
	Solid	Object	rigid-body, elastic-body, widget
		Particulate	
		Composite	

(b)

Figure 4. Sample of the (a) function sets (b) flow sets from reconciled function flow set [26]

Otto and Wood [25] propose two approaches for modeling and generating function trees: Function Analysis System Technique (FAST) which is a top down approach which focuses on building function trees from the primary function of the product, and Subtract and Operate Procedure (SOP) which is a bottom up approach used for generating function trees for an already existing product.

Function modeling has been leveraged for concept generation where concepts and components from previous products are stored in a design repository database and reused to generate new solutions [27]-[29], including a novel 'form follows form' approach in [30]. Functional modeling is used in [31] to identify modules and determine the product architecture using function clustering heuristics, namely *dominant flow, branching flow and convert-transmit flow.* Functional decomposition has been used to develop a product portfolio architecture in [32] by leveraging the intersecting function sets to identify the product platform from the unique components.

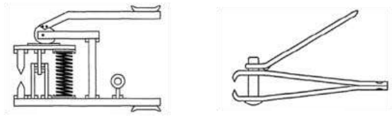
Therefore, function modeling has been used as a qualitative tool for a number of critical design tasks. In this paper, we develop a quantitative tool to support the use of function modeling for integrating products into a single architecture. Before we present the approach, in the next section the necessary tools for product architecture representation and evaluation are discussed.

2.2.2 Product architecture representation

The Design Structure Matrix (DSM) is a popular representation and analysis tool for system modeling [33]. A DSM is a square matrix with identical row and column labels. An off diagonal value represents the dependency/ relationship of the corresponding components. A Domain Mapping Matrix (DMM) [34], on the other hand is a non-self mapping matrix that captures interactions between different domains. A Function Component Matrix (FCM) is one such matrix falling under DMM, wherein the relationship between various functions (rows) and the components (columns) are captured using binary elements. [35].

In [36], a product function (PF) matrix is used to analyze the similarity between products in the repository. A function adjacency matrix (FAM) representing the product's function connectivity has been used to aid in generation of new concepts [30]. These representations add a quantitative element to function structures which facilitates their comparison. When functions can be compared quantitatively, it allows for function sharing among components to be considered.

Function sharing, as defined in [37], is the simultaneous implementation of several functions with single structural elements. Figure 5 illustrates a nail clipper without function sharing (a) and one with function sharing (b). In [37], a three step process is proposed to identify function sharing in products. The process focuses on using the secondary or less prominent functions of the product components to eliminate neighboring components that perform the same function. For example in the case of the nail clipper, the functionality of the spring is incorporated into the clipper plates by exploiting its cantilever property which is a secondary function based on its structure.



(a) (b)

Figure 5. Illustration of function sharing using a nail clipper (a) without function sharing (b) with function sharing [37]

The concept of function sharing is fundamental to the approach we present in this paper. However, we do not apply the concept of function sharing within a single product; instead we apply it between two products to identify functions from two products that can be shared. The proposed approach is discussed in the next section.

3 APPROACH

The approach is presented in three phases. In the first phase (Section 3.1) the overall function structure of the reconfigurable product is generated using the function structures of the existing single state products. In the second phase (Section 3.2) the concept of function sharing is implemented and the functions are categorized into four types. In the final phase (Section 3.3) the function information is mapped to the components of the existing products and the architecture of the new reconfigurable product's is derived. Figure 6 shows the outline of the approach and the major steps involved in each of the phases.

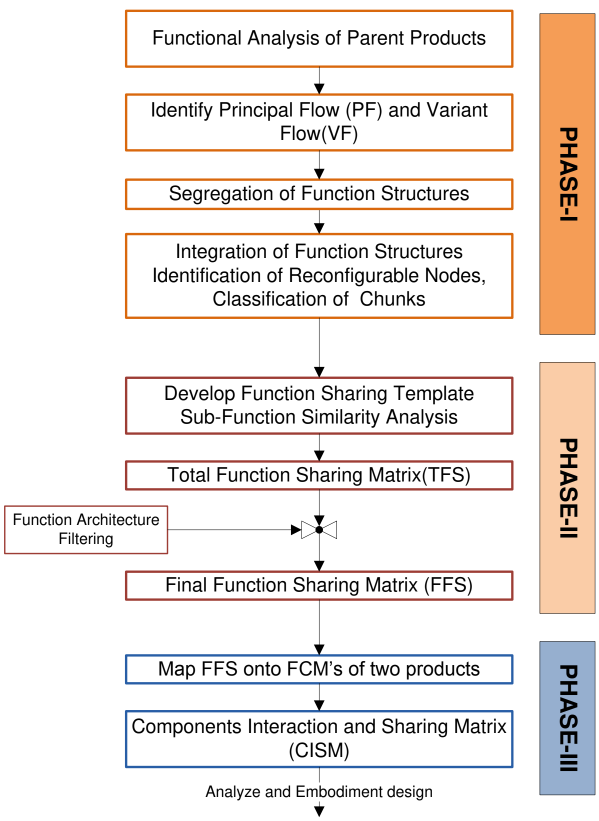


Figure 6. Outline of the Proposed Approach

3.1 Function Structure Generation (I)

In this phase the function structures of the two parent products are decomposed and re-integrated into a single function structure for a reconfigurable product. In order to generate the function structures and function-component relationships of the two products techniques such as SOP or FAST [25] can be used. Only the primary functions are considered and supporting functions of the components are neglected. The reconciled function flow set [26] is used for developing the function structures of the new product.

Principal Flow (PF): The most prominent flow that is common between each product is identified. This flow can be either material, energy, or signal. While material, energy, and signal are all going to be part of most function structures, the common flow that dominates the operation of the two products needs to be identified. If the principal flow of the products is different, then the integration of the two products will be difficult. Also, if there is more than one principal flow, then a principal flow can be identified for each major function chain.

Variant Flow (VF): Once the principal flow of each product is identified, the flow that distinguishes the two products, or the variant flow, is identified. The variant flow is responsible for differentiating the primary functions of these products. The VF may or may not be the same as the PF, depending on the parent products under consideration.

As an example consider a wet vacuum cleaner and a dry vacuum cleaner. The PF for both of these products is energy, and the VF that differentiates the two products is material since the dry vacuum cleaner operates on *solid* + *gas* debris whereas a wet vacuum cleaner operates on *solid* + *gas* + *liquid* debris.

Function Structure Segmentation: Based on the PF and the VF, the function structures of the two parent products are decomposed into similar PF and varying VF blocks or chunks. The term chunks, while previously used in a product architecture context [22], has also been used to refer to identified modules in the component Design Structure Matrix (DSM) [34, 38]. In this paper, we define a chunk to be a continuous chain of functions that have the same PF or VF passing through them.

Integration of Function Structures: The same PF chunks are denoted to be the *common core structure* of the new reconfigurable product. The VF chunks become the *reconfigurable* chunks. The auxiliary functions, which are not related to the PF and VF chunks, are categorized separately as an *auxiliary* chunk. The juncture separating the common core structure chunks from the reconfiguring chunks is represented by a reconfiguration node, which indicates that some form of reconfiguration is to switch from one primary function to another in the final reconfigurable product.

Once the primary function chunks are identified, then a more detailed analysis of each function of the two parent products is carried to identify the function sharing characteristics.

3.2 Function Sharing and Streamlining (II)

In this phase the functions that can be shared by the same components based on their functional similarity are identified.

3.2.1 Heuristics to Determine Function Sharing

Function sharing between any pair of product functions is facilitated by identifying the primary class, the secondary class, and the tertiary/correspondents class function/flow descriptors (see Figure 4[1]). As we move from primary to tertiary, the level of abstraction decreases. In other words, the functions become more and more specific in nature. This leads us to the following principle:

> *The higher the level of similarity between the two functions at all three classes of function and flow sets, the higher the feasibility of them being shared by the same component.*

For example, if there are two functions – one from each product – that need to be fulfilled by one component, the ease of combining these functions is related to how many levels the functions share the same description. If the two functions under consideration vary from each other at the highest primary class, then there is a low probability of them being shared by the same component without major modifications. However, when two functions share the same function descriptors down to the lower levels then these functions show a greater potential of function sharing.

3.2.2 Function Sharing Matrices

In order to quantitatively assess the function sharing capabilities of various functions between the two parent products a set of matrices for function sharing are created. These matrices are of order *i* x *j,* where *i* and *j* are total number of functions in product 1 and product 2, respectively. The general arrangement of chunks for these matrices is shown in Figure 7 where the functional chunks from each product are aligned on each axis. As shown, function sharing is analyzed only within the respective chunks in the pair which enforces the modularization of the resulting design as function sharing across non-corresponding chunks is prevented. The rows and columns are arranged in feed forward fashion. That is, the functions are listed in order of their operation in the product.

In order to comprehensively analyze the function sharing capability of two products, a matrix similar to Figure 7 is created at each of the three levels of function abstraction: primary, secondary, and tertiary. Also at each level, a matrix is created to capture the input flow, the function itself, and the output flow. Therefore nine elementary matrices, denoted as elementary matrices, are created, as summarized in Figure 8.

[1] The designer can use the correspondent class if the component does not have a tertiary class descriptor.

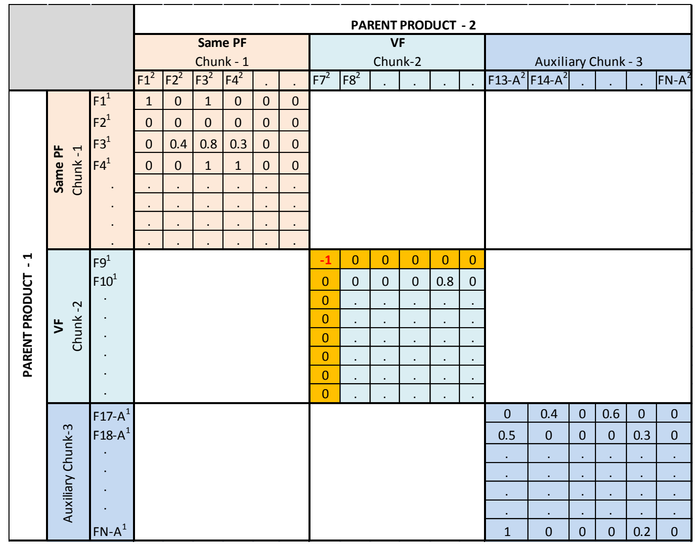


Figure 7. Function Sharing Matrix Template

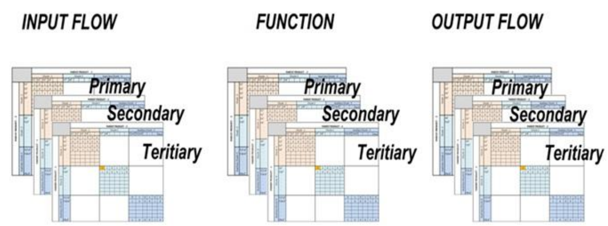


Figure 8. Nine elementary matrices

The elements in these matrices, x_{ij}, indicate the level of similarity for a pair of functions based on their primary, secondary, and tertiary class descriptor. These elements can assume the following values:

1. $x_{ij} = 1$: A value of 1 indicates that the corresponding functions *i* and *j* share the same function/flow descriptor.
2. $x_{ij} = 0$: Indicates that there is no similarity in the descriptor for the functions *i* and *j*.
3. $x_{ij} = -1$: Indicates that functions *i* and *j* are conflicting functions and that the components associated with these functions must undergo some kind of reconfiguration, as they cannot fulfill both functions at the same time.

Once these nine elementary matrices are constructed, the set of three matrices describing input flows, functions, and output flows are aggregated respectively, forming three new derived matrices: the Input Flow Sharing Matrix (IFSM), the Function Sharing Matrix (FSM), and the Output Flow Sharing Matrix (OFSM). The elements in each set of primary, secondary, and tertiary matrices are averaged to create the IFSM, FSM, and OFSM.

Together these derived matrices are aggregated into the total function sharing matrix (TFS). The elements in the TFS are calculated using Equation 1. If two functions are to be shared, they must at least share their primary class function descriptor.

This is captured mathematically in Equation 1 with the x_{ij}^{PFSM} term which has a value of 1 if functions i and j have the same primary class function descriptor and a value of 0 if they do not. The resulting term x_{ij}^{TFS} indicates the level of similarity between the two functions derived from the principle stated in Section 3.1 for function sharing.

$$x_{ij}^{TFS} = \frac{x_{ij}^{PFSM}}{3}\{x_{ij}^{FSM} + x_{ij}^{IFSM} + x_{ij}^{OFSM}\} \quad (1)$$

3.2.3 Function Architecture Filtering

It is assumed that only two functions can be shared in order to avoid a high degree of internal function coupling in the new product. Therefore, any function in the final TFS that has a positive value with more than one other function must be parsed further. For instance, in Table 1, $F5^2$ could potentially be shared with $F5^1$ or $F6^1$.

TFS			Parent Product 2				
			Chunk-2 **(VF)**				
			$F1^2$	$F2^2$	$F3^2$	$F4^2$	$F5^2$
Parent Product 1	Chunk -2 **(VF)**	$F1^1$	-1	0	0	0	0
		$F2^1$	0	0	0.4	0	0
		$F3^1$	0	0.7	0	0	0
		$F4^1$	0	0	0	0.7	0
		$F5^1$	0	0	0	0	0.4
		$F6^1$	0	0	0	0	1

Table 1. Hypothetical TFS

Also, the presence of functional sharing between $F2^1$ & $F3^2$ and $F3^1$ & $F2^2$ indicates a potential reversal of flow since it would require a feedback mechanism. Therefore, the feedback and dual function sharing are eliminated by setting the lowest entry equal to zero, essentially eliminating that function sharing. The resulting matrix, denoted as the Final Function Sharing Matrix (FFS) is shown in Table 2.

FFS			Parent Product 2				
			Chunk-2 **(VF)**				
			$F1^2$	$F2^2$	$F3^2$	$F4^2$	$F5^2$
Parent Product 1	Chunk -2 **(VF)**	$F1^1$	-1	0	0	0	0
		$F2^1$	0	0	0	0	0
		$F3^1$	0	0.7	0	0	0
		$F4^1$	0	0	0	0.7	0
		$F5^1$	0	0	0	0	0
		$F6^1$	0	0	0	0	1

Table 2. FFS

Based on the values of the elements in the FFS, the resulting functional behaviors are categorized as follows:

1. $\boldsymbol{x_{ij} = 1}$, the corresponding functions i (Product 1) and j (Product 2) are exactly the same and can be combined together into one single function – these functions become the **common core functions**.
2. $\boldsymbol{x_{ij} = -1}$, the functions i and j are **conflicting functions** and cannot be shared by the other parent product.
3. $[\boldsymbol{x}] = [\boldsymbol{0}]$, if every element in a row or column is zero these functions are not related to the functions of the other product and hence remain dormant when performing one of the functions of the reconfigurable product – these functions become **dormant functions**.
4. $\boldsymbol{0 < x_{ij} < 1}$, the functions i and j have similarity in the function and flow sets and hence indicate possible function sharing characteristics. In other words, these two functions can be shared by the same component and are denoted as the **functions to be shared**.

Note that the values of x are defined as $\{x \mid -1, 0 \le x \le 1\}$. That is, x can take on any value between 0 and 1, but the value of -1 simply marks the existence of conflicting functions that cannot be shared. In the final phase, the functions are mapped to the product components to determine which components can be shared.

3.3 Product Architecture and Evaluation (III)

Thus far, the arrangement of functional elements and their interaction has been captured using the functional model and the FFS matrices. In this last phase, the mapping of components to components is accomplished.

3.3.1 Function Component Matrices

In order to translate the Final Function Sharing matrix to components, a Function Component Matrix (FCM) of each parent product is used. In Table 3, two hypothetical function component matrices are shown for product 1 and product 2. The rows of the FCM^1 must be in the same order as the rows of the FSM template and the rows of FCM^2 must be in the same order as the columns of the FSM template. However the arrangement of components in the FCM does not affect the final results of this phase. This is because the propagation of functions sharing values from the FFS to the components of the FCM's occurs only through the functions of the products.

PRODUCT 1						
(FCM^1)	$C1^1$	$C2^1$	$C3^1$	$C4^1$	$C5^1$	$C6^1$
$F1^1$	1	0	0	0	0	0
$F2^1$	0	1	0	0	0	0
$F3^1$	0	0	1	0	0	0
$F4^1$	0	0	0	1	0	0
$F5^1$	0	0	0	0	1	1
$F6^1$	0	0	0	0	1	1

(a)

PRODUCT 2					
(FCM^2)	$C1^2$	$C2^2$	$C3^2$	$C4^2$	$C5^2$
$F1^2$	1	0	0	0	0
$F2^2$	0	1	0	0	0
$F3^2$	0	0	1	0	0
$F4^2$	0	0	0	1	0
$F5^2$	0	0	0	1	1

(b)

Table 3. (a) FCM of product 1 (b) FCM of product 2

3.3.2 Component Sharing Matrix

In order to create a matrix that captures the sharing of components in Product 1 to those in Product 2, a Component Sharing Matrix (CSM) is created using Equation 2. Here m and n are total number of components of product 1 and product 2 respectively. This equation maps the function sharing behavior of function pairs obtained in the FFS matrix onto the FCM matrices of product 1 and product 2, located to the left and right side of FFS respectively

$$[CSM]_{m\,X\,n} = [FCM^1]^T{}_{m\,X\,i} \quad \{*\} \quad [FFS]_{i\,X\,j} \quad \{*\} \quad [FCM^2]_{j\,x\,n} \qquad (2)$$

Note that the operator {*} in Equation 2 does not represent the usual matrix multiplication. This is because if the standard multiplication rules are used, the function sharing values would be added which does not make conceptual sense. Therefore, the {*} operator projects the FFS values onto FCM^1 and FCM^2 while at the same time preserving the unit normalization. In effect, it is an enhanced dot product of three matrices. The {*} is two step process; the mechanics involved in this equation and its multiplicative procedure are explained using simple matrices.

Consider Table 4 which shows the operation {*} for the first two matrices in Equation 2. The multiplication for the matrices is modified in the following manner,

1. When row 1 ($C1^1$) [1,0,0,0,0,0] of $(FCM^1)^T$ is multiplied with column 1 ($F1^2$) $[-1,0,0,0,0,0]^T$ of FFS, each element is multiplied with the corresponding element and is stored in a set S_{xy} as {1*-1,0*0,0*0,0*0,0*0} as denoted in Equation 3.
$$\{S_{xy}\,|M1 * M2\} \qquad (3)$$
This is simply the projection of the function relationship in the FFS onto the components of Product 1where M1 represents the elements of Matrix 1 and M2 the elements of Matrix 2.

$(FCM^1)^T$	$F1^1$	$F2^1$	$F3^1$	$F4^1$	$F5^1$	$F6^1$
$C1^1$	1	0	0	0	0	0
$C2^1$	0	1	0	0	0	0
$C3^1$	0	0	1	0	0	0
$C4^1$	0	0	0	1	0	0
$C5^1$	0	0	0	0	1	1
$C6^1$	0	0	0	0	1	1

(a)

{*}

FFS	$F1^2$	$F2^2$	$F3^2$	$F4^2$	$F5^2$
$F1^1$	-1	0	0	0	0
$F2^1$	0	0	0	0	0
$F3^1$	0	0.7	0	0	0
$F4^1$	0	0	0	0.7	0
$F5^1$	0	0	0	0	0
$F6^1$	0	0	0	0	1

(b)

Table 4. (a) $[FCM^1]^T$ of product 1 (b) FFS

2. Once the projection is obtained, we must identify the dominating term of the set S_{ij}, denoted as a_{ij}. Equation 4 represents how this is carried out.
$$a_{xy} = \begin{cases} 0 & S_{xy} = \{0\} \\ -1 & if -1 \in S_{xy} \\ y & if\ -1 \notin S_{xy}, y \in S_{xy} \\ & \text{such that } y \text{ is the minimum positive number in } S_{xy} \end{cases} \qquad (4)$$

The first condition, an empty set S_{xy}, identifies dormant components that bear no relation with components of the other product. The second condition identifies the conflicting components by detecting the presence of -1 in the set S_{xy}. The third condition ensures that only the lowest possible number in S_{xy} is taken into consideration when there are multiple positive numbers present. The lowest number conservatively reflects the minimum similarity exhibited by that component pair indicating the maximum redesign effort required.

Table 5, obtained by applying this multiplication algorithm shows the relationship between the components of product 1 with the functions of product 2. For Example, when row 3 ($C3^1$) of Table 4(a) is multiplied with column 2 ($F2^2$) we get S_{xy}={0,0,0.7,0,0,0} and after applying Equation 4 the element is reduced to 0.7 as obtained in Table 5.

$(FCM^1)^T\{*\}$ FFS	$F1^2$	$F2^2$	$F3^2$	$F4^2$	$F5^2$
$C1^1$	-1	0	0	0	0
$C2^1$	0	0	0	0	0
$C3^1$	0	0.7	0	0	0
$C4^1$	0	0	0	0.7	0
$C5^1$	0	0	0	0	1
$C6^1$	0	0	0	0	1

Table 5. Filtered table obtained using Equation 3 and 4

The two steps are applied to the second half of Equation (2), $[C^1F^2]_{m\,X\,j}$ {*} $[FCM^2]_{j\,x\,n}$, to produce the final component sharing matrix $[CSM]_{m\,X\,n}$. The CSM in Table 6 shows the relationship and interaction between the components of the two products.

CSM	$C1^2$	$C2^2$	$C3^2$	$C4^2$	$C5^2$
$C1^1$	-1	0	0	0	0
$C2^1$	0	0	0	0	0
$C3^1$	0	0.7	0	0	0
$C4^1$	0	0	0	0.7	0
$C5^1$	0	0	0	0	1
$C6^1$	0	0	0	0	1

Table 6. Component Sharing Matrix

The CSM matrix can now be used to identify the role played by each component in the final reconfigurable product. The different types of components in Table 6 are:

1. x^{CSM} = -1: The components $C1^1$ and $C1^2$ are conflicting.
2. $[x]^{CSM}$ = [0]: The components $C2^1$, $C5^1$, and $C3^2$ are dormant, indicating that they are not used in one of the reconfiguration states.
3. $0 < x^{CSM} < 1$: The components $C3^1$ and $C2^2$ have the potential to be redesigned into a single component that can perform both functions. The corresponding element x^{CSM} value in that cell indicates the function sharing index.
4. $x^{CSM} = 1$: The components $C6^1$ and $C5^2$ are part of the common core.

The values of x are defined in the same way as the values of x the FFS matrix (Section 3.2.3), $\{x \mid -1, 0 \le x \le 1\}$. In the next section, the approach is applied to a case study involving the integration of a power drill and a dust buster.

4 CASE STUDY

In this study, we evaluate the technical feasibility of combining a power drill and a dust buster, shown in Figure 9, into a single reconfigurable product. The process outlined in Section 3 is applied.

Figure 9. (a) Power drill (b) Dust buster

4.1 Phase I

Product Dissection and Function Structure Formation: The function structure of each product was created using the component information in the Design Repository at Oregon State University [39], and the Subtract and Operate Procedure [25]. These function structures are shown in Figure 10 and 11 respectively.

Principal flow (PF) and Variant Flows (VF): The PF for both products is energy as it is the most common dominant flow that passes through many of the functions. Once the PF is identified, the function structure is decomposed into chunks involving the same type of energy. Chunks 1, 2, and 3 in Figure 10 and 11 are a result of this decomposition. Table 7 summarizes the various identified chunks that use the same energy flow in Figures 10 and 11.

	Parent Product 1: Power Drill (Figure 10)	Parent Product 2: Dust Buster (Figure 11)
PF	Electrical Energy Chunk **(1)**	Electrical Energy Chunk **(1)**
PF	Mechanical Energy Chunk **(2)**	Mechanical Energy Chunk **(2)**
VF	Change Mech. Energy Chunk **(3)**	Pneumatic Energy Chunk **(3)**
A	Auxiliary Chunk **(4)**	Auxiliary Chunk **(4)**

Table 7. Identified chunks based on PF and VF

From Table 7 we can see that Chunks 1 and 2 for both products involve the same PF energy flows which are electrical and mechanical respectively. Therefore, they are directly part of the common core. The amount of function sharing between these chunks is analyzed in Phase II.

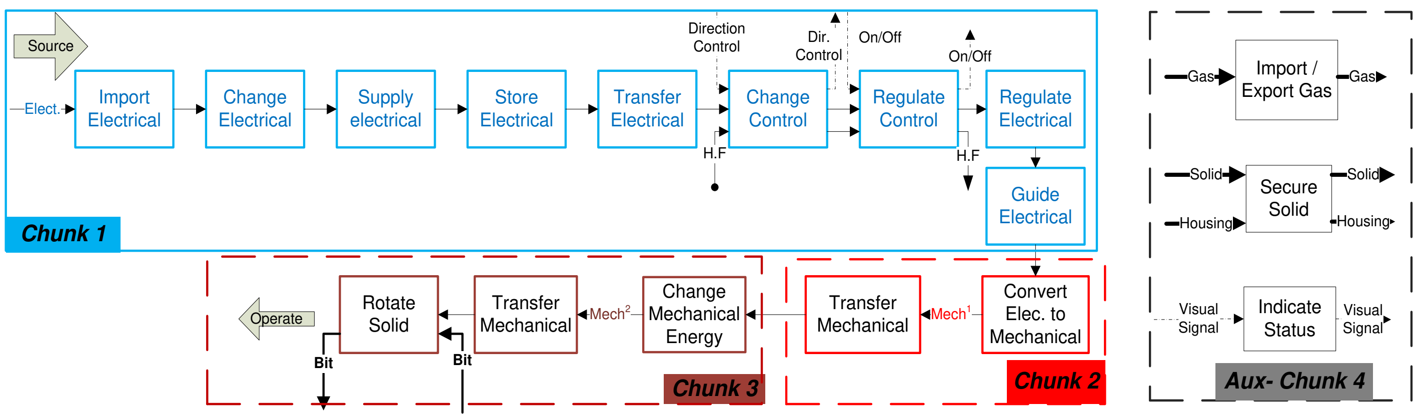


Figure 10. Function Structure of Power Drill arranged with respect to the PF and segregated into chunks (Color Coded)

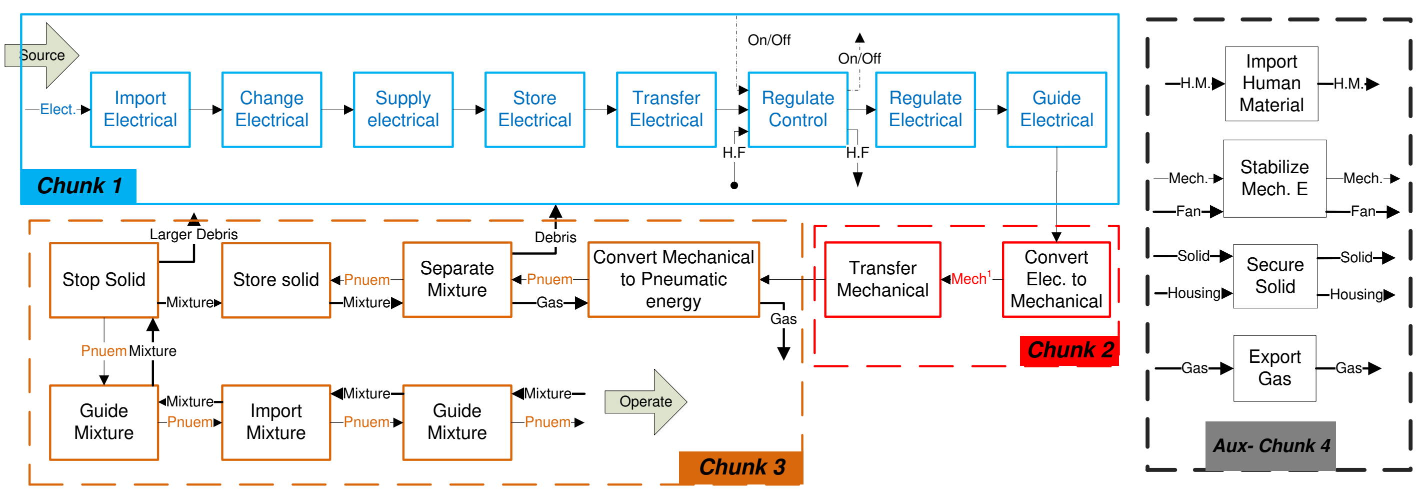


Figure 11. Function structure of dust buster arranged with respect to the PF and segregated into chunks (color coded)

In Chunk 3, the transformation of energy changes between the two products as the *change mechanical energy* (Chunk 3, Figure 10) and *convert mechanical to pneumatic energy* (Chunk 3, Figure 11) functions are completely different for the power drill and dust buster. This difference in energy flow distinguishes the primary function and operation of the two parent products and is denoted as the variant flow. As a result these chunks are classified as reconfigurable chunks since the flow has to be switched between these two chunks to fulfill the primary function of drilling or vacuuming.

These reconfigurable chunks contain **essential conflicting functions** as the *change mechanical energy* function of the power drill and the *convert mechanical energy to pneumatic energy* function of the dust buster perform conflict with each other. However the other functions that follow these two functions could potentially be performed by the same components. For example, a shaft in the power drill that *transfers mechanical energy* could be modified into a hollow shaft to *guide mixture* for the dust buster. Also, the chuck in the power drill that *rotates a solid* could be redesigned to perform the *guide mixture* function of the dust buster nozzle by making use of its opening, shown conceptually in Figure 12.

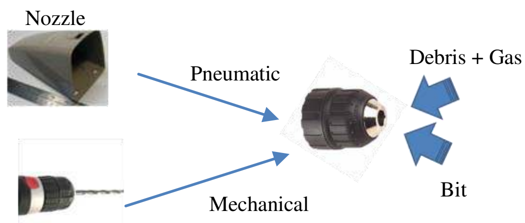


Figure 12. Non –conflicting functions

While these examples are presented to illustrate some potential function sharing solutions, developing more formal principles to guide the development of function sharing solutions is part of the current research. Integration with the principles and facilitators from the transformer theory [1] or with the principles from the theory of inventive problem solving (TRIZ) [40] could be leveraged to provide novel function sharing solutions.

Integration of Function Structures: The integration of the function structures for the two products is shown in Figure 13. The functional flow proceeds from the common core to the reconfigurable chunks. The reconfiguration node, indicated by the black circle with RCFG, provides the transition between the conflicting or reconfigurable chunks. This node is analogous to a *'switch'* that directs some type of flow. In this case, mechanical energy from chunk 2 which is common for the both products has to be directed and switched between the two chunks. The common mechanical energy can be passed only to one of the chunks at any instance. Note that the auxiliary chunks are not shown in the figure.

4.2 Phase II

Elementary and derived matrices: As presented in Section 3, nine function sharing matrices are created to evaluate the function sharing potential of the power drill and dust buster. For brevity only the final aggregate values of the IFSM (Figure A1), the OFSM (Figure A2) and the FSM (Figure A3) are shown in the Appendix, representing the function similarity based on the *input flow*, the *output flow* and the *function* descriptors.

The common core chunks consist of very similar functions and flows. For functions and flows that are exactly the same at each level of abstraction such as *import electrical* (row 1 and column 1) the entry is 1. For the other function pairs that share the same flow and function descriptors at some levels of abstraction, the entries will be between 0 and 1.
For the reconfigurable chunks, the *change mechanical* (row 13) and *convert mechanical to pneumatic* (column 12) are the essential conflicting functions. Hence, the entry is -1 in Figures A1–A3. A few of the other functions in the reconfigurable chunk show some function sharing potential with non-zero entries. For instance, the functions *transfer mechanical, rotate solid* of the power drill show similarity with the *guide mixture, import mixture and guide mixture* functions of the dust buster. Similarly, in the auxiliary chunk the *secure solid import/export gas* functions of the power drill show similarity with respect to the *export gas, secure solid* functions of the dust buster.

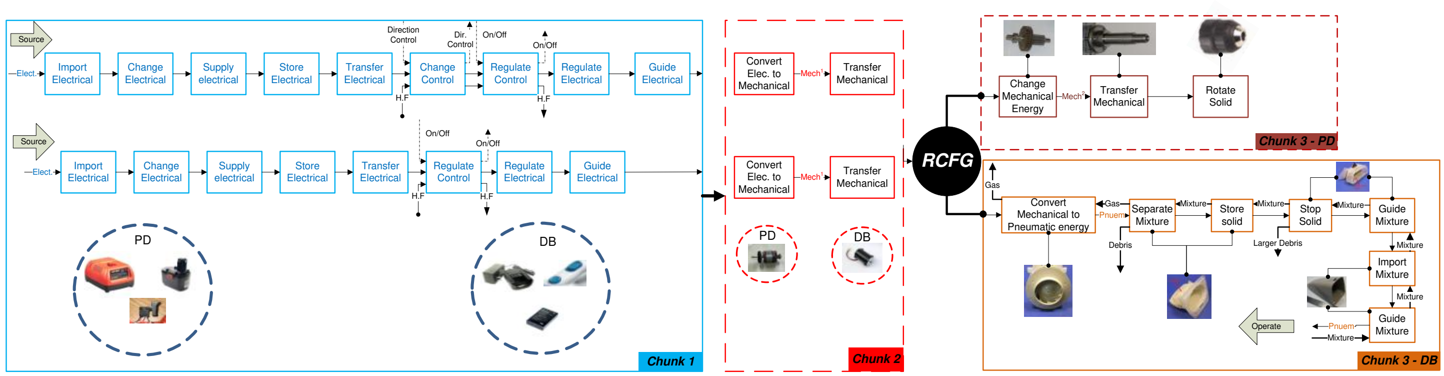


Figure 13. Integrated function structure schematic of reconfigurable drill and vacuum cleaner

TFS and FFS: Figure A4 shows the total function sharing (TFS) matrix which is the aggregation of the IFSM, OFSM, and FSM matrices using Equation 1. This matrix captures the function and flow similarity that exists between the functions of the two products. Since there are multiple functions of both products that could be shared, the most promising pairs of functions are kept in the Final Function Sharing matrix as shown in Figure A5. This is done to minimize the amount of functional coupling in the final product. For example, the TFS recommends that the functions *change control, regulate control, regulate electrical* (rows 7-9) of the power drill are coupled with the functions *actuate control* and *actuate electrical* (columns 7-8) of the dust buster. While possible, redesigning the necessary components to provide this level of function sharing may lead to very complex and unpredictable behavior. Therefore, the TFS is constructed to keep the sharing of functions as modularized as possible.

4.3 Phase III

The FCM^1 of the power drill is shown in Figure A6 and the FCM^2 of the dust buster is shown in Figure A7. The component sharing matrix (CSM) is generated by using Equations 2-4 along with the FCM^1, FCM^2, and FFS. The final CSM is shown in Figure A8.

4.3.1 Interpretation of CSM

The CSM shows the component interactions for the new reconfigurable power drill and dust buster product. The CSM is the outcome of mapping the function sharing capabilities identified in Phase II to the existing components of the two products. The magnitude of the entries determines how the components will be used in the new reconfigurable product. Table 8 illustrates the different categories of components using the guidelines from Section 3.3.2. The CSM value column indicates the entry from the CSM matrix.

Each product contributes seven components to the common core. These components could become the product platform if other related product variants were developed. The power drill has two components that would remain dormant when in the dust buster mode, while the dust buster has three components that would remain dormant when in the power drill mode. As noted in Section 4.2, the conflicting components – the planetary gear set of the power drill and the impeller of the dust buster – would require a reconfiguration node to switch between their operation.

Both the power drill and dust buster have four components that, with some amount of redesign, could be shared and eventually could become part of the common core. Note that the CSM value for the transistor of the power drill (row 6) and the diode of the dust buster (column 5) is 1 which would seem to indicate that these components should be in the common core. However, the transistor of the power drill has a CSM value of 0.8 with the on/off switch of the dust buster, indicating that the transistor may need to be redesigned for better function sharing with the on/off switch. If this happens, the transistor-diode sharing may no longer be ideal. On the other hand, if a designer decides to not enhance the function sharing of the transistor and on/off switch, then the transistor and diode could become part of the common core. This interrelationship between these components occurs because the transistor impacts both the *regulate electrical* and *guide electrical* functions as indicated in the FCM^1 of the power drill.

Considering the aggregate components for the new integrated product 62% of the total components are part of the common core, 31% exhibit dormant characteristics in one mode of operation and the remaining 7% are conflicting and must undergo reconfiguration. This information is useful in comparing other similar product combinations. For example, comparing a completely different power drill and dust buster could result in different component distributions.

POWER DRILL (Rows)	DUST BUSTER (Columns)	CSM value
Total Common Core Components: 7	**Total Common Core Components: 7**	
charger, adapter assembly (1)	adapter and cord (1)	1
batteries (2)	batteries (2)	1
contact plates and wires (3)	contact plates and wires (3)	1
motor (7)	motor (6)	1
motor shaft (8)	motor shaft (7)	1
housing (12) , housing opening (13)	housing (15), exhaust vents (14)	1
Total Dormant Components: 2	**Total Dormant Components: 3**	
direction switch (4)	filter bag (9)	0
leveler (14)	rubber flap (10)	0
	release button (13)	0
Total Essential Conflicting Components: 1	**Total Essential Conflicting Components: 1**	
planetary gear set (9)	impeller (8)	-1
Total Function Sharing Components: 4	**Total Function Sharing Components: 4**	
switch (5), transistor (6)	on/off switch (4)	0.8
transistor (6)	diode (5)	1
output shaft (10)	rubber flap holder (11)	0.1
chuck (11)	nozzle (12)	0.4

Table 8. Classification of components

This information would help determine the most effective pair of parent products to integrate. In Figure 14, a representative new architecture of reconfigurable product is shown. The 'R' node indicates the reconfiguration necessary to switch electrical energy between the dust buster fan and the power drill gear assembly. The proposed architecture uses the power drill's basic architecture and integrates the dust buster components into it. The power drill was chosen as the basic architecture because it has fewer dormant components than the dust buster. This way, the filter bag and other components from the dust buster that are dormant during the drilling mode, can be positioned for easy removal. Studying the relationship between the number of dormant components and the most effective basic architecture to use upon system re-design is an area of future work. For instance, while the number of dormant components may be one factor in determining the most effective basic architecture, the ergonomics of the resulting architecture, the customer response to the new product aesthetics, and the necessary re-design costs are other factors that need to be considered.

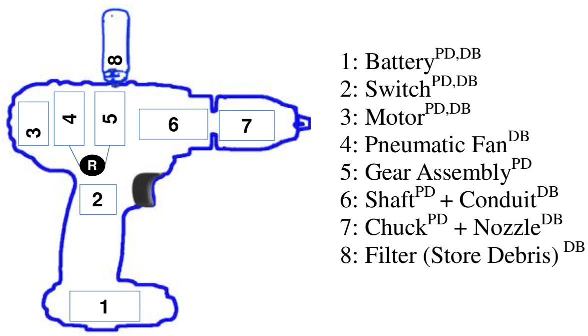


Figure 14. Reconfigurable drill & vacuum cleaner product

5 CONCLUSIONS

In this paper, we propose an approach to assess the feasibility of integrating two products into a new reconfigurable or multifunction product. The assessment identifies the common core components that could be used to create a product platform, the components that would remain dormant in one mode of operation, and those components that could be redesigned to accomplish some potential function sharing – and eventually becoming part of the common core after redesign.

One important consideration in the approach is the time it takes to populate the matrices. For the case study from Section 4, it required approximately three man-hours to populate the nine matrices. While the nine matrices are sparse matrices and only respective chunks need to be populated, the time required could be reduced by populating a repository of functional relationships that could then be mined to automatically create the matrices from the existing product function structures. The time could be further reduced by leveraging existing function component relationships in the Design Repository at Oregon State University. Lastly, since the output flows of functions typically become input flows to other functions, some of the information from the output flow matrix could be used to seed the input flow matrix. However, this is not always a direct mapping, as other intermediate flows occur within the function structure. Matlab was used to perform all the calculations.

The case study demonstrates how two products could be combined into one reconfigurable product. However, if the number of dormant components far outweigh the common core components, then it may be more advantageous to integrate the products into a multifunctional product. For instance, we found that the multifunctional coffee maker shown in Figure 1(b) has only a few components that are in the common core. Most are dormant components that only operate in one functional mode. Having many dormant components in a reconfigurable product will require significant hardware and/or software to support the reconfiguration between the dormant components, potentially increasing the costs. On the other hand, if performing multiple functions at the same time is preferred, then a multifunctional product could be designed to take advantage of the dormant components. A cursory investigation of ten current multifunctional/reconfigurable products and patents, some with a high number of dormant components and some with a high number of common core components, supported this observation. A more exhaustive version of this study will be the topic of future work.

One of the limitations of this approach is that the function sharing index values used in the TFS and FFS matrices qualitatively indicate the function similarity but do not directly quantify the amount of redesign required in the components. A more comprehensive metric relating functional similarity and the amount of redesign required for the components is an area of future work. Currently, the three levels of functions are treated as equally important. In the revised metric we will account for unequal functions, which may lend additional insight into the amount or type of redesign necessary.

Another promising area of future work is to automate this approach using cyber-infrastructure tools and integrate it with concept generation techniques. By linking this approach to a design repository of rich functional and component information, the designer could conceivably take a digital photograph of two products, and then utilize repository information to quickly assess the feasibility of integrating two products. A designer would have to identify the primary and variant flows. Apart from this, intelligent parsing algorithms, and function/component structures could be used to categorize the components as either common core, dormant, reconfigurable, or shared.

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APPENDIX

IFSM

Parent Product #1 Power Drill			Parent Product #2 Dust-Buster																					
			Common Core Chunk-1 & 2											RCFG Chunk - 3							Auxiliary Chunk - 4			
			import electrical	change electrical	export electrical	supply electrical	store electrical	transfer electrical	actuate control	actuate electrical	guide electrical	convert electrical to mechanical	transfer mechanical	convert mechanical to pneumatic	separate mixture	store solid	stop solid	guide mixture	import mixture	guide mixture	import human material	stabilize mechanical	secure solid	export gas
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Common Core Chunk - 1 & 2	import electrical	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	change electrical	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	export electrical	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	supply electrical	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	store electrical	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	transfer Electrical	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	change Control	7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	regulate control	8	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	regulate electrical	9	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	guide electrical	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	convert electrical to mechanical	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	transfer Mechanical	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
RCFG Chunk - 3	change mechanical	13	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
	transfer mechanical	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	rotate solid	15	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.7	0.3	0.3	0.3	0	0	0	0
Auxiliary Chunk - 4	secure solid	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	1	0.3
	indicate status	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	export gas / import gas	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.3	1

Figure A1. Input flow descriptors sharing matrix

OFSM

Parent Product #1 Power Drill			Parent Product #2 Dust-Buster																					
			Common Core Chunk-1 & 2											RCFG Chunk - 3							Auxiliary Chunk - 4			
			import electrical	change electrical	export electrical	supply electrical	store electrical	transfer electrical	actuate control	actuate electrical	guide electrical	convert electrical to mechanical	transfer mechanical	convert mechanical to pneumatic	separate mixture	store solid	stop solid	guide mixture	import mixture	guide mixture	import human material	stabilize mechanical	secure solid	export gas
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Common Core Chunk - 1 & 2	import electrical	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	change electrical	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	export electrical	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	supply electrical	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	store electrical	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	transfer Electrical	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	change Control	7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	regulate control	8	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	regulate electrical	9	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	guide electrical	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	convert electrical to mechanical	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	transfer Mechanical	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
RCFG Chunk - 3	change mechanical	13	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
	transfer mechanical	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	rotate solid	15	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.7	0.7	0.3	0.3	0.3	0	0	0	0
Auxiliary Chunk - 4	secure solid	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	1	0.3
	indicate status	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	export gas / import gas	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.3	1

Figure A2. Output Flow descriptors Sharing Matrix

FSM				Parent Product #2 Dust-Buster																					
				Common Core Chunk-1 & 2											RCFG Chunk - 3							Auxiliary Chunk - 4			
				import electrical	change electrical	export electrical	supply electrical	store electrical	transfer electrical	actuate control	actuate electrical	guide electrical	convert electrical to mechanical	transfer mechanical	convert mechanical to pneumatic	separate mixture	store solid	stop solid	guide mixture	import mixture	guide mixture	import human material	stabilize mechanical	secure solid	export gas
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Parent Product #1 Power Drill	Common Core Chunk - 1 & 2	import electrical	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		change electrical	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		export electrical	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		supply electrical	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		store electrical	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		transfer Electrical	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		change Control	7	0	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		regulate control	8	0	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		regulate electrical	9	0	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		guide electrical	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		convert electrical to mechanical	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		transfer Mechanical	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	RCFG Chunk - 3	change mechanical	13	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
		transfer mechanical	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.3	0	0	0	0
		rotate solid	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.7	0.3	0	0	0	0
	Auxiliary Chunk - 4	secure solid	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.3
		indicate status	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		export gas / import gas	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.3	1

Figure A3. Function descriptors Sharing Matrix

TFS				Parent Product #2 Dust-Buster																					
				Common Core Chunk-1 & 2											RCFG Chunk - 3							Auxiliary Chunk - 4			
				import electrical	change electrical	export electrical	supply electrical	store electrical	transfer electrical	actuate control	actuate electrical	guide electrical	convert electrical to mechanical	transfer mechanical	convert mechanical to pneumatic	separate mixture	store solid	stop solid	guide mixture	import mixture	guide mixture	import human material	stabilize mechanical	secure solid	export gas
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Parent Product #1 Power Drill	Common Core Chunk - 1 & 2	import electrical	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		change electrical	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		export electrical	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		supply electrical	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		store electrical	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		transfer Electrical	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		change Control	7	0	0	0	0	0	0	0.8	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		regulate control	8	0	0	0	0	0	0	0.8	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		regulate electrical	9	0	0	0	0	0	0	0.1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		guide electrical	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		convert electrical to mechanical	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		transfer Mechanical	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	RCFG Chunk - 3	change mechanical	13	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
		transfer mechanical	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0	0	0	0
		rotate solid	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.4	0.3	0	0	0	0
	Auxiliary Chunk - 4	secure solid	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.3
		indicate status	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		export gas / import gas	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.3	1

Figure A4. Total Function Sharing Matrix

		FFS		Parent Product #2 Dust-Buster																					
				Common Core Chunk-1 & 2											RCFG Chunk - 3							Auxiliary Chunk - 4			
				import electrical	change electrical	export electrical	supply electrical	store electrical	transfer electrical	actuate control	actuate electrical	guide electrical	convert electrical to mechanical	transfer mechanical	convert mechanical to pneumatic	separate mixture	store solid	stop solid	guide mixture	import mixture	guide mixture	import human material	stabilize mechanical	secure solid	export gas
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Parent Product #1 Power Drill	Common Core Chunk - 1 & 2	import electrical	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		change electrical	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		export electrical	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		supply electrical	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		store electrical	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		transfer Electrical	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		change Control	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		regulate control	8	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		regulate electrical	9	0	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		guide electrical	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		convert electrical to mechanical	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		transfer Mechanical	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	RCFG Chunk - 3	change mechanical	13	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
		transfer mechanical	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0
		rotate solid	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0
	Auxiliary Chunk - 4	secure solid	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		indicate status	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		export gas / import gas	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure A5. FFS

FCM[1] Power Drill		charger, adapter assembly	battery	contact plates and wires	direction switch	switch	transistor	motor	motor shaft	planetary gear set	output Shaft	chuck	housing	housing opening	leveler
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
import electrical	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
change electrical	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0
export electrical	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electrical	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0
store electrical	5	0	1	0	0	0	0	0	0	0	0	0	0	0	0
transfer Electrical	6	0	0	1	0	0	0	0	0	0	0	0	0	0	0
change Control	7	0	0	0	1	0	0	0	0	0	0	0	0	0	0
regulate control	8	0	0	0	0	1	0	0	0	0	0	0	0	0	0
regulate electrical	9	0	0	0	0	1	1	0	0	0	0	0	0	0	0
guide electrical	10	0	0	0	0	0	1	0	0	0	0	0	0	0	0
convert electrical to mechanical	11	0	0	0	0	0	0	1	0	0	0	0	0	0	0
transfer Mechanical	12	0	0	0	0	0	0	0	1	0	0	0	0	0	0
change mechanical	13	0	0	0	0	0	0	0	0	1	0	0	0	0	0
transfer mechanical	14	0	0	0	0	0	0	0	0	0	1	0	0	0	0
rotate solid	15	0	0	0	0	0	0	0	0	0	0	1	0	0	0
secure solid	16	0	0	0	0	0	0	0	0	0	0	0	1	0	0
indicate status	17	0	0	0	0	0	0	0	0	0	0	0	0	0	1
export gas / import gas	18	0	0	0	0	0	0	0	0	0	0	0	1	1	0

Figure A6. FCM of Power Drill

FCM^2 Dust-Buster		adaptor and cord	batteries	contact plates and wires	on/off switch	diode	motor	motor shaft	impeller	filter bag	rubber flap	rubber flap holder	nozzle	release button	exhaust vents	housing
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
import electrical	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change electrical	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export electrical	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply electrical	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
store electrical	5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
transfer electrical	6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
actuate control	7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
actuate electrical	8	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
guide electrical	9	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
convert electrical to mechanical	10	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
transfer mechanical	11	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
convert mechanical to pneumatic	12	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
separate mixture to gas and solid	13	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
store solid	14	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
stop solid	15	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
guide mixture	16	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
import mixture	17	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
guide mixture	18	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
import human material	19	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
stabilize mechanical	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Secure Solid	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
export gas	22	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

Figure A7. FCM of Dust Buster

CSM - PD DB				Parent Product #2 Dust-Buster														
				Common Core Chunks - 1 & 2							RCFG Chunk -3					Auxillary Chunk-4		
				adaptor and cord	batteries	contact plates and wires	on/off switch	diode	motor	motor shaft	impeller	filter bag	rubber flap	rubber flap holder	nozzle	release button	exhaust vents	housing
			#	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
Parent Product #1 Power Drill	Common Core Chunks - 1 & 2	charger, adapter assembly	*1*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		battery	*2*	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		contact plates and wires	*3*	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		direction switch	*4*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		switch	*5*	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0
		transistor	*6*	0	0	0	0.8	1	0	0	0	0	0	0	0	0	0	0
		motor	*7*	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		motor shaft	*8*	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	RCFG Chunk -3	planetary gear set	*9*	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
		output Shaft	*10*	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0
		chuck	*11*	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0
	Auxillary Chunk- 4	housing	*12*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
		housing opening	*13*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
		leveler	*14*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure A8. Components Sharing Matrix