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Collaborative Products: A Design Methodology with Application to Engineering-Based Poverty Alleviation

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Engineering-Based Poverty Alleviation

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ABSTRACT

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Collaborative products are created when physical components from two or more products are temporarily recombined to form another product capable of performing entirely new tasks. The method for designing collaborative products is useful in developing products with reduced cost, weight, and size. These reductions are valued in the developing world because collaborative products have a favorable task-per-cost ratio. In this paper, a method for designing collaborative products is introduced. The method identifies a set of products capable of being recombined into a collaborative product. These products are then designed to allow for this recombination. Three examples are provided to illustrate the method. These examples show that a collaborative block plane, apple peeler, and brick press, each created from a set of products, can increase the task-per-cost ratio of these products by 42%, 20%, and 30%, respectively. The author concludes that the method introduced herein provides a new and useful tool to design collaborative products and to engineer products that are valued in the developing world.

Keywords: collaborative products, product decomposition, reconfigurable products, poverty alleviation

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

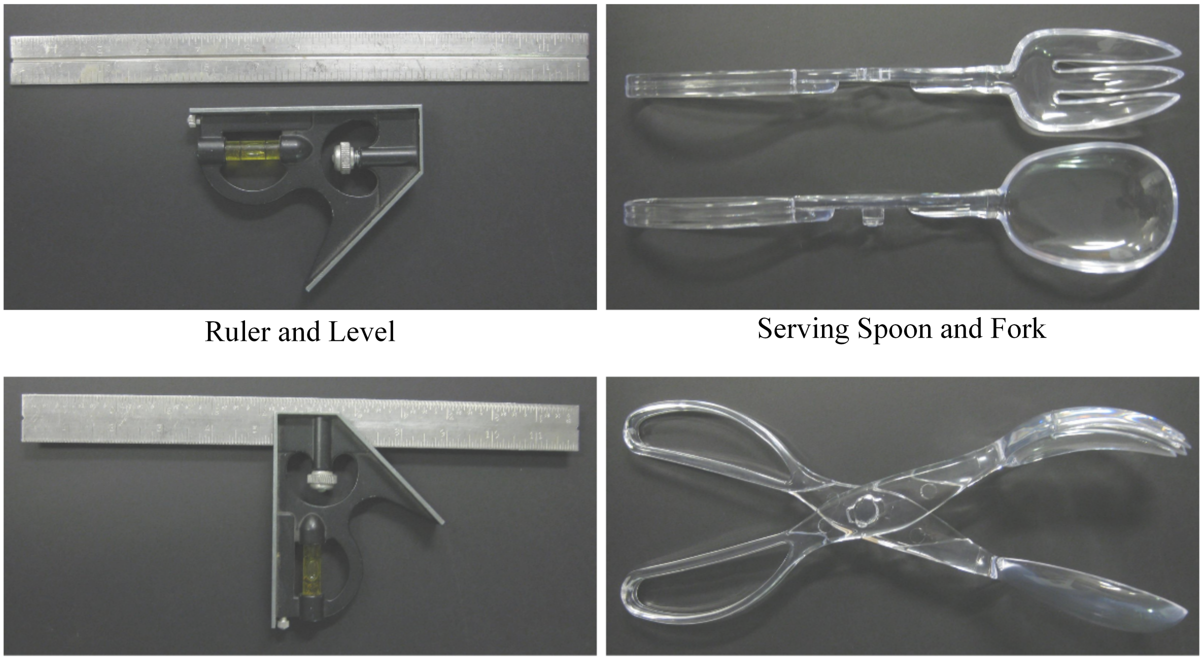
C	The collaboration factor of a product set
$\bar{C}$	The normalized collaboration factor of a product set
F	A vector containing the number of missing and additional components as required by a target product
I	The cost, weight, and size indicator of a product set
$\bar{I}$	The normalized cost, weight, and size indicator of a product set
M	A matrix containing the component information of all the products in a recombination table
N_a	The number of components included in a product set not required by a target product
N_c	The number of component columns within a recombination table
N_l	The number of products within a recombination table
N_m	The number of components missing from a product set required by a target product
N_p	The number of products within a product set
N_r	The number of components required by a target product
N_t	The theoretical minimum number of products required for the creation of a collaborative product
P	A vector containing the sum of a product set's component information, Size $(1, N_c)$
P_c	The total cost of a product set
P_s	The total size of a product set
P_w	The total weight of a product set
S	A vector identifying the products from a recombination table included in a given product set, Size $(1, N_l)$
T	A vector containing the component information of a target product, Size $(1, N_c)$
T_c	The cost of a target product
T_s	The size of a target product
T_w	The weight of a target product
w_a	The weight of N_a in an aggregate objective function
w_c	The weight of $\frac{P_c}{T_c}$ in an aggregate objective function
w_m	The weight of N_m in an aggregate objective function
w_p	The weight of N_p in an aggregate objective function
w_s	The weight of $\frac{P_s}{T_s}$ in an aggregate objective function
w_w	The weight of $\frac{P_w}{T_w}$ in an aggregate objective function

CHAPTER 1. INTRODUCTION

In 2005, the World Bank reported that approximately 1.4 billion people in the world were living on less than \$1.25 a day [1]. In recent years, an engineering focus on developing income-generating products has brought new optimism to achieving sustainability in poverty alleviation [2, 3]. These products are purchased and used by those living in poverty to increase their incomes, leading to better health and education [2]. Although such products have helped more than 12 million people escape poverty [2–4], many of the impoverished are either unwilling or unable to invest in these products because of the financial risks involved in purchasing them [2,3]. Therefore, a significant goal of the method introduced herein is to design income-generating products that are extremely affordable. As such, a greater number of individuals will be able to capitalize on the benefits of income-generating products.

An interesting condition that exists in the developing world is that individuals generally have a shortage of funds, while having low opportunity costs for their time and labor—a noticeable reversal of the conditions that exist in the *developed* world [3]. For those in the developing world, inexpensive products are often more desirable, even though more time may be required to use them. Additionally, reductions in product cost would be particularly beneficial for income-generating products, as it would reduce the risks associated with purchasing them. Collaborative products are capable of achieving these reductions and are the focus of this research. Collaborative products are created when physical components from two or more products are temporarily recombined to form another product capable of performing additional tasks. Thus collaborative products have great potential to increase the task-per-cost ratio of a set of products.

Although this research is focused on designing products for those living in the developing world, many living in poverty in the *developed* world have similar needs. In 2009, 14.3% of those living in the United States had incomes below the poverty threshold, as defined by family size, number of children, and age [5]. For example, an impoverished family of four lives on



Ruler and Level | Serving Spoon and Fork

Combination Square | Salad Tongs

Figure 1.1: Collaborative Products Currently Available

less than $22,050 a year, or about $15 a day per person. As a result of limited funds, many of these individuals live in small dwellings with limited storage space. For these individuals, inexpensive products with reduced weight and size and increased functionality would be beneficial. To illustrate this, an example of a collaborative apple peeler designed for those in the *developed* world is provided in Chap. 5.

Additional industries that could benefit from collaborative products are payload conscious industries such as aerospace and backpacking. Though few in number, examples of simple collaborative products can be found on the market today in categories such as kitchen tools (e.g., salad tongs created by joining a serving spoon and serving fork (see Fig. 1.1)) and carpenter's tools (e.g., a combination square that is created by joining a ruler and small level (see Fig. 1.1)).

The potential for collaborative products to positively affect those living in poverty merits the need for methods to design such products. As shown in Chap. 2, methods available in the literature serve as a foundation for the design of collaborative products; however, the literature does not provide specific methods for designing them or explore their use in poverty-alleviation strategies. Therefore, this research has been undertaken to meet these objectives [6].

The remainder of this thesis is presented as follows: A review of the literature is included in Chap. 2. In Chap. 3, the new method for designing collaborative products is presented. In Chap. 4 - 6, the design of a collaborative block plane, apple peeler, and brick press demonstrate the method. Concluding remarks are provided in Chap. 7.

CHAPTER 2. LITERATURE SURVEY

This chapter provides the basis for the method presented in this thesis by reviewing published literature. The pertinent topics reviewed here are: (i) *product modularity*, (ii) *product decomposition*, (iii) *reconfigurable systems and transformation*, and (iv) *engineering-based poverty alleviation*. Finally, a comparison between existing methods and the objectives of the new method is made to identify differences and to establish the need for the new method.

2.1 Product Modularity

The separable nature of collaborative products often benefits from a type of modularity identified in the literature as *Type II modularity* [7]. To better understand why Type II modularity facilitates collaborative products, a general discussion of modular architectures is first provided.

Modular architectures have two properties: (i) they embody one or more functional elements in distinct modules, and (ii) they clearly define interactions between modules that are generally fundamental to the primary function of the product [8]. Additionally, four pertinent types of modular architecture are defined in the literature. They are: (i) Slot-modular: where each component is designed to have a unique interface with a base module, (ii) Bus-modular: where each component is designed to have the same interface with a base module, (iii) Sectional-modular: where each interface is identical and there is no base module [8], and (iv) Type II modular: where each interface is unique and there is no base module [7].

Type II modularity is incorporated into the method presented in this thesis because of the distinct nature of collaborative products. That is, because they are formed by recombining various components from independently-functioning products to create a *new* product with *new* functionality. As this new functionality is not generally based upon or predominantly connected to a single component, no one component becomes a base module. Additionally, because collaborative products are designed to be recombined into a specific product (and are therefore not generally designed to be infinitely reconfigurable), there is no need to design common interfaces. Therefore collaborative products often have unique interfaces, as this is sufficient. The specific implementation of Type II modularity in the development of collaborative product interfaces is discussed more fully in Sec. 3.6.

A number of developments in modularity including reconfigurable systems and transformation (see Sec. 2.3) and product families have application to the design of collaborative products. Product families are generally used in mass customization to allow for the reuse of the same or similar modular components on various products. This allows customized products to be created from various modules in a *product family* [9–11]. Product families are related to collaborative products in that they allow for individual modules to be used on more than one separate product. However, the result of the method presented in this thesis is to offer the consumer a greater number of functional products for a given set of components, rather than to provide a structured approach to achieving a greater number of customized products at reduced costs. Additionally, with collaborative products, modules are generally combined at the consumer level, rather than as a manufacturing operation. Therefore, while product families are similar to the design of collaborative products, they are not specifically implemented in the method presented herein.

2.2 Product Decomposition

Product decomposition is the breakdown of products into components that completely describe a product [12]. Product decomposition is used in the presented method to decompose a set of products into components. These components are recombined to form another product capable of performing additional tasks. The literature presents various methods for decomposing products into both physical and functional components. These methods include, decomposition by user actions, customer needs, flow diagrams, hierarchy, and by documenting interactions between functional elements [8, 12–14]. The method presented herein, uses general decomposition approaches that result in the identification of components that when assembled together create the primary function of the product. Three decomposition approaches are implemented in the developed method. A discussion of these approaches is now provided.

Structural decomposition is the process of breaking down a product into physical subsystems and then breaking down those subsystems and their subsystems into basic physical components. These components are those required to make up the product's primary function [12, 13]. Since collaborative products are formed by combining physical components from other products, structural decomposition is a fundamental part of the method presented in this research. This decomposition serves as the basis for the other two decomposition methods used herein.

Functional decomposition is the representation of a product's behavior by its functions. In this case, a function transforms an input into an output. Various functional decomposition methods are identified in the literature [8, 12, 15–18]. In general, functional decomposition is the break down of a product's primary function into sub-functions that are then decomposed into further sub-functions [12]. Among other developments, recent approaches to functional decomposition have resulted in the creation of a common language used to uniformly identify functional information [16, 19]. This information is often captured in design repositories, where information can be used to assist in the design of other products [20, 21]. While similar approaches are not specifically implemented in the method presented herein, they could significantly benefit the design of collaborative products, as identified in Chap. 7.

Functional decomposition is also used in the presented method to assist the designer in identifying relationships between product components. However, to maintain a link between decompositions, facilitating proper recombination into collaborative products, this decomposition is performed individually on the components identified in structural decomposition. This means that each functional decomposition corresponds directly to a single component identified in structural decomposition.

To further assist in the identification of component relationships, a third decomposition approach is introduced here. This is another type of physical decomposition that instead represents components by physical characteristics, such as shape, size, and color. The identified physical characteristics are those characteristics that enable the primary performance of a component. For clarity, this decomposition is identified in this thesis as *characteristic decomposition*. This decomposition is performed similar to functional decomposition, where each component identified by structural decomposition is further decomposed by characteristic decomposition.

By further decomposing components identified by structural decomposition, more abstract descriptions are provided to assist in identifying component recombination relationships. This will potentially increasing the number of relationships identified between components. The implementation of these decomposition approaches is discussed more fully in Sec. 3.2.

2.3 Reconfigurable Systems and Transformation

Reconfigurable systems are capable of changing their architecture repeatedly and reversibly to meet new objectives. This allows products to achieve various configurations used to fulfill several purposes. In this sense, collaborative products are a type of reconfigurable system. There are three primary purposes for reconfigurable systems. They are: (i) Multi-ability: the ability to perform multiple functions over time but not concurrently, (ii) Evolution: the ability to morph the system into future configurations, and (iii) Survivability: the ability to maintain a level of functionality despite failures in some components [22–24]. Collaborative products are designed for multi-ability.

The literature describes another class of reconfigurable systems called *transformation products*. A product falls into this class when its own components can be reconfigured into a different product with new or enhanced functionality [25, 26]. Collaborative products, on the other hand, are formed when *two or more* independently functioning products – or components thereof – are combined to form an entirely new product. While the functional goals of transformation, reconfiguration, and collaborative products are similar, the means to achieve them is noticeably different. As the design of collaborative products requires simultaneous consideration of multiple products, a specialized method is needed and is presented in this thesis.

2.4 Engineering-Based Poverty Alleviation

There has been a significant amount of effort (mostly outside of engineering) dedicated to poverty alleviation, with over $2 trillion spent on foreign aid since the 1950's [27]. While there are various organizations that develop products to both sell and donate to those in poverty, the majority of the world's engineers develop products for the wealthy living in *developed* countries. As such, those living in poverty have rarely been the focus of engineering methods, tools, and solutions, even though they represent a significant untapped market [2].

Engineering-based poverty alleviation is the use of engineering principles and methods to assist in poverty reduction. In recent years, significant advances in this area have been made. This has included efforts in developing inexpensive products, environmentally-conscious products, and products that enable those in poverty to increase their incomes [2, 3, 28–30]. Various professional and educational organizations have contributed to these advances in engineering-based poverty alleviation. Their efforts have resulted in products used for irrigation, water purification, transportation, lighting, cooking, and health care, etc. [2, 3, 28, 31–33]. While these efforts have greatly benefited many living in poverty throughout the world, due to the number of individuals in need and the associated costs, the vast majority of individuals have been largely unaffected. Therefore, additional methods are needed to assist those in poverty to increase their incomes by providing tools at extremely low costs [2].

Income-generating products are products designed specifically to enable those in poverty to increase their incomes. A number of organizations have designed and produced various income-generating products, such as treadle pumps that help poor farmers increase their crop yield by providing them with greater access to water for irrigation [2, 3, 28, 34]. Research and implementation of engineering-based poverty alleviation has provided evidence that a greater benefit is achieved when income-generating products are purchased by rather than donated to those in poverty [2, 3]. These organizations have helped over 12 million people out of poverty through implementation of these practices. As identified in the literature, to be most effective poverty alleviating products need to be produced at low costs [2, 3]. As mentioned previously, a significant goal of the method introduced herein is to design income-generating products that are extremely affordable.

2.5 Comparison to the Literature

While parts of the decomposition approaches presented in the literature are used in the method presented herein, functional and characteristic decomposition methods are not implemented as stand alone approaches. Specifically, as will be seen in Chap. 3, each product is decomposed structurally and then each component of the product is described further through functional and characteristic decomposition. In each case products are decomposed with respect to the collaborative product to be designed, meaning that each product is compared to the structural, functional, and characteristic definitions associated with this collaborative product in order to identified components that are similar to one another. In this way, the functional and characteristic decompositions are used to inform the structural decomposition.

The method presented here for designing collaborative products differs from other methods presented in the literature for designing transformation products and other reconfigurable systems. The primary difference is that collaborative products allow for components from *multiple products* to be used to create additional products that perform *entirely new tasks*. Its application to poverty alleviation is particularly meaningful because it allows the impoverished to purchase individually useful products that can later be joined together to form another product, which is functionally different. The collaborative nature of the individual products has potential to increase the task-per-cost ratio, which is highly valued in the developing world.

While other methods facilitate the reconfiguration of products into functionally different products capable of performing additional tasks, the method for designing collaborative products is unique in that it facilitates the reconfiguration of components from *multiple products*. Additionally, the primary function of a collaborative product is generally a new distinct function previously unavailable rather than an enhancement of the primary function from one of the products it is created from.

CHAPTER 3. METHOD FOR DESIGNING COLLABORATIVE PRODUCTS

To assist in the design of collaborative products, a detailed approach is needed. To be effective, a good design approach should: result in reductions in cost, weight, and size of a set of products, provide a measure of how efficiently product components are used within a design, and provide an ability to effectively search a large design space.

This chapter presents a methodology for designing collaborative products. The presented method is a 7-step process, as illustrated in the flow chart presented in Fig. 3.1. This process is used to assist a designer in identifying and designing a set of products capable of being reconfigured into another product at reduced cost, weight, and size. At each step, the process guides the designer in making decisions, gathering needed information, and implementing design practices to achieve this goal. A discussion of each step is provided in this chapter.

3.1 Step 1: Perform Product Search

The method for designing collaborative products begins by performing a product search. The product search results in a group of products from a category such as tools, computer accessories, vehicles, toys, or any other combination of products or product groups selected by the designer. This group ultimately includes the collaborative product and its corresponding product set. In a practical sense, a product set is a group of products whose components are considered for recombination into a collaborative product. Search methods may include: prior knowledge, Internet search engines, product libraries, company resources/inventory, or any other product search method.

It is noted that an increase in the number of products identified will increase the time to complete the method, while a decrease in the number of identified products will likely result in a less suitable collaborative product. This trade-off should be considered in determining the number of products to identify. However, the author has observed that identifying 30 or more products, is

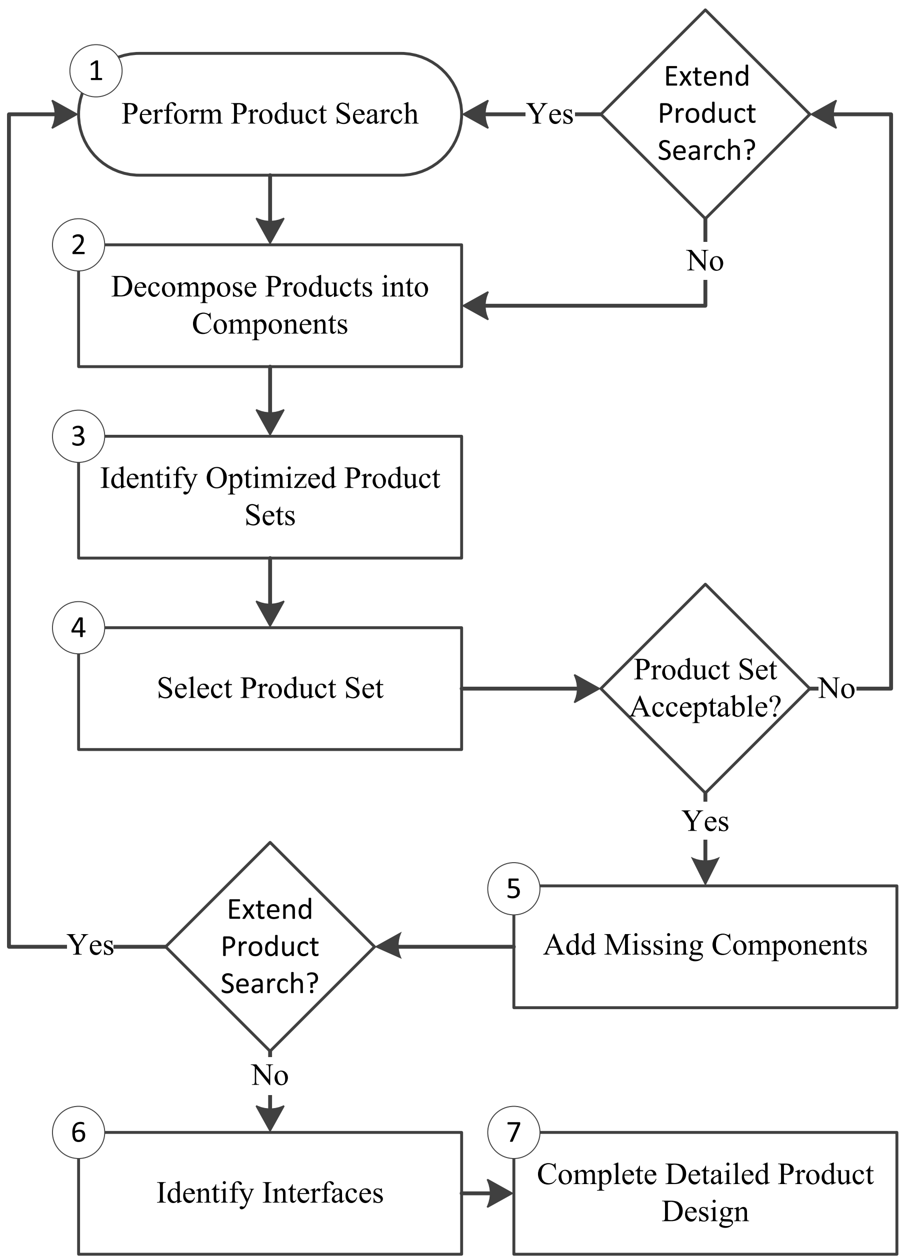


Figure 3.1: 7-Step Process for Designing Collaborative Products

more likely to result in successfully identifying a suitable collaborative product. When searching for products, it is suggested that products that are unlikely to be purchased by the end user be omitted from the list.

3.2 Step 2: Decompose Products into Components

To allow for product components to be temporarily recombined into a collaborative product, each product must be decomposed into components. To further guide this decomposition, one or more target collaborative products (termed *target products*) are first selected. Target products are those selected to become collaborative products. Generally, products are only decomposed into those components required to perform their intended function(s). Consequently, the decomposition activities will typically not include secondary components such as fasteners. Ultimately, numerous component combinations will be checked for compatibility and evaluated in search of suitable collaborative products.

To decompose the products identified in Step 1, a recombination table similar to Tab. 3.1 is created. Within this table, rows identify products and columns identify components. Values in the table link the components to the products. The *target* column is used to identify target products. This is done by placing a "1", when only one target product has been identified, or an alpha character, when multiple target products have been identified, in each corresponding row of the *target* column.

Target products are selected by the designer based on preference and customer needs. Target products generally: have a greater number of components than most of the other products in the recombination table; are desirable but generally not purchased due to high cost, weight, or size; and generally used less frequently than typical products, as the individual products from the product set are unusable while reconfigured into the target product. Once the target products are selected, they are decomposed into components and a column is created for each component identified. Each target product is decomposed using three decomposition approaches as follows:

1. Decompose the product structurally into components, where the resulting components make up the primary function of the product.

2. Decompose the product functionally by identifying the primary function of each component identified in structural decomposition.

3. Decompose the product by physical characteristics by identifying the pertinent characteristics, such as size, shape, and color of each component identified in structural decomposition.

These decompositions result in a more abstract description of each component, used to assist in further identifying non-target product components that could provide the same requirement as one of the components in a target product. In this method, each product is first decomposed structurally and then further described functionally and characteristically. This results in each structural decomposition having an associated functional and characteristic decomposition used to inform the structural decomposition. Figure 3.2 illustrates the relationship between these decompositions in terms of the physical/functional nature and the level of abstraction of each decomposition approach.

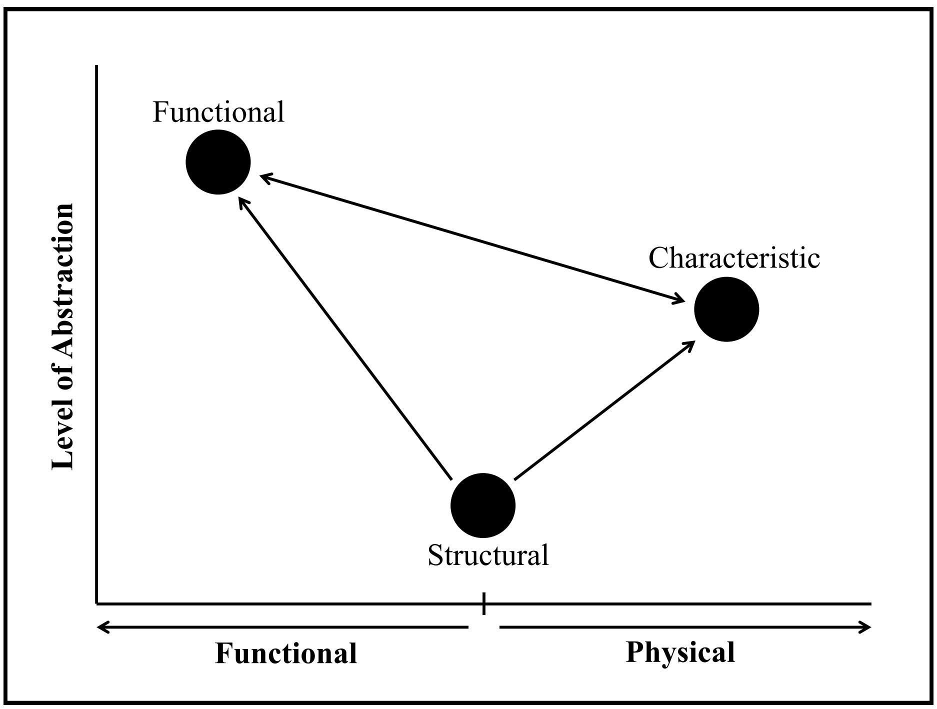


Figure 3.2: Decomposition Methods: Level of Abstraction

To illustrate the need for three types of decomposition, consider the following. If structural decomposition were the only decomposition approach considered in this method, then a bicycle wheel would only be available for recombination based on its structure alone. Meaning a bicycle wheel would only relate to other wheels. Including functional and characteristic decompositions allows for other wheels, similarly functioning components, such as a ski, or similarly shaped component, such as a flywheel, to be considered for recombination. The three decompositions for the bicycle wheel are provided in Fig. 3.3. As functional and characteristic decompositions further describe components already identified by structural decomposition (according to the three-step decomposition process defined above), there is no need to specifically identify them in the recombination table.

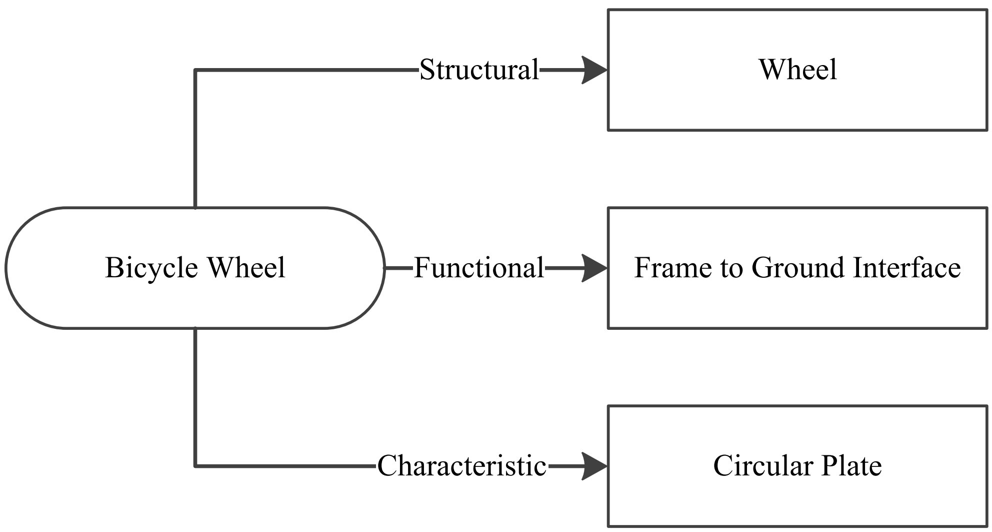


Figure 3.3: Bicycle Wheel Decomposition

After decomposing the target products, each non-target product is decomposed to identify components that could be recombined into a target product. To encourage practicality, if a product in the product set has the same general function as one of the target products, this product should not be considered in the creation of that target product. When decomposing products, each product is listed in the *Product Name* column and a "1" is entered for each component that comprises the product. The decomposition of non-target products is unique in that each non-target product is decomposed as it relates to a target product. Therefore, while a component in a non-target product may be structurally different than a component in a target product, it can still have the same decomposition. When a component from a non-target product is related to a component in more than one target product, the alpha character corresponding to each respective target product is instead entered into the appropriate column, as with the shovel in Tab. 3.1. The purpose for this is explained in Step 3. This is done for each product in the recombination table and another column is created each time a new component type is identified. For example, if a rake were added to the list given in Tab. 3.1, a “1” would be entered in the *Long Handle* column and a new column would be created for *Rake End*. If a product has more than one of the specified components (e.g., if it has two handles), the number of component instantiations should be placed in the corresponding column. An example of this, shown in Tab. 3.1, is the “2” in the *Long Handle* column of the wheelbarrow.

To further increase the recombination possibilities, decomposition is performed iteratively. This iterative process begins when non-target products are first examined to identify relationships with target products. Target products are then examined to determine whether altering the decomposition of the target products would allow for additional relationships to be identified. Reasonable changes can then be made to target product decompositions, as required.

The approximate cost, weight, and size of each product are also entered into the table. This information is used in the optimization routine in Step 3 to determine how closely the cost, weight, and size of a product set are to the cost, weight, and size of its corresponding target product. While these values do not directly correspond to the cost of the final products designed as collaborative products, they provide a relative comparison to other products in the recombination table. Additionally, they can be used to determine a reasonable approximation of the cost of the collaborative product. This information can be entered using any units consistent between products.

Table 3.1: Farming Tools Recombination Table

		Weights				**Components**							
		Cost	Weight	Size	**Target**	Long Handle	Plow Blade	Plow Frame	Wheel	Large Tub	Bottom Rest	Scythe End	Short Handle
Products	Plow	95	20	30	A	2	1	1	0	0	0	0	0
	Wheelbarrow	52	5	24	B	2	0	1	1	1	2	0	0
	Shovel	15	4	3	0	1	A	0	0	0	B	0	0
	Scythe	20	5	4	0	1	0	0	0	0	0	1	0
	Sickle	12	2	2	0	0	0	0	0	0	0	1	1

3.3 Step 3: Identify Optimized Product Sets

After the products are decomposed into components, a numerical optimization routine is used to identify an optimized product set, where an optimized product set is defined as:

1. A set containing a maximum number of components required by a target product (N_m)

2. A set containing a minimum number of products (N_p)

3. A set containing a minimum number of additional components (N_a)

4. A set resulting in a minimum cost (P_c)

5. A set resulting in a minimum weight (P_w)

6. A set resulting in a minimum size (P_s)

Note that while collaborative products are designed to *increase* the task-per-cost ratio of a set of products, as discussed in Chap. 1, the method presented herein does not intended to *maximize* this ratio outside the context of collaborative products. The optimization routine uses the relationships provided in the recombination table and the optimization formulation below to search for an optimized product set. The following is the multiobjective problem statement used:

$$\min_{S}(\bar{C},\bar{I}) \tag{3.1}$$

subject to:

$$0 \leq S_i \quad \forall i \in \{1,2,...,N_l\} \tag{3.2}$$

$$N_t \leq N_p \leq N_r \tag{3.3}$$

where:

$$\bar{C} = 1-(4C+1)^{-4C} \tag{3.4}$$

$$C = \frac{w_m N_m + w_p(N_p - N_t) + w_a N_a}{N_r} \tag{3.5}$$

$$\bar{I} = 1 - (I+1)^{-I} \tag{3.6}$$

$$I = (w_c \frac{P_c}{T_c} + w_w \frac{P_w}{T_w} + w_s \frac{P_s}{T_s}) * (\frac{N_r}{N_r - N_m}) - 1 \tag{3.7}$$

$$N_m = \sum_{i=1}^{N_c} (\text{real}(\sqrt{F_i}))^2 \tag{3.8}$$

$$N_a = \sum_{i=1}^{N_c} (\text{real}(\sqrt{-F_i}))^2 \tag{3.9}$$

$$F = T - P \tag{3.10}$$

$$P_i = \sum_{j=1}^{N_l} S_j M_{j,i} \tag{3.11}$$

$$w_a + w_m + w_p = 1 \tag{3.12}$$

$$w_c + w_w + w_s = 1 \tag{3.13}$$

$$0 \leq w_a, w_c, w_m, w_p, w_s, w_w \tag{3.14}$$

where the collaboration factor (C) and the cost, weight, and size indicator (I) are weighted aggregate objective functions [35]; w_a, w_c, w_m, w_p, w_s, and w_w are weights specified by the designer; and $\bar{C}$, F, $\bar{I}$, M, N_a, N_c, N_l, N_m, N_p, N_r, N_t, P, P_c, P_s, P_w, S, T, T_c, T_s, and T_w are defined in the nomenclature section of this thesis.

Equation 3.1 minimizes $\bar{C}$ and $\bar{I}$ by changing the values of S_i in vector S. $\bar{C}$ indicates how efficiently the product set meets the component requirements of the target product. $\bar{I}$ indicates how closely the cost, weight, and size of a product set are to the cost, weight, and size of its corresponding target product. $\bar{C}$ and $\bar{I}$ are nonlinear normalizations of C and I, respectively, that provide near linear approximations for suitable C and I values while compressing C and I values for less suitable regions, providing more emphasis to suitable regions, see Fig. 3.4. The theoretical minimum value of $\bar{C}$ and $\bar{I}$ is 0 while the theoretical maximum is 1, resulting in $\bar{C}$ and $\bar{I}$ values close to 1 for less suitable product sets. Vector S identifies products from the recombination table included in a product set. For example, a potential S vector for Tab. 3.1 could be $S = \{0,1,2,0,0\}$. This product set includes a wheelbarrow and two shovels.

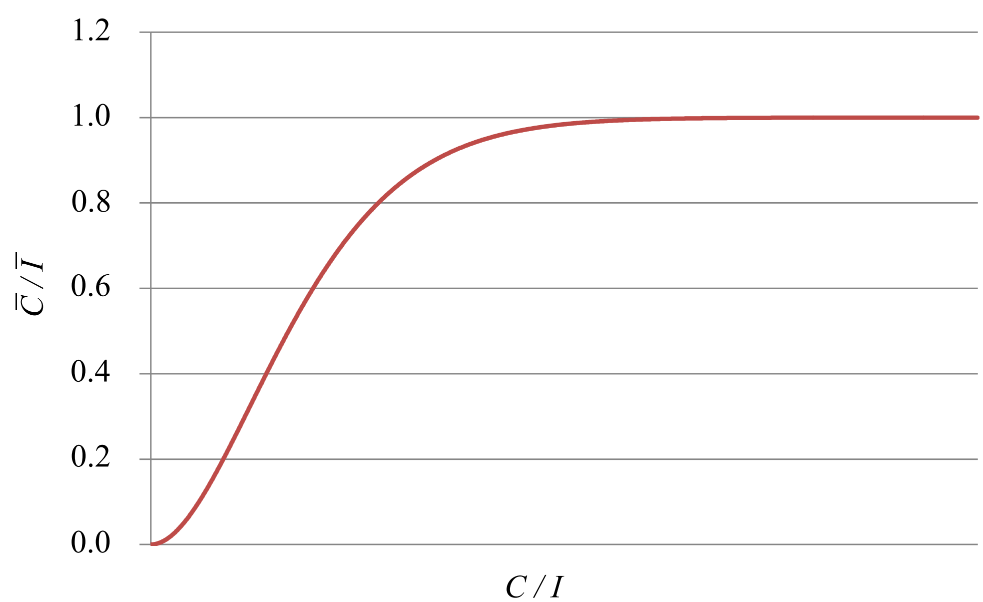


Figure 3.4: Normalization of $\bar{C}$ and $\bar{I}$

As a collaborative product is created from two or more products, the theoretical minimum number of products in a product set, N_t, is set equal to 2. Additionally, since an optimized product set requires each product to contribute at least one component required by the target product, N_r is the greatest number of products that can be identified in an optimized product set. Equations (3.8) and (3.9) sum the missing and additional components, identified in vector F as negative and positive values. The real part of the square root of each value in F is squared and summed to determine the number of missing components. The additional components are summed in like manner by first switching the sign of each value before continuing the process.

When more than one target product has been identified, the optimization routine is performed individually for each target product. This is done by setting the alpha character for the target product being examined to 1 and all other alpha characters to 0, for a given iteration. This allows components identified for multiple target products to be identified respective to the target product being examined in a given iteration.

3.4 Step 4: Select Product Set

The optimization formulation presented in Sec. 3.3 returns an optimized product set for each target product. The designer selects one of the product sets with which to complete the remaining steps of the method. Generally, this will be the product set with the lowest collaboration factor and cost, weight, and size indicator. However, when a single product set does not have both the lowest $\bar{C}$ and $\bar{I}$, the designer should decide which product set to select using multiple criteria decision making methods [36, 37].

If the selected set is deemed suitable based on $\bar{C}$ and $\bar{I}$ values and the unmodeled objectives of the designer, it proceeds to the remaining steps of the method. If it is not, the designer may select a different product set or return to a previous step and make adjustments to the information that is ultimately used in the optimization procedure. This will potentially improve the optimization results. For example, returning to Step 1 and updating the product search or returning to Step 2 to perform a more thorough product decomposition could be beneficial. However, as shown in Fig. 3.1, if a previous step is repeated, each subsequent step must also be repeated.

As identified in Sec. 3.3, the theoretical minimum value of $\bar{C}$ and $\bar{I}$ is 0 while the theoretical maximum is 1. The decision to return to previous steps is based on how close the set is to the theoretical minimum values of $\bar{C}$ and $\bar{I}$ and on review of the product set to determine if it is suitable.

3.5 Step 5: Add Missing Components

The optimized product set may not include each component required by the associated target product. This is most likely to occur when no other product in the recombination table contains the required components. If all the required component(s) have been included, this step is skipped. However, if the product set has missing component(s), one of the following methods should be used:

1. Return to Step 1 and add additional product(s) into the recombination table that contain(s) the missing component(s) and repeat Steps 2 - 5. This will most often result in the creation of new optimized product sets.

2. Add additional product(s) to the product set that have no other purpose than to fulfill the component requirement(s) missing from the product set. For example, if a required hinge component was missing from a product set, a hinge could simply be added to the product set. This will result in a product set where each product does not function individually.

3. Incorporate the missing component(s) into product(s) within the product set. A shovel, for example, could be altered to include a twisting motion if that function were needed within the product set. This will often lead to individual products in the product set with increased cost, size, and weight.

4. In the event that the missing component(s) are contained in product(s) already included in the recombination table that were not included in the optimized product set, those product(s) may be added to the product set. This is most likely to result in a product set with an increase in additional components.

Although these methods are similar, the selection of any one of these may result in either increasing the time to complete the method or impacting the performance of the products once design is completed. It is important to take into account the potential impact the selected method will have, especially on the cost, weight, and size of the final products by identifying the potential increase in the number of missing and additional components.

3.6 Step 6: Identify Interfaces

Before completing the detailed design of each product in the product set, component interfaces are identified in preparation for inclusion in the final design. These interfaces are an essential part of the user experience and fundamentally influence the reliability and safety of implementing a collaborative configuration. A detailed procedure for this step is not specified, as sufficient methods currently exist in the literature [38, 39]. However, some design guidelines to develop these interfaces are provided here.

When designing collaborative products it is important to recognize that collaborative product interfaces will likely involve tradeoffs. Specifically, they may increase individual product cost, decrease individual product functionality, and increase difficulty of switching between configurations. Therefore the designer should carefully assess the larger impact of interface decisions and should generally seek those with inexpensive interfaces in order to maximize the task-per-cost ratio discussed in Chap. 1.

Additionally, recalling the discussion of Sec. 2.1, the designer should consider the characteristics of Type II modularity, as many collaborative products can be cost-effectively implemented with this type of modularity. Finally, note that this step may be completed using traditional concept generation and selection methods [8, 15], which allow for a variety of interface concepts to be identified and the most desirable concept to be selected.

3.7 Step 7: Complete Detailed Product Design

Once product interfaces have been identified, detailed product design is completed for each product in the optimized product set. Although in many aspects the products in the optimized product set will be designed separately, it is important that the interactions between these products be well understood while completing the designs. Among other things, understanding these interactions is likely to influence: material choice, product geometry, stress/strain objectives, human factors, and product aesthetics.

CHAPTER 4. EXAMPLE 1: BLOCK PLANE

This chapter provides an implementation of the method presented in Chap. 3 through the design of a block plane. This block plane is created from a chisel and a sanding block, and results in an increase in the task-per-cost ratio of these products by 44% from 0.073 to 0.130. The purpose of this chapter is to present a simple example to allow for greater clarity of the method. Chapters 5 - 6 provide more complex examples. To provide further clarity, the example in this chapter identifies a single target product without applying the cost, weight, and size indicator aspect of the method identified in Sec. 3.3. These points of the method will be illustrated by the brick press example in Chap. 6.

4.1 Example 1 Step 1: Perform Product Search

The method begins with a product search. As this example is focused on designing an income-generating collaborative product for poverty alleviation, the search area of tools is identified. To focus the search, this area is narrowed to woodworking tools and mechanic's tools. Woodworking tools is selected because those in poverty are less likely to have automobiles. Also, since those in poverty are less likely to use power tools due to limited or no access to electricity [40], this area is narrowed further, and the search is conducted in the area of woodworking hand tools (see Fig. 4.1).

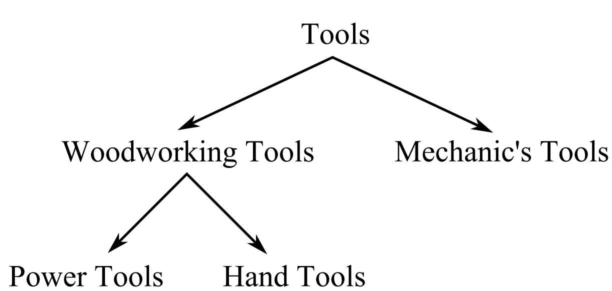


Figure 4.1: Woodworking Hand Tools Taxonomy

A list of woodworking hand tools is created using the following search methods: prior knowledge, Internet search engines, and product catalogs. Before beginning the product search, it is determined that the search will be concluded once 50 products are identified. During the search, products considered unlikely to be purchased by those in poverty, such as specialized woodworking tools, are not included in the search. A portion of this list of products is provided in the left side of Tab. 4.1.

Table 4.1: Woodworking Hand Tools Recombination Table

			Components												
		Target Product	Block	Blade	Handle	Punch	Back Saw Blade	Bar	Clamp	Short Screw	Bent-C	File	Ruler	Hammer Head	Square Handle
Product Name	Block Plane	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	Awl	0	0	0	1	1	0	0	0	0	0	0	0	0	0
	Back Saw	0	0	0	1	0	1	0	0	0	0	0	0	0	0
	Bar Clamp	0	0	0	0	0	0	1	1	0	0	0	0	0	0
	C-Clamp	0	0	0	1	0	0	0	0	1	1	0	0	0	0
	Cabinet Scraper	0	0	1	2	0	0	0	0	0	0	0	0	0	0
	Chisel	0	0	1	1	0	0	0	0	0	0	0	0	0	0
	File	0	0	0	1	0	0	0	0	0	0	1	0	0	0
	Ruler	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	Hammer	0	0	0	1	0	0	0	0	0	0	0	0	1	0
	Sanding Block	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	Square	0	0	0	0	0	0	0	0	0	0	0	1	0	1

4.2 Example 1 Step 2: Decompose Products into Components

The block plane is selected by the designer as the target product because it has a greater number of components then most of the other products in the recombination table, and a "1" is placed in the corresponding row of the target column. The block plane is then decomposed into components. This is done by first decomposing the target product structurally and then further decomposing the components both functionally and characteristically. Each of the other products in the recombination table are also decomposed into components. Components that are similar to the block plane's components are entered into corresponding columns and additional components are entered into subsequent columns of the recombination table. As this example does not implement the cost, weight, and size indicator aspect of the method, there is no need to included the cost, weight, and size of each product in the recombination table.

To provide further illustration of the decomposition, the decomposition of the block plane, chisel, and awl are presented in greater detail. The block plane is first decomposed into a block, blade, and handle. These decompositions are then further decomposed using functional and characteristic decomposition approaches. For example, the blade is decomposed functionally into a cutter and characteristically into a thin metal block. The chisel is decomposed structurally into a handle and a blade, each component corresponding directly to a block plane component. When decomposing the awl, however, a handle is again identified along with a thin rod. As this rod does not relate to the structural, functional, or characteristic decomposition of any of the block plane components, it is included in a subsequent column of the recombination table. To provide a simpler illustration, it was determined that for this example, only 12 products from the original recombination table would be presented in the recombination table provided in Tab. 4.1. However, in Sec. 4.3, the optimization routine is performed using the original recombination table.

4.3 Example 1 Step 3: Identify Optimized Product Sets

The information in the recombination table (Tab. 4.1) is used to form the relationships that govern the optimization routine presented in Sec. 3.3. The optimization routine is executed using weights of $w_m = 0.60$, $w_p = 0.24$, and $w_a = 0.16$. The product set returned by the optimization routine is a chisel and a sanding block with $\bar{C} = 0.00$. We note that because this simple example is designed to quickly illustrate the process, it is also one that is ideal in the sense that there is no tradeoff between the competing objectives in Eqn. 3.5. For this reason, the results are insensitive to the selection of weight values. For non-ideal problems, this will not be the case.

4.4 Example 1 Step 4: Select Product Set

In this step of the process, the optimized product set for the block plane is reviewed. It is concluded that this is a suitable product set because $\bar{C} = 0.00$ and a sanding block, chisel, and block plane are complementary woodworking tools that could be realistically used for income generation. Therefore, the set proceeds to the remaining steps of the method and there is no need to return to previous steps.

4.5 Example 1 Step 5: Add Missing Components

To complete the method, it is necessary to include each of the components required by the target product in the product set. In this example, this step is skipped as the optimized product set identified for the block plane contains all of the components required by the block plane. However, if a product set containing the chisel and c-clamp had been selected, the missing block component required by the target product would need to be added, as described in Sec. 3.5.

4.6 Example 1 Step 6: Identify Interfaces

Before detailed product design activities begin, interfaces between the chisel and sanding block are identified. To allow the block plane to function effectively, interfaces are required to secure the chisel blade to the sanding block. This is done by adding a groove to the sanding block and by using the plates that secure the sand paper to the sanding block to also secure the chisel blade to the sanding block. Additionally, as a handle is needed on the front of the block plane, interfaces with the chisel handle are identified for both the chisel blade and sanding block. This is accomplished by adding external threads to the chisel handle and by adding internal threads to both the chisel blade and sanding block. These component interfaces are shown in Figs. 4.2 - 4.3.

4.7 Example 1 Step 7: Complete Detailed Product Designs

The final step of the method is to complete the detailed design of the chisel and sanding block. The design of these products will ultimately determine the block plane design. Design of the chisel and sanding block are completed in parallel. Frequent consideration is given to the

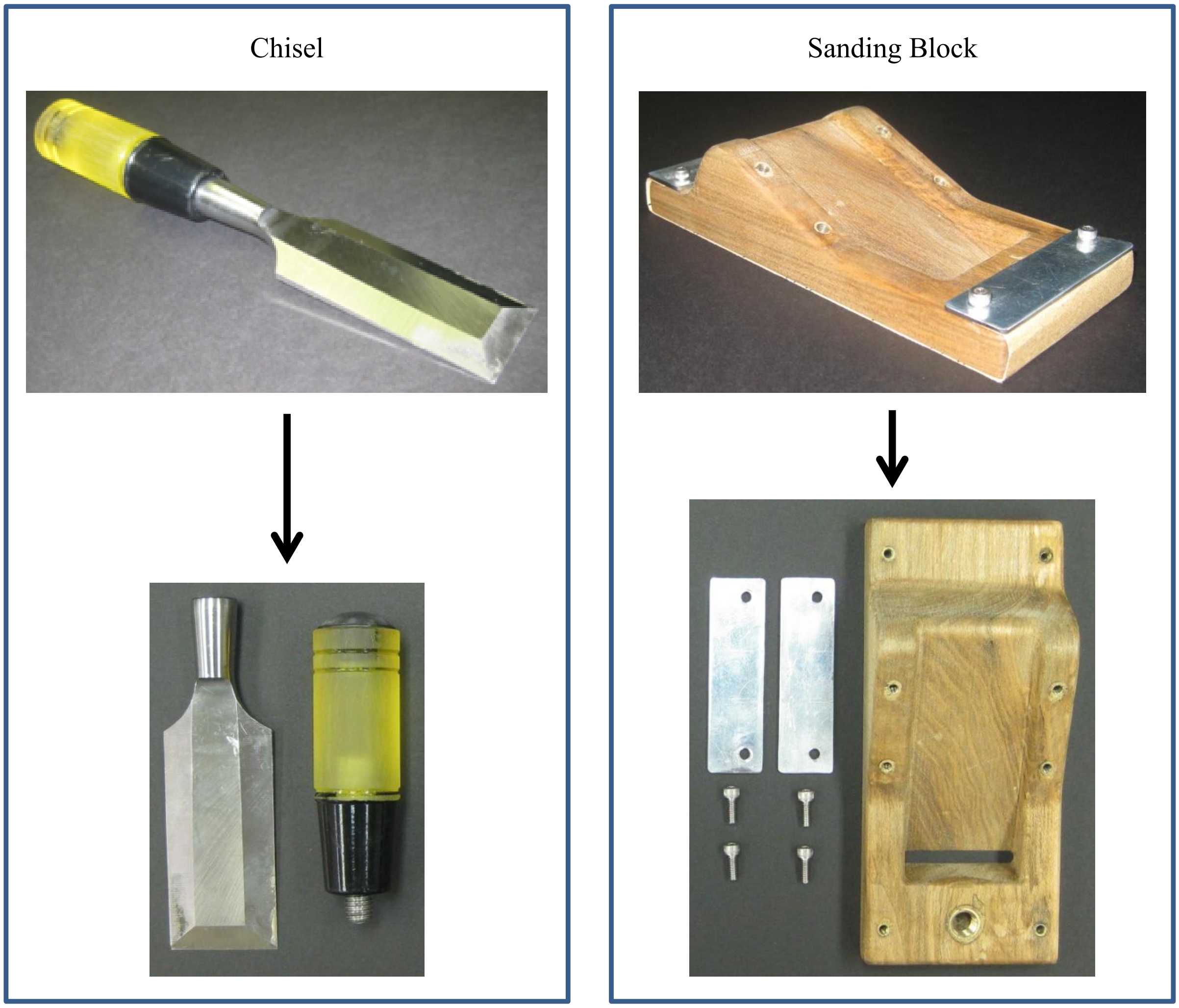


Figure 4.2: Block Plane Decomposition

appearance, performance, cost, weight, and size of the block plane. This results in an efficient design for each of the products.

4.8 Example 1 Results

The example presented in this chapter provided a demonstration of the method for designing collaborative products. The completed block plane design, as shown in Fig. 4.3, is created by joining components of a chisel and sanding block. The resulting product has additional benefits for poverty alleviation including reductions in cost, weight, and size. This occurs as a result of the block plane being created from the chisel and sanding block hardware. To further illustrate these

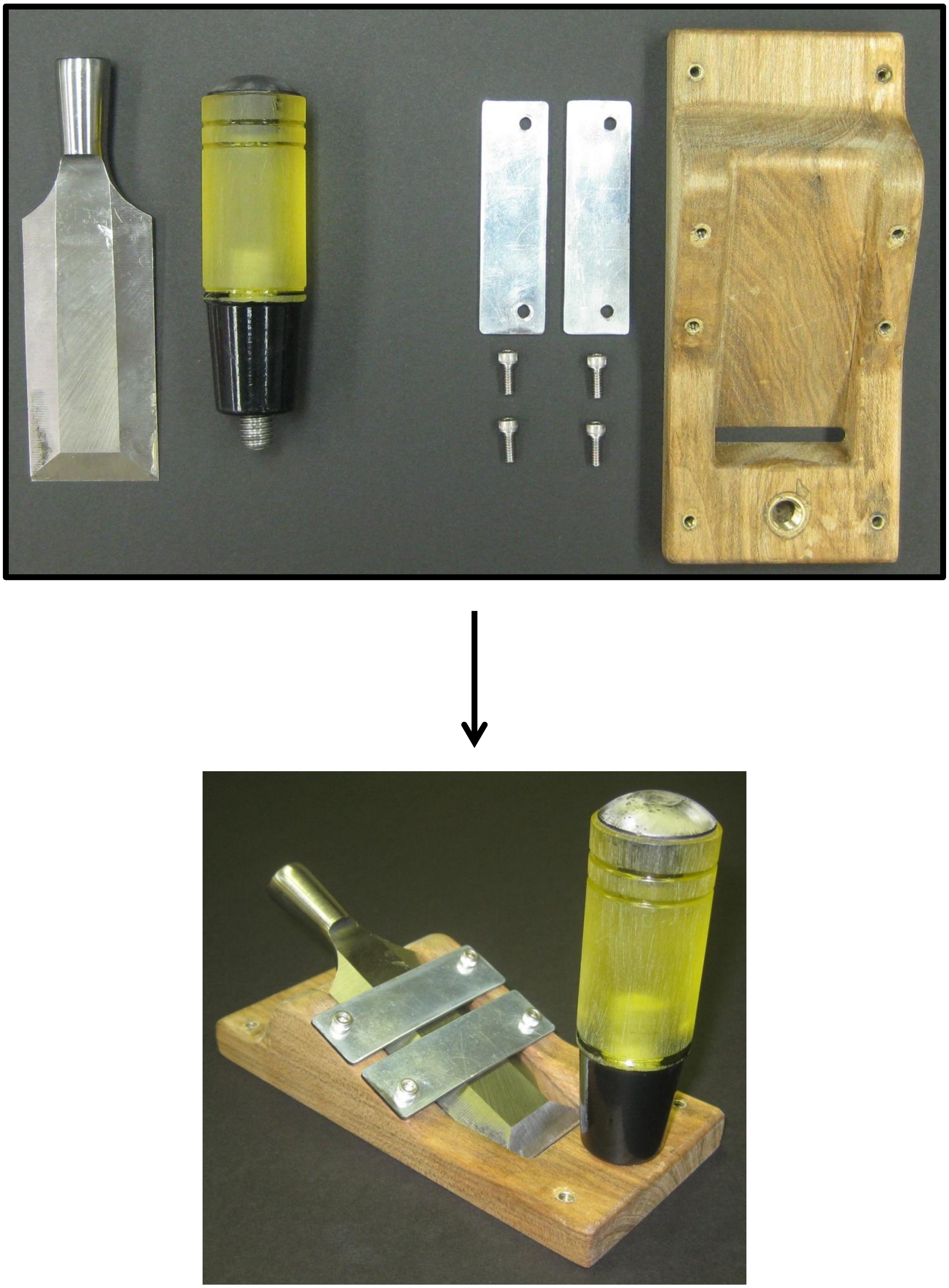


Figure 4.3: Block Plane Recombination

reductions, comparable chisels, sanding blocks, and block planes respectively cost approximately \$12, \$7, and \$22; weigh approximately 0.45 kg, 0.34 kg, and 0.68 kg; with approximate outer bounding box volumes of 107 cm^3, 221 cm^3, and 492 cm^3. This results in a total cost of \$41, a total weight of 1.47 kg, and a total volume of 820 cm^3.

In comparison, the collaborative chisel and sanding block will need several design and manufacturing changes to allow for the creation of an effective block plane, it is assumed that they will each cost an additional \$2, weigh an additional 0.06 kg, and increase in volume by 66 cm^3. The redesigned chisel and sanding block will respectively cost approximately \$14 and \$9, with weights of 0.51 kg and 0.40 kg, and volumes of 173 cm^3 and 287 cm^3. This results in a total cost, weight, and size of \$23, 0.91 kg, and 460 cm^3 with respective reductions in cost, weight, and size of 44%, 38%, and 44% as compared to the original \$41, 1.47 kg, and 820 cm^3. Additionally, this results in a $\bar{C}$ of 0.00, and compares over two thousand product sets in less than one minute.

This block plane has been designed to assist those in poverty. As seen in Fig. 4.4, the block plane was presented to a woodworker in Magugu, Tanzania. This woodworker identified the three-in-one nature of the collaborative block plane as a positive aspect of its design. Additionally, the increase in the task-per-cost ratio of 44% would be beneficial to these individuals.

Figure 4.4: Implementation of Block Plane in Magugu, Tanzania

CHAPTER 5. EXAMPLE 2: APPLE PEELER

This chapter provides another example of the method presented in Chap. 3 through the design of a collaborative apple peeler. This apple peeler is created from a paper towel holder, rolling pin, can opener, potato peeler, and c-clamp, and results in an increase in the task-per-cost ratio of these products by 20% from .081 to 0.102. As with the block plane, this example identifies a single target product without implementing the cost, weight, and size indicator aspect of the method identified in Sec. 3.3.

5.1 Example 2: Step 1: Perform Product Search

The method begins with a product search. This search is performed in the area of small kitchen tools, and a list of kitchen hand tools is identified. This is accomplished using the following search methods: prior knowledge and store catalogs. Before beginning the product search, it is determined that the search will be concluded once various store catalogs are thoroughly searched for pertinent products. While searching for products, those considered unlikely to be purchased for typical home use, such as professional appliances, are not identified in the search. A portion of the list of identified products is provided in the left side of Tab. 5.1.

5.2 Example 2: Step 2: Decompose Products into Components

The apple peeler is selected as the target product as it is less likely to be purchased by those living in poverty, and a "1" is placed in the corresponding row of the target column. The apple peeler is then decomposed structurally into components. Each of these components is then further decomposed functionally and characteristically. Each of the other products in the recombination table are also decomposed into components as they relate to the components in the apple peeler. Components that are similar to the apple peeler's components are entered into corresponding columns and additional components are entered into subsequent columns.

Table 5.1: Kitchen Hand Tools Recombination Table

Product Name	Target Product	Peeler Base	Peeler	Screw	Peeler Handle	Clamp	Can Opener	Handle	Towel Rod	Roller
		Components								
Apple Peeler	1	1	1	1	1	1	0	0	0	0
C-Clamp	0	0	0	0	0	1	0	0	0	0
Can Opener	0	0	0	0	1	0	1	0	0	0
Paper Towel Holder	0	1	0	0	0	0	0	0	1	0
Potato Peeler	0	0	1	0	0	0	0	1	0	0
Rolling Pin	0	0	0	1	0	0	0	2	0	1

To provide further illustration of the decomposition, the decomposition of the rolling pin and paper towel holder are presented in greater detail. The rolling pin is broken down into two handles, a roller, and a shaft. Each of these components is compared to the structural, functional, and characteristic definitions of the apple peeler components. When comparing the shaft to the apple peeler components, it is found that while there is not a connection between the apple peeler screw in terms of structure or function, the characteristic definition of the screw as a long shaft can be used. The shaft is therefore identified in the recombination table as a screw. Additionally, in order to identify a greater number of components from products in the recombination table that are similar to those components in the apple peeler, various configurations of each product are specifically compared to each of the apple peelers components. This is done to determine if some configuration has components that could be designed similar to an apple peeler component. For example, when decomposing the paper towel holder, various existing paper towel holders were identified. It was determined that one of the paper towel holders could be redesigned to provide a base similar to the apple peeler base.

A simplified recombination table is presented in Tab. 5.1. This is done to emphasize those products included in the optimized product set identified in Sec. 5.3 and therefore only includes these products. While the recombination table provided in this example has been simplified from the original, the optimization routine presented in Sec. 5.3 is performed using the original recombination table.

5.3 Example 2: Step 3: Identify Optimized Product Sets

The information in the recombination table (Tab. 5.1) is used to form the relationships that govern the optimization routine presented in Sec. 3.3. The optimization routine is executed using weights of $w_m = 0.60$, $w_p = 0.24$, and $w_a = 0.16$. The product set returned by the optimization routine is a paper towel holder, rolling pin, can opener, potato peeler, and c-clamp with $\bar{C} = 0.68$.

5.4 Example 2: Step 4: Select Product Set

The optimized product set for the apple peeler is reviewed. As an apple peeler, paper towel holder, rolling pin, can opener, potato peeler, and c-clamp are products that would realistically be found in a typical home and because $\bar{C} = 0.68$, it is conclude that this is a suitable product set. Note that while $\bar{C}$ is high compared to the collaborative block plane, it still results in a suitable collaborative product because it is in the suitable range of the $\bar{C}$ normalization identified in Sec. 3.3. Therefore, the set proceeds to the remaining steps of the method without a need to return to previous steps.

5.5 Example 2: Step 5: Add Missing Components

To complete the method, it is necessary to include each of the components required by the target product in the product set. In this example, this step is again skipped as the optimized product set identified for the apple peeler contains all of the components required by the apple peeler.

5.6 Example 2: Step 6: Identify Interfaces

Before detailed product design activities begin, interfaces between the apple peeler components are identified. These component interfaces are shown in Figs. 5.1 - 5.2.

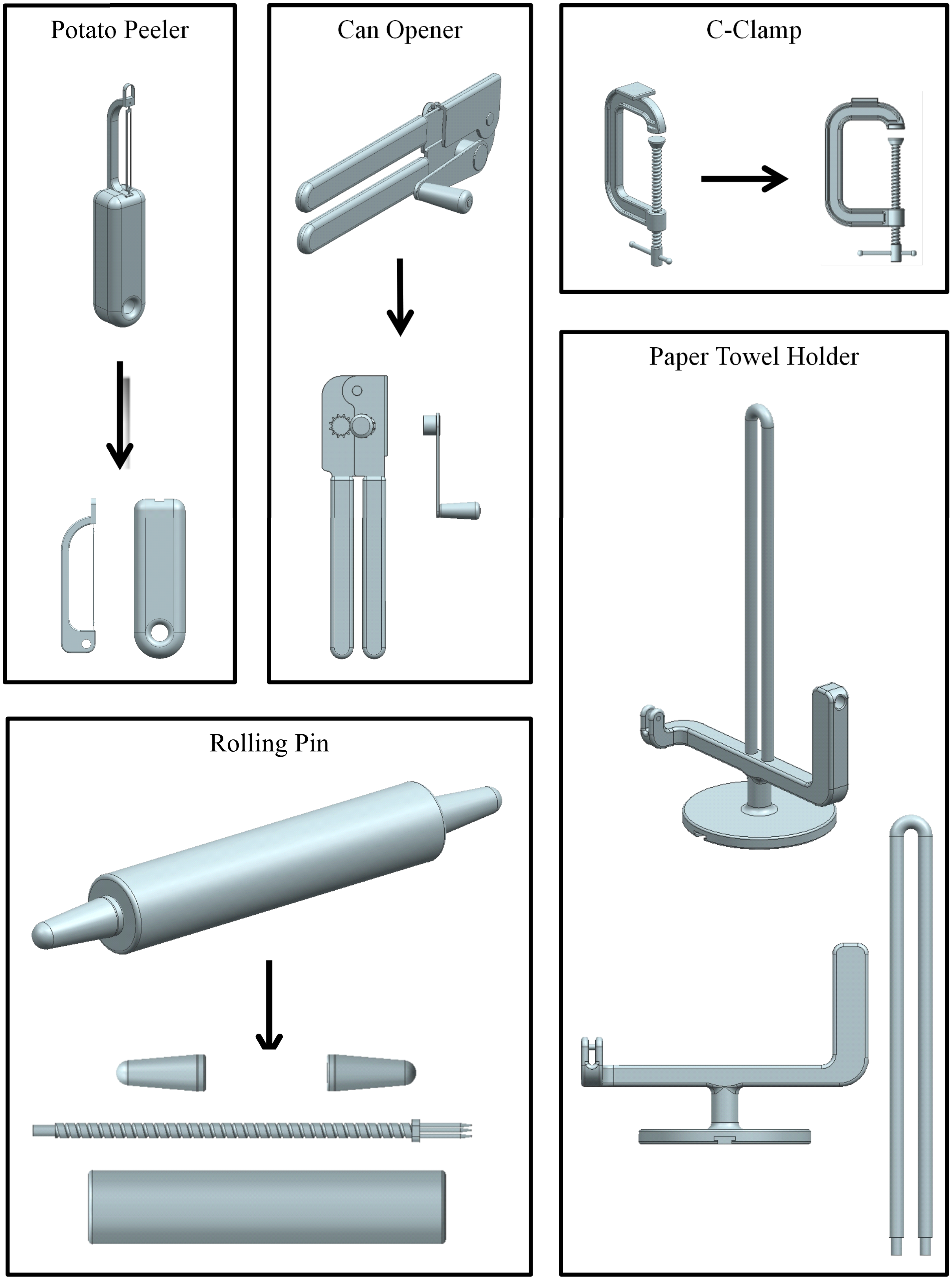


Figure 5.1: Apple Peeler Decomposition

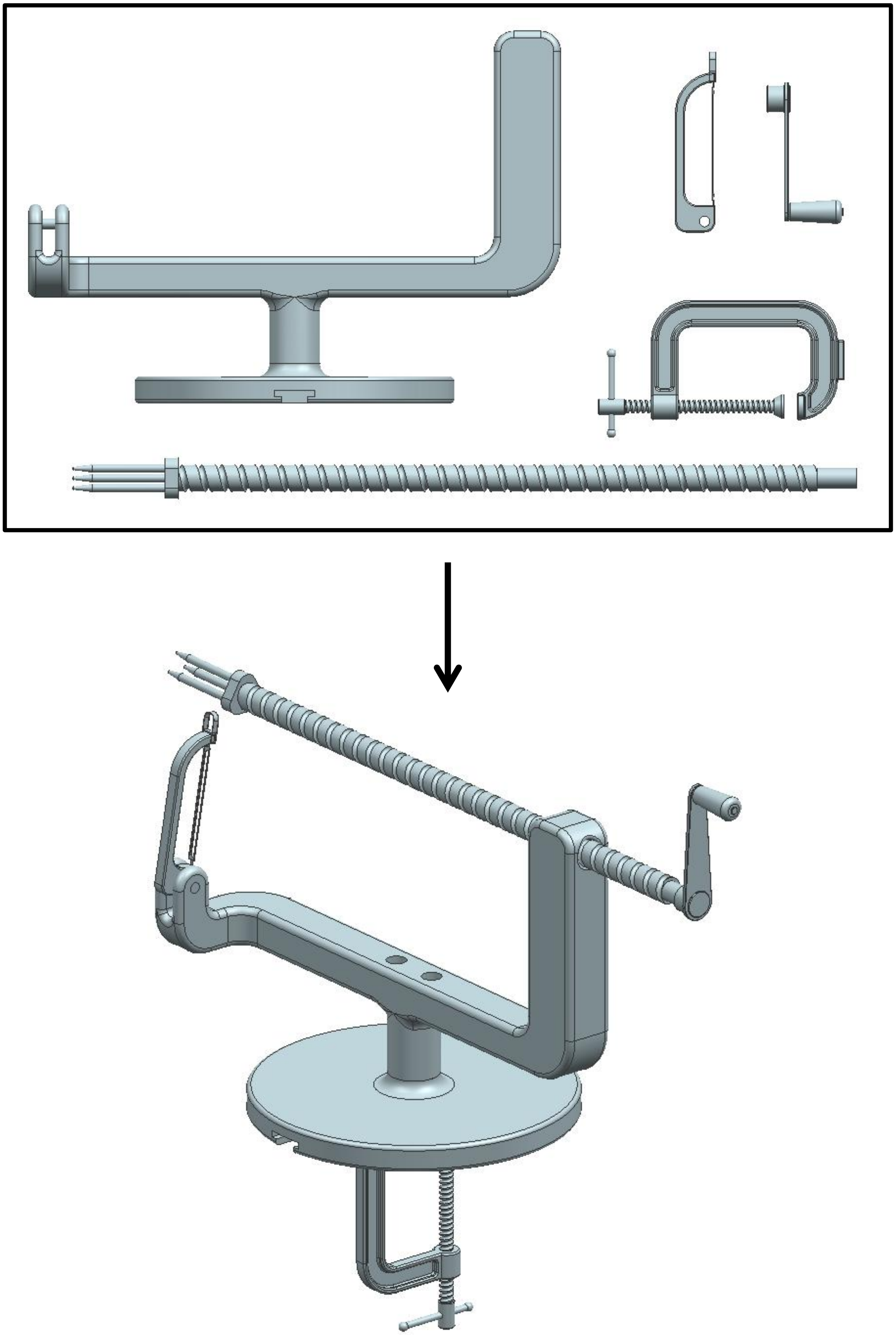


Figure 5.2: Apple Peeler Recombination

5.7 Example 2: Step 7: Complete Detailed Product Designs

The final step of the method is to complete the detailed design of the products in the apple peeler product set. The design of these products will ultimately determine the apple peeler design. Design of the products in the product set are completed in parallel, where frequent consideration is given to the appearance, performance, cost, weight, and size of the apple peeler. This facilitates an efficient design for each of the products.

5.8 Example 2: Results

The completed apple peeler, as shown in Fig. 5.2, is created by joining components of a paper towel holder, rolling pin, can opener, potato peeler, and c-clamp. This apple peeler is designed for use by those living in poverty in *developed* countries. An optimized product set was selected (using the method presented herein) from the products within the recombination table partially shown in Tab. 5.1. The result is a collaborative product with reductions in cost, weight, and size of 20%, 21%, and 24%, respectively, a $\bar{C}$ of 0.68, and compares over 300 thousand product sets in less than ten minutes. The products in the product set, the breakdown of the components, and the recombination of the components into the apple peeler are presented in Figs. 5.1 - 5.2.

CHAPTER 6. EXAMPLE 3: BRICK PRESS

This chapter provides a more complex example of the method presented in Chap. 3. This includes multiple target products and implementation of the cost, weight, and size indicator aspect of the method. This example results in the design of a collaborative brick press with reductions in cost, weight, and size of 30%, 26%, and 32%, respectively. These reductions are achieved when a brick press is constructed by recombining components from various products, as opposed to purchasing a brick press and its corresponding product set separately. Note that the task-per-cost ratio has improved by 30% from 0.040 to 0.057 when using this collaborative product approach.

6.1 Example 3 Step 1: Perform Product Search

The method begin with a product search. As this example is focused on designing an income-generating collaborative product for poverty alleviation, products in this area are identified. This is accomplished using the following search methods: prior knowledge, Internet search engines, and product catalogs. Before beginning the search, it is determined that the search will be concluded once 30 products are identified. Products considered unlikely to be purchased by those in poverty, such as electrical tools, due to limited or no access to electricity [40], are not identified. A list of these products is provided in the left side of Tab. 6.1.

6.2 Example 3 Step 2: Decompose Products into Components

The brick press and treadle pump are selected as target products as they are useful for income generation and less likely to be purchased by those in the developing world. Alpha characters "A" and "B" are entered into corresponding rows of the *target* column. The brick press and treadle pump are then decomposed into components. This is done by first decomposing each product physically and then functionally and characteristically to obtain three associated decompositions. The

Table 6.1: Poverty-Alleviating Tools Recombination Table

Product Name	Weights				Components																									
	Cost ($)	Weight (kg)	Size (m^3)	**Target Product**	Brick Mold	Mold Bottom	Mold Top	Long Handle	Cross Handle	Brick Base	Cross Bar	Fork Arm	Treadle Handle	Treadle	Cylinder	Pump Base	Cable	Cross Handle	Hose	Grill	Shovel Tool End	Water Drum	Wheel	Large Tub	Hammer Head	Axe Head	Scythe Blade	Irrigation Pump Shaft	Irrigation Pump Hoses
Brick Press	80	45	0.57	A	1	1	1	1	2	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Treadle Pump	90	43	1.00	B	0	0	0	0	0	0	0	0	1	2	2	1	1	1	2	0	0	0	0	0	0	0	0	0	0
Axe	12	2	0.06	0	0	0	0	0	A	0	0	0	0	0	0	0	0	B	0	0	0	0	0	0	0	1	0	0	0
Bucket	4	1	0.20	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
Cart	60	29	0.85	0	0	0	0	2A	0	0	0	0	2B	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0
Cement Trowel	10	4	0.08	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cook Stove	25	13	0.23	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Hatchet	10	1	0.06	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Hammer	8	1	0.03	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Hose	20	5	0.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Hoe	10	5	0.06	0	0	0	0	0	0	0	2A	A	0	0	0	0	0	B	0	0	1	0	0	0	0	0	0	0	0
Mallet	8	1	0.05	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Mattock	12	3	0.06	0	0	0	0	0	A	0	0	0	0	0	0	0	0	B	0	0	1	0	0	0	0	0	0	0	0
Pick Axe	12	3	0.07	0	0	0	0	0	A	0	0	0	0	0	0	0	0	B	0	0	0	0	0	0	0	1	0	0	0
Pitch Fork	11	6	0.10	0	0	0	0	A	0	0	0	0	B	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Plow	75	41	0.85	0	0	0	0	2A	0	0	0	0	0	2B	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Post Hole Digger	15	8	0.12	0	0	0	0	2A	0	0	0	0	2B	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Rake	10	5	0.06	0	0	0	0	A	A	0	0	0	B	0	0	0	0	B	0	0	1	0	0	0	0	0	0	0	0
Rain Barrel	12	5	0.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Rope	4	1	0.06	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Sickle	8	2	0.03	0	0	0	0	0	A	0	0	0	0	0	0	0	0	B	0	0	0	0	0	0	0	0	1	0	0
Scythe	15	5	0.14	0	0	0	0	A	0	0	2	0	B	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Shovel	10	5	0.06	0	0	0	0	A	0	0	0	0	B	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Small Irrigation Pump	30	7	0.14	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
Trowel	6	2	0.02	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Wash Basin	25	11	0.57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Water Roller	35	7	0.51	0	0	0	0	0	0	A	0	0	0	0	0	0	B	0	0	0	0	1	0	0	0	0	0	0	0
Water Storage	45	11	0.71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Watering Can	9	4	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Wheelbarrow	35	20	0.71	0	0	1	1	2A	0	0	0	0	0	2B	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0

decomposition of the non-target components is performed iteratively, resulting in modifications to the original decomposition.

To provide further illustration of the decomposition, the decomposition of the cook stove, long rod, and cross bar are presented in greater detail. The cook stove is broken down structurally into a grill, stove bottom, and stove enclosure. The structural definitions of the stove bottom and mold bottom are similar, and the stove bottom is identified as such in the recombination table. The stove enclosure, however, while not structurally similar to the brick mold, is characteristically similar. Therefore, the enclosure is identified in the recombination table as a brick mold. The grill, which is not similar to any of the brick press components is identified in a subsequent column of the recombination table. Additionally, the long rod and cross bar components were originally decomposed as a single upper handle component. When decomposing the shovel, the shovel handle did not meet this requirement. However, by adjusting the brick press decomposition to identify the upper handle as two separate components, the long handle component of the brick press alone is similar to the shovel handle.

The decomposition continues until each non-target product is decomposed. Components that are similar to the target products' components are entered into corresponding columns and additional components are entered into subsequent columns. When components from a non-target product are related to components from both the brick press and the treadle pump, such as the the handle component from the cart, the respective alpha characters are instead entered into the table. Products that are unlikely to be purchased or used in connection with a target product, such as a small irrigation pump with a treadle pump are not linked to that target product. The resulting recombination table is provided in Tab. 6.1.

6.3 Example 3 Step 3: Identify Optimized Product Sets

The information in the recombination table (Tab. 6.1) is used to form the relationships that govern the optimization routine presented in Sec. 3.3. The optimization routine is executed using weights of $w_m = 0.60$, $w_p = 0.24$, $w_a = 0.16$, $w_c = 0.85$, $w_w = 0.10$, and $w_s = 0.05$. The product set returned by the optimization routine for the brick press is a cook stove, small irrigation pump, shovel, rake, hoe, and two water transportation rollers with $\bar{C} = 0.35$ and $\bar{I} = 0.33$. The product set returned for the treadle pump is a plow, rake, rope, and two hoses with $\bar{C} = 0.44$ and $\bar{I} = 0.36$.

These products sets are identified as the product sets most suitable to be recombined into their respective target products.

6.4 Example 3 Step 4: Select Product Set

In this step of the process, the optimized product sets for the brick press and treadle pump are reviewed. The brick press is selected because it has lower $\bar{C}$ and $\bar{I}$ values than the product set for the treadle pump. Additionally, the products in the brick press product set are complimentary poverty alleviating tools that could be realistically used for income generation. Therefore, this set proceeds to the remaining steps of the method and there is no need to return to previous steps.

6.5 Example 3 Step 5: Add Missing Components

To complete the method, it is necessary to include each of the components required by the target product in the product set. In this example, this step is once again skipped as the optimized product set identified for the brick press contains all of the components required by the brick press. However, if the product set for the treadle pump had been selected, the missing cylinder components required by the target product would need to be added, as described in Sec. 3.5.

6.6 Example 3 Step 6: Identify Interfaces

Before detailed product design activities begin, interfaces between components of the brick press are identified. In order for the brick press to function properly, various interfaces are required to connect components of the brick press. As the brick press requires significant force to operate, robust interfaces are required. Interfaces resulting in the lowest additional cost while allowing the brick press to function efficiently are identified. This is done using interface design methods, as described in the literature.

6.7 Example 3 Step 7: Complete Detailed Product Designs

The final step of the method is to complete the detailed design of the cook stove, small irrigation pump, shovel, rake, hoe, and water transportation rollers. The design of these products will ultimately determine the brick press design. Design of each of the products in the product set is completed at the same time, where frequent consideration is given to the appearance, performance, cost, weight, and size of the brick press. For example, when designing these products, the shovel and rake handles are designed to withstand higher stresses required in the brick press configuration. This results in the successful design of each of the products, shown in Figs. 6.1 - 6.2.

6.8 Example 3 Results

The example presented in this chapter provided a demonstration of the method for designing collaborative products. The completed brick press design, as shown in Fig. 6.2, is created by joining components of a cook stove, small irrigation pump, shovel, rake, hoe, and two water transportation rollers. The resulting product has additional benefits for poverty alleviation including reductions in cost, weight, and size. This occurs as a result of the brick press being created from the products in the product set. To further illustrate these reductions, a comparable brick press, cook stove, small irrigation pump, shovel, rake, hoe, and water transportation rollers approximately cost a total of $200, weigh approximately 86 kg, with an approximate total outer bounding box volume of 1.6 m^3.

In comparison, the collaborative product set will require several design and manufacturing changes to allow for the creation of an effective brick press, it is determined that in total they will cost an additional $40, weigh an additional 23 kg, and increase in volume by 0.06 m^3. This results in a total cost, weight, and size of approximately $140, 64 kg, and 1.0 m^3 with respective reductions in cost, weight, and size of 30%, 26%, and 32% as compared to the original $200, 86 kg, and 1.6 m^3. Additionally, this results in a $\bar{C}$ of 0.35, a $\bar{I}$ of 0.33, and compares over one million product sets in less than 100 minutes.

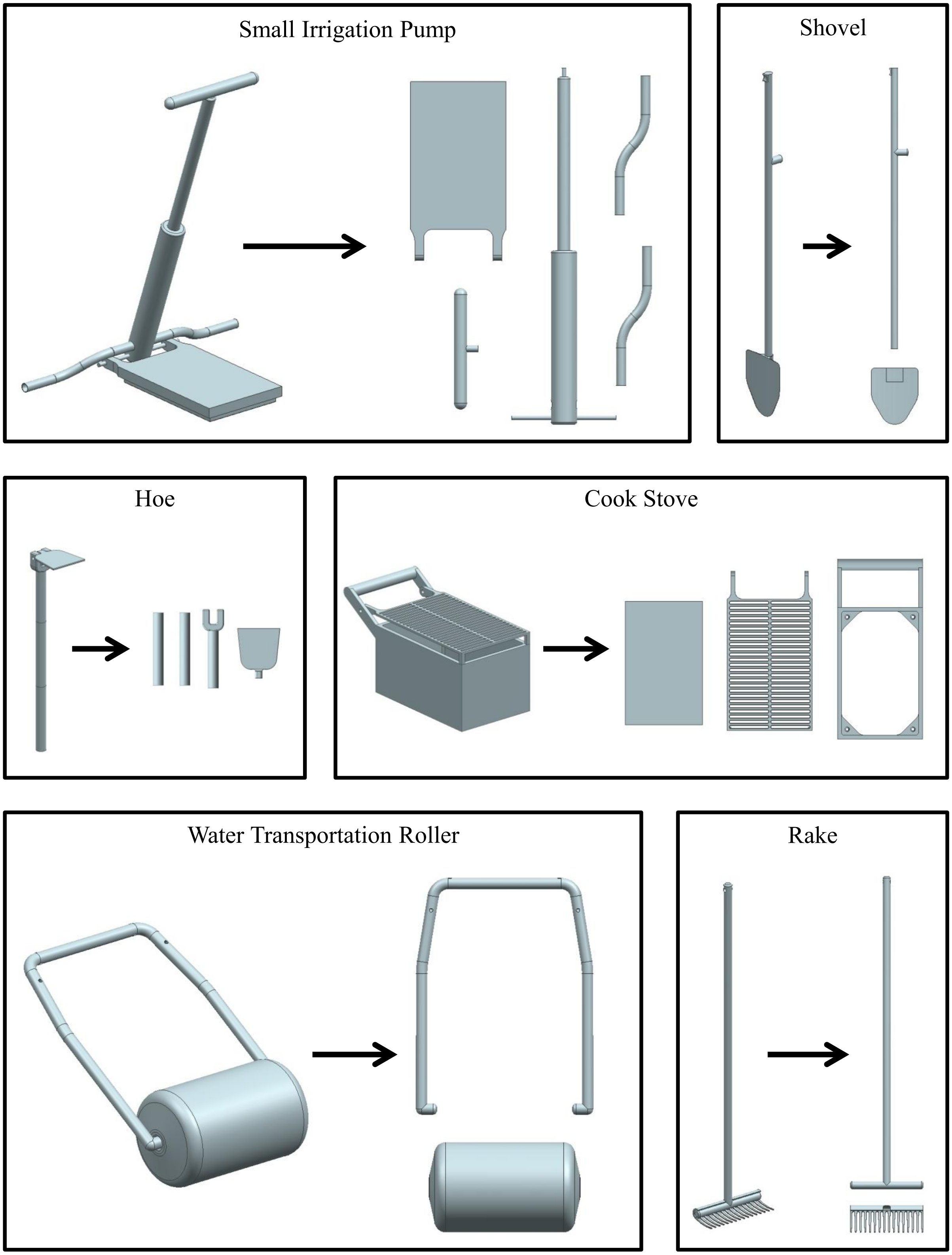


Figure 6.1: Brick Press Decomposition

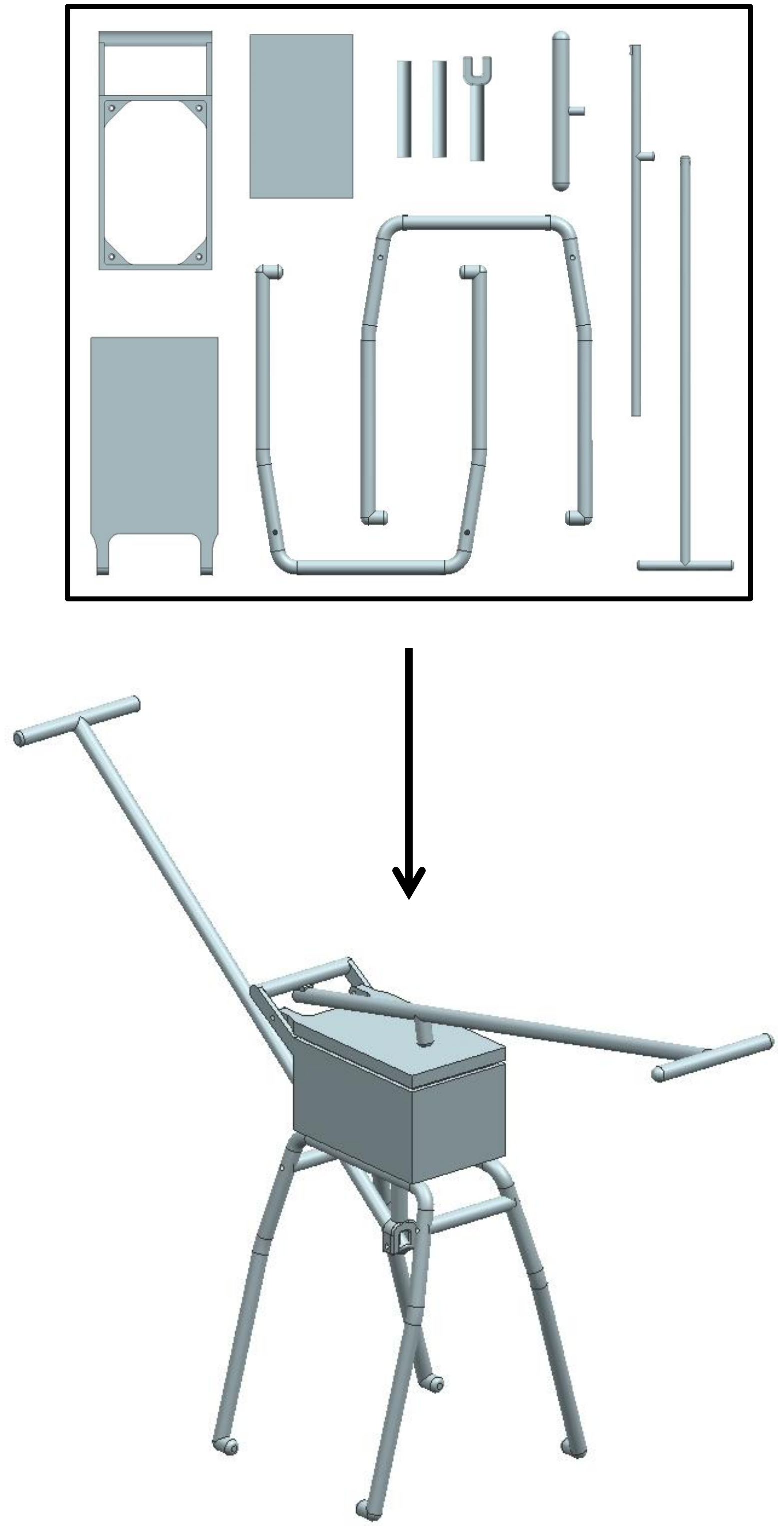


Figure 6.2: Brick Press Recombination

CHAPTER 7. CONCLUDING REMARKS

This thesis has presented a method for designing collaborative products for poverty alleviation. As illustrated in this thesis, the method presented herein is used to design collaborative products that are created when physical components from two or more products are temporarily recombined to form another product capable of performing entirely new tasks. In Chap. 3 a good collaborative design method was described as one that results in reductions in cost, weight, and size of a set of products, provides a measure of how efficiently product components are used within a design, and provides an ability to effectively search a large design space. The examples presented in Chaps. 4-6 illustrate reductions in the cost, weight, and size of 44%, 38%, and 44%, a $\bar{C}$ of 0.00, and comparison of over two thousand product sets in less than one minute for the block plane design; reductions in cost, weight, and size of 20%, 21%, and 24%, respectively, a $\bar{C}$ of 0.68, and comparison of over 300 thousand product sets in less than ten minutes for the apple peeler design; and reductions in cost, weight, and size of 30%, 26%, and 32%, respectively, a $\bar{C}$ of 0.35, an $\bar{I}$ of 0.33, and comparison of over one million product sets in less than 100 minutes for the brick press design.

From these examples, it is shown that the method presented herein in useful and effective in designing collaborative products. It can be seen from these examples that while product sets with a low $\bar{C}$ often result in suitable collaborative products, product sets with a higher $\bar{C}$ can also result in suitable collaborative products. Overall, the author has concluded that this method is capable of resulting in the design of suitable collaborative products, particularly in the area of poverty alleviation.

Additional research on this topic includes: creating a component repository to store structural, functional, and characteristic component decomposition information, researching methods to design components to be interchangeable with multiple collaborative products, and developing a method for designing the interfaces of collaborative products.

A number of design repositories have been created for storing design knowledge in terms of product function [17, 41, 42]. Similar to these repositories, it is suggested that a repository be created for storing component decomposition information in terms of function and physical characteristic as they relate to the structural definition of each component. In this repository, individual components would be identified structurally and potential functional and characteristic definitions would be included for each component. This information could then be used to assist a designer in identifying potential component definitions.

To illustrate the use of such a design repository, take for example the collaborative apple peeler presented in Chap. 5. In this example, the shaft of the rolling pin is also used as a screw when reconfigured into the apple peeler. When decomposing the rolling pin as it relates to the apple peeler, it is necessary to identify this connection within the recombination table. In using the suggested design repository, the designer could identify a shaft in the repository. This component would list other component definitions that could potentially be functionally or characteristically similar. For example, the shaft would likely include the following components: pipe, handle, screw, etc. While it is noted that each of these suggestions would not necessarily apply to the rolling pin, in this case, the screw needed for the apple peeler is similar to the rolling pin shaft. The shaft can then be identified as such in the recombination table. This would ultimately increase the potential for identifying components for recombination into collaborative products.

Further increases in the task-per-cost ratio of a set of products could also be achieved by increasing the number of target products associated with a product set. This would result in a single product set that could be recombined, one at a time, into two or more collaborative products. In this case, a single component may be used on several target products. This would ultimately make the design of these products more difficult, as components would be used to create a greater number of individual products. Therefore, research should be done on designing such products. This is likely to include methods for designing universal collaborative interfaces between components.

As mentioned in Sec. 3.6, various methods currently exist in the literature for designing product interfaces [38, 39]. However, additional research could be done on designing interfaces specific to collaborative products, especially where multiple target products are involved. This would primarily involve researching methods for designing interfaces that connect components to multiple target products while maintaining a high task-per-cost ratio.

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