INVESTIGATING THE USE OF (RE)CONFIGURABILITY TO REDUCE PRODUCT FAMILY COST AND MITIGATE PERFORMANCE LOSSES

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Abstract

Commonality amongst a family of products provides both technical and economic advantages. However, with an increase in commonality, a loss of product differentiation can occur, resulting in product cannibalization. Furthermore, there is generally a required tradeoff between performance and cost when incorporating commonality into a family of products. This paper synthesizes recent research in system flexibility, system reconfigurability, and product families to develop a formal design method, which may allow a design firm to decrease family cost, increase commonality, and maintain or improve system performance. The system configurations can be set before they reach the consumer or be capable of being set by the consumer. (Re)configurability is used to denote that the solution may be permanent once configured (i.e., a configurable system) or the changes can be repeatable and reversible (i.e., a reconfigurable system). Added benefits to incorporating principles of product flexibility and (re)configurability are the possibility for the systems to age gracefully, adapt to meet future demands and operating environments, and incorporate newly developed technologies.

1 Introduction and Motivation

Product families have become a key strategy in numerous industries, delivering a range of options to the consumer while maintaining design and manufacturing advantages for the corporation. The use of product families can cut costs by maintaining economies of scale, reduce design time and costs (for the family), and streamline training needs for service and manufacturing. Over the last ten years there has been a significant amount of research conducted examining commonality, platforming methodology, market considerations, and numerous other areas of research [1-5].

The general concept behind product families is to use form and function important to the consumer to distinguish family members, and what is not as important to the consumer is made common. Commonality amongst a family of products provides both technical and economic advantages. However, there is generally a required tradeoff between performance and commonality in a family of products [6]. In [7] the example of the Audi TT Roadster is discussed, which required an additional subsystem to be added to fix a performance issue which was a result of platform limitations. Furthermore, if products are too similar they can cannibalize each other [8]. Balancing commonality with diversity and performance is a nontrivial task, and has been examined in previous work [9-11].

It has been shown that reconfigurability comes at a price, but can be used to increase performance or extend operating ranges [12]. By combining principles of reconfigurability, system flexibility, and product families, there is significant potential to decrease cost, increase commonality, and obtain the desired performance levels (which can be chosen to reduce the chance of cannibalization). Furthermore, incorporating principles of product flexibility and reconfigurability offer the possibility for the design to age gracefully, incorporate new technology, or adapt to meet future demands and operating environments.

This paper discusses the challenges associated with incorporating reconfigurability in a product family, and looks to answer the question: What aspects of reconfigurable system design, flexible system design, and product family design can be combined and leveraged to achieve the outlined goal of a
streamlined product family which maintains appropriate performance levels and diversity?

This paper seeks to answer this question from both top-down and bottom-up viewpoints [13] and the design method proposed is useful for both sets of platforming approaches. A case study evaluating two existing power tools using configurable/reconfigurable product platforms is performed to demonstrate the bottom-up approach; how the approach can be used in a top-down design scenario is demonstrated with the design of a family of mountain bikes. The following section provides some relevant background for the research. This is followed by a discussion of the proposed design method, which is then applied to the two case studies. The paper concludes with areas of future work.

2 Previous Research

Many consumer products have been adapted from individual items to become part of a product family. This is done by creating a product platform. A platform is defined as “the set of parameters (common parameters), features and/or components that remain constant from product to product, within a given product family.” [13]

A component refers to a part of the family which cannot be further divided without causing a loss of functionality. In product families, components can belong to one of three categories: common, unique, or variant. Common components are used in multiple family members and are the exact same; this even includes aesthetic characteristics such as color, finish, etc. which can have a significant impact on unit cost. Unique components are used by only one member of the family (but may be used more than once). Variant components are used in more than one family member and are similar to other components in function but may differ in size, color, material, etc. [14]. A subsystem is a set of components that are assembled to create a higher order function. Both components and subsystems can be shared amongst a family.

Subsystems and components can be designed with a certain amount of design flexibility which allows their characteristics to be adjusted or set. A system configuration which can only be set once, either before it reaches the consumer or by the consumer, is a configurable system; if the changes are reversible and repeatable, it is a reconfigurable system [15]. (Re)configurability is used to denote that the solution may utilize either concept.

Reconfigurable systems have been shown to increase performance by allowing the system to adapt to the current system needs and operating conditions [16]. Performance increases can come in the form of adapting to perform a new function or extending the performance range of a current capability. However, there is a cost associated with reconfigurability, both from a monetary and a performance perspective. (Re)configurability requires additional design considerations, as well as components, adding time to the design process and weight to the system. With this being said, increased design time for a (re)configurable subsystem or component is shared by each member of the family utilizing it. Identifying where the benefits of (re)configurability can be leveraged is a nontrivial problem and one of substantial interest that motivates this research. Methods to facilitate adding (re)configurability to a system have also been identified [17]. However, in order for (re)configurability to be added to a product platform, the platform members will have to have a degree of system flexibility.

System flexibility can be summarized as “the property of a system that allows it to be changed easily” [15]. System flexibility is primarily aimed at reducing redesign cost and time, as well as enabling reconfigurable systems to be possible. Research has also been done on incorporating flexibility into product platforms, merging product platform research and flexible system research [18]. In [18], flexibility requirements are primarily identified by using change propagation analysis; change propagation refers to the rippling effect changing a design element can have. Elements which when changed require changes in other components when they would have otherwise been unnecessary are viewed as change multipliers [19], thus making them potential candidates for flexibility. This approach can be leveraged to identify where flexibility will be needed due to incorporating (re)configurability into the product family.

There has also been research looking to identify how to make products flexible for future evolutions, which can be applied to designing product families [20]. The evolutionary changes may or may not be perceived. Specific work has also been done examining how to evaluate the architecture of a product family in terms of its ability to adapt to perceived changes [21]. With the addition of (re)configurability and system flexibility, the question of how you determine if your platform is successful needs to be revisited.

Commonality indices have been used as a metric for evaluating product families. This metrics measure how much family members have in common to one another, evaluating parameters such as size, material, manufacturing process, etc.; a review of several commonality indices can be found in [1]. One of the most recent commonality indices, the Comprehensive Metric for Commonality (CMC) strives to obtain a more absolute measure of commonality in the product family. The CMC examines each member’s component’s size, geometry, material, manufacturing process, assembly, and costs while relaxing commonality requirements on differentiating components [14]. Differentiating components are components which allow a given family member to have unique characteristics [22]. However, the assumption made by the CMC is that all unique components are differentiating, and it does not directly account for the impact of performance losses.

The Commonality versus Diversity Index (CDI) is another commonality index which seeks to better capture how a family (or family of families) manages the tradeoff between commonality and diversity [11]. This is done by specifying which components should be shared, and which should not. The idea is that unique functions should be fulfilled using unique components, common functions should be fulfilled with common components, and variant functions should be fulfilled
with variant components. Certain components are penalized by
the CDI if they are common, because it could compromise the
diversity of the family. In this work, the argument is made that
(re)configurability may be able to allow common components and
subsystems to appropriately distinguish family members by
allowing the required changes, especially for variant
components.

The synthesis of system flexibility and (re)configurability
with existing product family methodology for consolidation and
design requires balancing the benefits of commonality with
performance. Through the use of product flexibility and
(re)configurability, performance losses resulting from
introducing commonality may be eliminated or minimized. The
following section outlines the proposed design method for
(re)configurable product families, highlighting where current
research is leveraged, and identifying where the current design
process procedures need to change. This proposed method is
intended to be used in conjunction with a firm’s general product
design philosophy and process.

3 Proposed Evaluation and Design Method

This research focuses on synthesizing the state of the art in
product family research, reconfigurable system design, and
flexible system analysis to develop a method to consolidate
existing systems into a cost effective product family (bottom-
up), or to assist in the development of new product families
(top-down). The overall method is the same, regardless of the
approach to product family design. However, the steps change
slightly as the information available in the two approaches
varies. The complexity of the family members may also effect
the depth of the analysis which is discussed in the following
sections where relevant. An overview of the method is shown in
Figure 1.

3.1 Step 1: Set Family Form and Functionality

The first step is to determine the form and functionality of
each family member required to cover the desired portion of the
market; this includes rough dimensions and performance
characteristics. This will require a thorough understanding of
the product family’s approach to market coverage (i.e. whether
there will be vertical leveraging, horizontal leveraging, or the
beachhead approach [2]). Additionally, this requires that how
the family members will vary to reach the different market
niches is known, meaning the differentiating aspects of the
family members are known. Family member differentiation can
come from a change in function, form, or combination of the
two.

“The function of a product is what it does as opposed to
what the physical characteristics of the product are.” [22] With
this being said, there are various levels of functions. In this
work, a system level function is defined as a primary function
that contributes substantially to a consumer need. A sub-
function is a function that contributes to completing a system
level function. The form of the object is used to refer to the
physical characteristics such as geometry, material, color,
surface finish, etc.

One example of a functional change is an overall change in
product functionality, such as adding or removing a system
level function. For the case of a coffee maker, “brew coffee”
and “keep coffee warm” are two system level functions. For a
coffee maker, the addition of an integrated coffee grinder adds
a system level function. A change in a sub-function can also lead
to differentiation. In the case of a coffee maker, changing the
power source used would be an example of a sub-function
change (e.g. from a 120V AC power source to a 12V DC power
source). Overall system functions can also have differentiating
characteristics. Many coffee makers have a warming plate;
adding the ability to adjust the temperature of the warming
plate is considered a characteristic of the system level function,
which leads to one or more sub-functions. The last way to
functionally differentiate a product is to change the
performance level of a system function. In a coffee maker this
could be how fast it can heat the water to brew a pot of coffee.

A change in form can be used to distinguish products
aesthetically or for more utilitarian reasons. For example, it is
often desirable for products to look unique, which may result in
a change in shape, color, or labeling. This is an example of an
aesthetic reason for changing the form of a family member. A
utilitarian reason for changing the form of a family member
would be to increase or reduce the size of a system to vary its
performance ranges or capacity. Figure 2 shows two different
style bike pumps made by Specialized Bicycle Components;
the change in size of the frame pump increases portability.
Figure 3 shows several models of the Boeing 737; the main

![Figure 1: (Re)configurable Product Family Design Method Overview](Image)
reason for the change in form is to achieve various ranges for several passenger capacities.

![Floor Pump](image1.png) ![Frame Pump](image2.png)

**Figure 2: Bicycle Pump Variation**

For the bottom-up approach, current functionality and form of the existing systems will be known, as well as the characteristics and performance levels of the different system functions. When consolidating individual products into a family in a bottom-up approach, the replacements should be able to deliver the functionality and corresponding performance levels which are at least equal to what currently exists, provided the current functionality is still deemed desirable by the design firm. Thus the current functionality and performance is used as the target values, unless there is evidence that a change in functionality needs to be made. The form characteristics which are important should be noted as well, namely those tied to differentiating the family members; these aspects should likely be preserved.

**Top-Down Approach**

For the top-down approach, the general form and functionality of the various family members needs to be determined. The details of the form do not have to be exact, but the differentiating aspects of the form for individual family members must be known. For example, if a company was designing a platform of bike pumps, it is reasonable that they can specify a rough geometrical envelope for the product; this could be as simple as a cylinder with a prescribed diameter and length. For system level functions, their performance ranges and notable characteristics must be clearly defined, as these targets are used in the next step. These differentiating aspects can be determined by expert opinion, with the help of a market segmentation grid, etc. Regardless of how the targets for the form and functionality of the family members are decided, once they are set the consolidation or design of the new family can begin.

**3.2 Step 2: Commonality Identification**

This step examines the sub-functions which work together to fulfill system level functions and achieve the target values. Performance characteristics of the sub-functions are compared to identify which can be completed using common components and subsystems, and which may require a unique or (re)configurable design solution. This comparison starts by decomposing the system level functions of the various family members.

Comparing the system level functions for different family members may reveal system level functions unique to some family members. However, simply because a function is unique does not mean that it cannot be achieved using common sub-functions and their associated components. The feasibility of using common or (re)configurable design solutions should be evaluated. Because the proposed design method uses the performance requirements to determine if a unique function requires a unique design solution it is likely to reduce unnecessary design solutions developed solely to differentiate a family member.

Product family members which share system level functions are ideal candidates for sharing components, and should be critically evaluated to see which components can be common. It should be noted that the analysis can also be conducted incorporating the use of modules or subsystems, but this paper primarily discusses design issues with respect to component level decisions, as individual modules could potentially share components and do not have to be used in product family design. If higher level subsystems are used, a hierarchical approach can be taken where subsystems are then designed with the same design method.

To identify the various sub-functions, a functional decomposition of each family member should be conducted. This step leverages research in functional decomposition [23]. The level of decomposition must be fine enough such that the engineers can identify the core sub-functions of each system level function, and their corresponding performance characteristics. However, because the exact level of detail is not crucial and functional models can become large, functional decomposition can be stopped at the discretion of the engineer.

After the functional decomposition of the different family members is complete, the designers can look for identical sub-functions, and identify which share similar performance characteristics. This part of the step is identical for both the bottom-up and top-down approaches. It should be noted that
when looking at the sub-functions, they do not have to belong to the same system level function. For example, it may be possible to use the same motor to convert electrical energy to mechanical rotational energy for multiple system level functions. Across the family there may be several instances of the same sub-function, but there may only be two significantly different ranges of performance. Thus, only two different design solutions may be needed. The next task is to connect these sub-functions to components.

There are numerous ways to complete any given sub-function, which may involve different components. Conversely, the form of a component is coupled to its function, at least to some extent, in terms of its impact on performance. Some aspects of a component’s form, such as material choice, have qualitative performance characteristics, like corrosion resistance which may not have clearly quantified requirements. Typically there are also constraints imposed on a component’s form.

The targets for family member form can place restrictions on which components can be made common or (re)configurable, as the form of certain components may be used in product differentiation. Also, to facilitate the use of (re)configurability to meet varying functional requirements, the form of some system components may require a degree of flexibility to achieve the (re)configurability and mitigate change propagation. Despite constraints, there are some components which are not strongly linked to performance characteristics or differentiation. The form of these components is an area where commonality should be achievable. If a common form cannot be used, the use of (re)configurability should be examined.

**Bottom-Up Approach**

For the bottom-up approach, the pertinent form characteristics of the current components and subsystems associated with the sub-functions can be identified. This includes how the sub-function is achieved, as well as other details such as the geometry and material of the components. For example, there are numerous ways to convert rotational mechanical energy to translational mechanical energy. Similarities can be noted, along with aspects of the various sub-function solutions which are dissimilar but have no reason to be (i.e. are non-differentiating and serve no unique function or performance level); these are areas which commonality can ideally be achieved. Dissimilar components or subsystems which perform similar sub-functions may be a result of interfaces with other components; these areas are additional candidates for incorporating (re)configurability to allow them to merge with the dissimilar components.

**Top-Down Approach**

In the top down approach, the design solutions to the sub-functions are not known (i.e. no physical solutions have been designed). This allows the product architecture for the various family members to be designed in such a way that the maximum benefits of (re)configurability can be obtained. Looking at the sub-functions, those which have small differences in performance requirements are the obvious candidates for common components. As the deviations in performance characteristics grow, the use of a common design solution increases the potential for compromise of the individual family member performances; unique components or subsystems developed for select family members increases the overall family cost. This is where the introduction of a (re)configurable design solution can be advantageous, as long as there are no form restrictions.

In the first step, the aspects of form used to differentiate family members were identified. When designing the product architecture, the components responsible for differentiation should be identified, as they may need to be unique to properly differentiate the family members. Other portions of the architecture should be viewed as potentially common or (re)configurable.

In both the top-down and bottom-up design approaches there are multiple ways of platforming. Modularization and scaling present two methods for creating product families and a combination of the two can be used as well [24]. Both methods (and their combination) lend themselves to incorporating (re)configurability. The approach will likely be dictated by the product architecture chosen. Once the product architecture is (re)defined and areas of potential (re)configurability are identified, the solutions for achieving the (re)configurability must be developed.

### 3.3 Step 3: Develop (Re)configurable Design Solutions

This step focuses on generating design solutions capable of (re)configuring to generate performance ranges which can span multiple market segments. When trying to develop (re)configurable solutions, it is helpful to have a concept generator facilitator. The study of Transformation Principles, while designed for reconfigurable systems, is relevant also to systems whose design changes may not be repeatable and reversible (i.e., relevant to configurable systems) [17]. The Principles for Flexibility for Future Evolution are relevant as well [20], as they assist with handling design changes. More importantly, both serve as a stimulus when (re)designing a component or subsystem to leverage the benefits of (re)configurability. Furthermore, both guidelines are generic enough that they should fit into any design process, regardless of corporate structure or the type of system being designed. These two methods are by no means exhaustive as to what design tools may be helpful, but are specific to reconfigurable and flexible system design. Other research which is more general is also applicable in this step.

Modular product architecture has also been identified as a key method for aiding design modification; this includes a one-to-one mapping of functions to components and decoupled interfaces between components [25]. Decoupled interfaces would allow different components to be attached for different family members, and would also facilitate (re)configuring a component in a family member. Modularity is also suggested in [21].
Some aspects of Design for Manufacturability can also be used to add (re)configurability. For example, many consumer products have a casing to contain the internal mechanisms which for manufacturing reasons is broken into two or more pieces. This offers the ability to make one or more pieces (re)configurable and have it mate with differentiating pieces, thus making a (re)configurable shell subsystem. Regardless of how the concepts for (re)configurability are created, they must be developed to the extent that the information required for the (re)configurability evaluation is available.

3.4 Step 4: (Re)configurability Evaluation
In the last step the proposed (re)configurable product family is evaluated to see if it better matches the corporation’s goals than a standard product family. Ideally the introduction of (re)configurable systems will have a positive impact for the company (e.g., increased profit for the company). The evaluation process should be decided by the corporation evaluating the product family and capture the goals of the corporation. One corporation may wish to maximize market coverage while satisfying certain cost constraints. Another corporation may wish to fulfill the target performance ranges while minimizing cost. If a market model can be developed, this may be used to drive an optimization or profitability comparison. While current commonality indices are not capable of evaluating (re)configurable product families, many of their concepts can be leveraged when evaluating whether incorporating (re)configurability has had a positive impact on the family.

Current commonality metrics would need some modification to evaluate a product family which contains (re)configurability. Examining the Comprehensive Metric for Commonality the focus of the metric is on evaluating common and variant components. This method is thorough in what it evaluates, however, as it assumes unique components are differentiating it may miss components that are not common and non-differentiating. More importantly, it relaxes the penalty on differentiating components, which again is another area which could be improved with (re)configurability. However, if these issues are addressed, it could be applied to two potential product families to evaluate which is more promising.

4 Case Studies
This section presents two case studies which demonstrate how the method can be used to create or improve a product family. The first case study looks at the bottom-up approach evaluating two power tools. The second case study looks at the design of a family of mountain bikes using the top-down approach.

4.1 Black & Decker® Power Tools
This case study looks at two power tools manufactured by Black & Decker®, the Handisaw (Figure 4) and one of their jigsaws (Figure 5). These saws represent members of two different market segments, as the Handisaw is cordless and the jigsaw is corded. Because of the similarity in power tool requirements substantial gains can be made platforming, and Black & Decker® currently takes advantage of many of these opportunities. However, as will be shown with this case study there is likely room to improve commonality through the use of (re)configurability.

4.1.1 Step 1: Set Family Form and Functionality
While the goal of both saws is to make cutting something easier for the user by converting electrical energy to mechanical translational energy, each have several of their own distinguishing characteristics. The Handisaw is marketed as a light weight, compact, cordless saw which can be used to cut various materials in a non-ideal position; the saw is essentially a scaled down version of a traditional reciprocating saw. The jigsaw is targeted at workshop use, with a more powerful motor, and a base designed for making more refined cuts, including beveled cuts, on primarily horizontal surfaces.

The overall function of the saws is the same (convert electrical energy to mechanical translational energy), but varies in scale (power) and physical implementation to differentiate the two saws. The differentiating aspects of the two saws which should be maintained during the redesign are listed below:

**Handisaw**
- **Functional** – store electrical energy
- **Form** – slender to accommodate tight spaces
- **Form** – ergonomic to accommodate two hands

**Jigsaw**
- **Functional** – power level of motor
- **Functional** – support beveled cuts

4.1.2 Step 2: Commonality Identification
Both saws take electrical energy, convert it to rotational mechanical energy with a motor, and then change the properties of the mechanical rotational energy before converting it to translational mechanical energy. These three common sub-functions and the three main subsystems which perform them are listed in Table 1. There are also a number of unique components.

The Handisaw has batteries in the handle which store the energy that it imports through its barrel jack, while the jigsaw imports the energy through its power cord and transfers it directly to the motor during use. These unique components contribute to differentiating the two saws, so there lack of commonality is justifiable. Furthermore, it is likely that these components can be platformed vertically and amongst members of their respective market segments. The cases for the two saws...
are unique as well, along with the Handisaw’s power train case, but are harder to platform vertically. The common sub-functions and their corresponding subsystems are now evaluated.

<table>
<thead>
<tr>
<th>Sub-function</th>
<th>Subsystem</th>
</tr>
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<tbody>
<tr>
<td>Convert Electrical Energy to Mechanical Rotational Energy</td>
<td>Handisaw – DC Motor</td>
</tr>
<tr>
<td>Change Properties of Mechanical Rotational Energy</td>
<td>Handisaw – Planetary Gear Train</td>
</tr>
<tr>
<td>Convert Mechanical Rotational Energy to Mechanical Translational Energy</td>
<td>Handisaw – Cam and Follower</td>
</tr>
</tbody>
</table>

Table 1. Mapping of Sub-function to Subsystem

*Convert Electrical Energy to Mechanical Rotational Energy*

The two motors are significantly different in geometrical size, use different types of current, and have different performance aspects (namely the power). While they both perform the same function, the performance values are such that the use of two unique subsystems is justifiable. If too powerful of a motor is used in the Handisaw it decreases the runtime between charges, which is undesirable (especially since the battery is integrated). Further, the size of the motor for the Handisaw must be small enough to fit in the compact envelope prescribed, and weight should be kept to a minimum. While the Handisaw and jigsaw may not share the same motor, it is a subsystem which other tools in their respective market segments could share. Once the electrical energy is converted to mechanical rotational energy, it is desirable to change the properties.

*Change Properties of Mechanical Rotational Energy*

Both saws have a gear train to change the properties of the mechanical rotational energy; the two gear trains increase torque and decrease the angular velocity. The Handisaw’s power train (see Figure 6) accomplishes this with a planetary gear set. This is done by attaching the sun gear to the motor’s shaft, fixing the ring gear, and using the planet carrier shaft as the output. The power train (see Figure 7) of the jigsaw accomplishes the change in torque and angular velocity using a standard gear reduction. While the gear trains are completely different in form, the difference in gear ratios is not extreme; for the Handisaw the ratio is 9:1, while the jigsaw has a gear ratio of 8.67:1. Even if these two ratios could be reconciled to only have one ratio for the two saws, the forms of the two solutions have their own benefits.

For the Handisaw, the planetary gear train is compact and fits in the desired envelope. The larger gear for the jigsaw is tied in to how the mechanical rotational energy is converted to mechanical translational energy, which is now evaluated.

*Convert Mechanical Rotational Energy to Mechanical Translational Energy*

In the Handisaw the planet carrier in the gear train (sometimes called the “arm”) drives a shaft which has a cam attached to it. The cam followers are attached to a bar which holds the blade clamp (a subassembly responsible for securing the blade during operation). These components are labeled in Figure 6.

The jigsaw’s power train converts rotational mechanical energy to translational mechanical energy using a Scotch Yoke. The last gear in the train is used as the crank and thus holds a pivot point. The bar which holds the blade clamp contains the yoke. A detailed view of this subsystem can be seen in Figure 8.
The two bars are quite similar in geometry (see Figure 9 and Figure 10) and function but are not common. The jigsaw does have approximately three eighths of an inch more travel than the Handisaw, which seems to be a reconcilable difference. Because of current differences, the two power tools use numerous unique components around the two bars. It should be noted that some of the components may be shared by other tools which were not examined, but they are unique with respect to the two power tools being examined. The redesign of these two subsystems is an area which can likely benefit from (re)configurability and additional platforming. Currently the Blade Clamp subassembly is the only portion of the two power trains which is common.

Both the crank pivot subassembly and cam follower subassemblies can rotate to reduce wear on the mating surfaces. Both have the same size engagement diameter and a comparable height and axle diameter. These two different subassemblies could likely be replaced by a common platformed subassembly.

The rest of the components depend on making the cross-section of the two bars identical, and ideally the same bar could be used for both saws. It is also desirable to make this change without changing the other components of the power train, such as the two gear trains to preserve the performance characteristics. To achieve this goal, it is suggested that (re)configurability be added to the two power trains.

4.1.3 Step 3: Develop (Re)configurable Design Solutions

By adding flexibility to the bar, as illustrated in Figure 11, it allows a portion of the power train to be configured to have either the two cam followers or a yoke fastened to it. By making this design change, it should be possible to increase the commonality and maintain identical performance characteristics.

Due to the current geometry of the yoke and the spacing between the two cam followers, multiple mounting points will need to be placed on the bar. By making the bar common through the use of flexibility, the sleeve bearings and wiper seals can become common components as well. Because the original geometry of the yoke is maintained, and the spacing of the two cam followers remains constant the majority of the other components of the two power chains do not have to be altered. Furthermore, their original performance characteristics
such as stroke length, speed, etc. are identical. However, the
(re)configurable bar for the Handisaw is now overdesigned to
ensure proper strength for the Jigsaw application. In order to
account for slight geometry changes around the bar, both cases
would have to be modified. Therefore, this change should be
made at a time when the cases require modification for other
reasons as well.

4.1.4 Step 4: (Re)configurability Evaluation

While no cost data was available, the change in
components should reduce manufacturing cost. The yoke can
be replaced with a stamped version. The linear bearings and
wiper seal are made common, thus removing two unique
components from the production process. Two bars are replaced
with the one flexible bar. With several components removed,
there is potential for a reduction in manufacturing cost.
However, as mentioned before there would likely have to be
slight changes to the two cases; if these cases do have to be
modified (which is quite costly) the benefits from removing
several simple components may not outweigh the cost of
changing the cases. Further, the configurable bar subsystem
adds an additional assembly step to the jigsaw’s power train, as
the yoke is no longer integrated.

These two products represent a fraction of the tools which
employ a reciprocating action; Black & Decker® also makes
power scrapers, reciprocating saws, a powered handsaw, etc.
While the tools were not available for this case study, the
possibility of incorporating the needs of these other power tools
into the (re)configurable bar should also be evaluated.

4.1.5 Black & Decker® Case Study Conclusions

While there was only one subsystem that can benefit from
adding (re)configurability, this subsystem can potentially be
used by a number of family members. With the bottom-up
approach the tradeoff between redesigning complex subsystems
may limit the benefits of (re)configurability, as many resources
have already been invested in the design of components and
their manufacturing processes. The gains of (re)configurability
should be greater in a top-down approach as there are no
existing design solutions to act as anchors. The top-down
approach is used in the next section to design a family of
mountain bikes.

4.2 Mountain Bike Family Design

The proposed method is now used in a design of a product
family of mid-range mountain bikes which spans three market
segments: cross-country, all-mountain, and downhill. These
three bike types represent the most popular off-road cycling
styles, all of which have their own unique form and
functionality.

4.2.1 Step 1: Set Family Form and Functionality

Cross-country bikes are designed to be ridden quickly,
while all-mountain bikes ride at mid-range speeds, and
downhill bikes at very slow speeds (when not racing down
steep slopes). Functionally, the three bikes in this mid-range
market segment are very similar. They all use the same system
level functions and sub-functions. The performance
characteristics of these sub-functions differentiate the bikes. A
portion of the functional diagram for a mountain bike is shown
in Figure 12. For the sake of brevity, only two of the main
subsystems associated with system level functions will be
discussed – the drive train and the front suspension.

In order to further differentiate the three bikes, there are
several key differences in their form; the most notable of these
is the frame geometry. While differences in the frame geometry
appear to be minimal, they are crucial to positioning the rider
properly for a given riding style. The downhill frame positions
the rider’s center of gravity toward the rear of the wheelbase to maintain balance and control. The cross-country bike’s frame focuses on positioning the rider to achieve maximum pedaling efficiency. The all-mountain frame is a balance between the two. Concerns for strength are paramount with the downhill bike, while the cross-country bike focuses on being lightweight and stiff. Again, the all-mountain is a compromise between strength and weight. Because of the importance of the frame geometry and construction, the frames will be unique. However, the components which mount to them to complete the family members will be examined to identify areas where commonality or (re)configurability is appropriate.

4.2.2 Step 2: Commonality Identification

The second step looks across the product family and identifies which sub-functions show potential to become common or (re)configurable. As all the higher level sub-functions are shared by the three bikes, the performance characteristics of them and the specific proposed design solutions will be the only deciding factors.

Couple System to Ground

The first system level function, Couple System to Ground, is fulfilled by the front suspension of each bike. The suspension of each mountain bike works as a damper by compressing and dissipating energy as the rider navigates over rough terrain, ensuring that a bike maintains contact with the ground during its normal riding conditions. However, the three market segments have drastically different working conditions, which results in significantly different performance range targets.

The suspension on cross-country bikes should only have to dissipate energy from rough terrain and small drop-offs. An all-mountain bike’s suspension sees rougher terrain than the cross-country suspension, requiring that the suspension be capable of handling higher energy inputs, such as moderate drop-offs. Lastly, a downhill bike’s suspension experiences the harshest shocks, with drop-offs of ten feet not uncommon.

To properly dissipate the energy, a specific stroke length is required. The stroke lengths range from roughly three inches on a cross-country suspension to ten inches on a downhill suspension, with the all-mountain stroke length somewhere in between. Thus to accommodate the different operating ranges it is not feasible to share common components. On top of the difference in travel lengths, there are other significantly different requirements for the three suspension systems. Cross-country bikes should have light suspensions to facilitate easier pedaling while climbing and accelerating. Both the all-mountain and downhill bikes require thicker stanchions and a stronger crown for added durability.

Analyzing the required performance ranges of each front suspension and their corresponding form requirements, it is concluded this subsystem is not a candidate for commonality or (re)configurability. Although the main sub-function is the same, the similarity in performance characteristics across each suspension type is minimal, thus unique subsystems will be used. This is justifiable as the suspension can be classified as a differentiating subsystem. A similar analysis on the rear suspension heeds the same conclusion. The next system level function evaluated is converting human energy to mechanical translational energy.

Convert Human Energy to Mechanical Translational Energy

This system level function is achieved through three sub-functions. The proposed design solution for these three sub-functions is the drive train which includes a chain, derailleurs, the pedals, crank arms, and gears. The set of gears in the rear of the bike is called the cassette. The gears in the cassette along with the gears attached to the crank arms determine the range of gear ratios.

Larger gears allow for slower speeds at a comfortable cadence and also increase the outputted torque (required for climbing hills). Smaller gears produce less torque, but achieve faster speeds at the same preferred cadence.

The speeds of the cross-country, all-mountain, and downhill bikes while pedaling are roughly 0-25mph, 0-20mph, and 0-15mph, respectively. The speeds that each cassette is designed to operate at are dependent on the size of the included gears. To satisfy the speed requirements of each mountain bike, important gears on the downhill cassette will be large, while those on the all-mountain bike will be mid-sized, and finally the important gears on the cross-country bike will be small. The relative sizes of each mountain bike cassette are shown in Figure 13. The gears needed to produce the performance ranges that each cassette is required to cover overlap; this was the missing factor in the front suspension analysis. With a potential area for (re)configurability identified, design solutions must be generated to realize the subsystem.

4.2.3 Step 3: Develop (Re)configurable Design Solutions

The third step of the proposed method is to generate the (re)configurable cassette design that will successfully satisfy
4.2.4 Step 4: (Re)configurability Evaluation

The fourth and final step checks to see whether the (re)configurable design meets the bicycle company’s goals better than a comparable static design. A static cassette design is one where none of the individual gears are removable or replaceable. This is the case when the gears and carrier are machined as one stand-alone piece, or all of the gears are riveted to a carrier. A one-piece cassette machined from a billet is expensive to manufacture, although it offers weight savings and increased stiffness; this type of cassette is reserved for the high-end market segment. The second static design where all ten gears are riveted to a single carrier typically is used for low-end bikes; riveting the gears together is required to obtain the desired stiffness as this design typically uses low-grade alloys.

The (re)configurable cassette uses two carriers to mount the largest six gears. These are split into two groups of three so the appropriate market segments can be hit. These larger gears, regardless of material quality require a carrier to achieve the proper stiffness. The remaining gears are small enough to be slid directly onto the cassette body. The (re)configurable cassette should be competitive in manufacturing cost to the riveted static design because of the shared manufacturing processes, but deliver the required quality and customizability for the mid-range market segment.

Implementation of a (re)configurable cassette will allow the bicycle manufacturer to achieve the desired performance ranges for each bike classification. Further, using this design also permits the cassette’s ratios to be reconfigured by the customer, who can remove the cassette and replace gears according to their own preferences. These form and functional characteristics make the design versatile and cost effective for the customer. The bicycle company should also see benefits from the fact that the three cassettes share numerous common gears and manufacturing processes.

4.2.5 Mountain Bike Family Case Study Conclusions

While several main components and subsystems had to be unique to differentiate the different mountain bikes, the similarities in drive train requirements allowed the bikes to share a (re)configurable drive train. Even if a substantial cost savings between fixed drive train components and (re)configurable drive train components does not exist, the (re)configurable drive train offers some additional benefits. Worn sections of the cassette can be replaced without having to replace the entire cassette. Also, the flexibility lays the foundation for customization.

5 Conclusion

This research looked at developing a formal method for introducing (re)configurability into product family design synthesizing recent work in system flexibility, system reconfigurability, and product families. The goal was to improve product family design by decreasing family cost while maintaining or improving system performance.

Much of the previous product family research has not focused on making differentiating components and subsystems common; while a common design solution cannot differentiate family members, (re)configurable design solutions could have a positive impact on increasing commonality while allowing the required range of performance characteristics to differentiate family members to be realized.

This paper introduces a design method which can be used to guide the design of a product family which will leverage the benefits of (re)configurability. This work uniquely leverages previous work in system flexibility, system reconfigurability, and product platform design which allowed for innovative modifications of two product families. While the case studies in the paper were of relatively simple engineering systems, there were still areas which could likely benefit from the introduction of (re)configurability. As more complex engineering systems are studied, there may be a greater benefit from introducing (re)configurability.

Product platforms have been used to speed the design of new family members. The increase in flexibility provided by adding (re)configurability should facilitate the design of new family members. There is also a potential additional benefit to a reconfigurable solution if the company participates in reusing and refurbishing. The ability to reconfigure a subsystem and place it in a different system than the one it was originally in can potentially increase the number of recycled components.

Future work includes identifying if generalized principles can be made to assist with identifying areas for (re)configurability. Some sub-functions may be better suited to incorporating (re)configurability than others. For example, the sub-functions responsible for manipulating energy characteristics may in general benefit more from (re)configurability than the sub-functions for converting energy.
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