Better Resource Usage through Biomimetic Symbiotic Principles for Host and Derivative Product Synthesis

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Abstract

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.

This research 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 leverage knowledge of natural symbiotic relationships to synthesize these post-market modules. It adds to 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). By using this methodology, the engineered products are designed on symbiotic principles found in nature.

Introduction

Congratulations Recent research efforts have shown that systematic methods that aid designers in finding design solutions, given a certain set of conditions, can be developed. In general, formal design methods break down the product development process into separate tasks and sub-tasks [1-4]. These sub-tasks can then be assigned to separate functional groups or can be can be worked on by all functional groups concurrently [2]. Successful implementations of concurrent engineering approach suggest that a product's physical structure, i.e. its architecture, is key to its value.

In fact, the use of product architectures to create value is a well-considered topic in the product design and development field [5]. Current research in modular architecture is focused on how companies can create efficient module structures that reduce a product's life-cycle costs, while maintaining or expanding its market appeal.

Much of that research focuses on modules that are inherently 'pre-market' in nature. However, the initial part of this research builds on the work of Baldwin and Clark [7] by formalizing the notion of post-market modules, and creating a method that aids designers create products that embody this modular architecture.

The next natural question relates to how designers will create these post-market modules, which in turn help identify new derivative products that add value to the original or existing product. To accomplish this, we need 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 [9]. This research 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 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.

In order to validate the concept generation methodology presented in this research, 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.

Background and Prior Work

The work in this research is related to two areas within the design research community: modular product architecture and biomimetic concept generation.

Concurrent Engineering, Modular Product Architecture, Augmentation and Reconfiguration, and Product Family Design

In that today's highly competitive consumer market, a product's development time, perceived quality, ability to meet specific customer needs, and its associated costs are key factors that affect its sales performance [11, 12]. 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. Research on concurrent engineering strategies is motivated by the inefficiencies and costs stemming from the sequential engineering development process [2].

Concurrent engineering is defined as, "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support" [13]. In terms of relevance to this research, two concurrent engineering methodologies stand out: Quality Function Deployment (QFD) and Design-for-X (DFX). The successful implementations of these methods show 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 [14].

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. Contrastingly, modular architecture features a one-to-one mapping between the functional elements and physical components. This research focuses on product modularity and an architecture scheme that stems from modular thinking: product family design.

Modularization enables the development of highly customized products that meet varied customer needs [2, 32, 33]. Pahl and Bietz [3] establish the notion of two different types of modules: production modules and function modules.

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. They in turn introduce the concept 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.

Many 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). Gershenson et al. [31] put forward the idea of life-cycle modules, while Kusiak and Huang [37] have developed a heuristic clustering algorithm based on a product's interaction graph. The design structure matrix (DSM) can be used to define modules in a product as shown by Holtta-Otto [15]. Jose and Tollenaere [16] present a review of the various modularization methods developed in the literature.

All the methods presented above are useful for creating and/or identifying modules during the development process. However, to assist in identifying post-market modules, this research uses a modularization method that combines graphical and heuristic tools developed by Stone et al. [8].

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 go on to discuss various concept generation methodologies, separating them into two categories: intuitive and directed. 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.

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 [17, 18]. However, if the desired natural solution to an engineering problem is unknown, nature, being a vast and largely undocumented field, becomes a challenging space within which to find a solution [9]. As a result, much biomimetic concept generation research focuses on the development of structured search methodologies that retrieve relevant biological information.

Tensley et al. [19] show that functional models of natural systems can help in identifying solution principles applicable to engineered systems of similar functionality. Taking this further, Strobe et al. [20] suggest that the functional abstraction of the engineering problem made using the functional basis can be used to search a biology text (or other body of knowledge) to inspire solutions. Vakili and Shu [9] present a 5-step, generalized method (algorithm) that can guide designers to natural solutions. In contrast to Strobe et al. [20], where the engineering-based function terms are searched directly, Vakili and Shu [9] make use of a keyword bridge that translates functional keywords in the engineered domain to equivalent keywords in biology. 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.

Defining Host and Derivative Products

Previous sections showed how the idea of post-market modules is connected to established notions of product modularization. However there is no clear understanding of the products in the post-market module space or its boundaries.

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 and compared to develop new terms describing products in the post-market module space. First, the product that is augmented is termed as the 'host product'. Second, the term 'derivative product' refers to the post market modules added to the product after it is sold to the end user. The derivative products advanced in this research, 'derive' their value from their association with a host product.

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

- Its usefulness is dependent on the presence of the host product in the market
- It does not replace a similar functionality already present on the host product
- It is of novel functionality or design (to prevent trivial functional extensions from being admitted into this design space)

The third and 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.

Research Approach

Having defined the host and derivative product space, the next step in this research is 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 and traditional product family design methods are not applicable.

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. 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 'nature'. 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 four design tools that support the developed methodology are discussed below.

1. Functional modeling and the functional basis

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 [22]. 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.

2. Modular heuristics

The direct application of traditional product modularization methods is of little use in this research, as the constituent functions of the desired product are unknown. However, 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.

Modular heuristics, developed by Stone, Wood and Crawford [8], 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.

In this research, modularizing the host product aids designers 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. This is because, when looking for function extending modules (derivatives), it makes sense to examine the analogous space using combinations of 'highly' related space using combinations of 'highly' related functions (i.e. intra-module functions), rather than combinations of unrelated functions (i.e. inter-module functions).

3. Biologically meaningful keywords
Searching the natural domain using engineering terminology produces sub-optimal results, because the language of engineering and the language of biology are both domain specific with little overlap [22]. Fortuitously, the work of Cheong et al. [10] presents a dictionary (of sorts) that translates the function descriptors from the Functional Basis into equivalent, biologically meaningful keywords. Cheong et al. presents a list of the identified biologically meaningful keywords along with their corresponding Functional Basis terms.

4. BioSearch
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. [23]. BioSearch was created by researchers at the University of Toronto (L.H. Shu et al. [24]) as tool that helps enhance creativity during conceptual design.

The 7-Step Methodology

This developed methodology helps designers translate the functionality of the 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 step is briefly discussed with an example of a bicycle as the host product.

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 [21], 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. The black-box model for a traditional bicycle is shown in Figure 1 below.

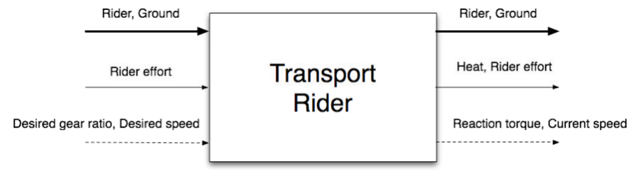

Figure 1: Black-box model for a typical bicycle

In the second step, function chains are created 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. Lastly, the separate function chains are connected together to make a complete functional model. 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. The functional model for a bicycle developed using this methodology is presented in Figure 2 below.

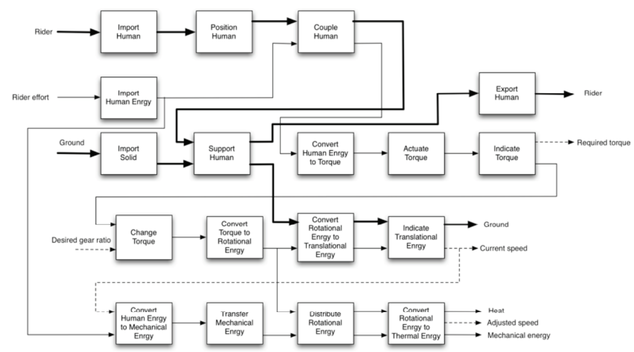

Figure 2: Fully aggregated functional model for a typical bicycle

Step 2: Modularizing the Host Product
This research uses the modular heuristics method developed by Stone et al. [8] to aid in the search for natural domain derivatives. This particular method was chosen because it identifies modules based on a system's functional model. The modules are defined based on three types of material, energy or signal flows: dominant flow, branching flow, and 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 for module determination..
For the bicycle functional model, 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. These are illustrated in Figure 3 below.

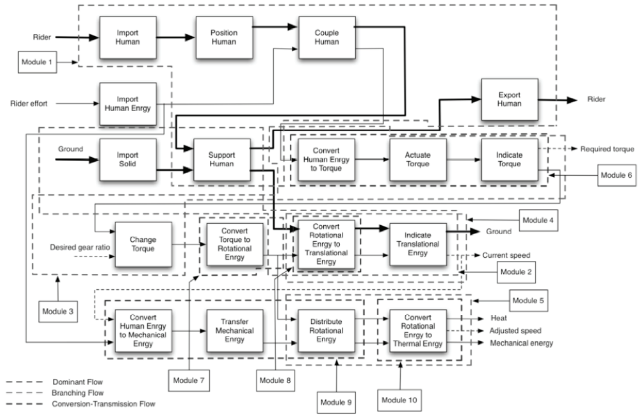

Figure 3: Modularized functional model of the typical bicycle

The three dominant-flow modules, modules 1, 2, and 3 result from the 'flow' of the rider, ground, and rider initiated torque through the system. 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. The last five modules arise from conversion-transmission relationships present in the system. Module 6 results from the conversion of the rider's effort into torque, while module 9 represents part of the braking system. Three of the identified modules of this type, modules 7, 8, and 10, consist only of singular conversion functions. 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.

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.

First, each sub-function used in the functional model is recorded. Table 1 shows the 11 sub-functions used in the bicycle function structure.

Table 1: List of sub-functions used in the bicycle model

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

With the sub-functions identified, the next step is to use the thesaurus provided by Cheong et al. [10] to translate these Functional Basis terms into biologically meaningful keywords. As mentioned earlier, not all of the biologically meaningful keywords provided by Cheong et al. [10] 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. 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. Additionally, this process of eliminating keywords is done in a product-independent fashion. Therefore, keywords that are not included for the bicycle's sub-functions are also not included for the same sub-functions in another product.

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 that meet the designated field criteria [23]. 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. The search is repeated with all possible pair combinations for each module separately.

Before translating the functional basis terms into biologically meaningful keywords, each module's functional basis terms must be aggregated. 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	Import	Change	Convert	Distribute
Position	Support	Convert	Indicate	Convert
Couple	Convert	Actuate		
Support	Indicate	Indicate		
Export				

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.

Step 5: Aggregating Results

For host product functional models that have a large number of modules, the number of pair-wise keyword searches would be larger and could be hard to track. Consequently, this research develops and details two tools that would help manage this problem.

The first tool leverages the product independent feature of the pair-wise search methodology. Often, product-to-product and, to some extent, module-to-module, many function combinations are repeatedly used. Consequently, once a keyword pair has been searched, there is no need to search that pair again. Taking advantage this, a block matrix called BioMatrix is constructed to document the searches that have been conducted. The second tool developed is called 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.

The numbers in the BioMatrix cells correspond to the position of the BioSearch identified passage in the B-RAD. Thus, the combination of the BioMatrix and the B-RAD gives the designer important information regarding overlapping and subset modules. This allows designers to organize the results for use in the subsequent steps of the methodology.

Step 6: Identifying Results for Analysis

With the BioMatrix results aggregated module-by-module, one can visually observe the B-RAD passages (obtained from BioSearch) associated with the functions in a particular module. 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.

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 modules. Pahl and Beitz [3] describe auxiliary modules as those modules that assist the basic modules in carrying out the overall product function. Thus, if a module is classified as an auxiliary module, its B-RAD results are analyzed; else the 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.

To effectively identify the basic and auxiliary modules in the bicycle's function model, it is important to first determine its overall function. The overall function of the product is gleaned from the system's black-box model. For the bicycle, the designated overall function is 'transport rider'. Under this scheme, module 1, along with modules 2, 3, 4, 6, 7, and 8, would also be classified as a basic module. The auxiliary modules for the bicycle are identified as modules 1, 5, 9, and 10.

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. 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. Thus, the B-RAD passages repeated within the auxiliary modules of the bicycle functional model are chosen for further consideration.

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. 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.

An example is the derivative product concept derived from B-RAD passage number 12 from module 1 of the bicycle. This passage number seen in Figure 4 is a result of a paired search of the biologically meaningful keywords 'diffuse' and 'bind'.

[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 4: The first five matches for B-RAD passage number 12

Match numbers 2 and 3, 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. 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 (shown in Figure 5) 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 5: Derivative product found is a bicycle basket [25]

Similarly the methodology leads to the development of additional derivative products for a bicycle. These include a steering wheel lock, a pump powered by the bicycle, training wheels, and a supercharger that supplies oxygen to the rider.

The 7-step methodology is used to generate 20 derivative concepts for 4 host products [26].

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.

In particular, a modular architecture adds value to and provides many benefits to a product. The research fully formalizes the post-market module space defined by Baldwin and Clark. This enables the use of modular heuristics to modularize functional models of a product after it has been given to the end user.

A 7-step design methodology that leverages nature's innovative interactions and relationships to identify new derivatives for existing host products is developed. The developed methodology is informed by the 5-step biomimetic concept generation procedure developed by Vakili and Shu [9]. This gives the method a biomimetic foundation that allows designers to create derivatives without having prior knowledge of the derivative's 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.

In terms of future work, the developed methodology would benefit from the automation of the keyword pair search process and the evaluation of its effectiveness using quantifiable metrics. Secondly, integrating structured concept generation tools and techniques into the 7-step biomimetic methodology could help increase the effectiveness of the process in terms of the derivative product ideas generated.

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