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Experimenting with concepts from modular product design and multi-objective optimization to benefit people living in poverty

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A B S T R A C T

Every discipline has its own specific knowledge that has been accumulated and refined over time. In the aerospace industry, for example, the domain knowledge of multidisciplinary optimization has grown and matured. The same has happened with domain knowledge related to modularity in the consumer product design industry. Knowledge from these domains has carried over to other domains such as automotive, medical, and defense, and has enabled advances in these disciplines. One domain that has been underserved by the advanced engineering methodologies coming from other disciplines is the domain of *design for the developing world*. Exploring the use of engineering domain knowledge to alleviate poverty is a valuable study that will open opportunities to use engineering to benefit resource poor individuals. This paper explores the domain knowledge of modularity and multi-objective optimization and applies it to the domain of design for the developing world by introducing the concept of collaborative products to assist the resource poor individuals. Can knowledge from one domain be used in a new domain, and if so, what would it look like? In this paper, a general methodology is presented, followed by a simple example to illustrate the design of a collaborative product for the developing world. The paper suggests that by using domain knowledge from a non-related domain paired with the method presented, products can be designed and optimized for collaborative performance with potential to both generate new income and save money for the end customers.

1. Introduction and background

This paper uses domain knowledge from one or more areas of engineering and applies it in the area of design for the developing world. We are motivated to do and report on this because we believe that many different areas of engineering expertise can be re-imagined and lead to new poverty alleviating products. In this paper we build on our own expertise in modular-product design and multi-objective optimization to create a new product category created specifically for issues faced by those in poverty. The new category is called collaborative products, which are created when physical components from two or more products are brought together to form a **different** product capable of performing additional tasks **that could not have been done with the individual products alone** (Morrise et al., 2011). The goal of the method introduced herein is to design products that generate income, and appeal to a greater number of individuals due to affordability.

Modular product design is an essential part of the design of collaborative products since it involves joining together multiple products. In the literature, this type of design is known as *Type II*

modularity. It is defined as the design of interfaces with modules that can only be attached to other specific modules through a unique interface, effectively reducing the complexity of the products (Strong et al., 2003; Yoo et al., 2012). Research has recently been aimed at bringing domain knowledge from the design of modular/reconfigurable products to the domain of design for the developing world (Lewis et al., 2010; Mattson and Magleby, 2001; Morrise et al., 2011; Weaver et al., 2010).

Collaborative products have the potential to significantly influence the impact that income-generating products can have on poverty alleviation efforts by reducing the cost of a set of products capable of performing a specified set of tasks. This is accomplished by increasing the task-per-cost ratio of a set of products (Morrise et al., 2011) so as to reduce the number of products needed to perform a set of tasks. It is this ability to perform a set of tasks with fewer products that effectively lowers the financial risk for the user and increases his or her likelihood of purchasing and benefiting from these products.

The basic strategy surrounding the notion of collaborative products is this: Designers begin by identifying a relatively complex product that is currently unaffordable for someone living in poverty. That product is

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then decomposed into sub-products that are designed to be useful and affordable as stand-alone products. Individuals living in poverty could then share the purchase of the complex product with others in their community by having each person buy independently useful portions (or sub-products) of the complex product. In some cases the sub-products may be used to generate income to support the purchase of additional sub-products, thus working toward the complex product, alone or as a community. Although not the focus of this paper, it is important to recognize that to be an effective strategy, the design, marketing, and sale of the collaborative products would need to be carefully planned so that users would know which sub-products work together and how they should be assembled.

The method presented in this paper for designing collaborative products also involves many changing and competing needs that must be addressed to successfully design a product. One way to meet these demands and resolve the competing nature of both present and future needs of a set of products is through multi-objective optimization (Kasprzak and Lewis, 2000; Messac and Mattson, 2002; Wu and Azarm, 2001). This technique serves as a fundamental foundation to the design method presented in this paper. Multi-objective optimization characterizes the trade-offs between design objectives by identifying a Pareto frontier or a set of non-dominated optimal solutions. These Pareto solutions are of importance because they show that design objectives have been improved to their full potential without sacrificing the performance of objectives in other areas (Kasprzak and Lewis, 2000; Messac and Mattson, 2002; Wu and Azarm, 2001; Lewis et al., 2010; Nordin et al., 2011).

A set of optimal solutions belonging to a Pareto frontier can be found through the following generic multi-objective optimization problem presented as *Problem 1* (P1):

$$\min_x \left\{ \mu_1(x, p), \mu_2(x, p), \dots, \mu_{\mu}(x, p) \right\} \quad (n_{\mu} \geq 2) \quad (1)$$

subject to:

$$g_q(x, p) \leq 0 \quad \forall q \in \{1, \dots, n_g\} \quad (2)$$

$$h_k(x, p) = 0 \quad \forall k \in \{1, \dots, n_h\} \quad (3)$$

$$x_{jl} \leq x_j \leq x_{ju} \quad \forall j \in \{1, \dots, n_x\} \quad (4)$$

where μ_i denotes the i -th generic design objective to be minimized (i.e., cost or size of a product); x is a vector of design variables that define the design of a product (i.e., length, width, height); p is a vector of design parameters (i.e., material yield strength, modulus of elasticity) that will be treated as constants in the optimization; x_{lj} and x_{uj} define the upper and lower bounds of the j -th design variable; g is a set of inequality constraints; and h is a set of equality constraints. Note that the objectives and constraints are functions of both x and p , and that the objectives will be minimized by changing the values of x .

Aside from the developing world context, collaborative products can also be applied in the *developed* world. Many individuals within the United States suffer from poverty, living in small dwellings with limited storage space (Bishaw and Macartney, 2010). Money is also limited for these individuals, and collaborative products are a way to help maximize available storage space while providing a set of product functions that are extremely affordable. Other identified areas that could benefit from collaborative products may include payload conscious industries such as aerospace and backpacking (Morrise et al., 2011).

Morrise et al. have developed a method for designing collaborative products, consisting of an eight-step process (Morrise et al., 2011). While this method serves as a basic foundation to the design of collaborative products, the authors of this paper propose a revised method that builds upon and strengthens this existing process. Again, the goal behind the method is to increase the earning potential and simultaneously decrease the financial risk for the user. By buying **all the products included** in the Collaborative Product System, a new

previously unattainable income generating task can be performed. By having a system of products that can perform **one task** as a collaborative product and where each product can perform **individual tasks**, the task-per-cost ratio is increased and the potential for income generation is also increased. The steps of the new method will be further explained in Section 2 of this paper.

The remainder of this paper is organized as follows: The theory for designing products for optimal individual and collaborative performance is found in Section 2. In Section 3, the design of a simple collaborative brick press demonstrates implementation of the presented method, followed by concluding remarks in Section 4.

2. Method of designing products for optimal collaborative performance

This section presents a method that seeks to understand customer needs and meet them through the use of individual and collaborative products. The method consists of a nine-step process which can be abbreviated as follows: (1) Understand customer needs, (2) Identify a product that satisfies a need, (3) Decompose the identified product, (4) Use the decomposed components to satisfy additional needs, (5) Identify the product interfaces (6) Characterize the collaborative design space, (7) Define the areas of Pareto offset, (8) Identify the designs that fall within the offset areas, and (9) Identify the optimal product designs.

2.1. Step 1: understand broad customer needs

The first step of the method is to seek out the broad customer needs that exist in society. This involves the study of groups and people as they go about their everyday lives. Research is carried out by immersing oneself in the culture and gathering information from individuals and potential customers of that society (Emerson et al., 2011). Other traditional methods used to gather this information include interviews, surveys, and observations (Pahl et al., 2007; Ulrich and Eppinger, 2008). When it is not possible for the designer to be on site, a complementor can be used to gather the needed information (Ottosson, 2015; Munksgaard and Freytag, 2011). Some other aspects to consider when developing products for the developing world is to have local knowledge and include on the design team the individuals that will be using the product (Mattson and Wood, 2014; Donaldson, 2006). By using one or multiple of these methods the designer is able to gather statements from the customer and translate them into customer needs. It is essential to have a clear understanding of the customer needs to determine how to best meet them.

One way to focus the efforts of gathering customer needs is to select and work within a need category. Examples of categories when designing for the developing world might include: farming, hunting, tools, education, housing, cooking, health care, transportation, etc. The goal is to find an area that would benefit from a task-to-cost ratio increase—an area where new opportunities for income generation may be found (Austin-Breneman and Yang, 2013). For individuals in the developing world, the financial risk is lowered as this ratio increases. As this ratio and the chance of income generation are increased, people living in poverty will have more financial resources, which can lead to a better life (Prahallad, 2010). If products can be affordable combined to complete a greater number of valuable tasks, the user will benefit from a lower cost. The end result of completing this step is to come to know the customer on a deeper level in order to gain an understanding of what could be done to benefit their lives.

2.2. Step 2: create/select a product that satisfies one of the broad needs

After the customer needs have been sufficiently understood, the designer identifies a product that satisfies one or more of those needs.

It can be a product that already exists in a society or one that is to be developed. Many design processes exist for creating new products, one of which consists of a five-step process (Pahl et al., 2007). The steps of this method are: (1) explore, (2) ideate and select, (3) engineer, testing and refinement, and (4) production ramp-up.

The explore step encompasses a wide range of activities including understanding the customer needs from Step 1 and defining the problem to be solved. The ideate and select step allows the designer to formulate new ideas based upon customer needs, evaluate those ideas, narrow them down, and ultimately select the most promising concept for further development. During the engineering of an idea, detail design commences. The selected concept is proven from an engineering design standpoint by defining part geometry, material type, and manufacturing steps. The selected design is then tested for weaknesses and refined as necessary. Design changes are implemented as needed to ensure the product satisfies the key customer needs. Production ramp-up will likely take place at the end of the collaborative product design process, rather than at this point in the method. It is a crucial step in the design process, but should be considered when all details of the collaborative product design have been established.

We note that it is here, in Step 2, that many of the design characteristics that cannot be quantified are chosen by the designer. Generally speaking, these characteristics will remain a fundamental part of the design even after the optimization search algorithm is used in Step 6 to fine tune the design parameters that define the characteristics chosen here.

The resulting product from Step 2, whether newly designed or already existing, will serve as the starting point to the creation of a collaborative product. This product typically will have the following qualities: be comprised of multiple if not many components; is desirable but generally not purchased by a customer due to its high cost, weight, or size; and is generally used less frequently than typical, everyday products. A product that is generally used less frequent tend to be a good candidate for becoming a collaborative product since the components used (other products), are unusable while they are configured into a collaborative product (Morrise et al., 2011).

2.3. Step 3: decompose the selected product into components

Step 3 requires the designer to decompose the selected product into its individual components. This step is necessary to begin learning about what products will make up the collaborative product and be able to satisfy additional customer needs. Generally, the selected product is decomposed only into the components required to perform an intended function. In other words, the decomposition will not include secondary components such as fasteners (Morrise et al., 2011).

This type of product is decomposed three ways—structurally, functionally, and by physical characteristics. From a structural standpoint, the product is decomposed where the resulting components make up the primary structure of the product. Functionally, the product is decomposed by identifying the primary function of each component identified in structural decomposition. Lastly, decomposition by physical characteristics is completed by identifying the relevant characteristics such as size, shape, and color of each component identified during structural decomposition.

An example of a bicycle wheel decomposition, provided by Morrise et al., helps to illustrate the decomposition process (Morrise et al., 2011). This example demonstrates the need for three types of decomposition and how each type brings clarity to the collaborative design process. See Fig. 1 for the bicycle wheel decomposition based upon structural, functional, and physical characteristics. If only structural decomposition was carried out, then a bicycle wheel would be viewed based on its structure alone. In other words, a bicycle wheel would only relate to other wheels and would not have any known relationship based on function. Decomposition to this extent allows the designer to

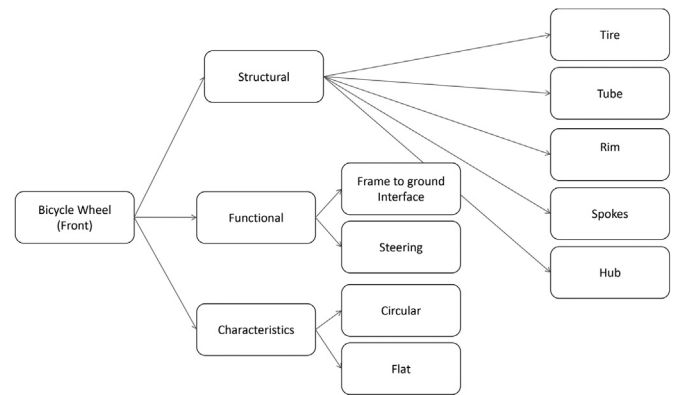


Fig. 1. Bicycle wheel decomposition adapted from Morrise et al. (2011).

better understand the components and characteristics that a selected product contains.

2.4. Step 4: determine what other products can be created from the components to meet different broad customer needs, while if desired, adding missing secondary components

In this step, additional broad customer needs are studied to determine other products that can be made from the decomposed product components. Tools such as concept combination tables, recombination tables, and morphological matrices can be used to assist in this step (Ulrich and Eppinger, 2016; Geum and Park, 2016). Needs are considered and thought is given to each decomposed product to determine how to best meet each additional need. The designer must be cautious of multiple products that may require concurrent use since the collaborative product will require use of all its components to function. Therefore, it may be best to select products that meet needs in different categories, activities, or seasons to prevent this from happening. If needs be, the designer can also add secondary components to complete a secondary design. Like Step 2, Step 4 is also centered on qualitative elements of the design that will simply be fine-tuned as part of the numerical search carried out in Step 6.

2.5. Step 5: identify the interfaces between components

Once all products have been chosen and the most important needs have been met, the designer must identify the interfaces between components. The addition of interfaces to the product may introduce weaknesses. However, it is because of these interfaces that the task-per-cost ratio is able to increase. As was stated in Section 1, this ratio is important to individuals in the developing world, as it defines the number of tasks a product can perform based on its cost. The higher this ratio is, the lower the financial risk will be for the end user. These interfaces are crucial to the functionality and reliability of the collaborative product as well as the safety of the user. They will determine how positive the user experience is and its usefulness as a collaborative product. Especially to reduce the onus placed on the end user regarding the complexity of knowing what and how to assemble the collaborative product, designers should focus on improving the user friendliness of transitioning between individual and collaborative product use. A detailed process for designing interfaces will not be discussed in this paper since sufficient methods already exist in the literature (Wie et al., 2001; Blackenfelt and Sellgren, 2000).

2.6. Step 6: characterize the collaborative design space of the product set and collaborative product

When designing a product that will be part of a collaborative product, optimal design for each component can not always be

achieved. This step must therefore start with the gathering of the knowledge of the product set and the corresponding collaborative product. Thus, the impact of design changes of both individual and collaborative product performance must be considered. All objective values must therefore be accounted for when performing a multi-objective optimization. The points along the Pareto frontier (graphically illustrated in Fig. 2) represent the best possible trade-offs between the selected design objectives of each product. Although a design is located on the Pareto frontier of an individual product, the corresponding performance of the collaborative product, and the other products in the set, are not guaranteed to be Pareto optimal in each product's objective space. Because of this, the collaborative performance of a product correlates to the measured offset of its design from the corresponding Pareto frontier. By maximizing the collaborative performance of each product simultaneously, a product set is defined with optimal collaborative performance. Like all mathematically assisted design methods, the designer must be aware of the fidelity of the mathematics involved and use judgment as to if the mathematics sufficiently capture the designer's intent.

Recognizing the inherent trade-offs and compromises in collaborative performance that must be explored, the purpose of steps 6–9 is to implement an optimization-based approach to mitigating these trade-offs. Figure 2 graphically represents the intent of balancing these trade-offs using the method presented in this section for two products that are combined to create a third product. Although the presented method is not limited to the simple case presented in Fig. 2, a limited number of products are used for simplicity of visualization purposes. From Fig. 2 it can be observed that the presented optimization routines select designs for each product that fall within identified offset areas within each objective space. In order to enable the use of optimization methods to explore possible design solutions, objectives for each of the products in the set and the collaborative product are identified, and models of these objectives are created that incorporate the intended product interfaces. Using the developed models, the design space of each product is determined by a multi-objective optimization problem similar to (P1).

To define each product and identify the variables that couple the design of each product in the set to the collaborative product, the design variables for each product are divided into three groups: interface variables (x_I), collaborative variables (x_C) and unshared (x_U) variables. The interface or platform variables are shared throughout the product set and define the connecting interface between each product. The collaborative variables are those connected to the elements of a product that are used to create the collaborative product. The unshared or unique variables are those connected to the elements of a product that are unique to each product in the product set. The characterization of the multi-objective design space for the i -th product in the set, and the collaborative product ($i = n_p + 1$), in terms of identifying the corresponding Pareto frontier (see Fig. 2) is presented as Problem 2

(P2):

$$\min_{\hat{x}^{(i)}} \left\{ \mu_1^{(i)}(\hat{x}^{(i)}, p^{(i)}), \dots, \mu_{n_\mu^{(i)}}^{(i)}(\hat{x}^{(i)}, p^{(i)}) \right\} \quad (n_\mu^{(i)} \geq 2) \quad (5)$$

subject to:

$$g_{q^{(i)}}^{(i)}(\hat{x}^{(i)}, p^{(i)}) \leq 0 \quad \forall q^{(i)} \in \{1, \dots, n_g^{(i)}\} \quad (6)$$

$$h_{k^{(i)}}^{(i)}(\hat{x}^{(i)}, p^{(i)}) = 0 \quad \forall k^{(i)} \in \{1, \dots, n_h^{(i)}\} \quad (7)$$

$$\hat{x}_{ji}^{(i)} \leq \hat{x}_j^{(i)} \leq \hat{x}_{ju}^{(i)} \quad \forall j \in \{1, \dots, n_{\hat{x}}^{(i)}\} \quad (8)$$

$$\hat{x}^{(i)} = \left[x_{I,1}, x_{I,2}, \dots, x_{I,n_I}, x_{C,1}, x_{C,2}, \dots, x_{C,n_C}, x_{U,1}, x_{U,2}, \dots, x_{U,n_U} \right] \quad (9)$$

$$x_C^{(n_p+1)} = \left[x_{C,1}^{(i)}, x_{C,2}^{(i)}, \dots, x_{C,n_C}^{(i)} \right] \quad \forall i \in \{1, 2, \dots, n_p\} \quad (10)$$

$$\hat{x}^{(n_p+1)} = \left[x_{U,1}^{(i)}, x_{U,2}^{(i)}, \dots, x_{U,n_U}^{(i)} \right] \quad \forall i \in \{1, 2, \dots, n_p\} \quad (11)$$

where $\hat{x}^{(i)}$ is a vector of design variables containing the interface (x_I), collaborative (x_C), and unshared (x_U) variables for the i -th product in the set. The design parameters are also represented for the i -th product in the set by the term $p^{(i)}$. The Pareto frontier of each product is obtained by evaluating (P2) $\forall i \in \{1, 2, \dots, n_p + 1\}$.

In Eq. (9), all variables that are included in the collaborate product ($i = n_p + 1$) contains all the collaborative variables from the product set. This coupling of the product set to the collaborative product design space is important since it illustrates to the designer the current collaborative nature of the product set.

2.7. Step 7: define the areas of acceptable pareto offset

In looking at the formulation of (P2), the resulting Pareto frontier for each product represents the best possible solutions for each of the products without considering the interaction between each product. As the number of products being combined increases, it becomes less likely that the designs capable of creating a collaborative product all fall on the Pareto frontier of the corresponding product. This is because the number of objectives and constraints to be satisfied, along with the complexities of the interactions between the products, increases with each additional product. As more interactions and trade-offs become apparent, the harder it is to meet all of the demands between products. In order to facilitate the selection of designs that will minimize the offset from these Pareto frontiers of the entire product set, the next step in the method is to use these Pareto frontiers to define areas of acceptable Pareto offset for each product (see Fig. 2).

This process is carried out by defining a single offset value (β) for each product that will limit subsequent optimization routines to only

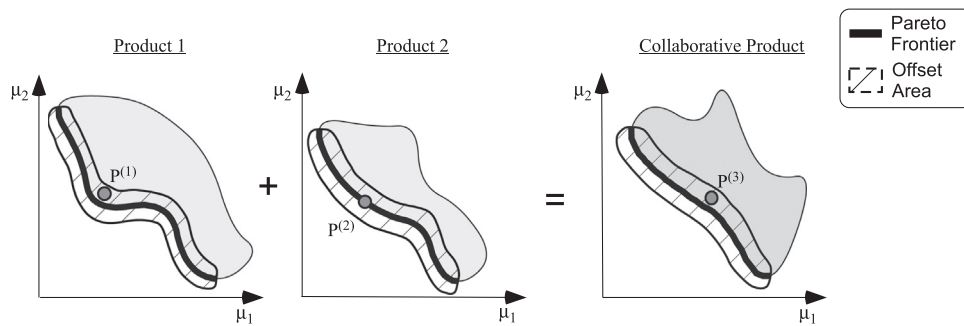


Fig. 2. Graphical summary of the intent of the method presented in Section 2, illustrating the feasible bi-objective design spaces for a theoretical product set and corresponding collaborative product. The Pareto frontier (bold line) defines the most desirable set of solutions in each design space. The designs selected for each product are identified as points $p^{(1)}$, $p^{(2)}$, $p^{(3)}$. Note that the selected designs are within identified areas of acceptable Pareto offset.

consider designs with offsets from the Pareto frontier that are less than β . In the case of a two dimensional model, the values of β would be equivalent to defining a circle of radius β around each identified Pareto point from Step 1. In n-dimensional cases, the value of β represents the maximum allowable length of an n-dimensional vector between a design option and the closest Pareto point. This value is determined by the designer based upon the extent to which he or she wishes to limit the search space and focus optimization searches to the identified offset areas.

2.8. Step 8: identify the designs that collaboratively fall within the areas of acceptable pareto offset

In order to identify the designs, a multi-dimensional design space is created using axes represented by the predicted Pareto offsets for each product in the set as well as the collaborative product. This design space represents a combination of feasible designs in terms of the individual products and the collaborative product. In the case illustrated in Fig. 2, these offset points would represent a three dimensional Pareto surface consisting of points from the offset area of each product. The offset space Pareto frontier is determined by a multi-objective problem statement presented as Problem 3(P3):

$$\min_{\hat{x}} \{O^{(1)}, O^{(2)}, \dots, O^{(n_p+1)}\} \tag{12}$$

subject to Eq. (6)–(9) and:

$$O_{q^{(i)}}^{(i)} \leq \beta \quad \forall q^{(i)} \in \{1, \dots, n_g^{(i)}\} \tag{13}$$

where $O^{(i)}$ is the n-dimensional offset length of a design of the i -th product from the corresponding Pareto frontier of that product.

The Pareto surface is constructed by adjusting the interface, collaborative, and adjustable variables. The interface and collaborative variables are shared between the optimized products and the collaborative product, while the adjustable variables are unique to each optimized product, but shared with the collaborative product. It should be noted that in cases where there are no more than two products being combined to create a collaborative product, the result of (P3) is a Pareto surface. For product sets greater than two, the graphical representation of this offset space can no longer be provided for all products simultaneously. Fortunately, a graphical representation is not necessary for this method to be useful.

2.9. Step 9: identify/select the optimal product designs

Since the goal of the method is to select the optimal design of each product while balancing the trade-offs required to create the collaborative product, this final step of the method uses the results of (P3) to select a single set of product designs. Under ideal circumstances, the selected designs are represented by a single Pareto point on the Pareto frontier of each product (i.e., the offset of each product is zero). One method of accomplishing this selection is through the use of an aggregate objective function (J) that represents the preferences and needs of the designer. If an aggregate objective function is used, one way of reducing the computation expenses related to the optimization problem evaluations, would be to replace Eq. (12) with an equation of the form of Eq. (14).

$$\min_{\hat{x}} J(O^{(1)}, O^{(2)}, \dots, O^{(n_p+1)}) \tag{14}$$

At the conclusion of the design process presented in Section 2, the designer will have an understanding of the customer needs and a way to meet those needs with individual products and a collaborative product. Through the multi-objective optimization theory presented in Steps 6–9, the designer is able to simultaneously and numerically evaluate the performance of multiple designs in multiple design spaces. These computations would be near impossible without the use of

computer aided calculations. This evaluation allows the designer to optimize the products to ensure they operate efficiently in both the individual and collaborative product states to effectively lower the financial risk for the end user.

3. Example: collaborative brick press design

This section demonstrates the implementation of the method presented in Section 2 through the design of a collaborative brick press. The concept for a collaborative brick press has been provided by Morrise et al. (2011). This design collaboratively uses the following six basic products to create the brick press: shovel, hoe, rake, water transportation roller, water pump, and a small cook stove. It is assumed these are potential products that a person living in poverty would be interested in purchasing as a way to improve his or her life situation. The ability to combine them together into an additional product would give individuals the potential to maximize their use and potentially increase their likelihood of purchasing these products. It should be noted that the intent of this example is not to show the feasibility and necessary logistics of implementing the collaborative brick press developed herein. Rather, the intent is to demonstrate the effectiveness of the method presented in Section 2 in identifying the optimal designs of a given collaborative product set.

The example is useful in illustrating this method because (i) it solves a challenging engineering design problem, (ii) it shows the use of complex interfaces between products and how they are addressed, (iii) it incorporates the use of actual products used or found in developing countries, and (iv) it demonstrates the use of a multi-objective optimization problem to deal with competing objectives from each product. Figure 3 illustrates the conceptual design and decomposition of each product in the identified product set, and Fig. 4 shows how the

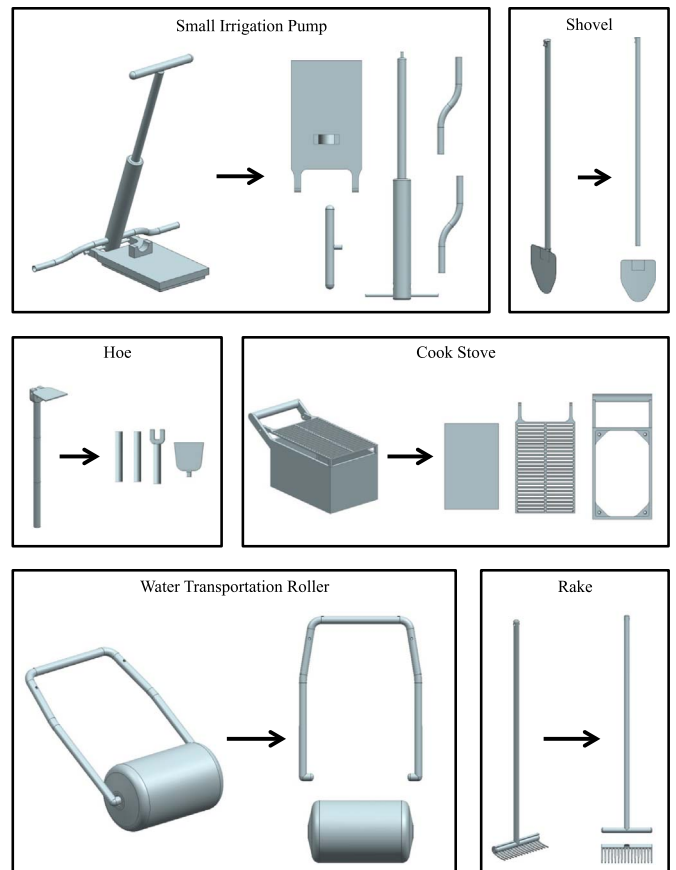


Fig. 3. Decomposition of each product in the identified product set to create a brick press.

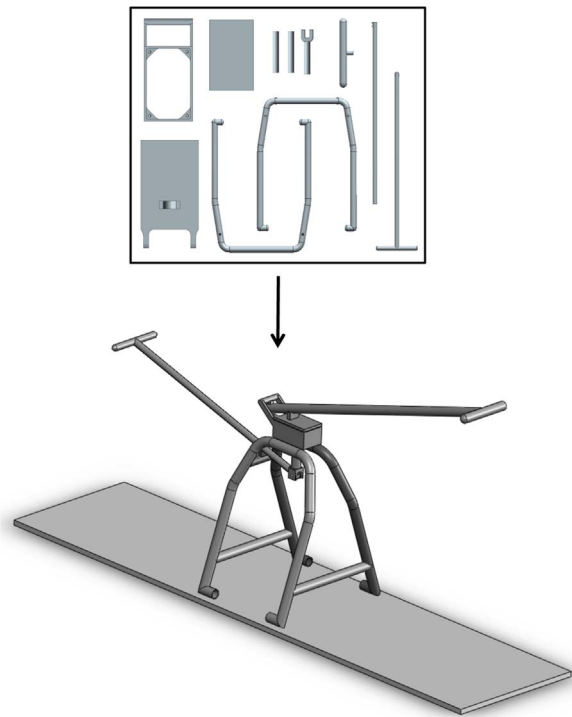


Fig. 4. Illustration of the recombination of the components from the product set in Fig. 3.

products are assembled into the collaborative brick press.

3.1. Example step 1: understand broad customer needs

To understand the needs of the customer is the first step and in this example the following needs were included: cooking, home building, gathering food, transportation, and access to clean water.

3.2. Example Step 2: create/select a product that satisfies one of the broad needs

The list of customer needs from step 1 was evaluated and the area of home building was chosen. A brick press was selected as a product that would be able to meet one customer need. A brick press serves as an ideal collaborative product candidate since it contains a large number of components, is desirable but typically not purchased due to its high cost, and is used less frequently than other typical, everyday products.

3.3. Example Step 3: decompose the selected product into components

A decomposition process was carried out after selecting the brick press to determine the component make-up. As is presented in Section 2.3, the product is to be decomposed by structure, function, and characteristics. See Table 1 for the completed decomposition of the brick press.

Table 1
Brick press decomposition.

Component	Structural	Functional	Characteristic
Press mold	Mold	Hold material	Rectangular basin
Legs	Long handles	Press to ground interface	Cylindrical tubes
Long posts	Long handles	Leverage	Cylindrical tubes
Handles	Short handles	Human to press interface	Cylindrical tubes
Mold cover	Cover	Pressure plate	Rectangular plate
Eject plate	Plate	Brick ejector	Rectangular plate

Table 2
Other products created to fulfill different customer needs.

Need	Component(s)	Product	Secondary component(s)
Cooking	Press mold, eject plate	Cook stove	Cook surface
Water transportation Fresh water	Legs Press cover	Water roller Water pump Base	2 water barrels Pump, hoses
Farming	Long handle 1	Shovel	Blade
Farming	Long handle 2	Rake	Tines
Farming	Short handles	Hoe	Blade

The decomposition allows the designer to easily see the make-up of the selected product and begin identifying components that can solve different broad customer needs.

3.4. Example Step 4: determine what other products can be created from the components to fulfill different broad customer needs, while if desired, adding missing secondary components

During this step the other broad customer needs identified in Section 3.1 were reviewed. This was done by determining what other products could be created from the components to fulfill these needs. In this example, components that make up the brick press were identified and it was determined how these components fulfilled other broad customer needs. The identified needs and the corresponding products used to fulfill each need can be found in Table 2. Also note that necessary secondary components were added to complete the design of each product in the table.

3.5. Example step 5: identify interfaces between components

To complete the collaborative design process, interfaces are then added to ensure complete usability of the products. The brick press will experience large forces during operation and will therefore require interfaces that ensure a robust design. It is important to identify interfaces that allow high functionality of the brick press in its collaborative state as well as in its individual state, but also achieve the lowest possible cost. As was stated in Section 2, these interface design methods exist in the literature (Wie et al., 2001; Blackenfelt and Sellgren, 2000).

3.6. Example step 6: characterize the collaborative design space of the product set and collaborative product

Once the collaborative product has been sufficiently developed, the designer then characterizes the collaborative design space of the six basic products as discussed in Step 6 of the presented method (see Section 2.6). This is carried out by constructing mathematical models of each product in the product set. It is important to construct robust models that accurately represent each product to ensure that they hold up to the optimization under realistic conditions. Table 3 summarizes

Table 3
Summary of the objectives that were selected for each product in the product set and collaborative product.

	↑/↓	μ_1	↑/↓	μ_2
Shovel	↓	Stress (psi)	↓	Cost (\$)
Rake	↓	Stress (psi)	↓	Cost (\$)
Hoe	↓	Stress (psi)	↓	Cost (\$)
Water roller	↓	Stress (psi)	↓	Cost (\$)
Cook stove	↑	Cook area (in ²)	↓	Cost (\$)
Water pump	↑	Flow rate (L/s)	↓	Cost (\$)
Brick press	↓	Stress (psi)	↓	Cost (\$)

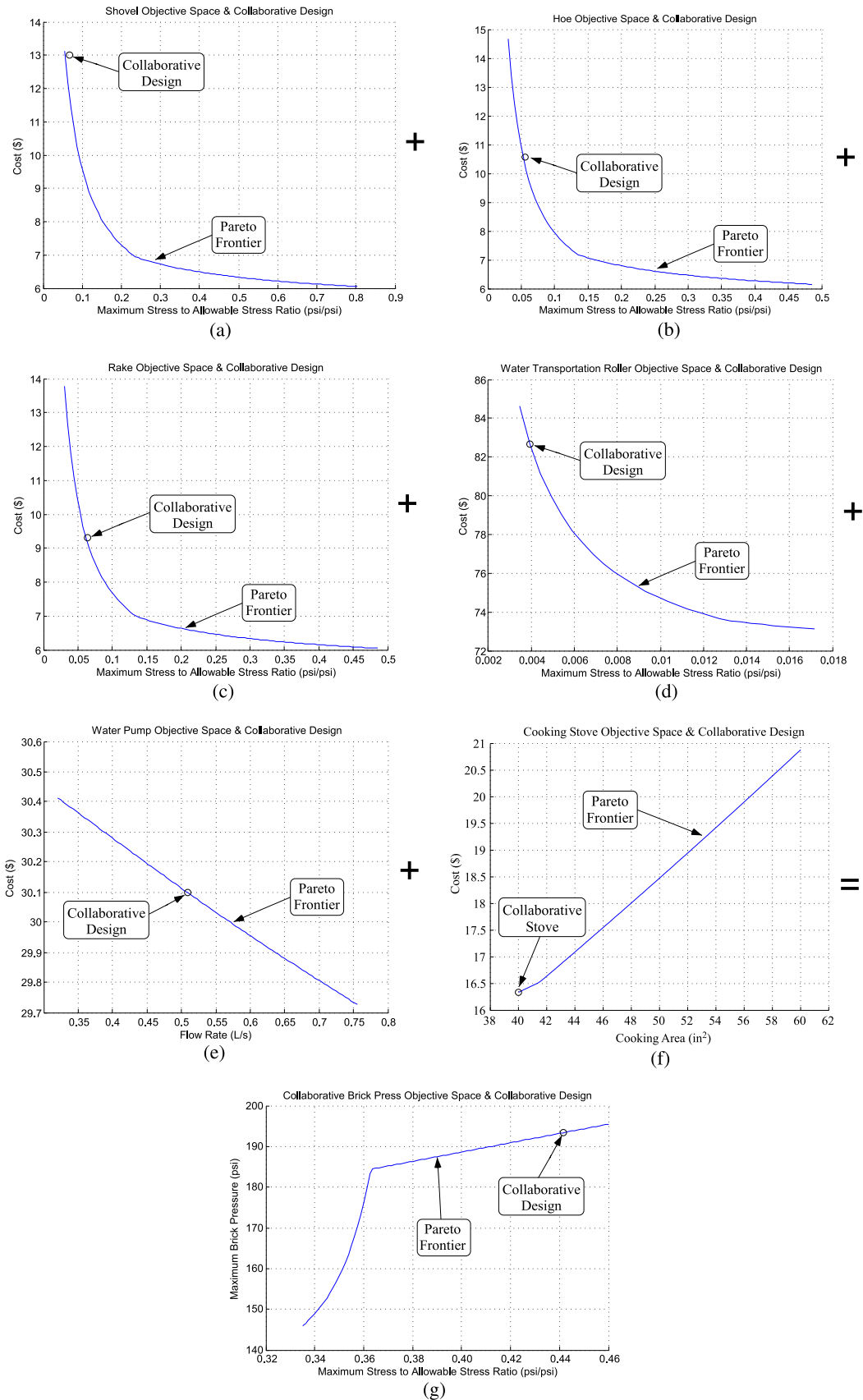


Fig. 5. Graphical illustration of the Pareto frontiers for each product obtained through Step 1 of the method, and the optimal collaborative design of each product identified in Step 4 of the method.

Table 4
Defined acceptable offset values (β) for the normalized objectives of each product.

	β value
Shovel	0.5
Rake	0.1
Hoe	0.1
Water roller	0.1
Cook stove	0.1
Water pump	0.1
Brick press	0.1

the objectives (\uparrow = maximize, \downarrow = minimize) that were selected to characterize the performance of each product. Definitions of the objectives presented in Table 3 are as follows: (i) for the shovel, rake, and hoe the objective μ_1 represents the maximum bending stress in the product's handle; (ii) for the water roller and brick press, μ_1 represents the maximum bending, shear, and buckling stress that each product could experience; (iii) for the cook stove, μ_1 represents the available area for cooking food; (iv) for the water pump, μ_1 represents the rate at which the pump can pump water; and (v) the objective μ_2 represents the cost to purchase each product.

From the models and their corresponding functions, design variables, and design objectives a multi-objective optimization problem was constructed in the form of (P2) in Section 2.1. From this optimization problem, the design spaces for each product was then defined with their corresponding Pareto frontiers (See Fig. 5).

3.7. Example Step 7: define the areas of acceptable Pareto offset

In this step, the area of acceptable Pareto offsets was defined. Since there are two objectives for each product in the product set and collaborative product, the value of β is equivalent to defining a circle of radius β around each identified Pareto point from Step 1. For these two-dimensional cases, the value of β represents the maximum allowable length of a two-dimensional vector between a design option and the closest Pareto point. For our example, the β offset values were defined as shown in Table 4 for each product.

3.8. Example step 8: identify the designs that collaboratively fall within the areas of acceptable Pareto offset

Once the offset areas were defined, the combinations of designs that fall in each offset area were identified using a multi-objective problem statement of the form of (P3) (see Section 2.3). Because it is a multi-objective optimization problem, a graphical representation of the results of evaluating this formulation carries no visualization value due to its dimensionality.

3.9. Example step 9: identify/select the optimal product designs

As was mentioned in Section 2.4, an aggregate objective function was used to select the optimal combination of product designs. In this example a weighted sum of offsets was used with all weights equal to one except for the brick press, which was equal to 10. The weights were selected with the goal of minimizing the offset of the collaborative product (brick press) from the corresponding Pareto frontier. The resulting design selection using these weights is illustrated in Fig. 5.

From the results presented in Fig. 5 it can be observed that the identified design for each product is located on the Pareto frontier of the corresponding product objective space. Although the selected aggregate objective function and weights were successful in identifying designs on or near the Pareto frontier of each product, the majority of these designs are located near the boundaries of the Pareto frontiers. If solutions are more desirable in a particular region of the identified

Pareto frontiers, additional constraints or alternative aggregate objective functions would need to be explored.

Illustrated in this example, the task-per-cost ratio of the collaborative brick press has increased. More specifically, and assuming that the calculated total cost of all components making up the newly designed brick press are \$160 and are capable of completing seven different tasks, the ratio will be 0.043. For comparison, a comparable brick press, cook stove, small irrigation pump, shovel, rake, hoe, and water transportation rollers approximately cost a total of \$200 with a ratio of 0.030. This illustrates that the task-per-cost ratio has improved by 30% from 0.030 to 0.043 through the use of this method (Morrise et al., 2011).

4. Concluding remarks

This paper has presented a method by taking *domain knowledge* and using the information when designing products for optimal collaborative performance with application to engineering-based poverty alleviation. The primary result of this method is the ability to optimize the collaborative performance of a set of products while dealing with the various, and often complex, performance interactions between the products and the collaborative product. To reiterate, all products are being simultaneously optimized not only on an individual level, but on a collaborative level. Through the optimization, the collaborative performance is optimized while dealing with the various trade-offs between the products and the collaborative product.

As described in the introduction, the task-per-cost ratio can be observed to more fully understand the potential impact a collaborative product may have on alleviating poverty. The method presented in this paper is an optimization-based strategy for selecting designs of a given collaborative product set. The ability of this method to optimize based on objectives like cost and task performance, enables the task-per-cost ratio of the product set to increase. As such, the resulting collaborative product would have a higher potential impact and application within the developing world. To illustrate application of this method, a collaborative brick press created by combining a shovel, hoe, rake, water transportation roller, water pump, and a small cook stove was provided. As stated earlier, we do not suggest that this brick press should go into production but that it is used to show that knowledge from one domain can be used when creating a collaborative product in another domain.

From the example, and the presented results, the authors believe that the presented method has the potential to be an effective tool for designing products for optimal collaborative performance. We recognize however that the paper presented here simply explores the idea that domain knowledge from modularity and multiobjective optimization can be applied to developing world situations. The potential benefit that collaborative products can have on poverty alleviation by reducing the cost, weight, and size of a set of products was presented as motivation for this work. Opportunities for future work that build on this method includes: (i) addition of design objectives and constraints that will ensure that the identified product designs embody these goals of reducing the cost, weight, and size of a set of products; (ii) further research in the correlation of the task-per-cost ratio to the impact and implementation of a collaborative product; and (iii) explore additional indicators, such as income generation-to-cost ratio, to better understand the impact that collaborative products will have on poverty alleviation.

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