HOST AND DERIVATIVE PRODUCT MODELING AND SYNTHESIS

A Thesis

by

MATTHEW LOUIS TURNER DAVIS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Daniel A. McAdams
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ABSTRACT

Host and Derivative Product Modeling and Synthesis. (August 2010)

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In recent years, numerous methods to aid designers in conceptualizing new products have been developed. These methods intend to give structure to a process that was, at one time, considered to be a purely creative exercise. Resulting from the study, implementation, and refinement of design methodologies is the notion that both the structure of the development process and the structure of the developed product are key factors in creating value in a firm's product line. With respect to the latter key factor, product architecture, but more specifically, modular product architecture has been the subject of much study. However, prior research in the area of modular product architecture has, with limited exception, focused on the construction of modules that are to be incorporated into a product before it becomes available to its end-users; that is, the modules are incorporated 'pre-market.'

The research contained in this thesis is focused on two tasks: advancing the notion of a modular product architecture in which modules can be incorporated into a product 'post-market,' and creating a method that aids designers in synthesizing these post-market modules. Researchers have examined the idea of post-market modules; however, they do not fully formalize language used to describe these modules, and they also do not give the product space created by post-market modularization well-defined boundaries. Additionally, the prior work gives no method that can be used to create post-market modules. The research presented here addresses these shortcomings in the prior work by first, defining the terms 'derivative product' and 'host product' to describe the post-market module and the product that the module augments, respectively. Second, by establishing three guidelines that are used to assess the validity of potential derivative products, giving the newly termed host and derivative product space defined boundaries. And lastly, by developing a 7-step, biomimetic-based methodology that can be used to create derivative product concepts (post-market modules). This developed methodology is applied to four case studies in which it is used to create five derivative product concepts for a given host product. Thus, 20 derivative product concepts are developed in this study, demonstrating the qualitative effectiveness of the 7-step methodology.

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NOMENCLATURE

B-RAD	BioMatrix Results Aggregation Document
DFA	Design for Assembly
DFM	Design for Manufacturing
DSM	Design Structure Matrix
HOQ	House of Quality
MFD	Modular Function Deployment
NIST	National Institutes of Standards and Technology
QFD	Quality Function Deployment
TIPS	Theory of Inventive Problem Solving

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Product design was long considered to be more of an art than a science. However, recent research efforts have shown that systematic methods that aid designers in finding design solutions, given a certain set of conditions, can be developed. These methods help give order to and bring about an understanding of a process that was at once dominated by the idea that great design was primarily the result of the innate creativity of the designer. Additionally, formal design methods are subject to modification, extension and critical inquiry in a way that purely creative processes are not.

There are many books that present formal development processes, which can be used to take any product from conception through to production and market release (see e.g. [1-4]). In general, these formal methods break down the overall development process into separate tasks. For example, Otto and Wood [2] separate the development process into three broad tasks: understanding the opportunity, developing a concept, and implementing a concept. They then decompose each task into four sub-tasks. It is in the set-up and execution of these sub-tasks where a product's value can be created and, consequently, where much research is focused.

In the past, the sub-tasks of a given product development process were assigned to separate functional groups based on the nature of the task. This way,

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This thesis follows the style of the Journal of Biomechanical Engineering.

everyone working in development process had a clear idea of the scope of their responsibilities based on the group to which they belonged. However, inefficiencies in this type of highly delineated development process led to the creation concurrent engineering strategies [2]. With a concurrent engineering strategy, an organization develops a product with input from all functional groups (e.g. marketing, engineering, and manufacturing) at each stage of the process. Successful implementations of concurrent engineering suggest that a product's physical structure, i.e. its architecture, is key to its value. With this in mind, the focus of this thesis is on developing the idea of a specific type product architecture, and constructing a method that helps designers create products which embody that architecture.

The use of product architectures to create value is a well-considered topic in the product design and development field. This is not surprising as Volkswagen is said to save $1.7 billion annually through the use of its product architecture schemes [5]. Ulrich [6] separates product architectures into two categories: integral and modular. In an integral architecture, the major sub-assemblies of a product can perform more than one function; with a modular architecture, the sub-assemblies map directly to one function on a product. Considering the modular architecture, much research has been focused on how companies can create efficient module structures that reduce a product's life-cycle costs, while maintaining or expanding its market appeal. However, much of that research focuses on modules that are inherently 'pre-market' in nature. Meaning, the desired modules are designed and incorporated into the product before it becomes available to end-users. Baldwin and Clark [7], on the other hand, put forward the notion of reconfiguration augmentations. These are modules that can be added to or excluded from a product based on the needs of its users. Augmentations, in this context, describe modules that are 'post-market' in nature. A post-market structure allows a product to have an extended function set and, consequently, a potentially wider operating range. This research intends to build on the work of Baldwin and Clark [7] by formalizing the notion of post-market modules, and creating a method that aids designers these modules' synthesis.

In order to justify the creation of a post-market modularization philosophy, this thesis will show how the idea connects with current modularization reasoning. One of the broad ideas behind using a modular product architecture is to reduce development and production costs while providing the marketplace with some level of product variety [8]. An established area of research stemming from this idea is product family design. This thesis will review the notion product family design in an effort to show that it, along with modular product theory in general, supports the creation a new, post-market modularization strategy.

Once the validity of post-market modularization has been accepted, the next natural question relates to how designers will create these modules. Tools for creating modules in existing designs have already been created [2, 9]. These tools rely on a functional decomposition of the existing product, which is then explored, in some way, for beneficial groupings of functions. That is, the designer looks for discrete groupings of overall functions within a set of known functions. Conversely, with a post-market module, the designer needs to look for an overall function with no prior knowledge of the module's constituent functions. In this way, the front-end question for the post-market modularization strategy is closely related to ideas in concept generation.

Concept generation is the stage in the product development process that requires designers to leverage their creative skills. However, this does not mean that generating concepts needs to be an ad-hoc exercise. Methods that aid designers in creating concepts do exist [2]. But many of these methods assume that designers have at least some knowledge of the desired overall function of the proposed product. Such knowledge is not available when designing a post-market module. What is needed in this case is an analogous space where, functionally speaking, the relationship between the platform (i.e. the product to which the post-market module is affixed, this will be discussed in detail later) and post-market module can be identified. Such an analogous space is nature.

A design that in some way imitates or evokes a natural phenomenon is known as a biomimetic design [10]. This thesis puts forward a systematic, biomimetic-based design method that aids designers in generating post-market module concepts for a given platform. The developed methodology does this by functionally translating the pre-market modules present in a platform product to the biological domain. In this domain, 'naturally' related products can be identified by a designer, and their biological function(s) can then be translated back to the engineered domain. In this way, the engineering parameters of a system are substituted for equivalent biological parameters.

However, making a clean substitution of biological parameters and functions for their engineering equivalents is not necessarily an easy or straightforward task. To that end, this research makes critical use of the research of Cheong et al. [11]. The results of this research enables the translation of a predefined set of engineering functions to a corresponding set of biological keywords. With this functional shift in domain made, a relational, biomimetic database developed by researchers at the University of Toronto is then used to search the biological domain for related functionalities. The engineering interpretation of these related functionalities serve as post-market modules concepts.

In order to validate the concept generation methodology presented in this thesis, four case studies are performed. These studies show how, for a given platform product, post-market module concepts can be generated in a systematic way.

2. BACKGROUND AND PRIOR WORK

The work in this thesis is related to two areas within the design research community: modular product architecture and biomimetic concept generation. In terms of the former, the first part of the goal of this research is to formalize the notion of the post-market module product space. However, before this formalization is made, the areas of research that motivate and inform the creation of the space are discussed. These areas include concurrent engineering, modular product architecture, augmentation and reconfiguration, and product family design. Reviewing these areas of research in the context of post-market modularization highlights the connection this novel product space has with established notions modular architecture and design.

In terms of the latter research area, the second part of the goal of this research is to develop a methodology that can aid designers in synthesizing post-market modules. Methodologies for creating and identifying potential modules in a given product already exist. These methodologies are rooted in the engineered domain, identifying modules based on a product's functional decomposition. It is argued here, however, that, in the post-market module space, the need to identify the global function without knowledge of constituent functions prohibits a direct application of these existing methodologies. Alternatively, the methodology proposed here makes use of pre-defined functional relationships in nature to inspire concepts for post-market modules. To this end, an overview of research in the areas of biomimicry and biomimetic concept generation is presented in this section.

2.1 Concurrent Engineering

It's no secret that today's organizations face a consumer market rife with global competition. As such, companies can no longer count on maintaining market dominance through brand name or shear size alone. A product's perceived quality, its ability to meet specific customer needs, and its associated costs are now key factors that affect its sales performance [12]. Furthermore, due to the rise in complexity of many of today's products, development times have increased which, if not controlled, can also adversely affect market performance [13]. A company's ability to produce a varied product line of high quality, low cost products in a timely manner is inherently a function of their development process.

Traditionally, the product development process is divided both functionally and temporally [14]. For example, the marketing department examines customer needs along with the market environment and decides what kind of products should be made. Then product designers and engineers determine engineering specifications and design the desired product. Lastly, the manufacturing department implements the product design, producing the actual physical product. However, this type of one-way, 'over-the-wall' process (known as sequential engineering) causes an increase in design changes late in the development process as 'down stream' departments are only able to give their input after the preceding department has finished its work [13]. These late design changes are expensive because the overall time-to-market becomes extended as the design iterates back through the relevant departments. Inefficiencies and costs stemming from the sequential engineering development process has led to the formation of concurrent engineering strategies [2].

As the name implies, a concurrent engineering strategy requires that the various development efforts take place in parallel rather than sequentially. Taking a more formal approach, concurrent engineering is defined as, "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support" [15]. This definition suggests that, under a concurrent engineering strategy, both design and manufacturing teams work together, designing a product and its corresponding manufacturing process simultaneously. Crawford and Di Benedetto [1] go further in suggesting that marketing, finance, and other management functions should also be carried out concurrently with the product and process design efforts. With a concurrent engineering strategy, each functional department has input on the design of a product early in its development. This is critical because Syan [13] found that 60-95% of the total life-cycle cost of a product is determined during its design. This suggests that if significant savings can be achieved during the design of a product, the resulting value added can be passed on to the market.

Prasad [12] asserts that the concurrent engineering philosophy is based on eight fundamental principles: early problem discovery, early decision making, work structuring, teamwork affinity, knowledge leveraging, common understanding, ownership and consistency of purpose. These principles define ideal outcomes of a properly implemented concurrent engineering strategy. The question then becomes: How does one properly implement a concurrent engineering strategy? In an effort to answer this question, Prasad [12] goes on to describe various organizational structures and practices that can help a company embody the concurrent engineering principles. Similarly, Pawar [16] and Otto and Wood [2] emphasize the notion that team structure and the relationships developed within and among teams is a critical factor in the successful execution of concurrent engineering. Additionally, there are some specific methodologies that a company can use to focus its implementation of concurrent engineering.

In terms of relevance to this research, two concurrent engineering methodologies stand out: Quality Function Deployment (QFD) and Design-for-X (DFX). QFD is a methodology that demands the, "deployment of quality through the deployment of quality functions" [17]. This is done by first relating customer demands to certain quality characteristics, then ensuring that the final product has these characteristics by making certain that its constituent functions and processes have the necessary level of quality. One tool used to structure the QFD methodology is known as the House of Quality (HOQ) [18]. In its most broad form, the HOQ is a graphical diagram that shows the relationships between customer needs and engineering parameters. Generally, however, more information such as correlations between engineering parameters, a company's relative market position, and technical and cost assessments are included [19]. In this way, the HOQ connects the needs, concerns, and priorities of the various functional departments. The development team can thus use the HOQ to help facilitate communication and foster a common understanding (among departments) of various development issues, including possible impediments and design trade-offs [18].

DFX is a concurrent engineering methodology intended to focus the efforts of the development team on some specific "X" factor. DFX (like QFD) is opposed to the notion that the function of the final product alone is the key indicator of a successfully developed product [14]. Huang [20] states that the X factor in DFX can be manufacturability, assembly, recyclability, inspectability or any other linear combination of a life cycle business process and a performance measure. Two common DFX methods are, design for manufacture (DFM) and design for assembly (DFA). Taking a broad, product view, Boothroyd and Dewhurst [21] define DFM as a process in which a product's structure is designed in a way that reduces its manufacturing costs. They go on further to assert that the way to implement DFM is by simplifying the proposed product using the DFA methodology.

Syan and Swift [22] state that DFA has four main aims: reduce part counts, optimize the assembly of parts, optimize the handleability of parts, and improve quality and efficiency while reducing assembly costs. Ways to implement DFA fall into two categories axiomatic (heuristic) and quantitative. Otto and Wood [2] present a collection of heuristic DFA methods in their work. These methods put forward general guidelines designers can follow to help ensure that their products assemble easily. On the quantitative side, one technique that has been developed is known as the Boothroyd-Dewhurst method [21]. This method first requires designers to reduce part count by applying certain criteria that help determine if any components can be combined. Then, the costs of the various manufacturing processes that could be used to fabricate and assemble an identified component are estimated and compared.

Examples of successful implementations of concurrent engineering (to include QFD and DFX) can be found in the literature (see [15, 18, 23, 24]). Consequently, it is apparent that a collaborative approach to the development process can lead to market success over and above what can be achieved using traditional (sequential) approaches. But when these different functional departments/teams are collaborating, what are they collaborating to do? Syan [13] suggests that they are coming together to set forward a cost effective product design for a given set of customer needs. This is clearly seen with the HOQ, where customer needs are related directly to engineering parameters, and the various costs stemming from those relationships are assessed. It's also seen with DFM and DFA, where the structure of a product is designed so that it reduces costs. Thus, it can be concluded that when looking to add value to a product, one cannot consider functionality alone; significant value can be added through careful examination of how that functionality is implemented; that is, an examination of a product's structure.

2.2 Product Architecture

The first step in the Boothroyd-Dewhurst DFA process is to reduce a product's part count by combining components [21]. Taking this fact in combination with the documented success the Boothroyd-Dewhurst process has had in practice [23] indicates that having the right combination and configuration of components can add value to a product. Accordingly, a more in depth study of the structure or, equivalently, the architecture of products is warranted.

Ulrich [6] puts forward a three-part definition for product architecture: (1) the arrangement of functional elements, (2) the mapping of functional elements to physical components, and (3) the specification of the interfaces among interacting components. Before examining this definition further, the meanings of functional element and physical component must be established. Pahl and Beitz [3] define a function as the, "general input/output relationship of a system whose purpose is to perform a task." Functions can be arranged and connected to create a function structure, which shows the transfer of materials, energy, forces, and signals through the system [2]. In this configuration, the individual functions are known as the functional elements of the system. For example, on a typical household iron, one of the functions may be to spray water. This 'spray water' function is thus a functional element (among may others) within a function structure, where the structure defines the connection of elements necessary to accomplish the overall task of ironing clothes.

As for physical components, these are the entities that embody the core design concept, and perform the function(s) prescribed by the functional elements [25]. Ulrich [6] notes that the relationship among the functional elements and physical components depends on the level of detail being considered. If every spring and screw were to be considered a component of a system, then each functional element would require many physical components in order to perform its function. Using the iron example again, the 'spray water' functional element may be implemented by one or more physical components; for instance, a straw to guide the water up from a reservoir, a pump to move the water, and a nozzle to distribute the water. However, if one considers the straw, pump and nozzle to be one integrated component, then the 'spray water' function would be implemented by one physical component. Conversely, if at a certain level of detail, one component implements multiple functional elements, function sharing is taking place [26]. Clearly, whether function sharing is implemented or not, also depends on the level of detail used in the function structure.

Now that the language of functions and components has been established, the three-part definition of product architecture can be defined in those terms. Part 1 relates to the defined function structure of the system. That is, how the different functional elements can be arranged to accomplish the overall task. Part 2 of the definition relates to the level of function sharing within the system. And lastly, part 3 relates to how the physical components interact in the real system. Taking the collective view of this definition, it is apparent that the way the functional elements are defined and their relationship with their corresponding physical component(s) affects a product's architecture. To this end, Ulrich [6] defines two types of product architectures: integral and modular. In an integral architecture, multiple functional elements of the function structure map to a single physical component. That is, a level of function sharing is designed into the product. Modular architecture, on the other hand, features a one-to-one mapping between the functional elements and physical components.

Hölttä-Otto [27] notes that the distinction between integral and modular products is not exact; products are generally neither fully integral nor fully modular. However, practically speaking, products can be made to favor one architecture type over the other depending the customer needs, and the strategy of the firm developing the product. While an integral architecture scheme can provide some useful benefits (see Cutherell [28]), it will not be investigated in this thesis. Rather, the following subsections present an overview and review of product modularity along with a discussion of an architecture scheme that stems from modular thinking: product family design.

2.2.1 Modular Product Architecture

In the previous section, the 'spray water' function on a typical household iron was considered. It was posited that this function could be implemented by several physical components; specifically, a straw, a pump and a nozzle. If this were the case, there would be a three-to-one mapping of physical components to functional elements. This is the opposite of function sharing and thus, is not an integral-type architecture. The straw, pump, and nozzle configuration would not quite represent a modular architecture either, as that requires a one-to-one mapping of elements to components [29]. However, if one similarly considers a hand soap dispenser, it is apparent that the straw, pump and nozzle are joined to form a seemingly single component (Figure 1). This single (physical) component now has a one-to-one mapping with the functional element in the function structure responsible for the dispensation of liquid. Furthermore, one can observe that this straw-pump-nozzle component could (and often is) be used for a range of different liquids and liquid reservoirs. For example, lotions bottles, hand creams, hand sanitizers, shampoos, and so on. In this case, the straw-pump-nozzle component is considered to be a module of the soap-dispensing device.

Figure 1. The straw-pump-nozzle module of a standard soap dispenser.

Ericsson and Erixon [30] define modular architecture as one in which a product, (1) has similarity between its physical and functional architecture, and (2) minimizes the degree of interaction between its physical components. Similar to the definition in Ulrich [6], the first part of this definition specifies the one-to-one mapping of physical components to functional elements. A one-to-one mapping allows components to be more easily indentified with respect to their function in the overall device. Thus, a fully modular product would consist of a combination of discrete functional units which, when configured, produce some overall desired function [3]. Part two of the Ericsson et al. definition deals with the interactions between modules. In terms of the function structure, while, broadly speaking, the functional elements (or groupings thereof) can be said to represent modules, the material, energy, force and signal 'flows' can be said to represent the dependencies (interactions) between each module [2]. Ulrich [6] refers to these interactions as couplings. A coupling defines how two modules are affected by changes in either one. In a modular architecture, the goal is to have de-coupled interactions, or interfaces [6]. This means that a change in the specifications of one module does not require a change in the specifications of the other modules with which it interfaces. For example, with the hand soap dispenser, one could make a change to the volumetric size of the reservoir without, necessarily, having to change the dimensions of straw-pump-nozzle module.

Much like with any defined architecture scheme, the goal of modularization is to add value to a product. This value is added by extending the variety of customer needs a product can meet or by introducing efficiencies into the development process, or both. In terms of development efficiencies, Gershenson et al. [31] note that modularity can give designers the flexibility to deal with changing processes. That is, due to the interchangeability of modules, a required process change may only affect a small number of modules rather than a product as a whole. This reduces redesign costs and development times. Ericsson et al. [30] list several development-side benefits to modularity including: simultaneous development products, reduced material costs, improved quality, and a reduction in production lead times. They further note that modularity is a good way to reduce the deleterious effects of product complexity on the development process. Complex products can be broken-up into more manageable units, which can be designed by separate, often specialized, teams working in parallel. Additionally, Pahl and Beitz [3] indicate that economies of scale are effectively leverage with modular products because batch sizes of parts used in standardized modules can be increased.

Many companies are facing increasing demands from their customers for highly customized products [32]. This implies that customer needs, in some markets, are becoming increasingly varied. Instead of developing many separate products to meet these needs, a modularization strategy can be used to provide the desired mix of products to the marketplace [2]. For example, going back to the hand soap dispenser, if customers in the household use market prefer a light pumping force while industrial use customers favor a heavy pumping force, both needs could be satisfied by supplying different straw-pump-nozzle modules to the two markets. The modularization negates the need for manufacturing separate reservoirs for the two clients, as that module does not affect the required pumping force. Also, modules allow for easier upgrading when new technology becomes available [30]. In this way, companies can keep their products in line with the latest customer needs without incurring the cost of a total redesign.

Modularization allows companies to satisfy a desired range of market needs while achieving economies of scale in their design and manufacturing processes [33]. That is, modularization can provide both front-end and back-end benefits for a product development process. Where front-end refers to beneficial attributes of a product that customers can appreciate and back-end refers to beneficial attributes the company developing the product can gain. To this end, Pahl and Bietz [3] establish the notion of two different types of modules: production modules and function modules. Production modules are those modules that are designed without regard for their actual function. They are developed exclusively to add value during the production phase. In terms of this research, however, production type modules are of little relevance. The idea behind post-market modularization is to extend the functionality of a product beyond its original capabilities. Whether or not imparting those original capabilities on a product can be done more efficiently with a modularization scheme, is not the focus here.

Function modules, on the other hand, provide a basis for this thesis. Function modules are those modules that, "help to implement technical functions independently or in combination with others," [3]. These types of modules are the ones that contribute to the overall function of the final product. Pahl and Beitz [3] classify function modules in 5 ways:

(1) basic modules – these are invariant modules can fulfill the overall product function singularly or in combination with other modules.

(2) auxiliary modules – these type of modules assists the basic modules in carrying out the overall function of the product.

(3) special modules – are modules that carry out task-specific sub-functions and may not appear on all variants in a product line.

(4) adaptive modules – are used to adapt a product to other systems and to conditions that are unforeseen by the designers.

(5) non-modules – these modules handle customer-specific functions and are uniquely designed for a special task.

The way in which each of these types of modules is included in a function structure defines a particular modularization scheme. While not stated directly, the first four classifications given by Pahl and Beitz seem to define modules that are to be incorporated before a product becomes available to its end users (pre-market). The non-module appears to be the classification nearest to the notion of a post-market module as Pahl and Beitz indicate that this module lies outside of the main function structure; again, however, this is not explicitly stated.

Unfortunately, the literature does not extend Pahl and Bietz's module classifications directly. Rather, a more architectural based view of function modules is taken [34]. Ulrich and Tung [29] define three types of structural based modularity:

(1) Component-swapping modularity – this type of modularity is when two or more components are combined with a module to create a product variant. An example of this type of modularity would be a piece of farm equipment that can be configured (with the addition modules) to perform several tasks [35].

(2) Component sharing modularity – also called slot modularity, this type of modularity is characterized by the sharing of one component among many products in a product line. The straw-pump-nozzle module from the hand soap dispenser would be an example of slot type module.

(3) Bus modularity – is when a base product allows for the number and position of basic components attached to it to vary depending on the desired functionality [36]. An example of this type of modularity is the rail systems used on modern military rifles to attach various mission specific hardware.

Unlike the module classifications given by Pahl and Beitz, these classifications do not give any consideration to a module's actual function. For example, Otto and Wood [2] use cordless drill batteries to illustrate slot modularity. The batteries are classified slot modules not because they supply power to the main platform (i.e. their function), but because of the way in which they are designed to interface with a variety of products in the cordless drill's product line. Under the Pahl and Bietz [3] scheme, the batteries would be classified as auxiliary modules because their role (function) is to assist the basic modules. Similar to Pahl and Beitz [3], however, Ulrich and Tung [29] do not explicitly consider pre-market versus post-market modules. Both [3] and [29] put forward the general proposition of modular products and present vocabularies and guidelines that can be used by product developers to aid them in creating modular products.

2.2.1.1 Augmentation and Reconfiguration

Baldwin and Clark [7] advance the notion of post-market modularization directly. They begin by defining six, so-called, modular operators: (1) splitting, (2) substituting, (3) augmenting, (4) excluding, (5) inverting and (6) porting. Through various combinations of these operators, one can describe the evolutionary path of any modular product's structure. The first two operators describe processes that can be used to make non-modular products modular. Splitting is the act of breaking previously integrated systems or components into separate functional modules. In terms of the function structure, this can be described as taking a product that is best represented by a single, 'black box' function, and partitioning it functionally such that it can be represented by multiple, interconnected black box functions. Once this is done, modules can be substituted for one another based upon the market (or production) advantage the company is trying to achieve. For instance, going back to the hand soap dispenser, if a more environmentally friendly reservoir module is designed after the product reaches market, the new reservoir can be substituted for the original without having to design a new straw-pump-nozzle module.

Unlike the first two, the last two operators, inverting and porting, describe processes that can only be applied to products with a modular structure. Looking at inverting first, this describes the process of generalization of a module or function. That is, instead of having a module or function interacting with only one other module or small group of modules, it's redeployed to interact with several different modules or groups of modules. Related to inverting, porting describes how a module can be generalized so that is available for use by more than one system (as opposed to just more than one module). This requires the porting module to not only have 'hidden' internal functions (or modules), but also external modules that translate incoming and outgoing signals so that the attached systems can understand one another. In terms of this research, porting can be described as, effectively, the means by which post-market modules interface with the supporting platform.

While splitting, substituting, inverting, and porting describe certain modularization processes and effects, they do not necessarily suggest or give guidance to a post-market modularization strategy. The remaining two operators on the other hand, embody the core notion of post-market modules. Baldwin and Clark [7] describe the augmenting and excluding operators as inherently linked, as they are two sides of the same coin: augmenting means adding a module, while excluding means leaving one out. In an architecture that supports augmenting and excluding, modules can be added or subtracted by companies based on their business strategy, or by end users based on their needs. The process of users adding and subtracting modules based on their needs is termed reconfiguration. Using previously established language, three types of reconfigurations are defined: substitutions, augmentations and exclusions. Substitutions refers to module upgrades; that is, functional enhancements. Exclusion reconfiguration refers to users removing modules that are no longer needed. What is of interest, in terms of this research, are reconfigurations (post-market modules) that extend functionality rather than enhance it or take it away. This is the idea behind reconfiguration type augmentations. Users perform an augmentation reconfiguration when they desire a product to have new type of functionality. In this way, the useful range of a product can be extended at the discretion of its end users.

Thus, Baldwin and Clark [7], through the terminology of reconfiguration augmentation, have defined the post-market module space that will be further explored in this thesis. In fact, they also investigate the value of product augmentations to a firm by examining a number of case studies. They conclude that augmenting adds value to not only to the product being augmented, but also to the class of products to which the platform belongs. This is because new augmentations spark ideas for further augmentations that may be able to be applied to a wider class of systems. Also, co-investment increases with an augmentation strategy, as the third parties that supply the modules have a greater stake in the platform’s success. The work in [7], however, does not fully formalize the notion of a post-market module. For example, they do not clearly distinguish between augmentation, which they define as, "the act of adding a new module to a preexisting modular system," and reconfiguration type augmentation, as it is defined in the preceding paragraph. Additionally, Baldwin and Clark [7] do not present a methodology that can be used by designers to create post-market modules (augmentations). They instead look at cases of successful post-market module implementations in industry. Also, the case studies presented are focused on computer software and computer related peripherals; post-market modules in other industries and contexts are not considered.

2.2.1.2 Identifying and Creating Modules

With the validity of a modular architecture strategy having been broadly accepted, many subsequent authors have considered different ways to create and/or identify modules in products. Ericsson and Erixon [30] have developed a modularization technique called Modular Function Deployment (MFD). MFD is a five-step process, which, similar to QFD and the House of Quality, uses a fundamental document to relate customer needs to functional engineering requirements. However, different from HOQ, once the engineering requirements are identified, they are grouped according to function, and the resulting potential modules are assessed against the key module drivers (i.e. the strategic business motivators for using a modularization strategy). From this assessment, more refined module candidates are identified, and then evaluated based on criteria such as required interfacing and economic factors.

Gershenson et al. [31] put forward the idea of life-cycle modules. These are groupings of system components that not only contribute to a defined functional goal, but also have similar life-cycle process requirements. In this way, the definition of a module is extended from a simple form-function relationship to a form-function-process relationship. To illustrate life-cycle modularity, Gershenson et al. [31] give the example of tuner and volume knobs on a stereo system. These two components have entirely separate functions but are manufactured using similar processes; as a result, combining them into a single module could prove beneficial. Under this life-cycle view, potential modules are identified through a four-step process. The first two steps involve a decomposition of a product from the module down to the component level, and an identification of the manufacturing processes corresponding to each component. In the third step, similarity and dependency matrices are constructed. These matrices rate the relationship among the components of a product based on six similarity-dependency descriptors. Lastly, the relative modularity of the original modules of the product is calculated; a higher relative modularity (relative to the other modules in the product) indicates more modularity in that module. Modules with the lowest relative modularity are considered for redesign or reconfiguration.

Graphical based methods for determining potential modules have also been examined. Kusiak and Huang [37] developed a heuristic clustering algorithm based on a product's interaction graph. The interaction graph shows each component as a node, modules as boundaries enclosing groups of nodes, and interactions as directed lines connecting the various nodes. Each interaction is weighted based on the frequency with which the two nodes it connects to functionally interact. A ratio of weights to the number of interactions (called the weight density) inside a module determines the quality of that module. With the interaction graph created, a six-step heuristic algorithm is implemented. The goal of the algorithm is to, (1) minimize the total weight density of intra-modules and (2) maximize the total weight density of inter-modules. In this way, the functional correlation between modules and physical components can be made high and the interactions among separate modules can be minimized. Kusiak and Huang state that their method can not only be used to create modules for increased product variety, but also to create modules that maximize a product's performance under certain constraints, such as space restrictions in printed circuit boards.

Hölttä-Otto [27] notes that the design structure matrix (DSM) can be used to define modules in a product. This is done by mapping components to one another and rating their level of interaction; much like in the life-cycle method presented in [31]. Jose and Tollenaere [38] present a review of the various modularization methods developed in the literature. They group these methods into 5 categories: (1) clustering methods, (2) graphical and matrix methods, (3) mathematical programming, (4) artificial intelligence methods, and (5) genetic algorithms and heuristics. For this research, a method that combines graphical and heuristic tools developed by Stone et al. [9] will be used to assist in the identification of post-market modules. A detailed description of this method will be presented in the

'Research Approach' section of this thesis. In general, however, Stone et al.'s [9] method requires the creation of a function structure (specifically, a functional model) as a first step in the process. A functional model contains information about the 'flow' of materials, energy and signals through a system's constituent functions without regard for the exact nature of artifacts that implement those functions. The next step in the heuristic method is to characterize the flows in one of three ways based on their path through the constituent functions: (1) dominant flow, (2) branching flow or (3) conversion-transmission flow. Based on the boundaries that enclose each type of flow, a module is defined.

All the methods presented above (MFD, life-cycle modularization, heuristic clustering, DFM methods, modular heuristics), are useful for creating and/or identifying modules during the development process. However, to accomplish this, each of these methods relies on knowledge of a known or proposed internal product structure. That is, they partition a product based on the relationship among its known constituent functions. This is not the case with the type of modules that are proposed in this work; what is sought here is the (global) function of a related, augmenting module that has unknown constituent functions. Thus, directly applying these methods to the problem of post-market modules is not possible.

Ericsson and Erixon [30] state that the difference between a module and a simple subassembly is that while a subassembly may result out of manufacturing necessity, a module is chosen for strategic business purposes. That is, modules are created to give a company a pre-defined marketplace advantage. As stated previously, two ways modularization can impart an advantage to a company are by reducing development costs and/or by efficiently increasing the variety of products the company can offer. Modularization techniques that can be used to achieve the latter advantage have been the subject of much study [33]. In terms of this thesis, an area of research worth considering in this regard is product family design.

2.2.2 The Product Family

As stated previously, Feitzinger and Lee [32] note that demand for highly customized products is increasing in some markets. The question for companies then becomes: How does one increase product offerings efficiently? One answer is to use a product platform strategy [39]. Robertson and Ulrich [39] define a product platform as, "the collection of assets shared by a set of products." These assets are, most often, a set of components or modules that provide common functionality for a wide set of products. For example, Meyers and Lehnerd [40] discuss Black & Decker's development of a common motor design, which served as a platform for many of its power tools. This platform design resulted in an annual savings of $1.28 million in terms of materials and labor. While the motor in this example is called a product platform, the array of power tools that use that particular motor forms a product family.

Formally, a product family is defined as a group of products that share a common platform but have distinguishing functionalities and features based on their intended market segment [41]. Each marketable product within a certain product family is commonly referred to as a derivative [2]. Using a product family strategy, companies are able to introduce a variety of products to the market while creating or maintaining economies of scale in their manufacturing and development processes [41]. Additionally, Sawhney [42] lists six benefits that stem from having a platform-based product family strategy: speed, cost, design quality, coherence, referenceability, and option value.

The body of literature related to product family design is quite extensive, as is evidenced by the literature reviews presented in Jiao et al. and Simpson [33, 43]. What is relevant to this research are product family-based techniques or methods that guide one in creating derivatives. However, such methods are not prevalent in the product family literature. Rather, many of the methodologies used for creating product family derivatives are the same as those used to create and identify product modules [33]. Some marketing-based methodologies have been developed to identify opportunities for derivatives. For example, Meyer and Lehnerd [40] put forward the idea of using a market segmentation grid (Figure 2). This is a graphical representation of the different market tiers a given product family is designed to serve. The horizontal axis of the market segmentation grid displays the market segments, while the vertical axis shows the corresponding market tier for each derivative. The market tier defines the type of quality level (or consumer level) that the derivatives are designed to meet; e.g. low cost/low performance or high cost/high performance, etc. With this visual representation in hand, designers can use it to help create family derivatives based upon a market tier strategy. This market tier strategy, however, while useful in trying to identify the level of consumer a derivative should target, it does not necessarily identify an overall functionality a particular group of consumers may find appealing. Thus, it is not very useful in solving post-market module problem posed in this research.

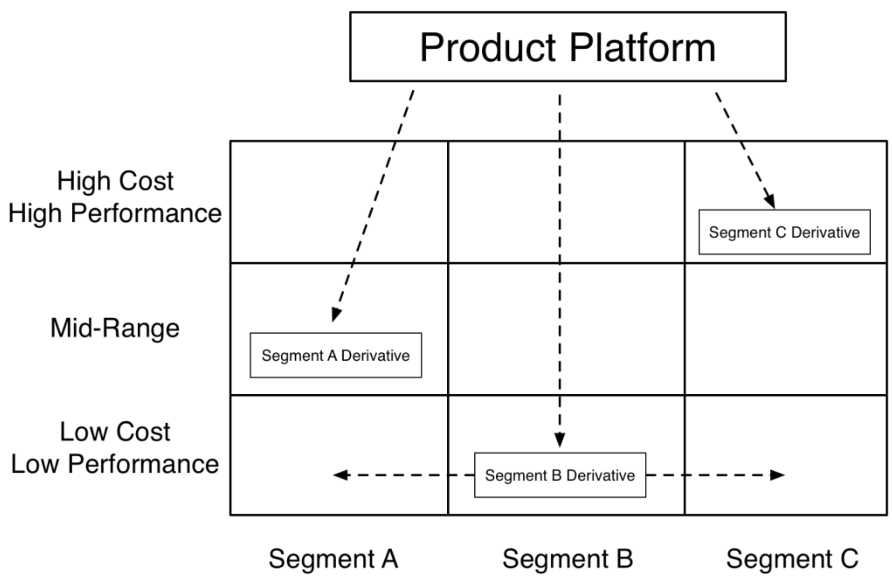


Figure 2. A market segmentation grid (adapted from [40]).

Much of the research into product families is focused on determining the optimality of a particular architecture or strategy with respect to certain constraints. Gamba and Micalizzi [44], for instance, present a real options model to find the optimal investment between two product strategies. The first strategy is one in which a main product is released into the marketplace, with a complementary follow-on product being released at a later time. The second strategy is similar to the first, except that when the follow-on product is released, the main product is removed from the market; they refer to this strategy as 'substitution.' The former strategy represents a product family-type (and post-market module-type) scheme. Gamba and Micalizzi [44] conclude that the net present value is highest when a complementary and highly correlated follow-on product is developed. That is, an investment in producing a follow-on product can add value to a product line if the combined value of the main product and follow-on product is higher than the sum of both products' individual value, and if the revenue profiles of the two products are (positively) correlated. This is as opposed to using the substitution product strategy. The results achieved by Gamba and Micalizzi [44] are useful in confirming the potential value present in the post-market module space; however they do not give any insight into how to determine the functionality of potentially profitable follow-on products (post-market modules).

Gonzalez-Zugasti and Otto [45] consider modular product families, developing an optimization-based method to identify the best mix of modules and corresponding module specifications. Their method takes as inputs a vector of design variables for each family derivative, as well as the mix of modules that are present in each variant. These inputs serve as the variables in an objective function equation, which is, in turn, minimized by the optimization routine. Gonzalez-Zugasti and Otto state that the actual form of the objective function is dependent the desired optimal outcome. For instance, designers may want to reduce the production cost of a family, or they may want to maximize the power output of a particular module. With the inputs and objective function determined, the optimization proceeds subject to four constraints: family capacity, variant capacity, sharing, and module compatibility. The output of the method is an optimized set of design variables for each family variant using the specified objective function. In terms of the product space considered in this research, while this method may be helpful in determining the 'optimal' post-market module from a set of candidate modules, it cannot determine the function of the modules in the candidate set. Thus, implementing this method to solve the problem posed in this thesis would be of little value.

Taking an aggregate view, with respect to the post-market module space, product family research provides an important theoretical foundation and set of motivating factors. The research in this area clearly indicates the benefits of using augmented common platforms over creating custom products and processes for each targeted market segment. The notion of post-market modules put forward in this research attempts to access a similar set of benefits. Thus, the end goal of the post-market module strategy is a 'family' of products that serves a variety of market segments. The difference is, however, that the configuration of any particular derivative in the family is left to the discretion of the end-user. Despite the similarity in the desired outcomes of post-market modularization and product family design, the methods put forward in product family research are (largely) unsuitable to solve problem of post-market modules posed here: determining module function. Although, once a set of functions has been determined, the analysis tools of product family design could be leveraged to identify an optimal set of configurations; this line of investigation, however, is not considered in this thesis.

2.3 Biomimetic Design

According to Otto and Wood [2], after determining a product's desired attributes, the next step in the development process is to generate concepts for products that have those attributes. They define this concept generation process as, "the divergent development of many alternatives, where the focus is on innovation, structural layout, and function satisfaction." Otto and Wood [2] go on to discuss various concept generation methodologies, separating them into two categories: intuitive and directed. Intuitive methods include techniques such as brainstorming and free sketching while directed methods include techniques like the Theory of Inventive Problem Solving (TIPS) and the use of axiomatic (rule-based) design principles. Pahl and Bietz [3], however, go further than [2] in defining, what they term, 'conventional' concept generation methods. Under this banner, they identify the analysis of natural systems as a method for generating design concepts. They argue that analyzing natural phenomenon can help to stimulate the creative imagination of designers.

Vincent [46] notes that man has looked to nature for design inspiration for thousands of years. Bar-Cohen [47] states that this imitation and study of nature's methods, designs and processes is known as biomimetics. Biomimetics is useful avenue for engineers to explore because, through billions of years of evolution, nature has determined what design solutions work in practice, and has optimized those solutions for their respective environments [47]. Using abstraction, designers can translate these natural solutions into solutions in the engineered domain. Consequently, much biomimetic design research is focused on creating engineered solutions from abstractions of specific natural phenomenon. For example, Clark et al. [48] document the design and fabrication of a biologically inspired six-legged robot. This robot achieves dynamically stable walking by mimicking the biomechanics of a cockroach. Other examples of this type of biomimetic design can be found in Northen and Turner [49] who detail the creation of a gecko inspired dry adhesive, and Solga et al. [50] who explore the mechanism by which the lotus flower achieves water repellency, and its application to engineered surfaces. Ultimately, this research will produce a similar outcome: a post-market module abstracted from some natural phenomenon. However, unlike the previous examples, the specific natural phenomenon that is used is not a primary concern; and, in fact, will be constantly changing. Thus, what is important here is the how the abstractions from nature are made, rather than each abstraction's specific form.

The question of how one makes abstractions of natural phenomenon is the province of biomimetic concept generation research. Nature abounds with functional solutions to problems arising from the multi-facetted demands of various environments. One can imagine that the six-legged cockroach that formed the basis for Clark et al.'s [48] hexapedal robot design resulted from an evolutionary need for robust mobility. Thus, if the engineering need were similar, the cockroach provides a potential solution concept. However, if the desired natural solution is unknown, nature, being a vast and largely undocumented field, becomes a challenging space within which to find a solution [10]. As a result, much biomimetic concept generation research focuses on the development of structured search methodologies, and on the tools that enable those methodologies to retrieve relevant biological information.

Tinsley et al. [51] investigate the usefulness of functional models in biomimetic concept generation. They do this by taking existing biomimetic designs and creating functional models of both the natural and engineered systems. They then analyze these models for instances of similarity and difference, and determine the analogy between the two systems. Through the analysis of four case studies, Tensley et al. conclude that functional models of natural systems can help in identifying solution principles applicable to engineered systems of similar functionality.

Stroble et al. [52] put forward a search algorithm that aids designers in retrieving biological information that can be used to inspire engineered domain solutions. As a first step, the algorithm requires a functional abstraction of the engineered domain problem to be made using the language of the Functional Basis.

The function terms from the Functional Basis-defined abstraction are then searched in a biology text (or other body of knowledge), and the nouns that appear in proximity to the function term most frequently are identified. Next, the identified nouns are paired with the function terms, and each pair is searched in the text in order to identify the most relevant biological phenomena. Lastly, the identified phenomena are analyzed by the designer, and, in turn, used to inspire physical solutions to the engineered domain problem.

Similar to Stroble et al., Vakili and Shu [10] present a 5-step, generalized method (algorithm) that can guide designers to natural solutions. However, their methodology focuses more on bridging the gap between the bases of knowledge of biology and engineering. To that end, the process given in Vakili and Shu [10] makes use of a keyword bridge that translates functional keywords in the engineered domain to equivalent keywords in biology. This is in contrast to the method presented by Stroble et al. [52], where the engineering-based function terms are searched directly, with no keyword translation. Searching the base of biological knowledge with the translated functional keywords may identify a more relevant set of natural phenomenon related to the engineered system being considered.

3. DEFINING HOST AND DERIVATIVE PRODCUTS

The goal of this research is two-fold: 1) formalize the notion of product-augmenting, post-market modules, and 2) develop a method that can aid designers in synthesizing these types of modules. Toward advancing the former, the previous sections showed how the idea of post-market modules is connected to established notions of product modularization. In fact, Baldwin and Clark [7] defined the post-market module space when they put forward the idea of having a class of products that are reconfigurable through augmentation. However, what Baldwin and Clark do not do is formalize the post-market module space in terms language and substance. Having a clear understanding of the products in the post-market module space, and of the boundaries of that space, is a prerequisite for the creation of a synthesis methodology. Thus, it is necessary to codify the language used to describe products in post-market module space, and to fully define its boundaries before the latter part of the goal of this research is addressed.

In order to establish a formal language for products in the post-market module space, terminologies from Baldwin and Clark [7] and from product family design are examined. Overlaying the vocabularies of two bodies of research is useful in highlighting some parallel terminology. In Baldwin and Clark [7], the product to which augmentations are affixed is known as the modular system; in product family literature, it is known as the product platform [41]. As for the actual augmentations described by Baldwin and Clark, in product family research these are simply additional modules; however, they are assumed to be pre-market in nature [7]. The last bit of parallel terminology has to do with how the final version of the augmented, or reconfigured product is described. In the product family lexicon, this entity is known as a derivative; Baldwin and Clark simply refer to it as 'the system.'

With the terminologies of both Baldwin and Clark and product family design examined and compared, new terms describing products in the post-market module space are put forward. The first term recast is the one that describes the product that is augmented. In product family language it is known as the product platform; here, it is termed the 'host product.' Using the word 'host' fits with the notion that the product platform, under the Baldwin and Clark reconfiguration scheme considered here, serves to accommodate the augmenting modules. In accordance with the research presented in [7], host products, are marketable, stand-alone products capable of being augmented. In this way, a host product can be thought of as a product *for* which many products can be made.

The second term recast is the one describing the post-market modules themselves. The term 'post-market module' was created for this research in an attempt to convey the notion of a modularization scheme in which the modules are added to the product after it's been sold to the end user. Baldwin and Clark [7] term the post-market modules 'reconfiguration augmentations.' Here the term is recast to 'derivative product.' Using this term somewhat conflicts with the product family understanding of derivative products as product variants within a larger family of products. However, the notion of derivative products put forward here stems from the financial definition of derivative. In the context of finance, a derivative is a product that 'derives' its value from some, more fundamental, underlying asset [53]. Such is the case with the derivative products advanced in this research; they 'derive' their value from their association with a host product.

In order to formalize the substance of the host and derivative product space, that is, define the boundaries of the space, three guidelines for valid derivative products have been formulated:

1) Its usefulness is dependent on the presence of the host product in the market
2) It does not replace a similar functionality already present on the host product
3) It is of novel functionality or design

Much like a set of boundary conditions in a boundary value problem, these guidelines set the bounds for a product space within which derivative products reside. The first guideline establishes the nature of relationship between the derivative and host product. In this relationship, the derivative augments the functioning of the host rather than enabling its function. This relationship is not explicitly stated in Baldwin and Clark [7], however, it is implied. Guideline 2, as is evident by its construction, intends to exclude from the host and derivative product space products that simply replace a functionality that is already present on the host product. For example, replacing the factory tire rims on a car with rims that allow the car to achieve a higher level of road performance. Although such a product may be quite useful in enhancing the overall function of the car, it is not considered a derivative under the construction put forward here. The construction of guideline 2 parallels the description of reconfiguration augmentation presented in [7]. Guideline 3 is set forward to prevent trivial functional extensions from being admitted into this design space. This guideline is not based on any exposition (implicit or explicit) in [7], and is open to interpretation.

The last term recast in this research is the one that describes the host product after it has been appropriately augmented with the desired derivatives. This entity is termed the 'final variant' in this research. In terms of host and derivative products, the final variant is a liquid artifact. This is because the nature of the host/derivative relationship is such that end users are able to define, through augmentation and exclusion, the functionality of the final variant based on their needs or the demands of their environment. Customer needs and environmental demands are two factors that can change in a fluid manner.

4. RESEARCH APPROACH

Now that the host and derivative product space has been defined, this thesis will turn to the task of specifying a methodology that can be used to create derivative products for a given host. Unlike in the case of traditional modularization, the constituent functions of the product being sought (the derivative in this case) are unknown. As a result, standard module identification methods such as MFD, heuristic clustering and DFM based methods cannot be used, directly, to find potential derivative products. Traditional product family design methods are also not applicable. They, generally, assess different product architectures in the context of pre-defined economic trade-offs or use manufacturing and/or market data to identify the 'optimal' module structure from a known set of attributes (see, e.g. [54]). Such knowledge is not available under the problem formulation used in this research. Thus, what is required here is a method to determine the global function of the derivative 'module' without knowledge of its composite functions.

Uniquely, in the host and derivative product design space, the two types of products have a known relationship that is defined by the three guidelines put forward in the previous section. The overall goal of the methodology developed in this thesis is to provide designers with a strategy that can be used to identify products that abide by these guidelines for a given host. However, the relationship between host and derivative, as set by the guidelines, is difficult to expand upon (entirely) in the engineered space. For example, trying to conceptualize a derivative product for a personal computer using only the fact that it must be novel, function extending, and wholly dependent on the computer, presents the designer with an expansive and unfocused space of possible design solutions. As a result, this research uses a domain analogous to the engineered space in order to help identify a relationship between a host and an as yet unknown derivative. The analogous domain used is the nature. This domain shift is supported by notions of biomimetic design and concept generation as found in, for example, [10, 46, 47]. Shifting to the natural space affords the designer the ability to examine well established natural relationships among biological entities. These natural relationships, in turn, may help to identify functionalities that can serve as the basis for derivative products in the engineered domain. The need to effectively shift domains (engineered to natural) in order to identify derivative product concepts forms the basis for 7-step methodology developed in this work.

Supporting the methodology developed in this thesis are several tools from both the engineering and biomimetic design communities. Specifically, four design tools will aid in the overall process: functional models using the Functional Basis, modular heuristics, biologically meaningful keyword translation, and BioSearch. The developed 7-step methodology for identifying derivative products for a given host product is as follows:

1) Functionally model the host product using the Functional Basis
2) Use modular heuristics to modularize the host product’s functional

model

3) Translate the Functional Basis terms found in each module in to their corresponding biologically meaningful keywords

4) Search each unique pairing of biologically meaningful keywords found within each module using BioSearch, then record the resulting passage

5) Aggregate all results module-by-module

6) Identify results to be used to find potential derivative product concepts; placing special emphasis on repeated results and results contained within auxiliary modules

7) Examine the identified passages for potential derivative design solutions and translate those solutions from the natural domain to the engineered domain

4.1 The Four Design Tools

The concept of host and derivative products along with the 7-step methodology developed in this thesis represent a new and unique way to analyze and synthesize new products. However, supporting these new concepts are classic design philosophies and tools. In terms of the 7-step methodology, four design tools are used to assist designers in translating host products from the engineered domain to the natural domain. In the following subsections, the relevant background information and implementation procedures for each of the four design tools leveraged in this effort are discussed.

4.1.1 Functional Modeling and the Functional Basis

Pahl and Beitz [3] note that solving technical problems requires knowledge of the relationships between a system's inputs and outputs. The way to represent these relationships, they argue, is through the use of a clear and reproducible function structure. Pahl and Beitz [3] go on to set forward a type of function structure in which a system is represented by a series of sub-functions, connected through combinations of material, energy and/or signal 'flows'. Works subsequent to [3] refer to this type of function structure as a functional model (see e.g. [2, 55]). One of the main advantages of functional models stems from their ability to represent a product's required functionality without regard to the physical components that implement that functionality. That is, functional models specify a form-independent solution to a design problem; in this way, the functional model provides a level of abstraction away from the actual (physical) system under consideration [2].

The functional models and associated methodology used in this research are similar to the those given in [2, 55, 56]. These functional models start from what is known as a 'black-box' model. As the name implies, the function of the black-box model is to capture the overall (or black-box) function of a system without concern for the constituent sub-functions necessary to implement that function. The overall function defined in the black-box model consists of a verb-noun pair as is specified in Pahl and Beitz [3]. For example, the black-box model for a vacuum cleaner may contain the verb-noun phrase 'clean-floor.' Also contained in the black-box model are the system's overall input and outputs. These are graphically represented by directed line segments and represent the in-flow and out-flow of materials, energy and signals from the system. Using the vacuum cleaner again, an example of a material in-flow could be the dirt from the carpet, an energy in-flow could be the electrical energy required to run the vacuum and a signal in-flow could be the vacuum's on/off status. As for the material, energy and signal out-flows, these could be the air from the filter, heat from the motor and the sound produced by a clear floor, respectively.

Before proceeding to discuss the constituent sub-functions that support a system's black-box function, it is necessary to discuss the reconciled Functional Basis. Much like the black-box function, the sub-functions that constitute a functional model are represented as verb-noun (or verb-object) pairs. The key difference between a black-box function and its constituent sub-functions, however, is that in the sub-functions, the verb-object pair represents the direct utilization and/or modification of a set of flows. Given the number and diversity of engineered systems in the current and prospective product spaces, the possible combinations of verbs and objects that can be use to describe the functions contained within these systems is rather substantial. And while, the verb-object type of representation is common among many functional decomposition methods (see [56]), a unified language for these verb-object pairs, at one time, was not. Stone and Wood [56] note that the benefit of a unified functional language, or, equivalently, Functional Basis is that it could provide a basis for: systematic model generation, design archiving and communication, design benchmarking and attribute quantification, and functional comparison. With similar goals to those given in Stone and Wood [56] in mind, Hirtz et al. [57] created the reconciled Functional Basis.

The reconciled Functional Basis is the result of the intersection and subsequent recombination of two functional modeling vocabularies: the National Institutes of Standards and Technology (NIST) taxonomy and the standard Functional Basis as presented in [56]. This version of the Functional Basis classifies functions and flows (the verb-object pairs) at one of three levels of specificity: primary, secondary and tertiary. The primary level contains the most general function and flow descriptors and tertiary contains the more specific. For example, at the primary level, an energy flow is described simply as, 'Energy'; at secondary level energy can be classified as mechanical, electrical, hydraulic, etc.; lastly, at the tertiary level (under, for instance, the mechanical descriptor), an energy flow can be classified either translational or rotational. Due to the limitations inherent in of one of the other tools utilized in this research (biologically meaningful keyword translation), only the primary and secondary levels of the reconciled Functional Basis will be used to describe the function of a particular sub-function.

Turning attention back to the models themselves, a complete functional model consists of a specified set of flows (shown graphically as directed arrows) and a specified set of sub-functions (shown graphically as rectangular blocks) acting on those flows. Inside each of the of the sub-function blocks are the Functional Basis terms describing both the flow (or flows) entering that particular block and the function that defines how that flow is acted upon. Taken in total, the interactions of the sub-functions with the related flows describes the how a product produces the overall, black-box function. For example, the vacuum cleaner moves based on the energy its user supplies to the system. In terms of a functional model, this movement could be described by the proper arrangement of the sub-functions 'import', 'position', 'couple', and 'convert', in concert with the flows 'human', 'human energy', and 'mechanical energy'.

In this research, representing a product in the form of a functional model gives a means by which to search the natural domain. Searching the natural domain directly for a physical component would prove difficult as engineering and biological vocabularies have little overlap [58]. For example, searching the natural domain for an entity that converts rotational motion to linear motion is likely to produce a better outcome than if the same space was searched, specifically, for a cam and cam follower.

4.1.2 Modular Heuristics

Section 2.2.1 of this thesis discusses the merits of modular product architecture, and presents several methods that can be used to identify modules in existing products. The reader will recall that it was stated that *direct* application of these modularization methods is of little use in this research, as the constituent functions of the desired product are unknown. However, *indirect* application of modularization will prove useful here. Indirect application of modularization means that instead of modularizing a product and looking within for the desired module, a product is modularized and the desired module is found by looking without. In this case, the product that is modularized is the host product and the 'module' that is found is the derivative product.

Jose and Tollenaere [38] provide a review of currently available modularization methods, placing these methods in 5 general categories (see Section 2.2.1.2). Many of these methods are highly computational in nature and rely on unique representations of functionality. One method mentioned in Jose and Tollenaere [38], modular heuristics, however, utilizes functional models along with the Functional Basis as a means to identify modules. Modular heuristics, developed by Stone, Wood and Crawford [9], help a designer identify potential modules through a flow classification scheme that is based on the way materials, energy and signals are distributed to a product's constituent sub-functions. This flow distribution is determined graphically through an examination of the functional model.

Stone et al. [9] present three classes of flows: 1) dominant flow, 2) branching flow, and 3) conversion-transmission flow. If a particular flow can be placed in one of these classes, then the boundary created by the 'start' and 'end' of the classified flow defines a module. The three classes of flows thus form the 'heuristics', or rules of thumb, this method relies upon for module determination. Stone et al. [9] assert that this heuristic methodology is empirical in nature as it has been proven valid through the study of 70 consumer products. Going into greater detail, each heuristic is defined as follows:

1) Dominant flow: this is a flow that passes through a series of sub-functions, unaltered, from its initiation until it either its exits the system or is converted to another flow. Dominant flows do not branch (split) to service parallel function chains. The interacting sub-functions of a dominant flow constitute a potential module with the boundaries of this module being defined by the flow's initiation and termination points.

2) Branching flow: a branching flow is a flow that divides to service parallel function chains within the function structure. Each separate chain is made up of sub-functions that constitute a potential module. The initial branching point and the termination point of the function chain form the boundaries of this type of module.

3) Conversion-Transmission flow: a conversion-transmission flow occurs when a material or energy flow is converted from one form to another with the converted flow being allowed to flow to subsequent functions in a system. This type of module can consist of a single conversion function, a conversion-transmission pair, or a conversion followed by a series of functions ending with a transmission of the flow. The entrance of the original flow into a conversion function and the exit of the converted flow form the boundaries of this type of module.

In this research, the host product is modularized in order to aid designers in the search of the natural domain. This aid comes in three ways: by breaking up the function structure into more manageable search units, by enabling search based on module type, and, lastly, by enabling search based on dependent rather that independent functions. In Section 4.1.4 of this thesis, the multi-field searchable database known as BioSearch is discussed in detail. At this point, what is important to note is that BioSearch is a biomimetic search engine that aids in the translation of the functionality of physical product from the engineered domain to the natural domain. The body of knowledge that BioSearch derives its search results from is contained within a standard biology textbook. For this research, what is input into BioSearch are biologically meaningful keywords associated with the Functional Basis terms used in the host product's functional model. The keywords are searched in BioSearch in a pair-wise manner, with the output of each search being a collection of instances of the relative adjacency of the two keywords within the biology text. Now, depending on the product being considered, the functional model can be quite extensive; containing many sub-functions and, consequently, demanding many pair-wise searches. By using modularization, however, the functional model under consideration is broken down into manageable units, and the search process takes place based on those units, rather than on the functional model as a whole. This, in general, reduces the number of searches required. For example, in this research, if the Basis functions 'support' and 'import' appear together in the same module, then all their respective biologically meaningful keywords are paired, and each keyword pair is searched using two of the fields in the BioSearch search engine. If, on the other hand, the 'support' and 'import' functions never appear together in the same module for the given host product, then their respective keywords are not 'cross-searched.' Hence, the biologically meaningful keyword searches performed in this research are based exclusively on intra-module function, with searches based on inter-module function not being performed. Figure 3 shows a visual representation of the paired keyword search strategy used in this research.

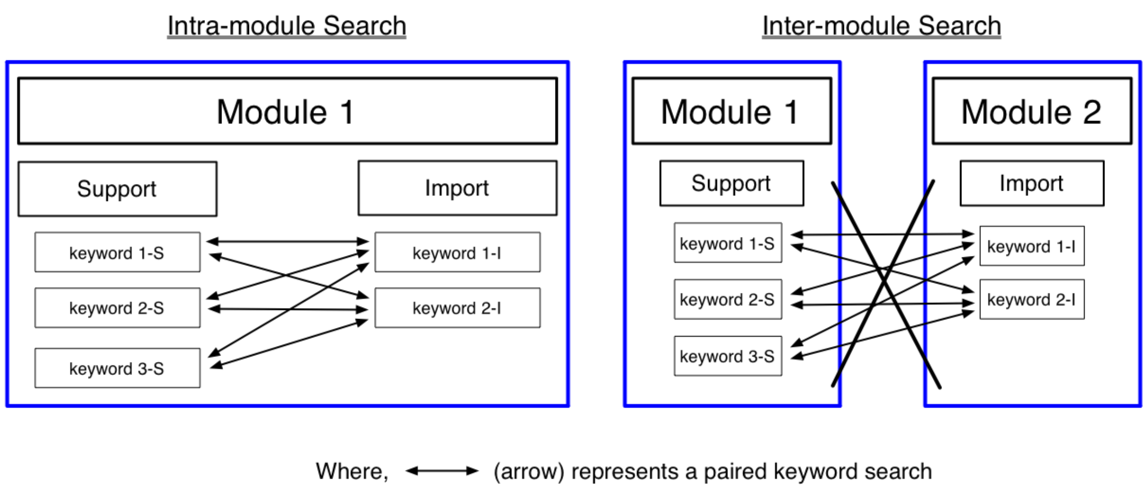


Figure 3. Diagram of the keyword search strategy.

Another way modularization aids in the search of the natural domain is by giving designers a means to search based on a module's type. Formally, there are different module type classification schemes presented in the literature. Section 2.2.1 of this thesis presents a scheme created by Pahl and Beitz [3] in which five module types are specified: basic, auxiliary, special, adaptive, and non-modules. With modularization, a designer can identify the module type using the scheme in [3] (or some other desired scheme), and then search the natural domain for entities that mirror that module's functional role. For example, if one wants to identify derivative product concepts that related more to the interfaces of a product rather than its core function, one could search the natural space using the functions contained within the auxiliary modules and disregard the functions in the basic modules.

The last way modularization aids in the search of the natural domain relates to the functional independence inherent in a modular structure. Ulrich [6] notes that each module in a product should be independent in function and have decoupled interfaces. This means each module in a product should (ideally) consist of a group of functions that are highly related, while adjacent modules should consist of, largely, unrelated functions. Also, the interactions among modules, that is, the flow dependency of each module, should be minimized. The basis for this assertion stems from the one-to-one mapping of functional elements to physical components that defines modular product architecture. With this in mind, when looking for function extending modules (derivatives), it makes sense to examine the analogous space using combinations of 'highly' related functions (i.e. intra-module functions), rather than combinations of unrelated functions (i.e. inter-module functions).

4.1.3 Biologically Meaningful Keywords

In Section 4.4.1, it was asserted that searching the natural domain using engineering language would produce sub-optimal results. The reason for this is that the language of engineering and the language of biology are both domain specific, having little overlap even when describing similar phenomenon [58]. As a result, using BioSearch directly, with functions stated in engineering language, is not ideal. What is required is a way to translate the functions contained within the modularized function structure into their biologically equivalent functions. With this type translation, the biologically equivalent functions can be paired and searched in the BioSearch database; producing more relevant potential derivative product concepts. Fortuitously, the work of Cheong et al. [11] presents a dictionary (of sorts) that translates the function descriptors from the Functional Basis into equivalent, biologically meaningful keywords.

In order to identify biological phenomenon associated with engineering function, Cheong et al. [11] only translate the verb part of the Functional Basis terms into biologically meaningful keywords. That is, the function term from the Functional Basis is translated while the flow term is not. To find a set of potential biologically significant keywords based on the Functional Basis terms, [11] first uses a four step search methodology. The first step is to search a biology text for instances of the usage of the Functional Basis terms. In an effort to increase the amount of results found, the Functional Basis terms are augmented with synonymic terms as identified by WordNet, an online word database that can be used to establish word relationships. Once the augmented Functional Basis words have been found in the text, the next step is to sift through these matches eliminating instances where the meaning of the word is not consistent with the intended, basis meaning. The third step is to identify bridge verbs. Bridge verbs are verbs (not in the Functional Basis) that frequently appear with nouns that themselves appear frequently with terms from augmented Functional Basis. The bridge verbs represent possible biologically meaningful keywords. The last step is to categorize and list the bridge verbs based on the manner in which they appear in a biological dictionary. Verbs that are explicitly defined in the dictionary are classified as 'biologically significant' while those verbs that appear as part of the definitions of other words in the dictionary are classified as 'biologically connotative'. Both classes of words are then listed along with their corresponding density (the amount of times they appear in the biological dictionary); the higher the density, the more likely the word will be biologically significant.

With candidate biologically meaningful keywords determined, Cheong et al. [11] present four guidelines that serve to identify the more useful of the candidate keywords. Each of the four guidelines is based on the way in which a biological keyword is paired with another keyword (biological keyword or Functional Basis term) in the biology textbook. The four types of pairing identified are: the synonymous pair, the implicitly synonymous pair, the biological specific form, and the mutually entailed pair. The reader can refer to [11] for a full description of each pair; however, in general, each of the pair guidelines defines a specific type of relationship between two keywords. For instance, the synonymous pair implies that two keywords are equivalent while the biological specific form implies that one keyword is in a subset of the other.

Cheong et al. presents a list of the identified biologically meaningful keywords along with their corresponding Functional Basis terms. Each keyword is ranked based upon how many times it appeared in proximity to terms from the WordNet augmented Functional Basis, during the search of the biology textbook. Cheong et al. [11] notes, however, that this ranking doesn't necessarily imply that a word has more or less relevance when used to search the natural domain.

4.1.4 BioSearch

The biologically meaningful keywords from [11] are used, in this research, to translate the functions from the modularized function structure into their biological equivalents. With this translation complete, the biological keywords that represent the function of a particular module on a host product can be used in BioSearch to help indentify derivative product concepts. In this way, BioSearch enables the full translation of the host product from the engineered domain into the natural domain.

As stated previously, BioSearch is an online, multi-field biomimetic search engine that uses a biology textbook as its base of reference. The textbook used, in this case, is *Life: The Science of Biology, Ninth Edition* by Sadava et al. [59]. BioSearch was created by researchers at the University of Toronto (L.H. Shu [60]) as tool that helps enhance creativity during conceptual design. Broadly, what BioSearch does is it takes in multiple search criteria (multiple fields) and searches Sadava et al. [59] for instances in which those criteria are met. In the main search box, BioSearch can accept as many as four keyword phrases. Additionally, 10 word phrases can be excluded from the search results. For example, one could search the keywords 'specialize' and 'bind' while excluding the words 'contain', 'hold', and 'contact'. BioSearch would then seek out instances in [59] where the two keywords appear in proximity to each other, but without proximity to the three excluded words. The allowable proximity of the keywords and excluded words can be controlled in the BioSearch interface. The 'search tightness' field specifies the maximum number of characters that can separate instances of keywords, and it also defines the boundaries within which excluded words cannot appear. Search tightness is default set to 100 characters; this is also the value used for all searches conducted in this research.

After a BioSearch search is conducted, any results from that search are displayed on separate webpage. Search matches are numbered and the corresponding section number where the match occurred is given. The section title then follows and after that, the page number where the section begins and the number of characters between the section's start and sentence containing the match is presented. The actual match itself is contained within a sentence excerpt from the text. Sentence(s) immediately adjacent to the target sentence are also included in order to give context to the phenomenon being discussed. Figure 4 shows a typical search result; the keywords specified in this case were 'specialize' and 'pass through'.

Output notes:
1. Section numbering, e.g., 1.2.3, are not labeled in hard copy of text.
2. Number immediately following section title, preceding '/' is page number where *section* containing match *starts*, i.e., NOT necessarily where *sentence* containing match starts.
3. Number following '/' after section title is the approximate number of characters from the beginning of the section to the sentence containing the match - there are approximately 50 characters in each double-columned line in the hard copy of the text.

Confirmation of search parameters:
Debug mode is 0
keyword[1] is diffuse.
keyword[2] is anchor.
Maximum number of matches is 200.
print section is 0.
search tightness was 100.

******* SEARCH RESULTS *******
Match #1: Section 16 4 2 Single cells can induce changes in their neighbors 302 /1489: The **anchor cell produces an inducer that **diffuses out of the cell and interacts with adjacent cells. Cells that receive enough of the inducer become vulval precursors; cells slightly farther from the anchor cell become epidermis.

********** End of Search **********

Figure 4. BioSearch search result screen for a typical search (adapted from [60]).

It is important to note that BioSearch is capable of searching the World Wide Web for instances where the designated search criteria are met. This functionality, however, was not used for this research, as strictly biology-based matches were desired. Additionally, BioSearch has a field where the user can designate the maximum number of matches to be displayed. This number was kept at the default setting of 200 and did not affect the results achieved here, as no search that was conducted produced greater that 200 matches.

4.2 The 7-Step Methodology

The 7-step methodology presented in this thesis aids designers in translating the functionality of a physical host product from the engineered domain to the natural domain. Using this type of translation, designers can identify the global (black-box) function of potential derivative modules by examining entities that already have a host/derivative relationship. Once this host/derivative relationship has been determined in the natural domain, the functionality of the 'natural' derivative can be translated back to the engineered domain; resulting in a physical derivative product. In the following subsections, each of the seven steps in the developed methodology is briefly discussed with particular emphasis on the mechanics of each step's implementation. Section 5 of this thesis will show the actual implementation of each step by applying the methodology to several case examples.

4.2.1 Step 1: Host Product Functional Modeling

Functional modeling the host product provides a way to represent the functionality of the product in an abstract (general), logical, and repeatable fashion. The level of abstraction inherent in function models, in particular, enables the translation of the host product from the engineered domain to the natural domain. The functional models used in this research are constructed using a defined methodology. This methodology is from Stone and Wood [56], and consists of three steps. The first step in the process is to make the host product's black-box model.

A black-box model shows a system's overall function along with its overall material, energy, and signal in-flows and out-flows. It is important to note that the in-flows and out-flows are often determined from some manner of customer needs analysis [2]. Such detailed analysis was not performed for this research, as the (host) products modeled here are already established in the marketplace and are thus not new conceptual designs.

The next step in the Stone and Wood [56] functional modeling process is to create function chains for each of the black-box model in-flows. A function chain is, essentially, a series of system sub-functions that act on a particular flow. Functions chains can be singular, with a flow passing through one set of system sub-functions serially; or they can be parallel, with a flow branching and passing through multiple sets of sub-functions. So, for instance, if electrical energy were one of the black-box model in-flows, a function chain for this flow would be constructed by sequentially arranging the system sub-functions that act upon the electrical energy. If the electrical energy branches, then those parallel function chains must be modeled as well. This chain construction process continues, separately, for each black-box in-flow.

The last step in the process presented in [56] is to aggregate all the separate function chains. This means that each of the separate function chains is connected together to make the complete functional model. Stone and Wood [56] note that this process may require the addition of new sub-functions in order to bridge-a-gap in functionality or it may require the deletion functions made redundant by the aggregation.

4.2.2 Step 2: Modularizing the Host Product

As stated previously, modularization of the host product is performed in order to aid in the search for natural domain derivatives. While many modularization methods are available, this research makes use of modular heuristics developed by Stone, Wood, and Crawford [9]. This particular method was chosen because it identifies modules based on a system's functional model. The implementation of the process given in [9] is quite straightforward. The reader will recall that modules are defined based on three types of material, energy or signal flows: dominant flow, branching flow, and conversion-transmission flow. With a well-defined host product functional model, instances of each flow type are identified, and boundaries encompassing the identified module's constituent sub-functions are drawn.

In this research, every possible module (as can be identified by the modular heuristics) is found and, in turn, labeled on the host product functional model. From the model, each of the function terms (i.e. the verb in the verb-object pair) from a module's sub-functions is recorded, module-by-module. It's important to note that modules that consist of single sub-functions (e.g. some conversion-transmission modules) are also identified and recorded; however, they are not used in the natural domain search, as the identified functions within modules are searched, in the natural domain, in a pair-wise fashion.

4.2.3 Step 3: Translation to Biologically Meaningful Keywords

Once each function in a host product's modules has been identified and recorded, the translation of those functions into the biological domain can begin. The biomimetic approach used in this research necessitates this translation because of the lack of significant overlap in terminology that exists between the engineering and biology communities. Facilitating the translation from engineering functional descriptions to their biological equivalents is the research of Cheong et al. [11]. Cheong et al. [11] provides a dictionary that translates terms from the Functional Basis to equivalent, biologically meaningful keywords.

Implementing the translation scheme presented in [11] is straightforward. The module-by-module breakdown of the host product's sub-functions is broken down further to include the corresponding biologically meaningful keywords. Each Functional Basis termed sub-function, generally, has several associated biologically meaningful keywords. For example, the Functional Basis term 'import' has 10 associated biologically meaningful keywords (Figure 5).

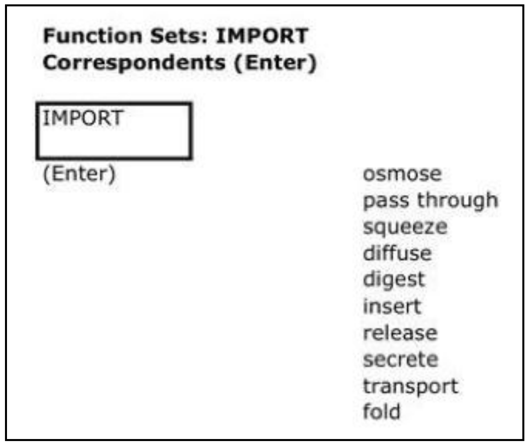


Figure 5. Biologically meaningful keywords for the Functional Basis term 'import' (adapted from [11]).

A point of consideration, however, is that, for this research, not all of the designated biologically meaningful keywords for a given Functional Basis term are used in subsequent searches of the natural domain. This is done primarily to reduce the number of pair-wise searches required for each module. Words are eliminated based on their relative accessibility in the given context, and whether or not their essential meaning is captured by a keyword that is included in the search list. For example, for the Functional Basis term 'import', five of the 10 keyword terms are eliminated: 'fold', 'transport', and 'squeeze' are eliminated based on context while 'release' and 'digest' are eliminated because their meanings are captured by other keywords that are included in the search; chiefly, 'osmose', 'diffuse', and 'secrete'. While eliminating terms in this manner may seem somewhat subjective, it is important to note that the objective here is to show that derivative product concepts *can* be found using the developed methodology, rather than to present an exhaustive search of the natural domain for those concepts.

4.2.4 Step 4: Searching with BioSearch

Full translation of the functionality of the host product from the engineered domain to the natural domain is achieved through the use of BioSearch. Multi-field searches with BioSearch produce a set of short passages from a biology textbook ([59]) that meet the designated field criteria. For this research, the field criteria used in BioSearch consists of two biologically meaningful keywords corresponding to two separate sub-functions from one host product module. For instance, a module that contains the Functional Basis functions 'import' and 'convert' would have their corresponding biologically meaningful keywords paired and searched using two (of the four) BioSearch fields. Figure 6 shows the eight (out of 20 possible) biologically meaningful keywords used for the Functional Basis term 'convert'. Thus, in this example, the keyword 'osmose' from the basis term 'import' and the keyword 'specialize' from 'convert' would be paired and searched together in BioSearch. This process continues until all possible pair combinations are searched; in this instance, that requires 40 such searches.

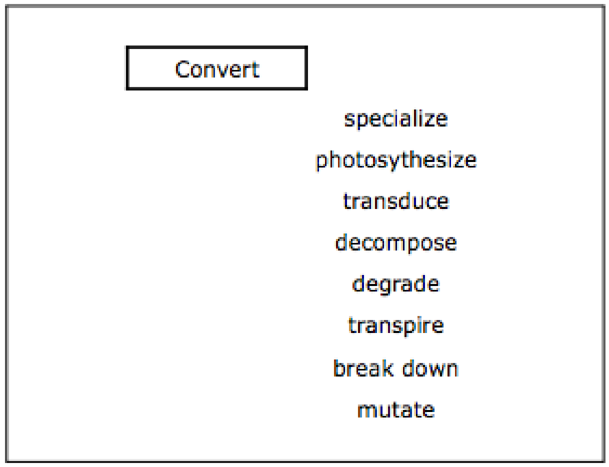
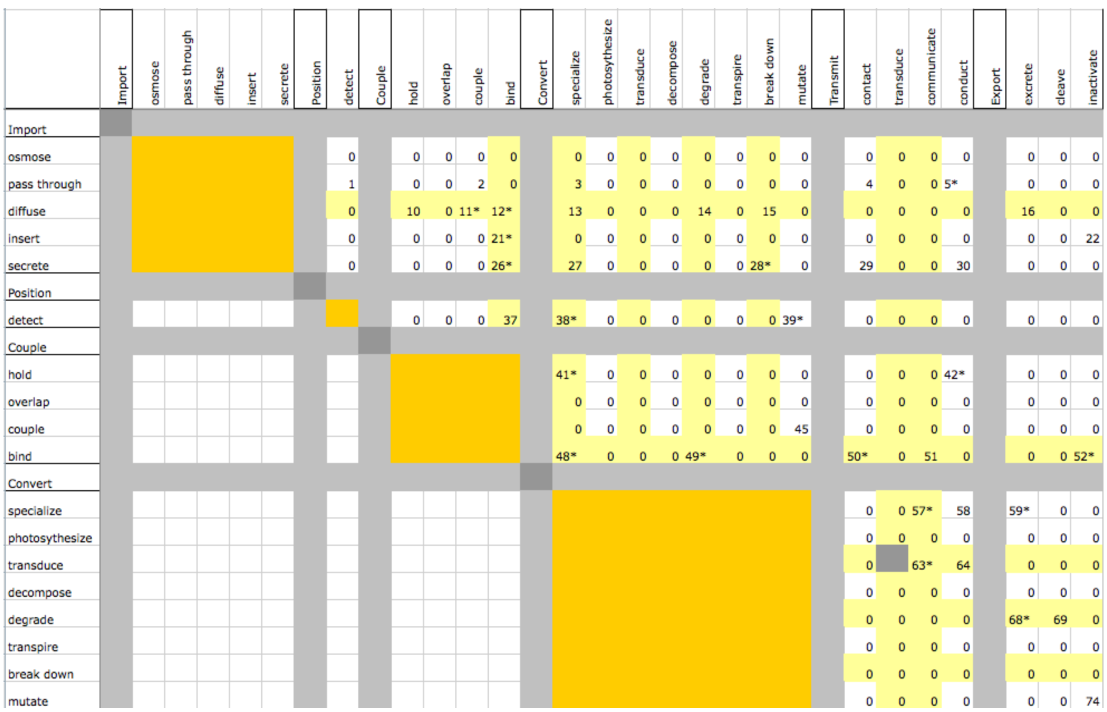


Figure 6. Biologically meaningful keywords for the Functional Basis term 'convert' (adapted from [11]).

The required number of searches for a given multi-module host product can be quite large. However, product-to-product and, to some extent, module-to-module, many function combinations are repeatedly used. That is, there is some overlap of keyword searches among sets of products and modules. Consequently, once a keyword pair has been searched, there is no need to search that pair again, even if that it appears in a different product. Thus, the actual search process can be performed in a product-independent fashion. Taking advantage of the product-independence of the search process, a block matrix is constructed to document the searches that have been conducted. This matrix, termed here the 'BioMatrix,' is similar in design to the design structure matrix (DSM) in that it is a function vs. function (or keyword vs. keyword in this case) matrix. Hence, the left-most column of the BioMatrix contains the entire set of biologically meaningful keywords used in this research, with the top-most row being identical to that column. The interior cells of the BioMatrix, in turn, represent the intersection of two keyword terms; with each intersection indentifying a paired keyword search that must be conducted. This keyword vs. keyword construction of the BioMatrix makes it upper triangular form, with the diagonal representing the intersection of identical sets of biologically meaningful keywords. Figure 7 shows a portion of the BioMatrix constructed for this research.



	Import	osmose	pass through	diffuse	insert	secrete	Position	detect	Couple	hold	overlap	couple	bind	Convert	specialize	photosysthesize	transduce	decompose	degrade	transpire	break down	mutate	Transmit	contact	transduce	communicate	conduct	Export	excrete	cleave	inactivate
Import																															
osmose								0		0	0	0	0		0	0	0	0	0	0	0	0		0	0	0	0		0	0	0
pass through								1		0	0	2	0		3	0	0	0	0	0	0	0		4	0	0	5*		0	0	0
diffuse								0		10	0	11*	12*		13	0	0	0	14	0	15	0		0	0	0	0		16	0	0
insert								0		0	0	0	21*		0	0	0	0	0	0	0	0		0	0	0	0		0	0	22
secrete								0		0	0	0	26*		27	0	0	0	0	0	28*	0		29	0	0	30		0	0	0
Position																															
detect										0	0	0	37		38*	0	0	0	0	0	0	39*		0	0	0	0		0	0	0
Couple																															
hold															41*	0	0	0	0	0	0	0		0	0	0	42*		0	0	0
overlap															0	0	0	0	0	0	0	0		0	0	0	0		0	0	0
couple															0	0	0	0	0	0	0	45		0	0	0	0		0	0	0
bind															48*	0	0	0	49*	0	0	0		50*	0	51	0		0	0	52*
Convert																															
specialize																								0	0	57*	58		59*	0	0
photosythesize																								0	0	0	0		0	0	0
transduce																								0		63*	64		0	0	0
decompose																								0	0	0	0		0	0	0
degrade																								0	0	0	0		68*	69	0
transpire																								0	0	0	0		0	0	0
break down																								0	0	0	0		0	0	0
mutate																								0	0	0	0		0	0	74

Figure 7. A portion of the BioMatrix constructed for this research.

Looking at Figure 7, there are a few points worth noting. First, the diagonal of the BioMatrix is shaded; and thus, excluded from the required searches. The reason for this is that each Functional Basis term's corresponding biologically meaningful keywords represent mutually equivalent descriptors. Consequently, searching the natural space using these equivalent descriptors amounts to searching the internal functionality of the associated Functional Basis term. However, what is sought in this research is the natural domain relationship between 'related' functions, not the relationship a function has with itself. The second point of note is the numbers that appear with in the cells of the upper triangular portion of the BioMatrix. Each intersection of keywords (i.e. each cell) in the upper triangle of the BioMatrix represents a pair-wise BioSearch search, and the number contained within the corresponding cell represents the result of that search. Cells that contain the number '0' indicate that BioSearch returns no results for that combination of keywords. However, cells that contain numbers greater than zero signify that the BioSearch search using those keywords returns a result. The number itself represents the results' given position on a separate document that aggregates all the BioSearch results found in this research. For example, according to BioMatrix, a search using the keywords 'diffuse' and 'degrade' produces result number '14'. This number 14 corresponds to a position on, what is termed here, the BioMatrix Results Aggregation Document (B-RAD). The B-RAD is a catalogue of all the passages found by BioSearch for any given pair of biologically meaningful keywords that, according to the BioMatrix, has been previously searched. Figure 8 shows a portion of the B-RAD that includes result number 14.

[13] Match #1: Section 48_2_1 Respiratory organs have large surface areas 852 /-51: Respiratory organs have large surface areas 852 @ Many anatomical adaptations maximize the **specialized body surface area (A) over which respiratory gases can **diffuse. External gills are highly branched and folded elaborations of the body surface that provide a large surface area for gas exchange with water (Figure 48.

[14] Match #1: Section 41_4_4 Responses to hormones can vary greatly 729 /3163: The extent to which hormones are bound to carrier proteins limits their ability to **diffuse out of the blood to reach their target cells, to be **degraded in the liver, or to be excreted by the kidney.

[15] Match #1: Section 9_4_5 Nuclei re-form during telophase 164 /259: The chromosomes begin to uncoil, continuing until they become the **diffuse tangle of chromatin that is characteristic of interphase.

[16] Match #1: Section 41_4_4 Responses to hormones can vary greatly 729 /3163: The extent to which hormones are bound to carrier proteins limits their ability to **diffuse out of the blood to reach their target cells, to be degraded in the liver, or to be **excreted by the kidney.

[17] Match #1: Section 16_5_3 Plants and animals use positional information 305 /914: Other signals may **diffuse from the stem tip and root tip, establishing positional information along the plant's axis.

Figure 8. A portion of the BioMatrix Results Aggregation Document (B-RAD) (adapted from[60]).

The last point of note has to do with the asterisks that appear after some of the numbers in the BioMatrix cells. This asterisk indicates that for that pair of biologically meaningful keywords, BioSearch returns more than one passage that meets the designated field criteria. It is not concluded in this research whether multi-passage BioSearch results signifies a more or less relevant keyword pair. However, such results may prove useful in future efforts.

4.2.5 Step 5: Aggregating Results

As stated previously, the number of modules in any given host product can potentially be quite large. Consequently, the number of pair-wise keyword search matches gleaned from the BioMatrix can also be quite large. For this reason, all the possible BioMatrix results for each module are compiled before the B-RAD is consulted. Figure 9 shows a portion of a module-by-module aggregation of

BioMatrix results for a host product. Under each module heading is the Functional Basis pair and the numbers from the cells where the associated biologically meaningful keyword pairs (searched in BioSearch) returned results. Again, the numbers from the cells correspond to the position of the BioSearch identified passage in the B-RAD.

Module 1 results	
import/position	1
couple/import	2,10,11,12,21,26
export/import	16,22
couple/position	37
export/position	none
couple/export	52

Module 2 results	
couple/export (m1)	52

Module 3 results	
import/position (m1)	1
couple/import (m1)	2,10,11,12,21,26
export/import (m1)	16,22
couple/position (m1)	37
export/position (m1)	none
couple/export (m1,2)	52

Module 4 results	
couple/export (m1,2)	52

Module 5 results	
import/store	6,17,18,19,23,31,32,33
import/supply	15,18,14,23,28,33
actuate/import	7,8,12,20,21,24,25,26,34,35,36
store/supply	70,88,73,71,92
actuate/store	87,89,90,91,93
actuate/supply	91,72,49

Figure 9. Module-by-Module aggregation of BioMatrix results for a host product.

Looking at Figure 9, one can observe that modules 1 and 3 have complete overlap and modules 2 and 4 are completely contained within modules 1 and 3. This relationship is indicated by the ‘m1’, ‘m1,2’, and ‘m1,2,3’ found next to the Functional Basis terms in modules 2, 3, and 4, respectively. Overlapping and subset modules such as modules 1 through 4 are identified in order to help the designer during their search of the B-RAD and, subsequently, during the derivative product concept generation phase. In terms of the research presented in this thesis, the identification of overlapping and subset modules is done to reduce the number required B-RAD searches, as these types of modules will not be re-searched after the first instance of their appearance. However, identifying overlapping and subset modules could help in other ways. For instance, an overlap of two or more modules may point to a highly relevant set of functionalities, worthy of extended investigation and consideration. This research, though, makes no conclusions in this regard.

4.2.6 Step 6: Identifying Results for Analysis

With the BioMatrix results aggregated module-by-module, one can visually observe the B-RAD position numbers associated with the functions in a particular module. This leads to the next step in the developed methodology, which is to identify the B-RAD position numbers that will be examined for potential derivative product concepts. As stated earlier, the B-RAD consists of a series of short passages from BioSearch’s base of reference ([59]). These passages are catalogued (in the B-

RAD) to correspond to the pair-wise biologically meaningful keyword searches that have been conducted. By analyzing the biological phenomenon described in a particular passage, designers can potentially identify a host and derivative type relationship among natural entities, which can subsequently be translated back to the engineered domain. However, depending on the complexity of a product's functional model and corresponding modular beak-down, the number of B-RAD passages requiring analysis can be substantial. As a result, for this research, the number of B-RAD passages analyzed for derivative product concepts is restricted based on two criteria: the module type that contains a particular result, and a result's level of occurrence within that module.

Looking back at Figure 9, module 1 refers the designer to 11 B-RAD passages, and module 5 refers to 38 passages. In total, the first five modules of this host product present 49 passages for analysis to designers. While this may potentially result in a large number of derivative product concepts, the nature of the objective of illustrating the methodology demands a way to focus the concept generation efforts. Moreover, in practice, designers may want a means by which to determine how to concentrate their resources in the early stages of derivative product development. The first way to do this is to restrict the number of B-RAD passages analyzed based on module type. In this research, consideration is given to only those deemed to be auxiliary. Section 2.2.1 discusses the Pahl and Beitz [3] classification scheme that separates modules into five different categories: basic modules, auxiliary modules, special modules, adaptive modules and non-modules.

The basic modules are those that fulfill the overall function of product (host product in this case). Using a vacuum cleaner as an example, again, a basic module from that product could be the electric motor and associated impeller assembly. Auxiliary modules, on the other hand, are those modules that assist the basic modules in carrying out the overall product function. For the vacuum cleaner, an example auxiliary module could be the air filter assembly.

Using just the basic and auxiliary module classifications (leaving out the special, adaptive and non-module categories), a designer can readily separate the identified modules into one of the two types. So, if module 1 from Figure 9 is classified as an auxiliary module, its B-RAD results are analyzed; if, on the other hand, it is classified as a basic module, its B-RAD results are excluded. The exclusion of the basic modules from consideration is not indicative of any lack of effectiveness they have in terms of helping to generate derivative product concepts. They are excluded here primarily in an attempt to focus the concept generation efforts by reducing the space of potential derivative solutions considered. In practice, such decisions are left to the discretion of the designer.

The second way the number of passages analyzed is restricted is by examining only those B-RAD passages that appear more than one time within a particular auxiliary module. Just as it was posited in the previous section that overlapping and subset modules may point to highly relevant sets of functions, it may be that B-RAD results that are repeated within a given module point to a highly relevant host and derivative relationship. For example, module 5 from Figure 9 refers designers to 30 unique B-RAD passages out of the total 38; thus, four passages are repeated in this module. The repeated passages are numbers ‘18’, ’23’, ‘33’, and ‘91’. Under the scheme presented here, these four B-RAD passages are given priority in terms of analysis, as the functionality from which they result may have high relevance within the module.

Module 1 from Figure 9, however, illustrates a potential problem that can arise when using the repeated result paradigm: What happens when a module has no repeated B-RAD passages? In this instance, the discretion of the designer is key. For this research, in situations where there are no repeated results or a very limited set of repeated results, each B-RAD passage in that module is reviewed, and passages that, in terms of content, have high level of relative accessibility and relevance are singled out for further analysis.

4.2.7 Step 7: Examining and Translating Results

The passages contained in the B-RAD, ideally, highlight a relationship between two natural entities. By analyzing this natural relationship in the context of the functionality of a particular host product, a designer may be able to arrive at a concept for a derivative product in the engineered domain. For example, Figure 10 shows the first matching passage for B-RAD position number ‘117’. This passage resulted from the pair-wise search of the biologically meaningful keywords ‘hold’ and ‘stretch’. The passage discusses the relationship between the material properties of a fiber and the stability of a web constructed of that fiber. Now, for the sake of discussion, assume that this B-RAD passage resulted from a pair-wise search using the keywords from a module contained within a vacuum cleaner's functional model. The question then becomes: How does one examine, and then translate the natural relationship described in the B-RAD to a relationship in the engineered domain, and thus into a derivative product? The broad answer to this question is that this process is carried out using the experience and creativity of the designer. However, the process can be given a qualitative structure.

[117] Match #1: Section 3 Macromolecules: Their Chemistry and Biology/413: On the other hand, the fibers **holding the web together cannot **stretch too much, because they must be strong enough to hold the entire structure in place and not let the web wobble out of control.

Figure 10. First matching statement for B-RAD passage number 117 (adapted from [60]).

The analysis of a designated B-RAD result should place an emphasis on the relationships any identified entities have amongst each other. As stated previously, traditional biomimetic design focuses on how a particular natural entity implements a function, and in turn seeks to imitate that implementation in the engineered domain. Rather, what is sought here is how the identified natural entities relate in the natural domain, which can in turn be used, through imitation or inspiration, to develop a derivative product. For example, referring back to the B-RAD passage shown in Figure 10 there two nature entities that are described: fibers and a web made of those fibers. Examining this passage using a relational emphasis, one observes that the relationship between the fibers and the web is one where the fibers provide the structural support for a web system constructed of those fibers (in this instance, the relationship is actually explicitly stated in the passage). One may go further and investigate the underlying phenomenon that is described in the B-RAD passage. This phenomenon can be determined from the section title that appears adjacent to the section number in the BioSearch results (see Section 4.1.4). For number '117', the section is titled 'Macromolecules'. By examining macromolecules in some depth, a designer may be able to gain a better understanding of how the fiber and the web fit into a larger, biological context. With this new knowledge, a clearer indication of relationship shared by the fiber and web may be gleaned, and, thusly, translated into a host and derivative relationship in the engineered space.

5. CASE STUDIES

In Section 3, it was stated that the two-fold goal of this research is to 1) formalize the host and derivative product space, and 2) create a method that aids designers in synthesizing products for that space. The preceding two sections of this thesis have advanced this goal towards realization. In terms of the first part of the goal, the notion of reconfiguration augmentation put forward by Baldwin and Clark [7] has been codified in definition and recast in language in order to fully define the host and derivative product space. With respect to the second part of the goal, the 7-step methodology described in Section 4 presents an biomimetic-based approach designers to can use to identify derivative product concepts. However, the developed approach, while based on methodologies proven valid in their own right, must shown to be valid in the context of the host and derivative product space that is considered here.

A robust validation methodology would, no doubt, include the participation of a subject group; with the group using the 7-step methodology on a variety of host products, during multiple trials. In other words, the developed methodology would be shown valid based on a statistical analysis of the results of a controlled experiment. As it happens, however, the research contained in this thesis is very much at the forefront of investigation of this topic. It lays the groundwork for further consideration and study of the host and derivative product space and methods to aid designers therein. Consequently, as alluded to in Section 4.2.3, the objective here is to show that the developed, 7-step methodology *can* be used to identify derivative product concepts. That is, to show that the method works in the context set forward by this research. The quantifiable extent to which the developed methodology can be shown to be valid, and its measurable performance relative to other strategies is not considered.

The following subsections present four case studies in which the 7-step methodology is utilized to generate derivative product concepts for an established host product. The four products chosen for this study are: a bicycle, an iPod, a military assault rifle, and a Black & Decker Multi-Tool. These products were chosen for two reasons. The first reason is they represent a range of different consumer activities and markets. This is important because it shows that the host and derivative product space and the 7-step methodology are not limited to a certain category of products; for example, consumer electronics or automotive. The second reason these products were chosen is that they already have derivative products developed for them. This is done to ensure that the products analyzed can serve as a host product. Thus, if the methodology fails to produce satisfactory derivatives for any of the products studied, then it may reflect a deficiency in the method. By choosing to apply the developed methodology on established host products, the ensuing case studies can be seen as idealized models of a derivative products synthesis exercise. Constructing the case studies in this way is in keeping with the notion that these results are meant to be illustrative of the mechanics of application and the effectiveness of the 7-step methodology, rather than an application and analysis that accounts for all potential variables.

Of the four case studies, only one, the bicycle, will be presented in full depth. The step-by-step application of the developed methodology on one host product is sufficient to demonstrate the procedure used for all four of the case studies. The remaining three products, the iPod, the military assault rifle, and the Multi-Tool, have only their resulting derivative product concepts presented in this section. Work product associated with the development of these concepts (e.g. function structures, modular break-down, etc.) is contained in the Appendix section. Five derivative product concepts are developed for each host product; this gives a total of 20 derivative products concepts produced for this study.

5.1 Case Study: The Bicycle

There is a broad range of bicycles on the market today. Consumers can choose the bicycle that best fits their lifestyle or intended activity profile; for example, road racing, mountain biking, beach cruising, or dirt biking. Each of these activity categories demands a different set of functionalities be included on the bicycle. In this research, however, a typical bicycle, with standard functionality is modeled (Figure 11). This functionality includes an adjustable gear set, brakes, and a standard frame. Functionalities unique to a certain activity category, such as an articulating suspension and aerodynamic augmentations, are not considered here.

Figure 11. A picture of the typical bicycle modeled for this research.

Step 1: The first step in the developed 7-step methodology is to create a functional model of the host product. As outlined in Section 4.2.1, this three-step process begins with the creation of a black-box model. This shows the system's overall function along with its in-flows and out-flows of materials, energy, and signals. Figure 12 shows the black-box model developed for the bicycle.

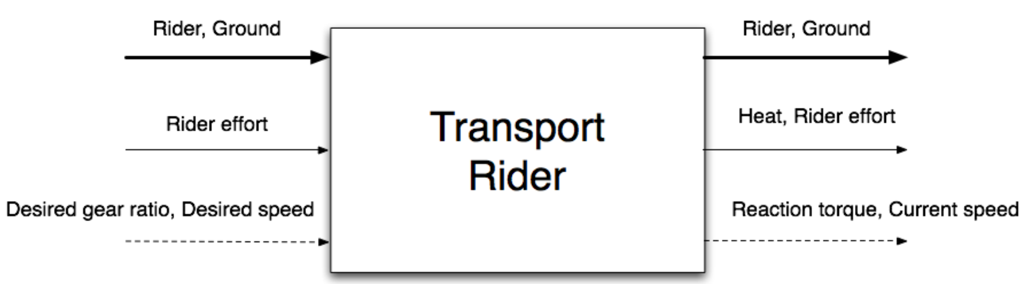


Figure 12. Black-box model for a typical bicycle.

The material inputs for a typical bicycle include the bike's operator and the road surface. Both entities exit the system in the same form in which they enter. The only energy in-flow into the bicycle comes from the rider, and is a direct result of his or her physical effort. An argument for the addition of a mechanical energy input representing the energy produced by a bumpy road or a jump can be made; however, a dedicated suspension system that accounts for this energy is not assumed to be present on this typical bicycle model and, consequently, the additional mechanical energy input is not specified. Lastly, the desired gear ratio and speed are assumed to be the only user-controllable signal inputs. The gear ratio sets the required torque and is controlled by the rider with a lever or switch. The speed of the bicycle is a function of effort the rider exerts at a given gear ratio; however, this speed can be further adjusted/controlled by applying braking to the system.

After the black-box model has been established, the next step in the process is to create function chains for each of the system's in-flows. These function chains define how each of the in-flows is acted upon by the constituent functions of the system. Unlike the black-box model, the functions and flows of each chain are defined in the language of the Functional Basis. Figure 13 shows the function chain for the 'rider effort' flow.

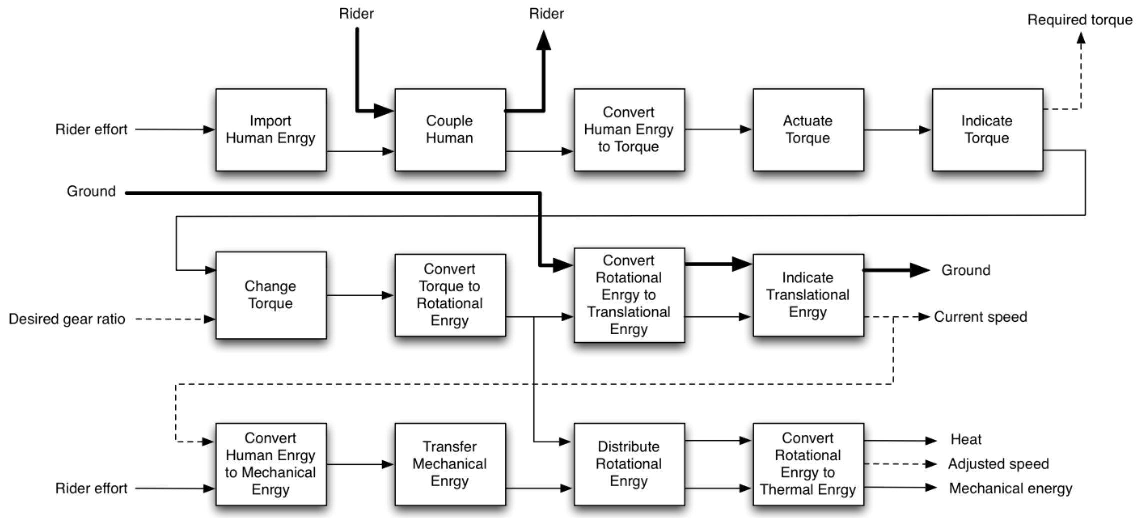


Figure 13. Function chain for the 'rider effort' input flow.

This function chain consists of two 'rider effort' flow entry points; the chain corresponding with the upper entry point represents the conversion of a rider's energy into the translational motion (energy) of the bicycle, and the lower entry point chain represents the retardation of that translational energy. In terms of the upper chain, once the rider and his or her associated energy are imported and coupled to the system, that energy can begin to be converted into the torque necessary to move the bicycle. The torque required to induce motion is indicated to the rider by the resistance of the torque-actuating mechanism. This required torque can be adjusted by altering the gear ratio. Once the proper ratio has been set, the torque generated by the rider can then be fully converted to rotational energy. This rotational energy is transferred to the ground through the tires where, with the help of friction, it is converted into the translational energy of the bicycle.

The bike's translational motion relative to the ground indicates the magnitude of that translational motion; that is, it indicates the bike's speed. With knowledge of the speed of the bicycle, a rider can determine whether that speed is too high, too low, or within acceptable limits. In the instance that the speed is deemed to be too high, the rider can apply braking to slow the bicycle. The lower 'rider energy' chain in Figure 13 shows a functional description of the bike's braking system. On a typical bicycle, the rider manipulates a mechanical system that, in turn, transfers the energy it receives to the wheels. The rotational energy of the wheels is then dissipated in the form of (mostly) heat by this application of mechanical energy.

The last step in the creation of a functional model is to aggregate all the function chains created for the system. This aggregation of function chains produces the final functional model. Figure 14 shows the fully assembled functional model for the bicycle.

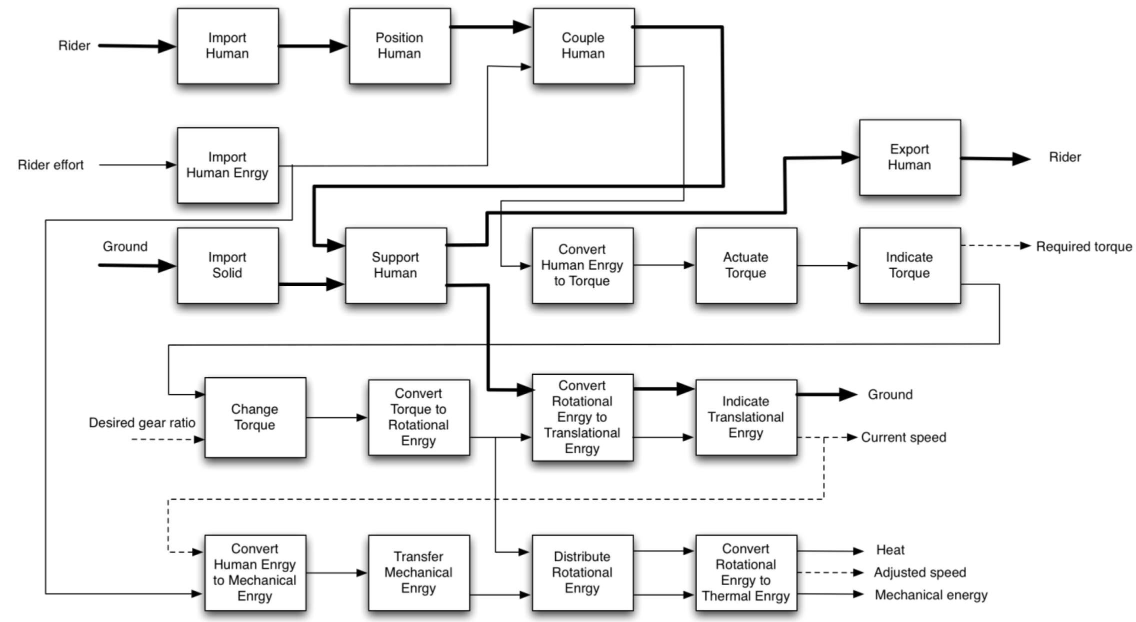


Figure 14. Fully aggregated functional model for a typical bicycle.

Comparing Figures 13 and 14, it can be seen that only two new function chains are added to the 'rider effort' function chain. These chains represent the flow of the 'rider' and the 'ground' through the system. The functions added to the model mainly specify how the rider and the ground enter and exit the system; however, of note, a 'support human' function was added. This function intends to model the bicycle frame and associated supporting elements.

Step 2: The second step in the 7-step methodology is to modularize the developed functional model. As stated previously, this research makes use of the modularization procedure laid out in Stone et al. [9]. This method determines module boundaries based on the how the individual 'flows' progress through the system. Three categories of flows are identified: dominant-flow, branching flow, and conversion-transmission flow. Figure 15 shows the modularized function structure for the bicycle.

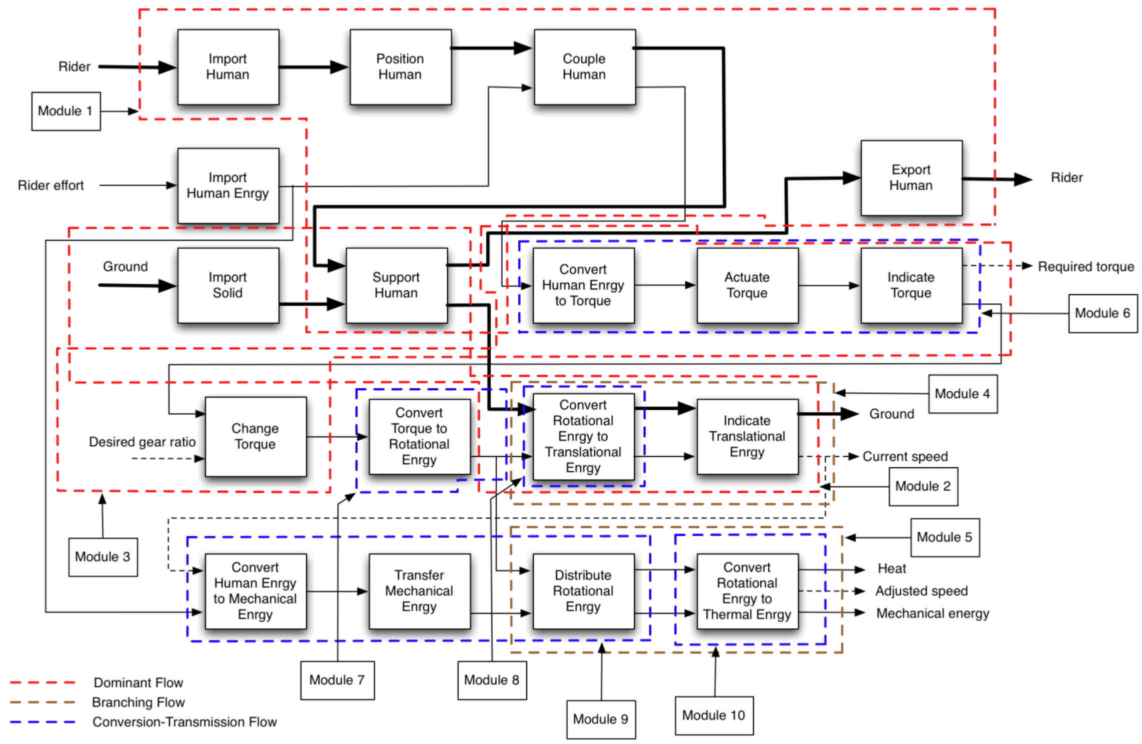


Figure 15. Modularized functional model of the typical bicycle.

A total of 10 modules are identified using the modular heuristics: three of the dominant-flow type, two of the branching flow type, and five of the conversion-transmission flow type. The first two dominant-flow modules, modules 1 and 2, result from the 'flow' of the rider and the ground through the system. The third dominant-flow module is defined by the flow of torque. This torque is initiated by the rider and is direct result of his or her physical effort. The torque flow terminates when it is converted to rotational energy; the initiation point and the conversion point set the boundaries for module 3.

There is only one branching point in this bicycle functional model. Consequently, there are only two branching-flow modules: modules 4 and 5. The branching point is a result of a split in the rotational energy flow. Looking at Figure 15, the rotational energy in the upper branch (i.e. module 4) gets transferred to the ground and converted into translational energy. The rotational energy in the lower branch (module 5) gets dissipated (distributed, in the Functional Basis language) by the braking system and converted into heat. Thus, these modules define the two ways in which rotational energy is manipulated in the system.

The last five modules arise from conversion-transmission relationships present in the system. Three of the identified modules of this type, modules 7, 8, and 10, consist only of singular conversion functions. In and of themselves, these are valid modules according to the heuristics of Stone et al. [9]. However, due to the pair-wise search methodology used in this research, they have no impact on the results achieved, and are identified here only for completeness. The remaining two modules, 6 and 9, each consist of three functions, and thus can be searched pair-wise as is required in step 4 of the developed methodology. Module 6 results from the conversion of the rider's effort into torque, and the subsequent indication of the torque required to move the system in the desired fashion. That is, the rider's effort is converted into torque, and that torque is transmitted back to the rider. Module 9 represents part of the braking system and is constructed similarly to module 6. In this case, the rider's effort is converted into mechanical energy, which, in turn, is transmitted to the wheels, dissipating rotational energy.

Step 3: The next step in the developed methodology is to translate the Functional Basis terms from the system's sub-functions into their equivalent biologically meaningful keywords. As a first step in this process, each sub-function used in the functional model is recorded. Figure 16 shows the 11 sub-functions used in the bicycle function structure.

Bicycle Sub-Functions	
1	Actuate
2	Change
3	Convert
4	Couple
5	Distribute
6	Export
7	Import
8	Indicate
9	Position
10	Support
11	Transfer

Figure 16. List of sub-functions used in the typical bicycle model.

With the sub-functions identified, the next step in this process is to use the thesaurus provided by Cheong et al. [11] to translate these Functional Basis terms into biologically meaningful keywords. As mentioned in Section 4.2.3, not all of the biologically meaningful keywords provided by Cheong et al. [11] are used for this research. Keywords are eliminated based on one of two criteria: 1) the word's relative accessibility in context of the meaning of the Functional Basis term, and 2) whether or not the keyword's essential meaning is captured by another, included keyword. This process of eliminating keywords is done in a product-independent fashion. The keywords that are not included for the bicycle's sub-functions are also not included for the same sub-functions in another product. For example, for the Functional Basis term 'import', 5 of the 10 biologically meaningful keywords are eliminated; those 5 eliminated keywords are excluded for all products that include an 'import' function. Table 1 shows the included and eliminated keywords for the sub-functions that appear in the bicycle's functional model.

Table 1. Included and eliminated biologically meaningful keywords for the bicycle model.

Functional Basis Terms	Included Keywords	Eliminated Keywords
Actuate	Bind Activate Stick Excite Regulate	Change Shape Change Structure Absorb Adapt Evolve
Change	Evolve Specialize Adapt	No keywords eliminated
Convert	Specialize Photosynthesize Transduce Decompose Degrade Transpire Break Down Mutate	Cut Recombine Stimulate Transcribe Fuse Contract Divide Activate Synthesize Reproduce Generate Heat Coil
Couple	Hold Overlap Couple Bind	Extend Project Stretch Activate
Distribute	Diffuse Hydrolyze Circulate Stretch Change Shape Evaporate Break Down	Burst Discharge Stimulate Fuse Be Concentrated Pass Through Segregate Bind Secrete Lyse Oxidize Decompose Condensate Fold
Export	Excrete Cleave Inactivate	Digest Contract Attach Break Down Bind Fuse Denature
Import	Osmose Pass Through Diffuse Insert Secrete	Squeeze Transport Fold Digest
Indicate	Signal Communicate	No keywords eliminated
Position	Detect	No keywords eliminated
Support	Anchor Connect Wrap Bind	Develop Divide
Transfer	Conjugate Transport Change Shape Organize Shift	Beat Couple Break Pollinate Bind Attract

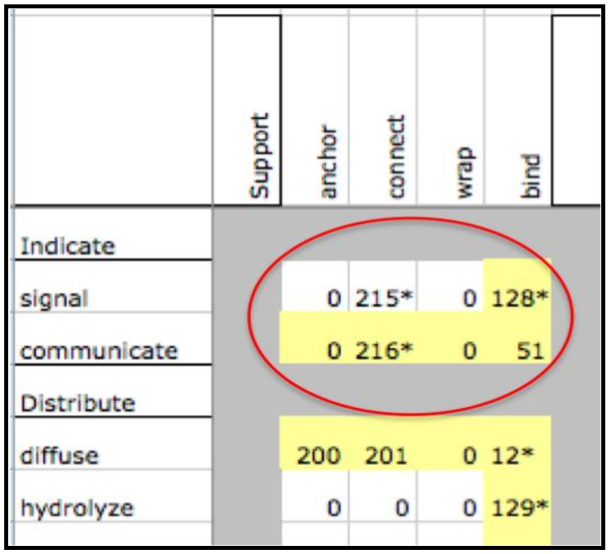
Step 4: In this step, the identified biologically meaningful keywords within each module are paired and searched in the BioSearch database. The first step in this process is to determine the module-by-module break down of the Functional Basis-termed sub-functions present in a given product. Table 2 shows this break down for the bicycle.

Table 2. Module-by-module aggregation of Functional Basis terms for the typical bicycle.

Bicycle				
Module 1	Module 2	Module 3	Module 4	Module 5
Import Position Couple Support Export	Import Support Convert Indicate	Change Convert Actuate Indicate	Convert Indicate	Distribute Convert
Module 6	Module 7	Module 8	Module 9	Module 10
Convert Actuate Indicate	Convert	Convert	Convert Transfer Distribute	Convert

The next step in this process is, within a particular module, to pair and search each Functional Basis term's corresponding biologically meaningful keywords. For instance, in module 1 from Table 2, the five keywords for the basis term 'import' are paired with the one keyword from the basis term 'position'. Each pair is then duly searched in the BioSearch database and the result is recorded. This process continues until all the keywords for the 10 possible pairs of basis terms have been ‘cross-searched’. It’s important to note that inter-module and intra-function keyword pairings and searches are not performed. For example, in the bicycle model, the Functional Basis terms ‘support’ and ‘actuate’ never appear in the same module together, so their corresponding keywords will never be paired and searched. Also, the constituent keywords for ‘support’, such as ‘anchor’ and ‘connect’, are not paired and searched.

Taking advantage of the product-independence of the BioSearch search process (see Section 4.2.4), the BioMatrix is used to identify the pair-wise search results for the bicycle. If the Functional Basis terms of interest appear in the BioMatrix, then the requisite pair-wise searches have already been conducted, and the corresponding B-RAD result number is displayed. For example, from module 2, pairing and searching the keywords for the basis terms ‘support’ and ‘indicate’ yields four B-RAD result numbers. These result numbers are indicated in the BioMatrix (Figure 17). If, on the other hand, the Functional Basis term(s) do not appear in the BioMatrix, then cross-searches with the other relevant basis term(s) must be conducted using BioSearch.



	Support	anchor	connect	wrap	bind
Indicate					
signal		0	215*	0	128*
communicate		0	216*	0	51
Distribute					
diffuse		200	201	0	12*
hydrolyze		0	0	0	129*

Figure 17. BioMatrix cross-search results for Functional Basis terms 'support' and 'indicate'.

Step 5: In this step of the developed methodology, all the results identified from the BioMatrix are aggregated module-by-module. This is done in order to identify overlapping and subset modules, and to organize the results for use in the subsequent steps of the methodology. Figure 18 shows the module-by-module aggregation for the bicycle.

Module 1		Module 2	
Couple/Import	2,10,11,12,21,26	Convert/Import	3,13,14,15,27,28
Couple/Position	37	Convert/Support	49,61,206,207
Couple/Support	44,46,203,204,205	Convert/Indicate	57,63,135,141,143,145
Couple/Export	52	Import/Support (m1)	12,21,26,199,200,201,202
Export/Import	16,22	Import/Indicate	99,107
Export/Position	None	Indicate/Support	51,128,215,216
Export/Support	52		
Import/Position	1		
Import/Support	12,21,26,199,200,201,202		
Position/Support	37		

Module 3		Module 4	
Actuate/Change	61,62,131,132,182,186	Convert/Indicate (m2,3)	57,63,135,141,143,145
Actuate/Convert	49,61,62,72,75		
Actuate/Indicate	51,128,178,185		
Change/Convert	137,138,140,146		
Change/Indicate	57,135,154,198,197		
Convert/Indicate (m2)	57,63,135,141,143,145		

Module 5		Module 6	
Convert/Distribute	13,14,15,71,136,142	Actuate/Convert (m3)	49,61,62,72,75
		Actuate/Indicate (m3)	51,128,178,185
		Convert/Indicate (m2,3,4)	57,63,135,141,143,145

Module 7	Module 8
N/A	N/A

Module 9		Module 10
Convert/Distribute (m5)	13,14,15,71,136,142	N/A
Convert/Transfer	133,134,139,144,147	
Distribute/Transfer	98,144,188,189	

Figure 18. Aggregated B-RAD result numbers for the typical bicycle model.

Looking at Figure 18, a couple of notable features of the bicycle model are apparent. First, this model contains no overlapping modules. This means that each module contained within in the bicycle (except for modules 7, 8, and 10, which represent single conversion functions) is, functionally speaking, unique. The second point of note is that the model does contain subset modules. Modules 4, 5, and 6 all consist entirely of functions that are contained within other modules. With respect to this research, the subset modules are not given consideration during the subsequent concept generation activities. That is, for example, module 5 is not considered, as the functionality present in that module is given consideration during the analysis of module 9.

Step 6: The sixth step in the developed methodology is to identify the B-RAD passage numbers from Figure 18 that will be analyzed for derivative product concepts. As was stated in Section 4.2.6, the passages analyzed for this research are restricted based on two criteria: 1) the type of module in which the passage appears, and 2) the number of times the passage appears within a module of the specified type. Specifically, in order for a passage to be a candidate for analysis, it must be contained within an auxiliary module and, in general, be repeated within that particular module. In cases where there are a limited amount of repeated results in an auxiliary module of interest, other passages are reviewed and considered for analysis based on the relative accessibility of their subject matter to the researcher.

The first step in the process of determining candidate passages is to identify the basic and auxiliary modules within the product of interest. Doing this requires one to determine the overall function of the product being analyzed, and the modules directly carry out that overall function. As a result of the functional modeling scheme used in this methodology, the overall function of the product is gleaned from the system's black-box model. In the case of the bicycle, the designated overall function is 'transport rider'. Looking back at Figure 15 (the modularized functional model), six modules that directly carry out the function ‘transport rider’ are identified: modules 2, 3, 4, 6, 7, and 8. These modules, each at different levels, represent the conversion of human produced energy into rotational energy and, subsequently, translational energy: the basic function of the bicycle. An argument can be made the ‘support human’ sub-function in the functional model represents basic function of the bicycle in that it specifies a provision for a platform on which the rider is transported. Under this scheme, module 1, along with modules 2, 3, 4, 6, 7, and 8, would also be classified as a basic module. However, in this research, the basic function of a product is thought of as not only the overall function of that product, but more specifically, the function that uniquely separates the product from other products that may provide the same black-box function. In the case of the bicycle, the functions that separate the bicycle from, for example, a car, are those that define the way in which a rider’s energy is converted into translational motion.

The next task in this step of the methodology is to determine, specifically, the B-RAD passages that are to be analyzed. Using the two criteria that were presented above, this process is quite straightforward. The auxiliary modules for the bicycle have been identified as modules 1, 5, 9, and 10. Module 10, however, is excluded because it only consists of a single sub-function, and cannot be cross-search in the BioSearch database. Module 5 is also excluded; it is simply a subset of module 9. This leaves two modules that contain candidate passages for analysis: modules 1 and 9. Looking at Figure 18, five B-RAD passage numbers are repeated within module 1: 12, 21, 26, 37, and 52. The passages represented by these numbers are given consideration during the derivative product concept generation process detailed in the 'Step 7' portion of this section. As for module 9, there is only one repeated passage number: 144. In order to find more candidate passages, each of the passages within the module is reviewed for accessibility and relevance. This process is inherently subjective, as it is based on the level of prior knowledge the designer has obtained or believes he or she can readily obtain. However, choosing passages in this manner is appropriate for this research because, again, the objective is to determine whether or not the developed 7-step methodology can be used to synthesize derivative products, not to perform an exhaustive examination of the solution space. The B-RAD passages identified as candidate passages based on their relevance and accessibility are presented and discussed in 'Step 7'.

Step 7: The last step in the developed methodology is to analyze the identified B-RAD passages, and use the relational aspect of the natural entities described therein to inspire derivative product concepts. As discussed in Section 2.2.3, traditional biomimetic design focuses on adapting an observed natural phenomenon to create an engineering solution. In other words, an engineered solution is created based on, more or less, a direct emulation of the functionality of the indentified natural entity. For example, Clark et al.'s [48] use of cockroach walking as a basis for their hexapedal robot design. In this research, however, using direct abstraction to inspire products that adhere to a host and derivative relationship is, in general, not possible. As a result, the process of creating derivative product concepts based on the natural entities identified in a particular

B-RAD passage is heavily dependent on the creativity and experience of the designer.

Before proceeding on to discuss the derivative product concepts created in this research, there are a couple of points worth noting. First, after the candidate B-RAD passages are identified, no formal method or procedure is used to bring about the creation of the derivative product concepts presented here. Rather, the researcher considers each candidate B-RAD passage (and the relationship shared by the entities described therein) in the context of the functionality of the host product, and duly conceptualizes a valid derivative product. Second, without loss of illustrative value, only those candidate B-RAD passages that produce derivative product concepts for the bicycle are detailed in the subsequent paragraphs.

The first derivative product concept achieved is derived from B-RAD passage number 12 from module 1 of the bicycle. This passage number is a result of a paired search of the biologically meaningful keywords 'diffuse' and 'bind', and contains 13 individual passages. Each individual passage is given a match number by the BioSearch database. Figure 19 shows the first five matches for result number 12.

[12] Match #1: Section 8_7_2 Some plants have evolved systems to bypass photorespiration 149 /2749: The role of this acceptor is to **bind CO2 from the air in the leaf and carry it to the interior cells, where it is "dropped off" at rubisco.

Match #2: Section 15_2_2 There are several types of receptors 283 /367: Estrogen, for example, is a steroid and can easily **diffuse across the plasma membrane and enter the cell; it **binds to a receptor inside the cytoplasm. Insulin, on the other hand, is a protein hormone that cannot diffuse through the plasma membrane; instead, it binds to a receptor that is a transmembrane protein with an extra-cellular binding region (Figure 15.

Match #3: Section 15_2_2 There are several types of receptors 283 /518: Insulin, on the other hand, is a protein hormone that cannot **diffuse through the plasma membrane; instead, it **binds to a receptor that is a transmembrane protein with an extracellular binding region (Figure 15.

Match #4: Section 15_3_5 Nitric oxide is a gas that can act as a second messenger 289 /1580: The NO formed is chemically very unstable and although it **diffuses readily, it does not get too far.

Match #5: Section 15_4_3 Different genes are transcribed 291 /535: Binding of the ligand allows the ligand/receptor complex to enter the nucleus, where it binds to hormone-responsive elements at the promoters of a number of genes.

Figure 19. The first five matches for B-RAD passage number 12 (adapted from [60]).

Looking at match numbers 2 and 3, it is apparent that these passages discuss a feature of two objects: estrogen and insulin. The feature discussed has to do with the manner in which the two molecules travel across a cell membrane. Estrogen can easily travel across the membrane but insulin cannot; it must bind to a receptor that is trans-membrane in order to access the interior of a cell. Thus, the insulin needs an extra entity in order to interact with the cell. This extra entity, the trans-membrane cell receptor, can be thought of as the derivative product, and the cell itself can be thought of as the host. Analyzing the relationship shared by the cell, the cell receptor, and the insulin molecule under this host and derivative construction, one can conclude that the cell receptor provides a means for the insulin to travel within the cell. Taking this to the engineered domain, a bicycle basket (Figure 20) produces an equivalent set of relationships. The bike basket is bound to the bicycle and, in turn, creates a provision for additional objects to be coupled, and travel with the bike.

Figure 20. A bicycle basket [61].

Moving to B-RAD passage result number 52 from module 1, this result is produced by the paired search of keywords 'inactivate' and 'bind', and contains three individual matching passages. Figure 21 shows the three matching passages for result 52.

[52] Match #1: Section 6 Energy, Enzymes, and Metabolism/2353: Indeed, when an enzyme is **inactivated, either by the **binding of an inhibitor such as hirudin that keeps the enzyme from binding to its target or by some error leading to an alteration in its three-dimensional structure, its function is destroyed.

Match #2: Section 18_4_4 Two kinds of genes are changed in many cancers 344 /3667: In the active form, it encodes a protein that **binds to and **inactivates transcription factors that are necessary for progress to the S phase and the rest of the cell cycle.

Match #3: Section 19_1_2 Immune system proteins bind pathogens or signal other cells 354 /1201: Different cytokines activate or **inactivate B cells, macrophages, and T cells.

Figure 21. The three matching B-RAD passages for the keywords 'inactivate' and 'bind' (adapted from [60]).

Considering match number 1, this passage describes the ways in which an enzyme can be inactivated. Two methods of inactivation are identified: through the binding of an inhibitor and, through the alteration of the enzyme's structure. Regardless of the method of inactivation, the passage indicates, the function of the enzyme is destroyed. Taking a look, specifically, at the inhibitor method of inactivation, the inhibiting agent prevents the enzyme from binding to its target. Overlaying a host and derivative structure, the enzyme can be seen as the host product and the inhibitor the derivative. In this context, the relationship between the host and derivative is one where the derivative prevents a third, external entity, from binding to the host. Extending this to the engineered domain, the conceived derivative product is one that prevents, or inhibits, potential riders from using the bicycle in its intended manner. This functionality is much the same as is provided by a bicycle lock; however, in adherence to relationship described in the passage, the conceived derivative secures the host by preventing the 'binding' of a rider to the bicycle. A derivative of this type may be of a form similar to that of 'The Club', a popular method for securing the steering wheel of a car (Figure 22).

Figure 22. Picture of 'The Club'. The second developed derivative product concept may have a similar form and function [62].

The third derivative product concept results from B-RAD passage number 133 in module 9. Passage 133 is not one of the repeated passages in module 9; in fact, that module only contains one repeated passage number: 144. However, passage 133 is chosen because of the accessibility of the subject matter contained within its matches. Figure 23 shows three (of five) matching passages represented by B-RAD number 133. These matches are the result of a paired search using the keywords 'specialize' and 'transport'.

Match #2: Section 28_2_2 Most present-day plants have vascular tissue 502 /1133: Tracheophytes differ from liverworts, hornworts, and mosses in crucial ways, one of which is the possession of a well-developed vascular system consisting of **specialized tissues for the **transport of materials from one part of the plant to another. One such tissue, the phloem, conducts the products of photosynthesis from sites where they are produced or released to sites where they are used or stored.

Match #3: Section 29_3 The Angiosperms: Flowering Plants 521 /2740: Angiosperms are also distinguished by the possession of **specialized water- **transporting cells called vessel elements in their xylem, but these cells are also found, in anatomically different form, in gnetophytes and a few ferns.

Match #4: Section 40_1 Homeostasis: Maintaining the Internal Environment 694 /319: Most cells of a sponge or a jellyfish are in direct contact with seawater, or are close enough that they can receive nutrients and eliminate wastes without **specialized organs to **transport nutrients and wastes around their bodies. This lifestyle is quite limiting, however.

Figure 23. Three matching passages from B-RAD passage number 133 (adapted from [60]).

Match 2 is considered in the development of the third derivative product concept. This passage discusses several artifacts of a (biologically) technical nature; however, the functional relationship the natural entities share is quite clear. Tracheophytes possess a vascular system made up of specialized tissues, such as phloem, that are used to transport materials from one part of the structure to another. Thinking about this relationship in the host and derivative context, one can consider the Tracheophyte as the host entity and its vascular system as the derivative. Under this framework, the relationship can be recast: the derivative uses the energy of the host in order to move materials from one point to another. While the bike basket derivative product conceived earlier fits this description, the functionality of a vascular system suggests a specific form of transport: flow. The derivative resulting from this line of thinking is a bicycle-powered pumping device (Figure 24). The envisioned pump uses the effort of a rider to generate the power necessary to convey a fluid.

Figure 24. A picture of a pump. The third derivative concept is a product similar in function, though powered by the bicycle [63].

Staying with B-RAD number 133, the fourth developed derivative product concept results from an analysis of match number 4 (Figure 23). This passage discusses how the body structures of sponges and jellyfish take advantage their close contact with seawater. The passage indicates that because of this close contact, these natural entities are able to take in nutrients and eliminate wastes without the use of specialized organs. However, according to the passage, this lack of specialized organs results in a limiting lifestyle. Taking a somewhat different tact than was used for the generation of the previous derivative product concepts, a 'natural' host and derivative are not identified. Rather, a derivative that takes advantage of the host's close association with another entity is sought. In the case of the bicycle, one closely associated entity is the road surface. Considering a derivative product that takes advantage of a bicycle's near constant attachment to the ground, this research has identified training wheels (Figure 25). Training wheels fit all three derivative product guidelines and, in congruence with the passage, must have contact with the road surface in order to function properly. Additionally, while the use of training wheels provides the benefit of stability, they limit some the functionality of the bicycle. Although, like the bike basket, not a novel derivative product concept, the conceptualization of training wheels illustrates that the developed methodology can be used to create derivatives that have (or will have) practical utility.

Figure 25. Training wheels [64].

The last developed derivative product concept comes as a result of the analysis of a passage cataloged under B-RAD number 144. Number 144 is the only repeated result that occurs in module 9 of the bicycle function structure. This result contains two matching passages that result from the simultaneous search of keywords ‘transport’ and ‘break down.’ Figure 26 shows the two matching passages for result number 144.

[144] Match #1: Section 34_2_5 Xylem transports water from roots to stems and leaves 608 /814: These cells secrete a waterproofing substance into their cell walls, then **break down their end walls, and finally die and disintegrate. The result is a hollow tube through which water can flow freely.

Match #2: Section 48_5_2 Regulating breathing requires feedback information 864 /6726: In the disease emphysema, the fine structures of alveoli **break down, resulting in the formation of larger air cavities in the lungs.

Figure 26. The two matching passages corresponding to B-RAD result number 144 (adapted from [60]).

Considering match number 2, the biological phenomenon detailed is quite understandable. Emphysema is a disease that degrades the lungs' capacity to hold air. The specific mechanism through which this occurs is a break down in the structure of alveoli. At this point, a natural host and derivative could be identified, and the analysis of this passage could proceed from that basis. However, in this case, a more strategic level of analysis is used. The relationship between emphysema and the lungs is that the disease reduces the lungs' capacity to hold air. Translating this relationship to the engineered domain, in the context of the bicycle, does not necessarily produce a desirable result. The preferred result in that context is an increase in the lung capacity of the rider. This leads to the fifth derivative product concept: a device that increases the lung capacity of a bicycle's operator. Such products already exist for automobiles; these include turbochargers, superchargers (Figure 27), and ram-air devices. These devices use mechanical energy generated by the movement of a car to compress air before it enters the cylinders of the engine. Having more air in the cylinders of an internal combustion engine increases its power output. A similar benefit may be gleaned by increasing the oxygen intake of a bicycle's rider.

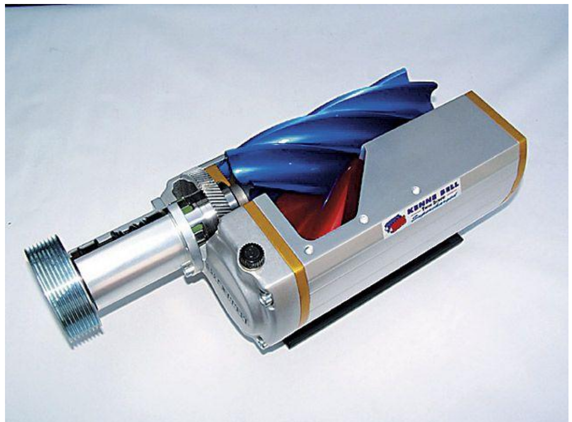


Figure 27. A picture of a supercharger. The form and function of the fifth developed derivative may be similar [65].

5.2 Additional Case Studies

As mentioned in the opening of this section, the three remaining host product case studies, the iPod, the military assault rifle, and the Black & Decker Multi-Tool, have only their resulting derivative product concepts presented. The procedure used to create these concepts is the same as was used to create the derivative products for the bicycle (i.e. the 7-step methodology). The modularized function structures, module-by-module aggregated B-RAD results, and the passage statements used to create derivatives for these three remaining host products are located in the Appendix section. In this section, the developed derivatives are presented in table format. The left column of each table contains a short description of the envisioned derivative, the middle column identifies the B-RAD passage and match numbers that inspired the derivative, and the right column displays a visual approximation of the concept.

5.2.1 The iPod

Figure 28 shows a picture of the typical iPod modeled for this case study. The functionality of the iPod is heavily dependent on the software that is installed on the device. However, in the study presented here, this 'virtual' functionality is not modeled, and only the mechanical and basic electronic functional elements are specified. Table 3 shows the five derivative product concepts developed for the iPod in this study.

Figure 28. Photograph of a typical iPod music player.

Table 3. Derivative product concepts for the iPod.

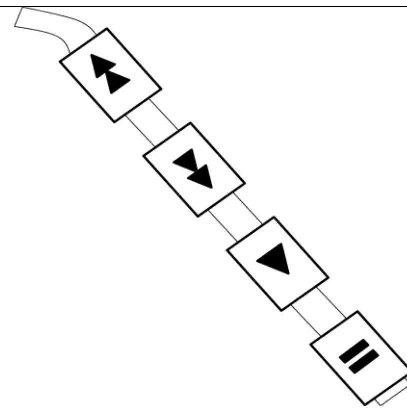
Derivative Concept	Module B-RAD Passage Match Number	Visual Approximation
Mechanical battery charger → This is a product that uses mechanically developed energy to power or recharge the iPod. The envisioned functionality is similar that of a Rolex watch or a hand-crank radio.	Module 1 B-RAD #2 Match #1	 [66]
String controller → A tubular or string-like controller that allows the user to control the basic functions of the iPod without interacting directly with the main interface. This could prove especially useful while exercising or commuting	Module 4 B-RAD #59 Match #1	
Remote screen → This is a device that allows the information displayed on the screen of the iPod to be viewed from a remote location. The form and function of this derivative is much the same as a computer monitor.	Module 1 B-RAD #26 Match #2	 [67]

Table 3 continued.

Derivative Concept	Module B-RAD Passage Match Number	Visual Approximation
Pre-amp/Sound enhancement → The sound quality of an iPod may be lacking compared to other mediums. This derivative enhances sound quality much in much the same manner as a pre-amp. Such a device may require its own power source.	Module 4 B-RAD #68 Match #1	 [68]
Suite of environmental sensors → These sensors use the processing and electrical power of the iPod to enable their function. An example of a derivative that could be a part of the suite is a thermometer.	Module 4 B-RAD #63 Match #1	 [69]

5.2.2 The Military Assault Rifle

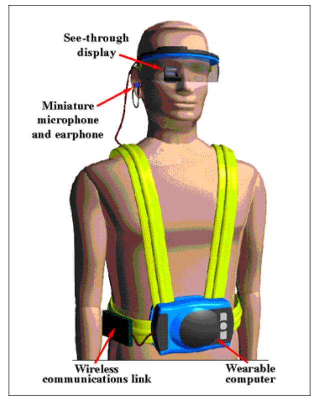
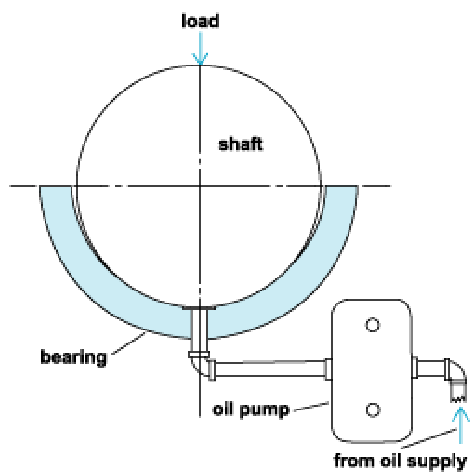
The two key functionalities that differentiate an assault rifle from a typical hunting rifle are the automatic cycling of rounds in and out of the chamber, and the use of a detachable magazine. With respect to the former, this functionality, although modeled in the function structure, resides (mostly) inside a basic module, and is not considered during the concept generation process. However, the latter functionality, being modeled as an auxiliary module (module 2), is considered, and directly results in two derivative product concepts. Figure 29 shows a picture of a typical assault rifle, and Table 4 shows the five derivative product concepts developed for this product.

Figure 29. Photograph of a typical military assault rifle [70].

Table 4. Derivative product concepts for the military assault rifle.

Derivative Concept	Module B-RAD Passage Match Number	Visual Approximation
Additional safety device →This device serves as an additional means by which to secure the weapon. The form and function of this derivative could be similar to current gun locks.	Module 10 B-RAD #74 Match #1	 [71]
Gun light/light detection system → A gun light illuminates the target area, making hostile entities easier to acquire. The passage also suggests a derivative system that detects light. This system could function in the same manner as an infrared camera.	Module 1 B-RAD #1 Match #1	 [72]
Heat management system → Excess heat can cause parts to become deformed and fail. This derivative controls the heat that builds up during long firing sequences. A car radiator and a computer heat sink provide a similar functionality.	Module 2 B-RAD #220 Match #1	 [73]

Table 4 continued.

Derivative Concept	Module B-RAD Passage Match Number	Visual Approximation
Advanced targeting system → Such a system may augment a user's senses by amplifying sound and/or light. Also, an on-board processing capability could aid in threat identification, analysis, and facilitate communication.	Module 2 B-RAD #221 Match #1	 [74]
Anti-jamming/lubrication system → This derivative would prevent jams by keeping the bullets from binding to the internal surfaces of the rifle. A similar system that prevents the gun from malfunctioning in cold weather environments could also be developed. Fluid film bearings may serve as a model for the function of this derivative.	Module 10 B-RAD #68 Match #2	 [75]

5.2.3 The Black & Decker Multi-Tool

The Black & Decker Multi-Tool presents an interesting problem in the context of the host and derivative product space. The Multi-Tool is a cordless drill-like device that features interchangeable modules, each of which provides a different functionality (Figure 30). For instance, if the 'drill' module is attached, then the Multi-Tool functions as a drill, if the 'sanding' module is attached, then it is a sander. Using the vocabulary of this thesis, the Multi-Tool is designed to function exclusively with the addition of post-market modules. But, is the Multi-Tool a valid host product? And if so, are the post-market modules that are made for it derivative products? Taking on the first question, under the strictest interpretation, it seems that the Multi-Tool is not a host product, as it is not 'stand-alone.' However, assuming that the base model of the Multi-Tool is sold with a basic set of functional modules (e.g. the drill module), then it could be considered 'stand alone' at the time of purchase. In terms of the second question, the first and third requirements of the derivative product guidelines are met: any additional modules developed for the Multi-Tool would be dependent on it for their usefulness, and they would likely be novel. As for the second guideline, an added module would not replace similar functionality already present on the Multi-Tool; ostensibly, the newly developed module would provide new functionality. Table 5 shows the five derivative product concepts developed for the Multi-Tool.

Figure 30. The Black & Decker Multi-Tool [76].

Table 5. Derivative product concepts for the Black & Decker Multi-Tool.

Derivative Concept	Module B-RAD Passage Match Number	Visual Approximation
Powered sprayer/injector → This derivative is an attachment that uses the mechanical motion generated by Multi-Tool to pump and convey a liquid. The liquid could be paint, glue, or an insulating foam product. A paint sprayer has a similar function.	Module 3 B-RAD #34 Match #3, 4, and 5	 [77]
Laser rangefinder, leveler or thermometer → This passage suggests a laser-based measurement device. Looking at current technology, this derivative could function to measure distance, produce a level line, or measure temperature.	Module 3 B-RAD #8 Match #1	 [78]

Table 5 continued.

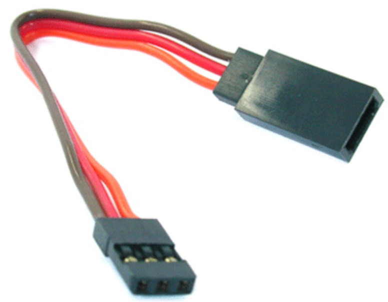
Derivative Concept	Module B-RAD Passage Match Number	Visual Approximation
Belt battery pack → The entire weight of the Multi-Tool is contained on the tool itself. If this weight were distributed, the Multi-Tool would likely be easier to wield, especially during extended use. Having a derivative that allows the battery pack to be carried on the belt would effectively lighten the load on the user. An extension cord has an analogous functionality.	Module 2 B-RAD #200 Match #1	 [79]
Electromagnet → This derivative could function to pick up loose metal objects such as screws and nails. Also, functionality similar to that of an endoscope could be incorporated to allow the magnet to reach into tight places, such as the engine well of a car.	Module 3 B-RAD #77 Match #2	 [80]

Table 5 continued.

Derivative Concept	Module B-RAD Passage Match Number	Visual Approximation
Wet hole drill →While a drill offers functionality similar to that likely to be on the basic Multi-Tool model, the addition of a slurry dispensing mechanism gives this device the unique function required to be classified as a derivative. The envisioned device would allow users to effectively drill through tile, cement, and certain metals.	Module 7 B-RAD #144 Match #1	 [81]

6. CONCLUSIONS AND FUTURE WORK

The stated two-fold goal of this research is to 1) formalize the notion of the post-market module space, and 2) develop a method that aids in the synthesis of products for that space. The motivation for the former part of this goal comes from previously developed notions of product architecture and modular product design. These areas of research put forward the idea that a well-considered structure can increase the value of a product and, in turn, add value to the organization that produces that product. In particular, a modular architecture provides many benefits. Products with this type of structure are, in general, easier to produce, maintain, upgrade, and extend than their integral counterparts. Moreover, modular products enable the use of portfolio strategies, such as the product family, to create efficiencies in marketing, design, manufacturing, and distribution processes. Much of the prior work in this area focuses on creating and analyzing pre-market specified product modules. That is, modules which are defined and integrated into a product before it becomes available to its end-users. In contrast, Baldwin and Clark [7] put forward the notion of a modularization strategy in which modules are added to a product, post-market.

This thesis builds on the work of Baldwin and Clark, fully formalizing the post-market module space they defined. This is done in two ways: first, by recasting and codifying the language used to describe products in the post-market module space, and second, by setting the boundaries that define the space. With respect to language, the newly developed terms, host product, derivative product, and final variant, provide a unified lexicon with which to describe products associated with post-market space. The new terms also reflect the space's relationship with established areas of research; chiefly, modular product design and product family design. In terms of boundaries, three guidelines for valid derivative products are developed. These guidelines are derived from both the explicit and implicit description of the post-market module space given by Baldwin and Clark [7]. By codifying language and setting boundaries, the host and derivative product space is formally established, and is now subject to critique, inquiry, and extension.

In order to achieve that latter part of the two-fold goal, this work develops a 7-step methodology that can be used to synthesize derivative products. The development of this methodology is necessary as Baldwin and Clark do not put forward a method for synthesizing these types of products, and methodologies from modular product design and product family research are inadequate. The developed methodology is informed by the 5-step biomimetic concept generation procedure developed by Vakili and Shu [10]. This gives the method a biomimetic foundation that allows designers to create derivatives without having prior knowledge of the derivatives' desired function. In addition, the methodology's use of established design tools such as functional modeling, the Functional Basis, and modular heuristics, helps to ensure its effectiveness.

The 7-step methodology is shown to be effective in generating derivative product concepts through its application on four established host products. The 20 derivative product concepts developed for these hosts not only demonstrate the adroitness of the methodology in performing its function, but they also hint at the method's quantifiable validity. Ultimately, due to scope of this research, the reader must evaluate the effectiveness of the method by assessing the novelty and reasonableness of the derivative products that are developed. However, this evaluation must be informed by the fact that the objective of the validation procedure used here is to show that derivative products *can* be synthesized using the 7-step methodology.

In terms of future work, the concept of the host and derivative product space produces many potential avenues of investigation. One such avenue is the determination of the general qualities that successful host products share. This will require a concentrated study of a substantial number of established host products from a variety of market segments. An analysis of the function, structure, or other definable characteristics these products have, may yield a pattern that can be generalized into a set of common host product attributes. Armed with knowledge of these common attributes, designers will be able to efficiently synthesize effective host products.

A second avenue of investigation is the evaluation of the effectiveness of the 7-step methodology using quantifiable metrics. This will require researchers to first establish metrics, and then to produce a data set that can be evaluated against those metrics. This data set will likely result from a designed experiment, where the participating subjects use the methodology, or some portion of the methodology, under a set of highly defined conditions.

Another area of investigation relates to the search process itself. For this research, each pair-wise search of biologically meaningful keywords is performed manually. This requires the researcher to input all keyword pairs into BioSearch one-at-a-time. For instance, to cross-search the keywords 'anchor', 'bind', 'diffuse', and 'cleave' requires six separate searches, with each keyword being input when it's searched. Additionally, when results are achieved, they are recorded on the BioMatrix and in the B-RAD individually. The developed methodology would thus benefit from an automation of this process. A program constructed to take in keywords and return the (properly cataloged) results of their cross-searches will substantially reduce the time needed to generate the required set of BioSearch passages.

The last avenue of investigation corresponds with the last step in the 7-step methodology. This research posits that translating the identified natural relationships and phenomenon into derivative products in engineered domain requires designers to leverage their creativity and experience. However, this step in the methodology may benefit from the imposition of a more structured process. Pahl and Beitz [3] detail several structured concept generation methodologies such as brainstorming, the method of 6-3-5, and the consultation of subject matter experts (Delphi Method). Augmenting step 7 with these, and/or similar methodologies may serve to increase the effectiveness of the developed methodology in helping designers conceive derivative products.

REFERENCES

[1] Crawford, M., and Di Benedetto, A., 2006, *New Products Management*, McGraw-Hill/Irwin, New York.

[2] Otto, K. N., and Wood, K. L., 2001, *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Upper Saddle River, NJ.

[3] Pahl, G., and Beitz, W., 1996, *Engineering Design: A Systematic Approach*, Springer, London.

[4] Ulrich, K. T., and Eppinger, S. D., 2004, *Product Design and Development*, McGraw-Hill/Irwin, Boston, MA.

[5] Bremmer, R., 1999, "Cutting Edge Platforms," Financial Times Automotive World, September, pp. 30-38.

[6] Ulrich, K., 1995, "The Role of Product Architecture in the Manufacturing Firm," Journal of Research Policy, **24**, pp. 419-440.

[7] Baldwin, C. Y., and Clark, K. B., 2000, *Design Rules: The Power of Modularity*, MIT Press, Cambridge, MA.

[8] Dahmus, J. B., Gonzalez-Zugasti, J. P., and Otto, K. N., 2001, "Modular Product Architecture," Design Studies, **22**(5), pp. 409-424.

[9] Stone, R. B., Wood, K. L., and Crawford, R. H., 2000, "A Heuristic Method for Identifying Modules for Product Architectures," Design Studies, **21**(1), pp. 5-31.

[10] Vakili, V., and Shu, L. H., 2001, "Towards Biomimetic Concept Generation," ASME 2001 DETC & DTM Conference, ASME, Pittsburgh, PA.

[11] Cheong, H., Shu, L. H., Stone, R. B., and McAdams, D. A., 2008, "Translating Terms of the Functional Basis into Biologically Meaningful Keywords," ASME 2008 IDETC & CIE Conference, ASME, New York City, NY.

[12] Prasad, B., 1996, *Concurrent Engineering Fundamentals: Integrated Product and Process Organization Volume 1*, Prentice Hall, Upper Saddle River, NJ.

[13] Syan, C. S., 1994, "Introduction to Concurrent Engineering " *Concurrent Engineering: Concepts, Implementation and Practice*, C. S. Syan, and U. Menon, eds., Chapman & Hall, London, pp. 3-23.

[14] Finger, S., and Dixon, J. R., 1989, "A Review of Research in Mechanical Engineering Design. Part II: Representations, Analysis, and Design for the Life Cycle," Journal of Research in Engineering Design, **1**(2), pp. 121-137.

[15] Winner, R. I., Pennell, J. P., Bertrand, H. E., and Slusarczuk, M. M. G., 1988, "The Role of Concurrent Engineering in Weapons System Acquisition," Institute for Defense Analysis, Alexandria, VA.

[16] Pawar, K. S., 1994, "Organizational and Managerial Issues," *Concurrent Engineering: Concepts, Implementation and Practice*, C. S. Syan, and U. Menon, eds., Chapman & Hall, London, pp. 49-74.

[17] Akao, Y., 1990, "An Introduction to Quality Function Deployment," *Quality Function Deployment: Integrating Customer Requirements into Product Design*, Y. Akao, ed., Productivity Press, Cambridge, MA, pp. 1-24.

[18] Hauser, J. R., and Clausing, D., 1988, "The House of Quality," Harvard Business Review, **66**(3), pp. 63-73.

[19] Menon, U., O'Grady, P. J., Gu, J. Z., and Young, R. E., 1994, "Quality Function Deployment: An Overview," *Concurrent Engineering: Concepts, Implementation and Practice*, C. S. Syan, and U. Menon, eds., Chapman & Hall, London, pp. 91-99.

[20] Huang, G. Q., 1996, "Introduction," *Design for X: Concurrent Engineering Imperitives*, G. Q. Huang, ed., Chapman & Hall, London, pp. 1-18.

[21] Boothroyd, G., and Dewhurst, P., 1988, "Product Design for Manufacture and Assembly," Manufacturing Engineering, April, pp. 1-18.

[22] Syan, C. S., and Swift, K. G., 1994, "Design for Assembly," *Concurrent Engineering: Concepts, Implementation and Practice*, C. S. Syan, and U. Menon, eds., Chapman & Hall, London, pp. 117-149.

[23] Boothroyd, G., and Knight, W., 1993, "Design for Assembly," IEEE Spectrum, **30**(9), pp. 53-55.

[24] Chelsom, J. V., 1994, "Concurrent Engineering Case Studies: Lessons from Ford Motor Company Experience " *Concurrent Engineering: Concepts, Implementation and Practice*, Chapman & Hall, London, pp. 25-48.

[25] Henderson, R. M., and Clark, K. B., 1990, "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," Administrative Science Quarterly, **35**(1), pp. 9-30.

[26] Ulrich, K. T., and Seering, W. P., 1990, "Function Sharing in Mechanical Design," Design Studies, **11**, pp. 223-234.

[27] Hölttä-Otto, K., 2005, "Modular Product Platform Design," Ph.D. thesis, Helsinki University of Technology, Helsinki.

[28] Cutherell, D., 1996, "Chapter 16 - Product Architecture," *The PDMA Handbook of New Product Development*, M. Rosenau, ed., John Wiley & Sons, Inc, New York.

[29] Ulrich, K. T., and Tung, K., 1991, "Fundamentals of Product Modularity," Proceedings of the 1991 ASME Annual Meeting Symposium on Issues in Design/Manufacturing Integration, ASME, Atlanta, GA.

[30] Ericsson, A., and Erixon, G., 1999, *Controlling Design Variants: Modular Product Platforms*, ASME Press, New York.

[31] Gershenson, J. K., Prasad, G. J., and Allamneni, S., 1999, "Modular Product Design: A Life-Cycle View," Journal of Integrated Design and Process Science, **3**(4), pp. 13-26.

[32] Feitzinger, E., and Lee, H. L., 1997, "Mass Customization at Hewlett-Packard: The Power of Postponement," Harvard Business Review, **75**(1), pp. 116-121.

[33] Simpson, T. W., 2004, "Product Platform Design and Customization: Status and Promise," Artificial Intelligence for Engineering Design, Analysis and Manufacturing, **18**, pp. 3-20.

[34] Miller, T. D., and Elgard, P., 1998, "Defining Modules, Modularity and Modularization: Evolution of the Concept in a Historical Perspective," Design for Integration in Manufacturing: Proceedings of the 13th IPS Research Seminar, Aalborg University, Fuglsoe.

[35] Stone, R. B., 1997, "Towards a Theory of Modular Design," Ph.D. thesis, University of Texas at Austin, Austin, TX.

[36] Huang, C. C., 2000, "Overview of Modular Product Development," Proceedings of the National Science Council-Republic of China, **24**(3), pp. 149-165.

[37] Kusiak, A., and Huang, C. C., 1996, "Development of Modular Products," IEEE Transactions on Components, Packaging, and Manufacturing Technology-Part A, **19**(4), pp. 523-538.

[38] Jose, A., and Tollenaere, M., 2005, "Modular and Platform Methods for Product Family Desgn: Literature Analysis," Journal of Intelligent Manufacturing, **16**, pp. 371-390.

[39] Robertson, D., and Ulrich, K., 1998, "Planning for Product Platforms," Sloan Management Review, **39**(4), pp. 19-31.

[40] Meyer, M. H., and Lehnerd, A. P., 1997, *The Power of Product Platforms: Building Value and Cost Leadership*, The Free Press, New York.

[41] Meyer, M. H., and Utterback, J. M., 1993, "The Product Family and the Dynamics of Core Capability," Sloan Management Review, **34**(3), pp. 29-47.

[42] Sawhney, M. S., 1998, "Leveraged High-Variety Strategies: From Portfolio Thinking to Platform Thinking," Journal of the Academy of Market Science, **26**(1), pp. 54-61.

[43] Jiao, J., Simpson, T. W., and Siddique, Z., 2007, "Product Family Design and Platform-Based Product Development: A State-of-the-Art Review," Journal of Intelligent Manufacturing, **18**, pp. 5-29.

[44] Gamba, A., and Micalizzi, A., 2007, "Product Development and Market Expansion: A Real Options Model," Financial Management, **36**(1), pp. 91-112.

[45] Gonzalez-Zugasti, J. P., and Otto, K. N., 2000, "Modular Platform-Based Product Family Design," ASME 2000 DETC and CIE Conference, ASME, Baltimore, MD.

[46] Vincent, J. V. F., 2001, "Stealing Ideas from Nature," *Deployable Structures*, S. Pellegrino, ed., Springer-Verlag, New York, pp. 51-58.

[47] Bar-Cohen, Y., 2005, "Biomimetics: Mimicking and Inspired-by-Biology," SPIE Smart Structures Conference, San Diego, CA.

[48] Clark, J. E., Cham, J. G., Bailey, S. A., Froehlich, E. M., Nahata, P. K., Full, R. J., and Cutkosky, M. R., 2001, "Biomimetic Design and Fabrication of Hexapedal Running Robot," IEEE International Conference On Robotics and Automation, IEEE, Seoul.

[49] Northen, M. T., and Turner, K. L., 2005, "A Batch Fabricated Biomimetic Dry Adhesive," Nanotechnology, **16**(8), pp. 1159-1166.

[50] Solga, A., Cerman, Z., Spaeth, B. F., and Barthlott, W., 2007, "The Dream of Staying Clean: Lotus and Biominetic Surfaces," Bioinspiration & Biomimetics, **2**(4), pp. S126-S134.

[51] Tinsley, A., Midha, P. A., Nagel, R. L., McAdams, D. A., Stone, R. B., and Shu, L. H., 2007, "Exploring the Use of Functional Models as a Foundation for Biomimetic Conceptual Design," ASME 2007 IDETC & CIE Conference, ASME, Las Vegas, NV.

[52] Stroble, J. K., Stone, R. B., McAdams, D. A., Goeke, M. S., and Watkins, S. E., 2009, "Automated Retrieval of Non-Engineering Domain Solutions to Engineering Problems," CIRP Design '09 International Conference, Cranfield University, Cranfield.

[53] Kwok, Y. K., 2008, *Mathematical Models of Financial Derivatives*, Springer, Berlin.

[54] Fujita, K., and Yoshida, H., 2001, "Product Variety Optimization: Simultaneous Optimization of Module Combination and Module Attributes," ASME 2001 DETC & CIE Conference, ASME, Pittsburgh, PA.

[55] Kurfman, M. A., Stone, R. B., Rajan, J. R., and Wood, K. L., 2001, "Functional Modeling Experimental Studies," ASME 2001 DETC Conference, ASME, Pittsburgh, PA.

[56] Stone, R. B., and Wood, K. L., 2000, "Development of a Functional Basis for Design," Journal of Mechanical Design, **122**(4), pp. 359-370.

[57] Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., and Wood, K. L., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," Journal of Research in Engineering Design, **13**(2), pp. 65-82.

[58] Chiu, I., and Shu, L. H., 2005, "Bridging Cross-Domain Terminology for Biomimetic Design," ASME 2005 IDETC & CIE Conference, ASME, Long Beach, CA.

[59] Sadava, D., Hills, D. M., Heller, H. C., and Berenbaum, M., 2009, *Life: The Science of Biology, Ninth Edition*, W. H. Freeman, New York.

[60] L. H. Shu, 2009, "Biomimetic Search," http://concept.mie.utoronto.ca/.

[61] The Bicycle Lady, 2010, "Bicycle Basket," http://www.basketlady.com/Bicycle-Basket-p143.html.

[62] Auto Insurance Magazine, 2010, "Anti Theft Devices - Can They Help: 2," http://autoinsurancemagazine.com/tg/anti-theft-devices/.

[63] Conair, 2009, "Pumps: RG Series Pumps," http://www.conairnet.com/product/conveying.html.

[64] Sullivan, C., 2007, "Training Wheels of Steel," http://www.pointsincase.com/blog/2007/06/training-wheels-of-steel.html.

[65] Chevy High Performance, 2010, "Superchargers Kenne Bell Supercharger," http://www.chevyhiperformance.com/tech/engines_drivetrain/induction_poweradders/0610ch_superchargers/photo_08.html.

[66] Random Good Stuff, 2009, "Giveaway: Solar/Hand Crank Radio," http://www.random-good-stuff.com/2009/11/24/giveaway-solar-hand-crank-radio/.

[67] LCD Monitor Reviews, 2010, "Acer AL-1931 19" LCD Monitor Review," http://www.lcd-monitor-reviews.com/lcd-monitor-reviews/acer-al-1931-lcd-monitor-review.html.

[68] Nisbeth, U., 2004, "The META42 Headphone Amplifier," http://www.nisbeth.dk/uffe/pages/gallery/meta.html.

[69] Hart-Davis, A., 1999, "Ice Melts at 0C Electronic Thermometer Glass Beaker Liquid Water Ice Cubes Melting Probe in Water White Backdrop 1 AJHD," http://gallery.hd.org/_c/natural-science/_more1999/_more05/ice-melts-at-0C-electronic-thermometer-glass-beaker-liquid-water-ice-cubes-melting-probe-in-water-white-backdrop-1-AJHD.jpg.html.

[70] HK Pro, 2010, "HK 33 Series," http://www.hkpro.com/index.php?option=com_content&view=article&id=85:hk33-series&catid=8:the-automatic-rifles&Itemid=5.

[71] Gun Accessories, 2010, "Keyed Alike Locks," http://www.gunaccessories.com/Master_Lock/index.asp.

[72] The Skeptical Viewer, 2007, "FLIR Footage from the Manson Murders Episode is Proven Doctored," http://www.skepticalviewer.com/doctored-manson-flir/.

[73] Tech Tree - TT Images, 2007, "91227 Heat Sink," http://images.techtree.com/ttimages/story/91227_heatsink.jpg.

[74] Najjar, L., Ockerman, J., and Huff, C., 1996, "Wearable Computer Components," http://www.lawrence-najjar.com/papers/Glancing_ahead.html.

[75] Answers.com, 2010, "Antifriction Bearing," http://www.answers.com/topic/antifriction-bearing.

[76] Deals Direct, 2010, "Black & Decker Quattro Try Me Multi Tool," http://www.dealsdirect.com.au/p/black-decker-quattro-try-me-multi-tool/.

[77] Hamsley, D., 2010, "Cup Gun," http://www.thisoldhouse.com/toh/article/0,,390416,00.html.

[78] Maynard, N. F., 2006, "The X3 Laser Level by Strait-Line," http://www.builderonline.com/products/the-x3-laser-level-by-strait-line.aspx.

[79] Euromodels, 2010, "Servo/Battery Extension Lead 150mm/6in (Jr/Hitec)," http://www.euromodels.com.au/index.php?main_page=product_info&products_id=997.

[80] Crystal Vision Endoscopy, 2009, "Flexible Endoscope," http://crystalvisionendoscopy.com/images/.

[81] FABCO Inc., 2010, "Review New Tank Installation by FABCO," http://www.fabco-nj.com/1657725.html.

APPENDIX

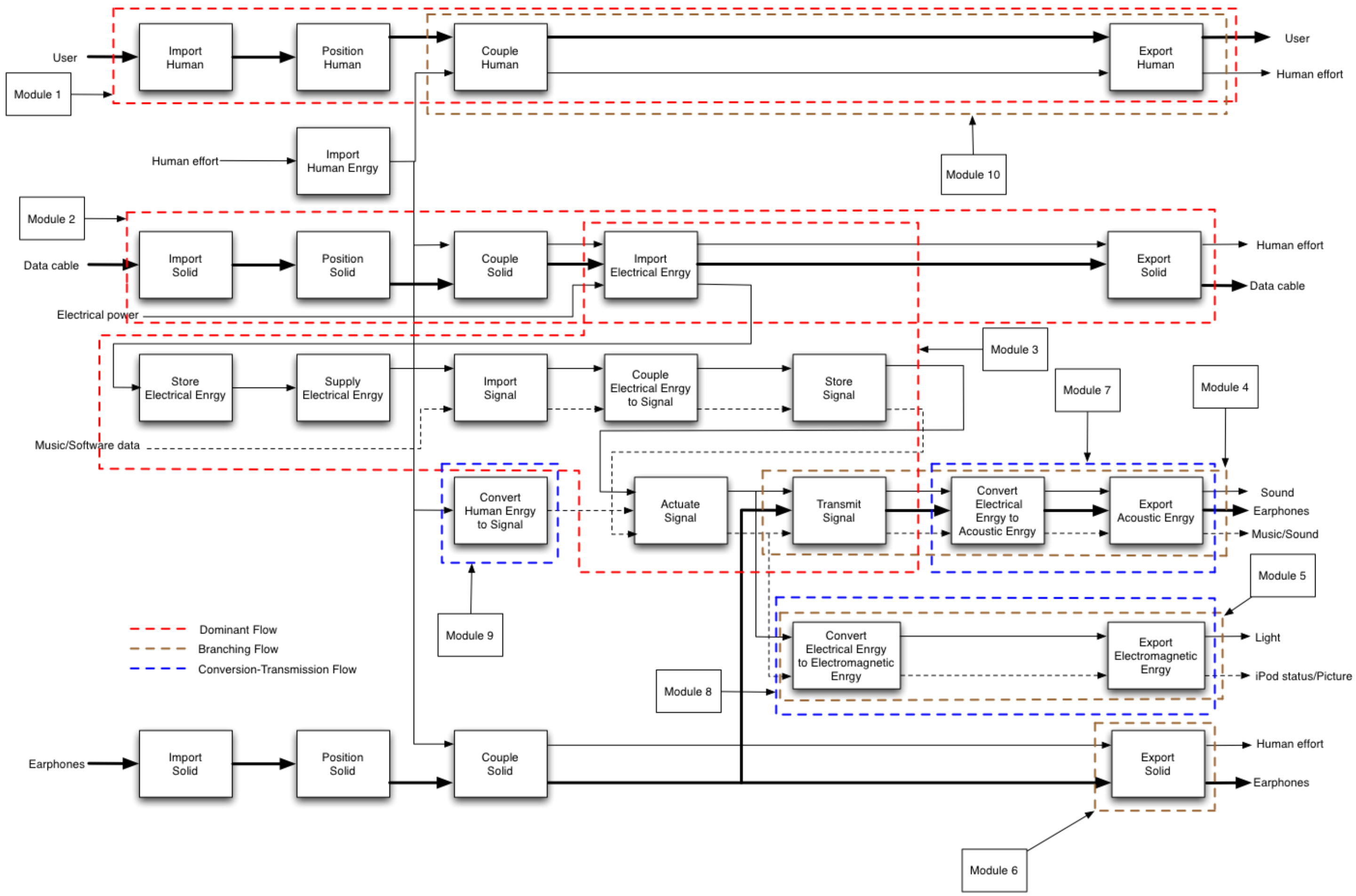


Figure A1. Modularized functional model for the iPod

Module 1		Module 2	
Couple/Import	2,10,11,12,21,26	Couple/Import (m1)	2,10,11,12,21,26
Couple/Position	37	Couple/Position (m1)	37
Couple/Export	52	Couple/Export (m1)	52
Export/Import	16,22	Export/Import (m1)	16,22
Export/Position	none	Export/Position (m1)	none
Import/Position	1	Import/Position (m1)	1

Module 3 (Basic Module)		Module 4	
Actuate/Import	7,8,12,20,21,24,25,26,34,35,36	Convert/Export	59,68,69,74
Actuate/Store	87,89,90,91,93	Convert/Transmit	57,58,63,64
Actuate/Supply	91,72,49	Export/Transmit	none
Actuate/Couple	44,46,53,54,55,56		
Actuate/Transmit	77,78,79,80		
Couple/Import (m1,2)	2,10,11,12,21,26		
Couple/Store	43		
Couple/Supply	49		
Couple/Transmit	42,50,51		
Import/Store	6,17,18,19,23,31,32,33		
Import/Supply	15,18,14,23,28,33		
Import/Transmit	4,5,29,30		
Store/Supply	70,88,73,71,92		
Store/Transmit	76,65		
Supply/Transmit	65		

Module 5		Module 6	
Convert/Export (m4)	59,68,69,74	N/A	

Module 7		Module 8	
Convert/Export (m4,5)	59,68,69,74	Convert/Export (m4,5,8)	59,68,69,74

Module 9		Module 10	
N/A		Couple/Export (m1,2,6)	52

Figure A2. Module-by-module aggregated B-RAD position numbers for the iPod.

Mechanical Battery Charger

[2] Match #1: Section 7_6_2 Active proton transport is followed by diffusion coupled to ATP synthesis 126 /5181: For the chemiosmotic mechanism to work, the diffusion of H+ and the formation of ATP must be tightly **coupled; that is, the protons must **pass through the ATP synthase channel in order to move inward. If a simple H+ diffusion channel (not ATP synthase) is inserted into the membrane, the energy of the H+ gradient is released as heat, rather then being coupled to the synthesis of ATP.

String Controller

[59] Match #1: Section 50_3_1 Tubular guts have an opening at each end 894 /188: Different regions in the tubular gut are **specialized for particular functions (Figure 50.

Remote Screen

[26] Match #2: Section 50_1_6 Nutrient deficiency diseases 892 /2167: Normally, cells in the stomach lining **secrete a peptide called intrinsic factor, which **binds to vitamin B12 and makes it possible for it to be absorbed in the ileum of the small intestine.

Pre-amp/Sound Enhancer

[68] Match #1: Section 41_4_4 Responses to hormones can vary greatly 729 /2551: Hormones are enzymatically **degraded in the liver, then they are removed from the blood in the kidney and **excreted in the urine. The presence of hormones in the urine is the reason that urine samples can provide important information in clinical tests.

Suite of Environmental Sensors

[63] Match #1: Section 44_4 Neurons in Networks 794 /720: Chapter Summary Nervous Systems: Cells and Functions · Nervous systems consist of cells that process and transmit information, · Sensory cells **transduce information from the environment and the body and **communicate commands to effectors such as muscles or glands.

Figure A3. B-RAD passages for the iPod derivative product concepts.

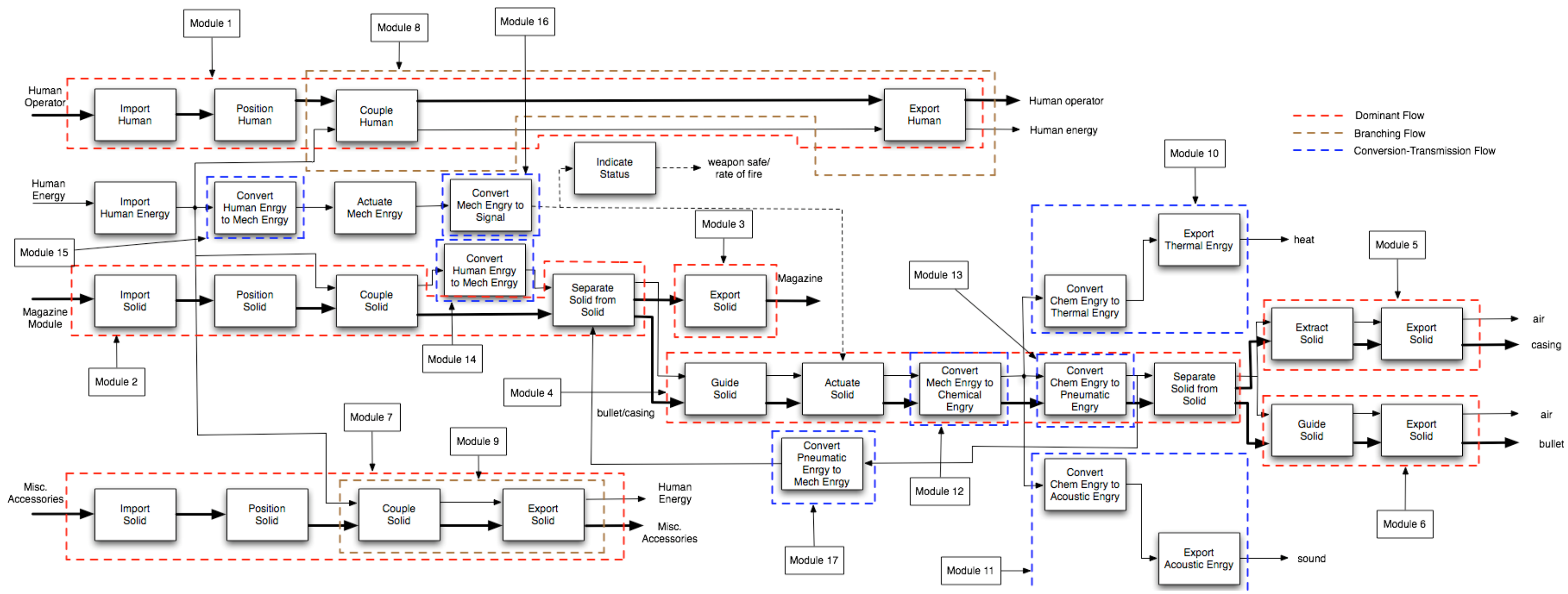


Figure A4. Modularized functional model for the military assault rifle.

Module 1		Module 2	
Couple/Import	2,10,11,12,21,26	Couple/Import (m1)	2,10,11,12,21,26
Couple/Position	37	Couple/Position (m1)	37
Couple/Export	52	Couple/Export (m1)	52
Export/Import	16,22	Export/Import (m1)	16,22
Export/Position	none	Export/Position (m1)	none
Import/Position	1	Import/Position (m1)	1

Module 3 (Basic Module)		Module 4	
Actuate/Import	7,8,12,20,21,24,25,26,34,35,36	Convert/Export	59,68,69,74
Actuate/Store	87,89,90,91,93	Convert/Transmit	57,58,63,64
Actuate/Supply	91,72,49	Export/Transmit	none
Actuate/Couple	44,46,53,54,55,56		
Actuate/Transmit	77,78,79,80		
Couple/Import (m1,2)	2,10,11,12,21,26		
Couple/Store	43		
Couple/Supply	49		
Couple/Transmit	42,50,51		
Import/Store	6,17,18,19,23,31,32,33		
Import/Supply	15,18,14,23,28,33		
Import/Transmit	4,5,29,30		
Store/Supply	70,88,73,71,92		
Store/Transmit	76,65		
Supply/Transmit	65		

Module 5		Module 6	
Convert/Export (m4)	59,68,69,74	N/A	

Module 7		Module 8	
Convert/Export (m4,5)	59,68,69,74	Convert/Export (m4,5,8)	59,68,69,74

Module 9		Module 10	
N/A		Couple/Export (m1,2)	52

Figure A5. Module-by-module aggregated B-RAD position numbers for the military assault rifle.

Additional Safety Device

[74] Match #1: Section 18_4_4 Two kinds of genes are changed in many cancers 344 /2181: But unlike oncogenes, in which one **mutated allele is all that is needed for activation, the full inactivation of a tumor suppressor gene requires that both alleles be turned off, which requires two mutational events.

Gun Light/Light Detection System

[1] Match #1: Section 11_6_1 The nucleotide sequence of DNA can be determined 214 /1898: The light emitted is then **detected, and the resulting information-that is, which ddNTP is at the end of a strand of which length-is fed into a computer, which processes it and prints out the sequence.

Heat Management System

[220] Match #1: Section 24_2 Determining and Comparing the Structure of Macromolecules 440 /2173: A single **insertion aligns the sequences in this case, but longer sequences and those that have **diverged more extensively require more elaborate adjustments.

Advance Targeting System

[221] Match #1: Section 44_1_1 Nervous systems process information 774 /658: The cnidarian's nerve net merely **detects food or danger and causes its tentacles and body to extend or **retract More complex animals that move around the environment and hunt for food and mates need to process and integrate larger amounts of information.

Anti-jamming/Lubrication System

[68] Match #2: Section 41_4_4 Responses to hormones can vary greatly 729 /3163: The extent to which hormones are bound to carrier proteins limits their ability to diffuse out of the blood to reach their target cells, to be **degraded in the liver, or to be **excreted by the kidney. For example, when the mineralocorticoid aldosterone is released, about 15 percent of it binds to carrier proteins, and its half-life is 25 minutes.

Figure A6. B-RAD passages for the military assault rifle derivative product concepts.

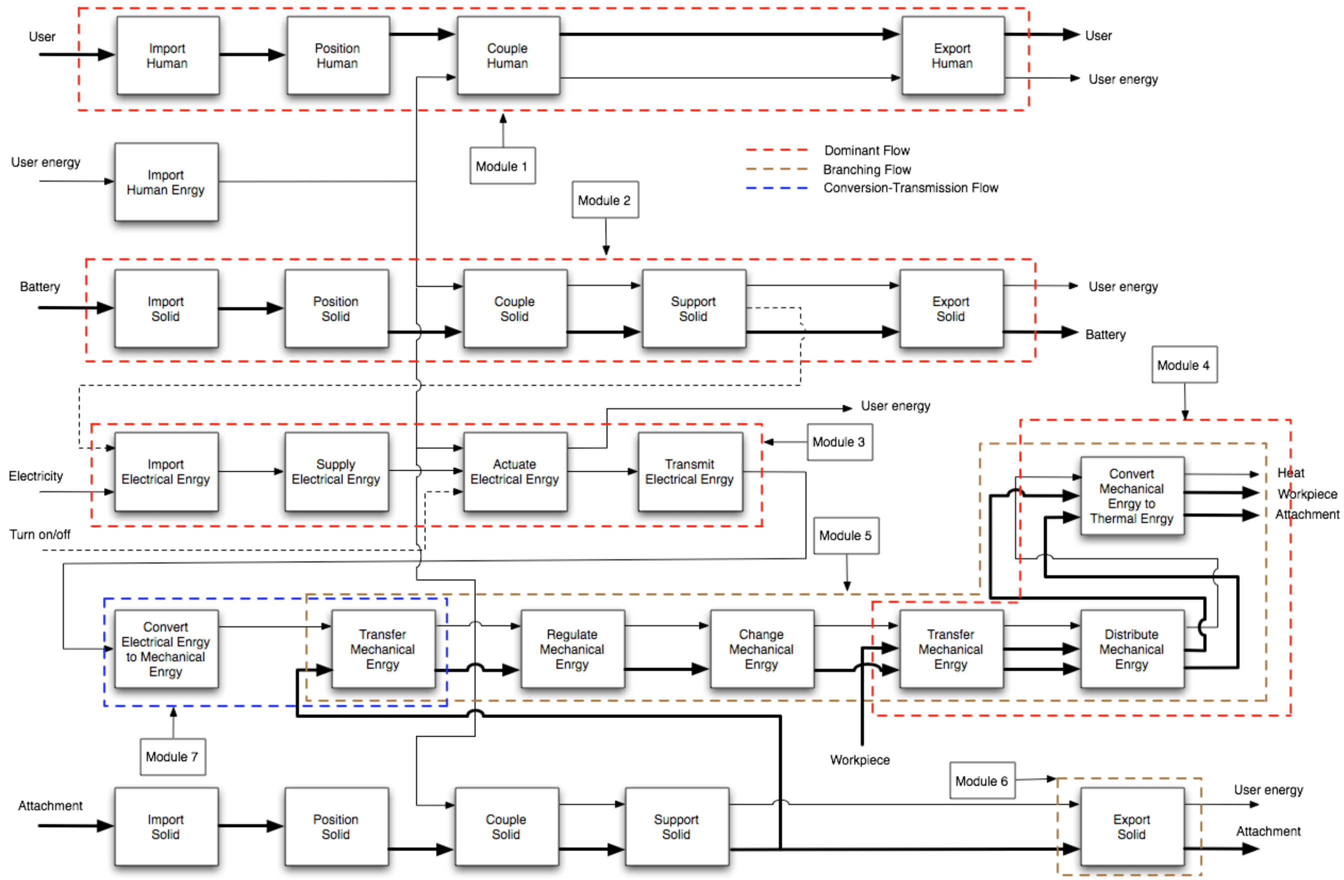


Figure A7. Modularized functional model for the Black & Decker Multi-Tool.

Module 1		Module 2	
Couple/Import	2,10,11,12,21,26	Couple/Import (m1)	2,10,11,12,21,26
Couple/Position	37	Couple/Position (m1)	37
Couple/Export	52	Couple/Support	44,46,203,204,205
Export/Import	16,22	Couple/Export (m1)	52
Export/Position	None	Export/Import (m1)	16,22
Import/Position	1	Export/Position (m1)	None
		Export/Support	52
		Import/Position (m1)	1
		Import/Support	12,21,26,199,200,201,202
		Position/Support	37

Module 3		Module 4	
Actuate/Import	7,8,12,20,21,24,25,26,34,35,36	Convert/Distribute	13,14,15,71,136,142
Actuate/Supply	91,72,49	Convert/Transfer	133,134,139,144,147
Actuate/Transmit	77,78,79,80	Distribute/Transfer	98,144,188,189
Import/Supply	15,18,14,23,28,33		
Import/Transmit	4,5,29,30		
Supply/Transmit	65		

Module 5		Module 6
Change/Transfer	133,134,190,191,194, 195	N/A
Change/Regulate	115,233,234,237,236	
Change/Distribute	13,101,102,136,146	
Change/Convert	137,138,140,146	
Convert/Transfer (m4)	133,134,139,144,147	
Convert/Regulate	115,235,238,239,240, 241	
Convert/Distribute (m4)	13,14,15,71,136,142	
Distribute/Transfer	98,144,188,189	
Distribute/Regulate	242, 243	
Regulate/Transfer	244, 245	

Module 7	
Convert/Transfer (m4,5)	133,134,139,144,147

Figure A8. Module-by-module aggregated B-RAD position numbers for the Black & Decker Multi-Tool.

Powered Sprayer/Injector

[34] Match #3: Section 37_5_7 Auxin promotes growth by acting on cell walls 656 /2554: It was suggested that hydrogen ions **secreted into the cell wall as a result of auxin action might **activate one or more proteins in the wall.
Match #4: Section 41_1_4 Endocrine glands secrete hormones 714 /424: Many hormones, however, are **secreted by a ggregations of endocrine cells that form secretory organs called endocrine glands.
Match #5: Section 50_3_2 Digestive enzymes break down complex food molecules 896 /1112: When **secreted into the gut, zymogens are **activated by another enzyme or by conditions in the gut (which, as you will remember, is outside the body).

Laser Rangefinder, Leveler, or Thermometer

[8] Match #1: Section 11_6_1 The nucleotide sequence of DNA can be determined 214 /1791: During the electrophoresis run, the fragments **pass through a laser beam that **excites the fluorescent tags. The light emitted is then detected, and the resulting information-that is, which ddNTP is at the end of a strand of which length-is fed into a computer, which processes it and prints out the sequence.

Belt Battery Pack

[200] Match #1: Section 16_4_2 Single cells can induce changes in their neighbors 302 /1489: The **anchor cell produces an inducer that **diffuses out of the cell and interacts with adjacent cells. Cells that receive enough of the inducer become vulval precursors; cells slightly farther from the anchor cell become epidermis.

Electromagnet

[77] Match #2: Section 45_5_3 Some fish can sense electric fields 812 /1834: Chemoreceptor cells have receptor proteins that can **bind to specific molecules that come into **contact with the sensory cell membrane. Review Figures 45.5, 45.

Wet Hole Drill

[144] Match #1: Section 34_2_5 Xylem transports water from roots to stems and leaves 608 /814: These cells secrete a waterproofing substance into their cell walls, then **break down their end walls, and finally die and disintegrate. The result is a hollow tube through which water can flow freely.

Figure A9. B-RAD passages for the Multi-Tool derivative product concepts.

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