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Sustainable manufacture of scalable product families based on modularity

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ABSTRACT

This article presents a redesign methodology based on modularity to minimize resource consumption and reuse components, avoiding the need to replace a whole product with another with higher functional performance. The method employs two decision algorithms to modularize product families that offer the same functionality in different levels (i.e., scalable functions) based on design parameters such as geometry, size, and functional relationships among components. The proposed approach's benefits are demonstrated through a case study of a family of upper limb prostheses. Significant improvements in the manufacturing stage, such as raw material and energy consumption, manufacturing cost, and complexity, were obtained from implementing the method. Other benefits in the use stage were also obtained from modularization, increasing the product family's reuse of components.

Introduction

Sustainable Manufacturing (SM) is rapidly gaining relevance in industrial and academic fields in the face of pollution problems, climate change, and resource depletion [1]. This change is in response to conventional manufacturing that has been solely oriented to production issues, without considering environmental burdens derived from transforming raw material into final products [2]. Besides, growing legislation initiatives and policies have enforced the adoption of sustainability in production processes to contribute to resource conservation and mitigation of environmental impacts [3,4]. Such impacts represent a critical issue in product development, especially when product families are designed without considering sustainability at the end of their lifecycle once they are discarded or do not suit the user requirements. Hence, during the last decade, research efforts have grown, addressing the need for new methodologies and approaches to generate more sustainable products from early design phases [5], where designers have the highest possibility of positively influencing the sustainability performance of products.

In terms of product development, designers and manufacturers have broadly employed the concept of modularity. Which is considered a key concept in new SM processes, enabling agility, rapid response, and flexibility to changes in the market and regulatory requirements [6,7]. However, the application of modularity has not been applied massively by companies yet during the last decade. Identified core research gaps concerning modularity for sustainable manufacturing are: (i) most related works associated with modularity are oriented to the use of removable and exchangeable modules, missing the existence of diverse product architecture principles that cost-effectively enable modularity; (ii) methodological manuscripts related to modularity are focused on manufacturing systems, and just a few are oriented to early design stages when impacts and future lifecycle considerations can be modified by adjusting geometry and materials [7]; and, (iii) modular architecture alternatives need to be included during early design phases approaches, where decision making involves a significant influence on further stages of the product lifecycle [8]. In addition to the research gaps, it is noticeable that modularity can be a key enabler during the implementation of circular economy strategies such as repair, remanufacture, and refurbishment of products, facilitating

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replacement and upgrading of components and longer product lifespans [9,10]. Thus, modularity has massive potential in product design, and it is necessary to do more research on new product design methodologies to integrate modularity and sustainability.

Aim, objectives, and scope

This modularity-based redesign approach proposed in this paper aims to enhance the sustainability performance during the manufacturing stage since the modular design reduces component variety, assembly/disassembly complexity, and the intensity of use of components, making them common among members of the product family. Scalable product families are defined here as product families comprised of products that vary in capacity and offer the same functionality at different levels. Scalable product families can be found daily using clothes, shoes, sport related products like skates, accessories like glasses, musical instruments, orthotics, and prosthetic devices that vary in size according to human growth or human size. On the other hand, scalable product families can be found in manufacturing industries based on product portfolios, which enable the use of shared resources to manufacture products with the same functional structure but different functional levels (size, capacity, power, storage, among others) like automotive products, material transportation systems, warehouses, power transmission systems.

Commonly, product replacement and its derived environmental issues are also driven by the need for a higher capability or size, which is typical of size-based products. The proposed approach consists of a method to modularize scalable product families without affecting their functional performance. The selection algorithms for modularization alternatives and a systematic procedure are presented to assist designers, practitioners, and academics in implementing the method. The following objectives are settled to address the aim of this article:

1 Define a modularity-based redesign methodology for scalable product families.
2 Apply the modularity-based redesign methodology to quantify sustainability improvements of product families through a case study

The proposed approach is mainly focused on products that require replacement due to changes in consumer requirements in terms of scalability. Therefore, the prosthetic devices' family is suitable and pertinent as a case study due to the need for product replacement once the user does not fit the product size.

Roadmap

This article is organized as follows: a literature review is described in Section “Literature review”. The proposed method is explained in Section “Sustainable manufacture of scalable product families based on modularity”. The case study substantiating the methodology is included in Section “Case study: product family of hand prosthesis”. Results and discussion are summarized in Section “Findings and discussion”, and finally, the conclusion and scope of future works are given in Section “Conclusions”.

Literature review

Sustainable manufacturing

Sustainable manufacturing (SM) can be defined as creating products minimizing energy and natural resource consumption,

Table 1
Selected works regarding modularity in SM after a detailed reviewing of literature.

Author	Description	Purpose	Indicators employed
Bataglin and Ferreira [19]	A novel method for the modularization of products based on the Triple Bottom Line	To develop sustainable products considering an overall sustainability approach	Generic Economic, Environmental and Social Indicators
Ko [5]	A novel green design method based on the extension theory and concept of green DNA (green technology, material, and manufacturing)	To convert conventional products into green products through decomposing-recomposing	Feasibility, Efficiency, and Design Solution Generation
Massimi et al. [20]	Heuristic-based method for optimizing modularity from an energy consumption perspective.	To minimize the energy consumption of the system	Energy Consumption
Mesa et al. [6]	Characterization of modular architecture principles	To compare and assess modular architectures providing a helpful guideline for designers.	Consumption resources, reusability, product replacement
Kim and Moon [21]	Method for developing eco-modular product architecture and assess modularity.	To enhance product recovery processes and reduce environmental impacts	Weight and Eco-Indicator 99
Miyajima et al. [22]	Modular design method and strategy based on supply chain management	To define a more suitable modular architecture and suppliers	Cost, environmental load in transportation, quality, and procurement lead time
Mutingi et al. [14]	Modular product design approach based on fuzzy grouping genetic algorithms.	To improve sustainability in the whole product lifecycle	Product complexity and costs
Ma and Kremer [23]	Modular product design approach based on key components and uncertain end-of-life strategy	To improve the product lifecycle performance for dimensions of sustainability	Costs, Environmental Impact, Labor Time, MSSI Index
Sheng et al. [24]	A Design process model of Product service system based on a lifecycle-oriented modular design	To improve the sustainability of products	Efficiency of modularization
Yan and Feng [17]	Method for sustainable design of modular products through clustering-based analysis	Enable 6R strategies in the whole lifecycle of products such as remanufacturing, reuse, and repair.	Modular dependency, product complexity, end of life potential
Wang and Tseng [25]	A methodological framework for modular design focused on end-of-life strategies	To help designers in the application of modular design and maximize the manufacturer's total value recovered from product end-of-life strategies	Value-recovered by reuse/manufacturing and cost of reuse/manufacturing
Seliger and Settl [12]	Module configuration software tool	To determine optimal modular product structure considering Lifecycle criteria	The benefit of the module configuration and module driver specification weight

removing unnecessary process outputs, including waste, toxic materials, and emissions over the product lifecycle [11,12]. Mihelcic et al. [13] defined SM as *"the design of human and industrial systems to ensure that use of natural resources and cycles do not lead to diminishing the quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment."* In that perspective, SM involves addressing environmental, economic, and social challenges [14], becoming a vast research topic inside the Sustainable Development concept. Concerning product manufacturing, the most distinctive approaches related to SM include: i) lean manufacturing [15], which involves the minimization of waste within manufacturing systems and the optimization of productivity; ii) product design [16], that covers all the methodological approaches to transform ideas into physical products to fulfill a requirement or satisfy a need, and iii) Rs strategies [17], oriented to create a recirculated flow of material maintaining functional value through reuse, repair, remanufacture, repurpose, recycle and recover of products and components. Notably, in the field of modular design, some relevant approaches [6,7,18] have demonstrated the usefulness of modularized products across the whole lifecycle in terms of sustainability and cost-effectiveness.

Modularity in sustainable manufacturing

This subsection includes the most relevant approaches found in the literature during the last two decades related to modularity or modular design in product manufacturing, primarily focusing on SM. Most relevant works were characterized considering the type of approach, the target of applicability, and the measurement indicators. The SCOPUS database was employed as the primary source of references in this section; keywords for the literature search included "sustainable," "manufacturing," and "modular," and additional filters such as language (English) and type of document (Journal article). The full search query employed was [TITLE-ABS-KEY (sustainable AND manufacturing AND modular) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))]. After a detailed review process, the search queries returned 70 articles, and 12 of those articles were identified and selected for this study. Table 1 summarizes the selected works, including a description, purpose, and indicators employed for each work.

An analysis of the selected works previously listed in Table 1 reveals several trends. First, none of the selected works considers or includes the product family concept in a formal manner. Most works focus on single products and do not analyze product replacement as a sustainability issue. Second, cost savings and financial issues are the most common targets of using modularity. In this case, resource optimization, costs, and reduction of complexity have been the common drivers for most authors. Third, the last five years show a growing trend in the number of modular design works to improve products' sustainability attributes. Most recent works consider environmental impacts as an issue with similar importance that cost or profitability. Finally, cost, time, and resource optimization are not directly oriented to sustainability issues or at least are not adequately addressed in environmental, economic, and social indicators.

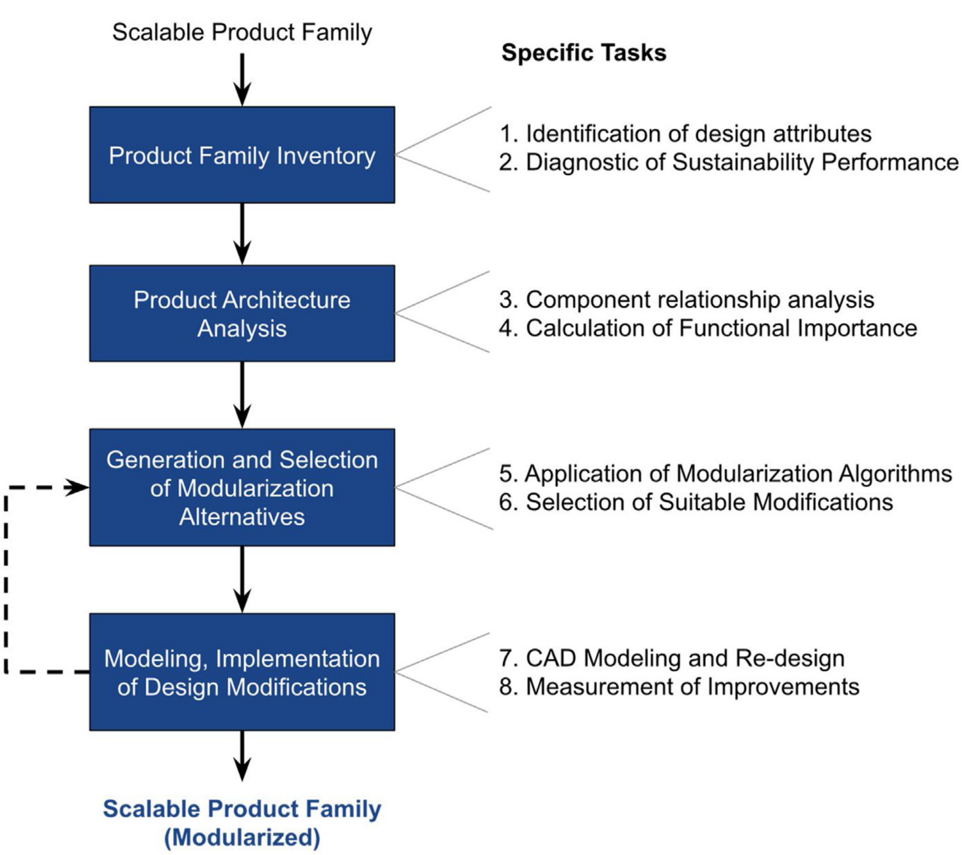


Fig. 1. The proposed approach, including specific tasks per stage.

Sustainable manufacture of scalable product families based on modularity

The proposed method consists of a systematic process of four steps dedicated to redesigning scalable product families' components to reduce raw material consumption during the manufacturing process without affecting the functionalities of the product families. The method is based on the modularity approaches proposed by Mesa et al. [6,18], who established a set of principles denominated Modular Architecture Principles (MAPs), categorized into two main groups: range variety principles, related to performing a single functionality at different levels or within an operational range; and functional variety principles, which involve the use of different functionalities in a single level. Two decision algorithms are proposed to suggest using seven MAPS according to each component's functional requirements in the product family. The proposed method includes tasks in the conceptual and basic design steps to provides a modularized version of the product family. Fig. 1 illustrates the proposed method and its main tasks. Each one of them is described in detail in the following sub-section. However, a complete understanding of the method can be reached after reviewing the case study section. It is essential to clarify that the proposed method aims to help generate modularized alternatives for each product family component. However, the results largely depend on the design team's experience and knowledge of the product architecture. Components can be modularized in different ways for each MAP; therefore, design results are not deterministic. The proposed method helps and assists during the modularization, assuring the generation of alternatives that require brainstorming sessions and discussions in several iterations before reaching a suitable modular version of the product family. The proposed method's new contributions include sustainability measuring and improvement, selection algorithms based on MAP's characterization to generate modularized components considering functional relevance in the product, and consideration of scalable product families.

Product family inventory

This first stage consists of the inventory of components and manufacturing performance diagnosis related to resource consumption and manufacturing efficiency. The inventory of components must include the number of products in the product family, the variety and quantity of components, and, preferably, an image (picture or CAD model) of each product and component. This first step identifies the number and variety of components within the product family and the overall interaction between components, which will then be used for the product architecture analysis and the comparison of indicators once a new modularized version of the product family is obtained applying the modularization algorithms. On the other hand, the manufacturing performance diagnosis covers the initial measurement of sustainability regarding mass and energy consumption, manufacturing time, costs, and product family complexity.

Product architecture analysis

This step includes the relationship analysis among components, identifying each component's functionalities, and the interaction with other adjacent components. Each component's relative functional importance must be determined to diagnose the most critical components in the product that involve possible functional constraints in terms of modularization. The functional importance is calculated according to Eq. (1), where F is the number of

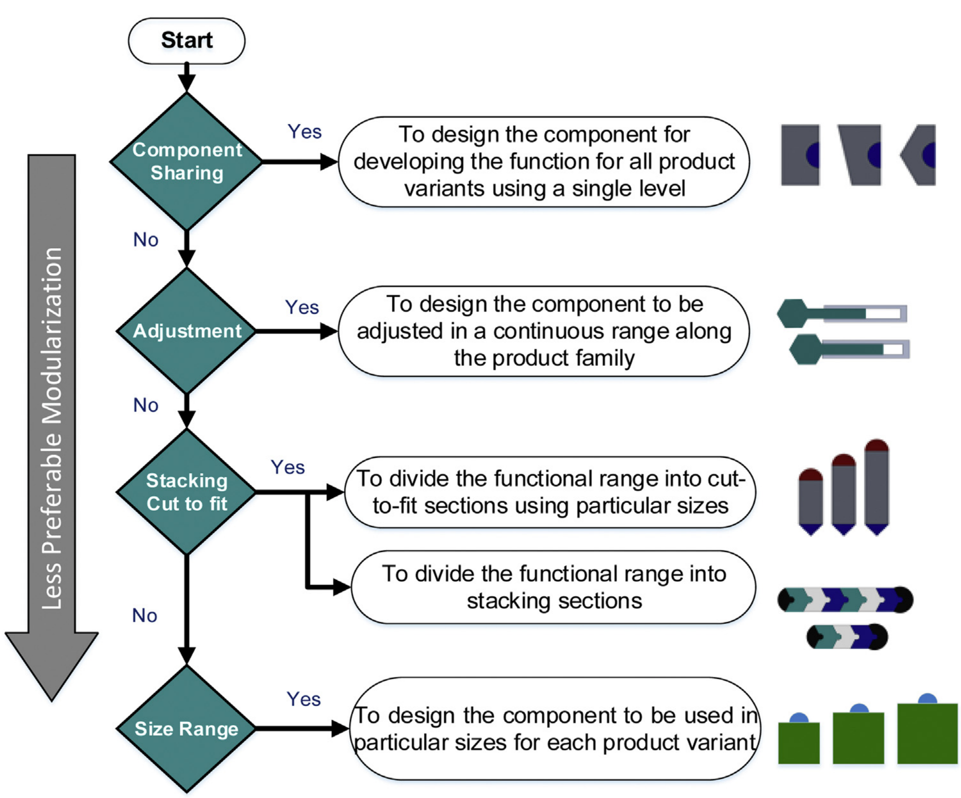


Fig. 2. Range Variety Modularization Algorithm.

functions of a component, n corresponds to the number of components in contact with the component, and N is the total number of components in the product. Then, the relative functional importance is calculated, dividing each component's functional importance by the total summation of the functional importance of all components in the product.

$$Functional\ importance = \frac{F*n}{N} \quad (1)$$

Functional importance is critical here to determine and compare functional dependence and assembly relationships between components. Thus, considering that modularization of components with higher functional importance requires additional attention, they involve more assembly relationships with other components within the product family. Modularization of high functional importance components must avoid interfering with assembly connections of adjacent components since it is possible to generate adverse affectations (assembly incompatibilities, geometry mismatches, deterioration of functions) in terms of functional performance of those components.

Generation and selection of modularization alternatives

This step includes the analysis of functional and range variety for all components within the product family and the algorithms' implementation to generate modularized alternatives for each component. The Analysis of functional and range variety consists of determining whether each component performs a unique function within all product family members and whether or not the component performs a single function at different levels. Once the identification of functional variety and functional range is complete, the next step is to perform the modularization algorithms' implementation. It is essential to clarify that each algorithm must be applied to each component's corresponding type of functional attributes (e.g., the functional variety algorithm must be applied to components that perform a functional variety function).

The output of this step is to determine possible modularization of each component within the product family considering two main categories: range variety, which involves a unique functionality performed in different levels and, functional variety, which includes the addition, removal, and exchange of single-level functionalities. Figs. 2 and 3 show the decision-making algorithms. Three main desirable aspects were considered in the definition of the modularization algorithms regarding the different MAPs: a) the product architecture can perform multiple functionalities within different operational ranges, b) the product architecture enables the performing of functionalities with minimum resource consumption and, c) modules are exchangeable among any product of the product family. A more in-depth explanation of MAPs definitions and examples can be found in [6,18].

Proposed algorithms are based on two main design principles: i) the use of minimum resources (preferable to use fewer modules) and ii) the ability to satisfy the product family functionalities. Such design principles were selected based on the avoidance principle of sustainability (to use the minimum possible amount of resources) and considering that the product family functionality will not be affected by the modularization process. The first MAPs of each algorithm are considered the most conservative in terms of sustainability (use of resources); as the user progresses into the algorithm towards other MAPs, the desirability decreases. However, the suitability of MAPs largely depends on the product geometry and distribution of functionalities across the product family. The first algorithm corresponds to Range Variety Modularization, which involves generating alternatives to satisfy a unique range-type functionality. The most and least desirable principles are Component Sharing and Size Range, respectively. The second algorithm corresponds to Functional Variety Modularization, which enables multiple functionalities through exchangeable modules. In this second algorithm, the most and least desirable principles are Widening and Narrowing, respectively. Functional Range and Functional Variety algorithms were proposed as a guide tool to assist the product redesign while selecting the most suitable modular architecture. Such algorithms must be

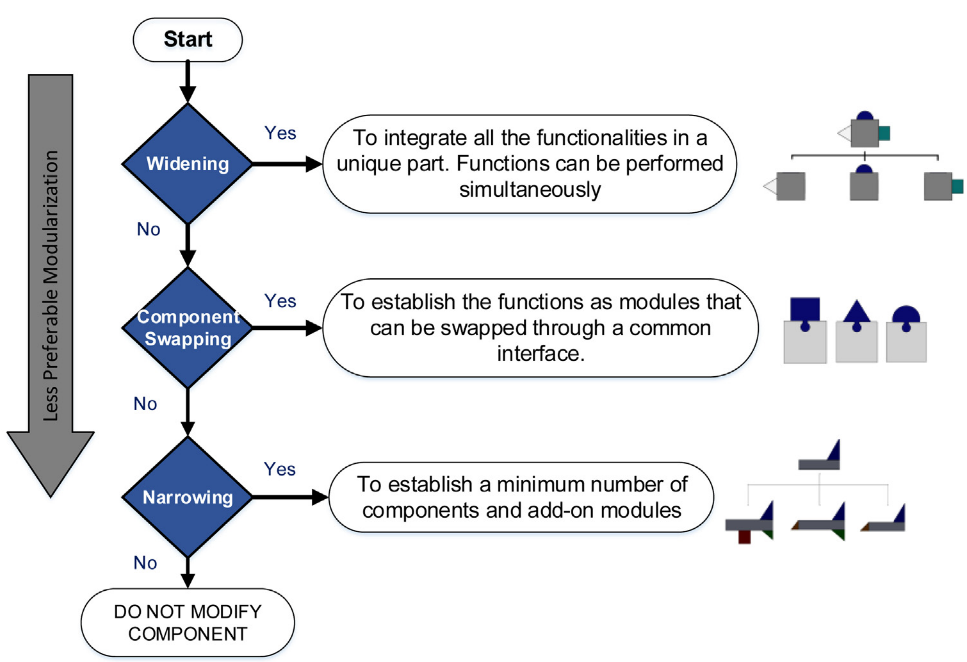


Fig. 3. Functional Variety Modularization Algorithm.

applied to each component of the scalable product family to generate modularization alternatives. It is essential to clarify that more than one modular architecture can be suitable for the redesign process; in such cases, an additional criterion should be included to determine the best modular architecture alternative.

Modeling and implementation of design modifications

This last step consists of modularization through the modification of each component according to the result of the previous stage, including the basic design of new modularized components. Therefore, during this stage is highly desirable to perform the geometrical modifications using proper CAD/CAE modeling software. Besides, this step includes measuring and comparing results between the modularized design obtained from the proposed method and the original version of the product family.

Case study: product family of hand prosthesis

The case study consists of the redesign of a 3D-printed hand prosthesis named “Cyborg Beast 2”. This device was designed for patients between 4 and 12 years with congenital partial hand reductions or acquired partial hand amputations. The Cyborg Beast 2 hand prosthesis's overall function was to moderately emulate the hand functionality, providing a similar anthropometric shape and range of motion compared to a human hand. Cyborg Beast 2.0 was conceived as a low-cost alternative for children with upper-limb reductions, especially for regions where insurance and public health funding are insufficient and the families' financial resources are limited [26]. Cyborg Beast 2.0 was designed as a body-powered device, which provides passive finger extension and active flexion using only the patient's wrist movement. Passive finger extension is achieved through elastic cords placed inside the dorsal aspect of the fingers. Fingers flexion is performed by non-elastic cords along the palmar surface of each finger and is driven by 20–30 degrees of wrist flexion [27]. Fig. 4 shows the Cyborg Beast 2.0 hand prosthesis for a left-handed patient. For the case study analysis, four hand prosthesis sizes (100%, 110%, 120%, and 130%) were chosen for both right-hand and left-hand patients. Such sizes correspond to children between 4 and 12 years of age. Hence, the product family inventory is comprised of those eight products.

The analysis of the prosthetic product family was focused on the functionalities provided to children and the social impact associated with its use. The market segment and regional context are also identified, and the current sustainability impacts are established as well. The case study's market segment consists of patients with ages between four and 12 years for both male and female children. Regional context encompasses two main aspects: a) the existing population of children with congenital partial hand reductions around the world (1 in 90.000 births) [28] and b) the number of children with finger amputations due to armed conflict and accidents.

After reviewing the product family, it was possible to identify the following improvement opportunities: a) The need for changing due to the natural limb growth entails short useful lives for each hand prosthesis size, and the generation of waste due to full discarded products (See Fig. 5). b) None of the components was designed to be reusable in more than one size within the product family for the current design. Moreover, c) Costs associated with manufacture can be improved by reducing complexity and increasing commonality among product family components.

Product family inventory

Identification of design attributes

A product family of eight products is chosen for the case study. Four left and right prosthetic hands are selected using 100%, 110%, 120%, and 130% sizes. A total of 128 components were identified from the case study product family. Tables 2 and 3 summarize the whole product family and its comprising components.

Diagnostic of sustainability performance

Table 4 shows the values corresponding to the sustainability performance diagnosis, including indicators from manufacturing and environmental aspects. In material consumption and manufacturing time, these parameters were estimated using the Makerbot® software. Similarly, energy consumption and carbon footprint were calculated using CES Selector® software from Granta Design.

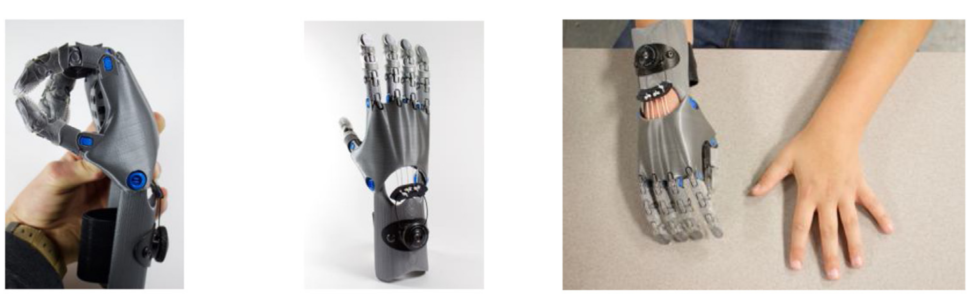
Product architecture analysis

Component relationship analysis

Functional Analysis for the prosthetic hand is performed to identify specific functionalities of each component and establish the most important relationships among them. This task provides useful information about the criticality of components in terms of modularization. The relative functional importance is calculated to determine the most critical components regarding assembly/disassembly and functional relationships within the product family. Fig. 6 shows the functional Analysis of components.

Calculation of functional importance

Table 5 shows the calculation of the relative functional importance of the case study. The number of functionalities of each component and the number of components in contact within the product assembly are calculated to measure the relative functional importance. In this case, the most critical component is the palm (62.5%), followed by the gauntlet (13.9%) and the wrist pin (8.3%). Therefore, the palm's modularization must be studied



a) b)

Fig. 4. a) 3D printed hand prosthesis (Cyborg Beast 2.0). b) Hand prosthesis in use.

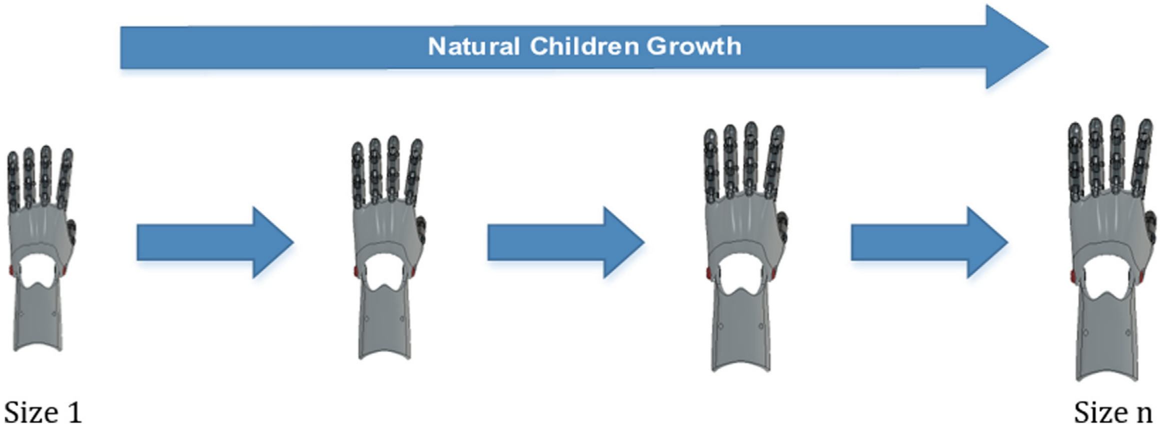


Fig. 5. Sequence of hand prosthesis required based on the natural growth of children. The scalability of the product family enables product adaptability to the user. However, it also generates a throw-away path once the product is replaced for a new size.

Table 2
Product family for the case study.

Products within the family of prosthetic hands (P1 to P8)				
	100%	110%	120%	130%
Left Hand				
	P1	P2	P3	P4
Right Hand				
	P5	P6	P7	P8

carefully to avoid functional losses or assembly/disassembly issues during manufacturing and use stages.

Generation of modularization alternatives

Application of modularization algorithms

The first step to generate modularized alternatives for components within the scalable product family is identifying functional variety and functional range. For the case study, it is possible to identify that the palm offers both functional range and variety within the product family. Meanwhile, the rest of the components provide only functional range. Table 6 shows the functional Range and Functional Variety identification for the components that comprise the prosthetic hand.

The implementation of functional variety and functional range algorithms is performed in detail below. Component modularization is developed following the algorithm sequences shown previously in Figs. 7 and 8. Table A1 (In Appendix A) shows the implementation of the functional variety analysis for the Palm. Furthermore, Table A2 (Appendix A) describes the functional range algorithm implementation for the rest of the prosthetic hand components. Ideas for modularization were obtained from a brainstorming session considering product family geometries and functional limitations. The following abbreviations are settled for each modular architecture principle: widening (WI), component swapping (CW), narrowing (NA), component sharing (CS), adjustment (AD), stacking (ST), cut to fit (CF), size range (SR).

Selection of suitable modifications

After completing the algorithms' application in all product family components and verifying the suitability of different modularization alternatives, three main modifications were selected for the case study. Table 7 summarizes the selected modifications for Palm, Gauntlet, and Connectors. The four design modifications do not affect products' functional performance and provide an alternative architecture for several components implying less resource consumption. Note that in the case of the gauntlet, two modularization alternatives were considered. In this case, the adjustment principle is the most suitable than stacking, which can reduce material consumption but still represent discarded components when necessary to update the size to fit the user arm and wrist.

Modeling and implementation of design modifications

CAD modeling and redesign

Once the modularization algorithms are implemented on the prosthetic hand components, three main redesign modifications were proposed: i) palm modularization using symmetry and an adapter for left and right thumb, ii) gaunlet modularization through symmetry and adjustment and, iii) modularization of pins and connectors using the component sharing principle. Each modification is shown in detail as follows:

i) *Palm Modularization* includes the following modifications: a) generation of symmetric palm able to work for both left and right-handed user, b) redesign of new interfaces using holes for thumb adapter for left or right thumb, and c) redesign of the adapter for left-handed and right-handed users (See Fig. 7).
ii) *Gauntlet modification* consists of a separation into two symmetric sections. Slots were added to provide a connection between sections through elastic bands. The user is available to dismantle the gauntlet or change the elastic band length is required to achieve higher comfort (See Fig. 8).
iii) *Connectors Modifications:* a single size replaced all connectors (pins and rings). Also, connection holes were adjusted to a

Table 3
Summary of components for the family of prosthetic hands.

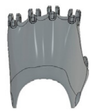
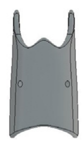
Components	CAD	Quantity per product	Variety of component	Number of components within the Product Family
Left Palm		1	4	4
Right Palm		1	4	4
Gauntlet		1	4	8
Finger		4	4	32
Thumb		1	4	8
Finger Pin		5	4	40
Wrist Pin		2	4	16
Wrist Ring		2	4	16
TOTAL				**128**

Table 4
Sustainability and manufacturing diagnosis for the family of prosthetic hands.

Calculation Parameters (for a whole product family)	Units	Original Design
Total Raw Material Consumption	Kg	1.87
Total Energy Consumption	MJ	140.44
Carbon Footprint	KgCO2/kg	9.91
Manufacturing Costs	USD	933.01
Manufacturing Time	hours	181.76
Number of components	–	128
Component Variety	–	28

unique size of pins. This modification enables the use of just one size of connectors for all eight products. (See Fig. 9).

Finally, Fig. 10 shows the full assembly for the modular prosthetic redesign, including the three modifications described previously. The new design provides a reduction in the number of components and the mass of the product. Therefore, energy consumption, manufacturing costs, and emissions are reduced as well.

Measurement of improvements

Improvements from the proposed redesign method are described and discussed in detail in this section. Key manufacturing parameters are also measured and compared to the original design. Calculations of raw material consumption were obtained through the MakerBot® software for 3D printing. Total Energy Consumption and carbon footprint were calculated using the CES Selector software from GrantaDesign®. The manufacturing cost is calculated using the model proposed by Ashby [29], which includes the mass of the product, the material cost, manufacturing time, and financial topics related to the equipment and operational costs. Eq. (2) shows the calculation model. Where *m*: the mass of the product family (kg), C_m: Material Cost (USD per kg), *T*: Manufacturing Time (hours), C_c: Capital cost (USD), t_{wo}: write-off time (hours) and, C_{oh}: Overhead rate (USD per hour). Table 8 summarizes the calculating parameters for the model and the total manufacturing cost for each product family. The manufacturing cost is calculated assuming user growth between predefined initial

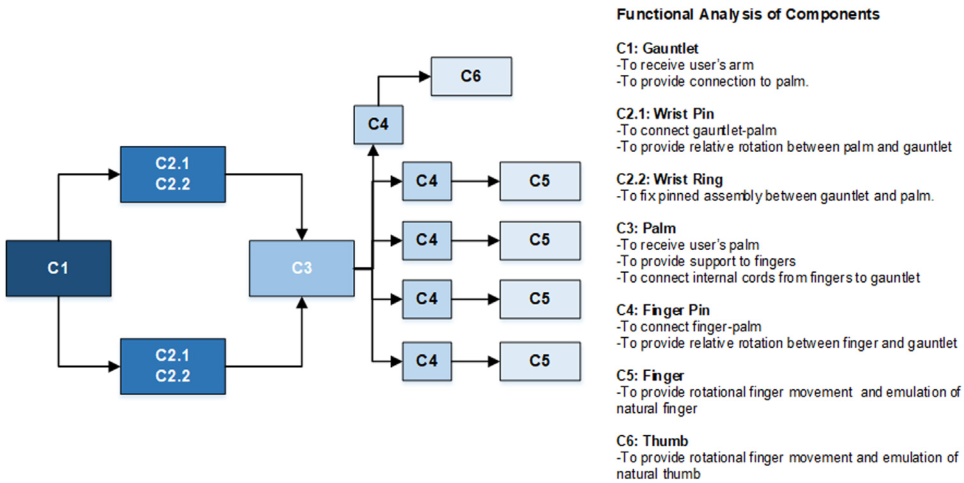


Fig. 6. Component relationship analysis for the prosthetic hand.

Table 5
The relative functional importance of components within the prosthetic hand.

Component	Number of Functions (F)	Number of components in contact in the assembly (N)	Number of components (n)	Functional Importance F*N/n	Relative Functional Importance
C1: Gauntlet	2	5	1	10	13.9%
C2.1: Wrist Pin	2	6	2	6	8.3%
C2.2: Wrist Ring	1	6	2	3	4.2%
C3: Palm	3	15	1	45	62.5%
C4: Finger Pin	2	10	5	4	5.5%
C5: Finger	1	8	4	2	2.8%
C6: Thumb	1	2	1	2	2.8%
TOTAL				72	100%

Table 6
Functional Variety and Functional Range Identification for the product family.

Component	Functional Variety Identification		Functional Range Identification	
	FV	Description	FR	Description
Palm	Y	Left Hand and Right Hand	Y	Scaling from 100% to 130%
Gauntlet	N	–	Y	Scaling from 100% to 130%
Finger	N	–	Y	Scaling from 100% to 130%
Thumb	N	–	Y	Scaling from 100% to 130%
Finger Pin	N	–	Y	Scaling from 100% to 130%
Wrist Pin	N	–	Y	Scaling from 100% to 130%
Wrist Ring	N	–	Y	Scaling from 100% to 130%

FV: Functional Variety, FR: Functional Range. Y: Yes. N: No.

sizes, thus four sizes for both left and right-handed users (100%–110%–120% and 130%).

$$Manufacturing\ \ Cost = m{*}C_m + T\left(\frac{C_c}{t_{wo}} + C_{oh}\right) \quad (2)$$

Table 9 summarizes the reductions obtained in total Raw Material Consumption, Energy Consumption, Carbon Footprint, Manufacturing Costs, Number of Components, and Component Variety. Calculations for Raw Material Consumption, Energy Consumption, and Carbon Footprint were based on the indicators provided by the CES Selector® software considering materials and manufacturing processes. In such parameters, it was possible to obtain a reduction of 36% concerning the original design. Similarly, Manufacturing costs and Manufacturing time obtained a reduction of 12% and 14%, respectively. In terms of complexity, the number of components was reduced by 39%, and the component variety, which decreased by 18%.

Findings and discussion

Design improvements

Raw Material Consumption was substantially reduced by applying the proposed algorithms. Consequently, the Energy Consumption and Carbon Footprint generated were reduced in the same proportion since those parameters were calculated using mass-based indicators (MJ/kg and $kgCO_2$/kg). The proposed method is focused on modifying the product architecture within the scalable product family. Mass reduction is achieved when modularity is employed to create component commonality among the scalable product family members. Other improvements, such as Manufacturing Cost and Manufacturing Time, are dependent on the product family mass. In this case, the manufacturing implied generating each part independently for each size of the case study. Now the modular design involves the manufacture of several parts that can be exchanged in all sizes (e.g., gauntlet and connectors). Complexity and assembly/disassembly relationships are improved through the modular design, enabling the reuse of connectors and gauntlet in different product sizes.

Table 10 shows a comparison between the original and the modular product family design. The commonality among components is zero for the original design. Meanwhile, the new design provides meaningful commonality relationships using the same gauntlet and connectors for all products of the product family. Regarding the product architecture, the modular product family

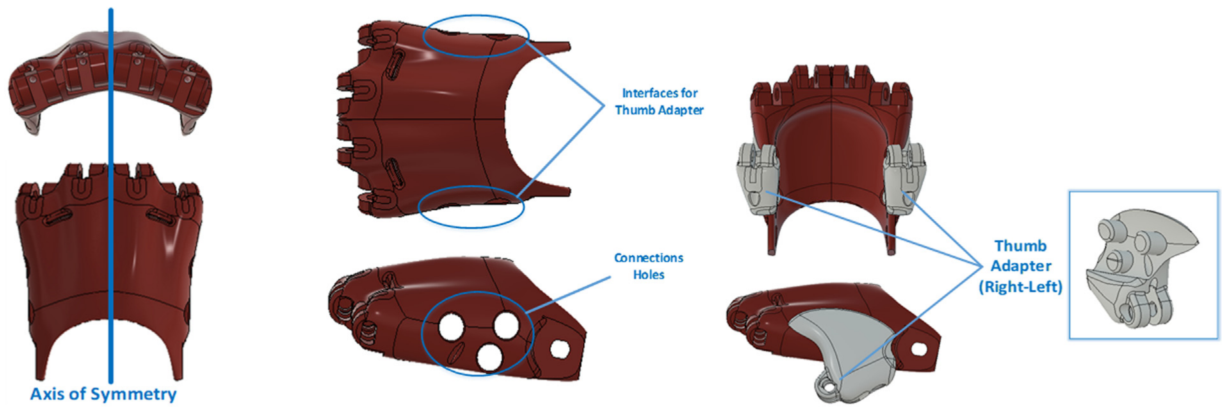


Fig. 7. Palm Modularization - Symmetry and adapter for left and right thumb.

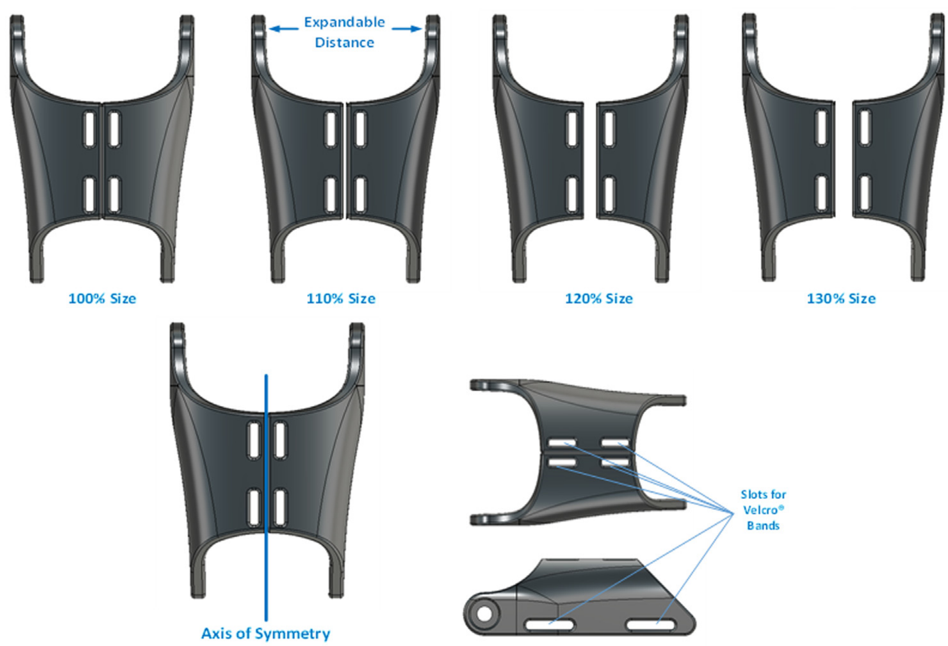


Fig. 8. Gauntlet Modularization.

Table 7
Summary of selected modifications (suitable modularizations).

Component	Functional Variety	Functional Range
Palm	To generate a symmetrical common palm capable of assembling both right and left thumb. The palm requires a symmetrical thumb interface to guarantee equal functional performance for both the right and left hand.	None
Gauntlet	None	All gauntlet sizes can be constructed using common adjustable sections. It involves the verification of joints between palm and gauntlet.
Finger Pin, Wrist Pin, and Wrist Ring	None	To use a unique wrist ring size for all products. It involves standardization of joining holes among gauntlet-palm subassemblies

consists of a reusable gauntlet and a set of connectors, reducing the number of parts and material required for manufacturing a complete set of four sizes. On the other hand, the new palm includes the main shape for both right and left-handed users. Modification represents a reduction from two to one variety of palm. Besides, the use of single sizes for connectors and holes enables different finger sizes in the palm according to the user's comfort. This second modification provided a reduction from four

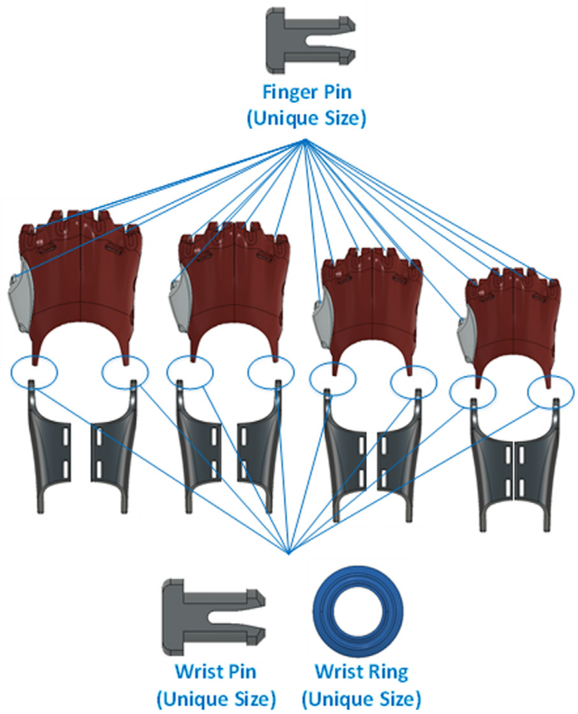


Fig. 9. Modularization of Connectors.

to one type of connectors. These modifications also require a new sustainable mindset in users who must be more conscious about reusing components and the generation of waste due to obsolescence in products.

The component-product relationship obtained with the modular design offers fewer components and component variety to satisfy the same functions with respect to the original design. Note that it is possible to generate more customized products using digitalization of user's parameters; however, in the case of size-based products, the flexibility of the digitalization could generate more consumption of resources since the user can generate not only four but almost unlimited sizes (discretizing the geometric parameters) within the 100–130% range. In the case study, it is assumed that users (children in this case) experiment short periods of tightening before changing size and loosening when they started using a new size. That condition is a consequence of the normal and inevitable growing process inherent to the user's nature.

A second and simpler case study is presented in Appendix B to demonstrate the generalization of the method. In such case, a family of bottles of different sizes is modularized to achieve a reduced product family comprised of one product (four in one bottle). This is an example of using the algorithm for modularization and generating a conceptual alternative using the Cut to Fit principle.

The novelty of the proposed method against other approaches such as design for modularity and design for configuration lies in five main topics: a) the focus on product sustainability improvement, which is reflected in the diagnostic and later comparison of material and energy consumption, carbon footprint and costs. b) the use of a previous characterization of seven modular architecture principles to identify functional requirements for each part in the product family based on two classifications: functional variety and functional range. c) the use of a selection algorithm to determine which modular architecture principle is suitable to generate conceptual modifications or modularization alternatives. d) the analysis of component's importance or relevance in terms of connections and assembly relationship within the product assembly. Which is taken into account to determine the suitability of conceptual modifications for each part. And e) the proposed method is oriented to redesign product families comprised of products with common functionalities in different levels, promoting the reuse of components and reducing sustainability impacts during the manufacturing stage and final disposal of products.

Product testing

For this case study, we used a remote fitting procedure described in a previous publication [26] and thermoforming of the palm section to allow comfort for patients with diverse morphology of the residual limb. A previous investigation [30] describing the remote fitting procedures reported high satisfaction and comfort on the QUEST and OPUS standard questionnaires after using a remotely fitted prosthesis. Furthermore, the thermoplastic (Polylactic Acid) used to manufacture this modular prosthetic device allowed post-processing customization of this device. The thermoplastic nature of the palm section of the device allowed the material to conform to various morphological shapes of the residual limb.

Additional assumptions and limitations

To guarantee a correct and successful implementation of the proposed method is required to satisfy several conditions. Here, a

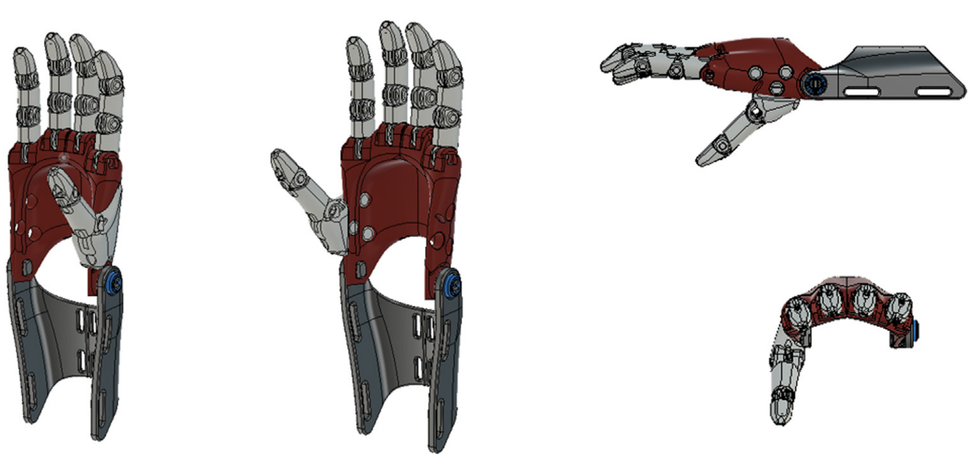


Fig. 10. Full Assembly – Modularized prosthetic hand.

Table 8
Calculation parameters for the manufacturing cost of product families.

Parameter	Original Design	Modular Design
Mass of the product component (m)	1.87	1.37
Material cost (C_m) USD	2.4	2.4
Manufacturing Time (T) hours	181.76	159.16
Capital Cost (C_c) USD	20000	20000
Write-off time (t_{wo}) hours	17520	17520
Overhead rate (C_{oh}) USD	5	5
Manufacturing costs USD	933.01	817.25

list of the most necessary conditions required to make the proposed approach successful:

i *User/Consumer behavior:* Consumer is a crucial factor in creating value from the perspective of sustainability. The positive impact on sustainability in the usage stage is directly related to consumer behavior and needs [7]. Although it is possible to redesign a product family to increase commonality and reduce resource consumption, it is also necessary for the user's self-consciousness regarding the sustainability benefits obtained from the redesign and future impacts reduced during the product family's usage.

ii *Implementation of a Circular Economy model:* designers and manufacturers are encouraged to facilitate the integration of products or components to new lifecycles through remanufacturing, repair, and reuse. Profits can be obtained from services related to repair, upgrade, and exchange, among others. Remanufactured products or components enable additional profits from second-hand markets as well.

iii *Material selection and design:* geometrical modifications can reduce material and energy consumption during manufacturing. However, selecting proper materials has the same relevance in terms of the whole lifecycle regarding extraction, processing, manufacturing, and recycling tasks. More environmentally friendly materials need to be considered as the first choice during the design process.

iv *Design for differentiated durability:* the modularization obtained from the proposed approach encompasses that several components need to be more durable (due to their use during more than one usable cycle) than others. Hence, the durability of components with less intensity use needs to be checked to

Table 9
Functional and complex comparison between original and modular design.

Calculation Parameters	Units	Original Design	Modular Design	Improvement
Total Raw Material Consumption	Kg	1.87	1.37	−36%
[a]Total Energy Consumption	MJ	140.44	89.60	−36%
[b]Carbon Footprint	KgCO2/kg	9.91	6.34	−36%
Manufacturing Costs	USD	933.01	817.25	−12%
[c]Manufacturing Time	hours	185.9	159.16	−14%
Number of components	–	128	78	−39%
Component Variety	–	28	25	−18%

[a] Energy consumption was calculated using the energy consumed per kg of material (MJ/kg).
[b] Carbon footprint was calculated using the equivalent CO_2 generated per kg of processed material($kgCO_2$/kg).
[c] Manufacturing time was calculated using the MakerBot® software to simulate the 3D printing process.

Table 10
Component-product relationships between original and modular product families.

Original Design

Component Variety	Product 1	2	3	4	5	6	7	8
Right Palm$_1$	1	0	0	0	0	0	0	0
Right Palm$_2$	0	1	0	0	0	0	0	0
Right Palm$_3$	0	0	1	0	0	0	0	0
Right Palm$_4$	0	0	0	1	0	0	0	0
Left Palm$_1$	0	0	0	0	1	0	0	0
Left Palm$_2$	0	0	0	0	0	1	0	0
Left Palm$_3$	0	0	0	0	0	0	1	0
Left Palm$_4$	0	0	0	0	0	0	0	1
Gauntlet$_1$	1	0	0	0	1	0	0	0
Gauntlet$_2$	0	1	0	0	0	1	0	0
Gauntlet$_3$	0	0	1	0	0	0	1	0
Gauntlet$_4$	0	0	0	1	0	0	0	1
Finger$_1$	1	0	0	0	1	0	0	0
Finger$_2$	0	1	0	0	0	1	0	0
Finger$_3$	0	0	1	0	0	0	1	0
Finger$_4$	0	0	0	1	0	0	0	1
Thumb$_1$	1	0	0	0	1	0	0	0
Thumb$_2$	0	1	0	0	0	1	0	0
Thumb$_3$	0	0	1	0	0	0	1	0
Thumb$_4$	0	0	0	1	0	0	0	1
Finger Pin$_1$	1	0	0	0	1	0	0	0
Finger Pin$_2$	0	1	0	0	0	1	0	0
Finger Pin$_3$	0	0	1	0	0	0	1	0
Finger Pin$_4$	0	0	0	1	0	0	0	1
Wrist Pin$_1$	1	0	0	0	1	0	0	0
Wrist Pin$_2$	0	1	0	0	0	1	0	0
Wrist Pin$_3$	0	0	1	0	0	0	1	0
Wrist Pin$_4$	0	0	0	1	0	0	0	1
Wrist Ring$_1$	1	0	0	0	1	0	0	0
Wrist Ring$_2$	0	1	0	0	0	1	0	0
Wrist Ring$_3$	0	0	1	0	0	0	1	0
Wrist Ring$_4$	0	0	0	1	0	0	0	1

Modular Design

Component Variety	Product 1	2	3	4	5	6	7	8
Palm$_1$	1	0	0	0	1	0	0	0
Palm$_2$	0	1	0	0	0	1	0	0
Palm$_3$	0	0	1	0	0	0	1	0
Palm$_4$	0	0	0	1	0	0	0	1
Gauntlet$_1$	1	1	1	1	1	1	1	1
Finger$_1$	1	0	0	0	1	0	0	0
Finger$_2$	0	1	0	0	0	1	0	0
Finger$_3$	0	0	1	0	0	0	1	0
Finger$_4$	0	0	0	1	0	0	0	1
Thumb$_1$	0	0	0	0	1	0	0	0
Thumb$_2$	0	0	0	0	0	1	0	0
Thumb$_3$	0	0	0	0	0	0	1	0
Thumb$_4$	0	0	0	0	0	0	0	1
R.T. Adaptor$_1$	1	0	0	0	0	0	0	0
R.T. Adaptor$_2$	0	1	0	0	0	0	0	0
R.T. Adaptor$_3$	0	0	1	0	0	0	0	0
R.T. Adaptor$_4$	0	0	0	1	0	0	0	0
L.T Adaptor$_1$	0	0	0	0	1	0	0	0
L.T. Adaptor$_2$	0	0	0	0	0	1	0	0
L.T. Adaptor$_3$	0	0	0	0	0	0	1	0
L.T. Adaptor$_4$	0	0	0	0	0	0	0	1
Finger Pin$_1$	1	1	1	1	1	1	1	1
Wrist Pin$_1$	1	1	1	1	1	1	1	1
Wrist Ring$_1$	1	1	1	1	1	1	1	1

facilitate their re-incorporation again in the lifecycle. On the other hand, components with higher durability requirements need to be designed to support the most adverse usage conditions.

As limitations of the method, we can mention the following aspects:

i Generation of modularization alternatives depends on the geometry of each component in the initial design. Therefore, it is possible that it will be necessary to make drastic geometrical changes to obtain a proper modularization alternative. In the case study, it was decided not to alter the function and assembly relationships of components.
ii The method is based on scalability within a product family. Thus, product families comprised of products with different architecture and functionalities are not suitable to be modularized following the proposed method. However, each product family member can be redesigned as a single project.
iii The success of the component modularization depends on the type of product. Therefore, it is highly recommendable to include in the design team an expert regarding the design and manufacturing of the product to be redesigned. It is important to remember that decisions in the design stage drastically affect the behavior of products in subsequent stages.
iv In the proposed method, modularization is oriented to reduce resource consumption, and the application is focused on conceptual design. Therefore, basic and detailed designs are still responsible for much of the reduction of resources in terms of material and energy when the product family is manufactured.

Conclusions

This article proposed a methodology to generate modular architecture alternatives in scalable product families to reduce their environmental impacts during the manufacturing stage. Two modularization algorithms were suggested to analyze modular architecture principles' suitability for each component in a product family. Implementation of the method demonstrated that it is possible to reduce material and energy consumption, carbon footprint, and manufacturing cost from the modularization of product families. The critical strategy consists of reducing the number of components facilitating their commonality and reusability. A product family of upper prosthetic limbs is used as a case study; the proposed approach results reveal reductions higher than 30% in energy and material consumption and carbon footprint.

Similarly, it was also possible to reduce by 12% of the product family's total manufacturing costs. Other aspects, such as product family complexity, were also reduced meaningfully. This article enables a useful framework regarding using different modularization principles to satisfy market requirements associated with operation ranges and multiple functionalities. Implementation of the proposed method implies several challenging issues regarding the SM model and the user/consumer behavior and cultural background. Future research efforts should be oriented to generate modularization techniques or approaches to product families with no inherent scalability, especially when required to include new functionalities and capabilities simultaneously. Here, the architecture of products is crucial to determine whether the product family is suitable for modularization. Therefore, there is a need for metrics and methods to analyze product architecture and geometry that respect their modularization potential.

Conflicts of interest

The authors declare that there is no conflict of interest.

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Author's contributions

Jaime Mesa: Conceptualization, Writing – Original draft preparation, Visualization, Investigation. **Heriberto Maury:** Methodology, Supervision. **James Pierce:** Drawing and CAD generation. **Jorge Zuñiga:** Validation, Writing – Reviewing, and Editing. **Iván Esparragoza:** Writing – Reviewing and Editing.

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Appendix A. Detail of design modularization alternatives for each component of the product family based on the algorithms for modularization proposed

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Table A1
Functional Variety Modularization (Just Palm).

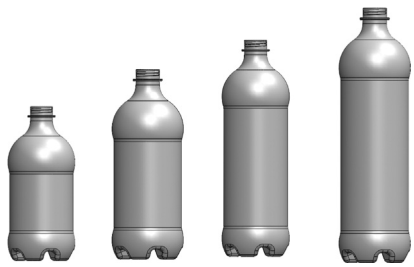
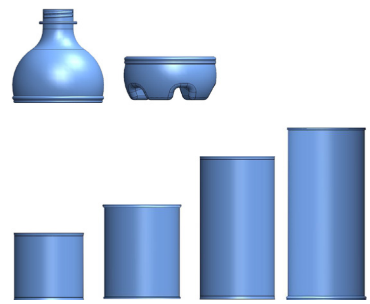
Part	Possible MAP	Ideas for Geometric and Assembly/ Disassembly Modifications	Design Implications	Suitable
Palm (HFI)	WI	To use a unique symmetric palm to satisfy both left and right hand. To design a six-finger hand with left and right thumbs. The palm requires one additional thumb interface.	Users do not need to use both thumbs simultaneously.	No
	CW	To swap the left and right thumb through a standard interface.	The thumb is symmetric. Therefore, the same thumb works on the right and left hand. A standard interface does not provide left-handed and right-handed functionalities.	No
	NA	To generate a symmetrical common palm capable of assembling both right and left thumb. The palm requires a symmetrical thumb interface to guarantee equal functional performance for both right and left hand.	The narrowing facilitates the manufacturing of the palm. Depending on the user, the palm can be adapted to the right or left hand.	Yes

Table A2
Functional Range Modularization (all parts).

Part	Possible MAP	Ideas for Geometric and Assembly/Disassembly Modifications	Design Implications	Suitable
Palm (HFI)	CS	To use a unique palm to satisfy all products. It requires the standardization of joining holes	A single level cannot satisfy all products due to the socket growth and increase of the distance between joining points.	No
	AD	To adjust a unique palm to satisfy all product incurs in the separation of palm sections. It involves new joints.	Separation of palm incurs incompatibility problems due to internal conduit connections	No
	ST	To separate palm into stackable sections It involves additional joints	Palm geometry does not allow the stacking of sections.	No
	CF	Geometry shapes do not allow to stack discrete palm sections. It involves additional joints	Palm geometry does not allow the cut-to-fit sections.	No
	SR (c)	–	–	Yes
Gauntlet	CS	To use a unique gauntlet to satisfy all products. It involves verification of joints between palm and gauntlet.	A single level cannot satisfy all product due to the arm growth	No
	AD	All gauntlet sizes can be constructed using common adjustable sections. It involves the verification of joints between palm and gauntlet.	It requires establishing a joining method for adjustable arc sections	Yes
	ST	All gauntlet sizes can be constructed using stackable sections. It involves the verification of joints between palm and gauntlet. Also, to create new joints between stacking sections.	It requires establishing a joining method for stackable sections and reduces wrist sizes.	Yes
	CF	To establish discrete gauntlet sections with standard add-on modules. It involves additional joints	Add-on modules require different shapes due to the joining points for the four gauntlet sizes	No
Fingers & Thumb	CS	To employ a unique size of fingers and thumb for all products. It requires the standardization of pinholes in joints.	It is necessary to use different finger and thumb sizes due to the child natural growth	No
	AD	To use an adjustable finger for all products. Fingers' rotational joints need to be removed, adding additional connectors. Conduits need to be also verified.	Separation of fingers and thumb involves supplementary connectors and joining tasks. Current rotational functionality and conduit alignment are affected.	No
	ST	To generate stacking sections of fingers and thumb. It involves an increase in the number of joints and connectors	Separation of fingers and thumb involves supplementary connectors and joining tasks. Current rotational functionality and conduit alignment are affected	No
	CF	Geometry shapes do not allow stacking discrete finger sections. It involves an increase in the number of joints and connectors	Separation of fingers and thumb involves supplementary connectors and joining tasks. Current rotational functionality and conduit alignment are affected	No
	SR (c)	–	–	Yes
Finger Pin	CS	To use a single finger pin size for all products. It involves standardization of joining holes among fingers-palm and thumb-palm subassemblies	It requires the verification of mechanical strength for all products.	Yes
Wrist Pin	CS	To use a unique wrist pin size for all products. It involves standardization of joining holes among gauntlet-palm subassemblies	it requires the verification of mechanical strength for all products.	Yes
Wrist Ring	CS	To use a unique wrist ring size for all products. It involves standardization of joining holes among gauntlet-palm subassemblies	It requires the verification of mechanical strength for all products.	Yes

(c): current architecture; HFI: Highest Functional Importance.

Appendix B. Preliminary Alternative to Modularize a family of scalable bottles

Original Product Family	Modularized Product Family
	
Product family comprised of four products that offer the same functionality at a different level (to store a fixed volume of liquid)	Modularization alternative comprised of six components (four in one) after applying the modularization algorithm (Functional Range). Selected MAP: Cut to fit (CF)
Pros: products can be used independently (e.g., four users)	Pros: reduction of material and resources for manufacturing (four in one product). Reduction of mass consumption, energy consumption, carbon footprint, and emissions during manufacturing.
Cons: higher consumption of material and resources for manufacturing.	Less storage volume for the four in one product
	Cons: just one middle section can be used. Leftover middle sections need to be stored until the user requires a different volume.
	User additional tasks: a simple assembly task is required for interchange middle sections.

References

1 Giret, A., Trentesaux, D., Prabhu, V., 2015, Sustainability in Manufacturing Operations Scheduling: A State of the Art Review. Journal of Manufacturing Systems, 37:126–140. http://dx.doi.org/10.1016/j.jmsy.2015.08.002.

2 Malek, J., Desai, T.N., 2019, Prioritization of Sustainable Manufacturing Barriers Using Best Worst Method. Journal of Cleaner Production, 226:589–600. http://dx.doi.org/10.1016/j.jclepro.2019.04.056.

3 Despeisse, M., Mbaye, F., Ball, P.D., Levers, A., 2012, The Emergence of Sustainable Manufacturing Practices. Production Planning and Control, 23/5: 354–376. http://dx.doi.org/10.1080/09537287.2011.555425.

4 Malek, J., Desai, T.N., 2020, A Systematic Literature Review to Map Literature Focus of Sustainable Manufacturing. Journal of Cleaner Production, 256120345. http://dx.doi.org/10.1016/j.jclepro.2020.120345.

[5] Ko, Y.-T., 2020, Modeling an Innovative Green Design Method for Sustainable Products. Sustainability, 12/8: 3351. http://dx.doi.org/10.3390/su12083351.

6 Mesa, J.A., Esparragoza, I., Maury, H., 2019, Modular Architecture Principles-MAPs: A Key Factor in the Development of Sustainable Open Architecture Products. International Journal of Sustainable Engineering, 13/2: 108–122. http://dx.doi.org/10.1080/19397038.2019.1634157.

7 Sonego, M., Echeveste, M.E.S., Galvan Debarba, H., 2018, The Role of Modularity in Sustainable Design: A Systematic Review. Journal of Cleaner Production, 176:196–209. http://dx.doi.org/10.1016/j.jclepro.2017.12.106.

8 Halstenberg, F.A., Buchert, T., Bonvoisin, J., Lindow, K., Stark, R., 2015, Target-oriented Modularization- Addressing Sustainability Design Goals in Product Modularization. Procedia CIRP, 29:603–608. http://dx.doi.org/10.1016/j.procir.2015.02.166.

9 Rajput, S., Singh, S.P., 2019, Connecting Circular Economy and Industry 4.0. International Journal of Information Management, 49/November 2018: 98–113. http://dx.doi.org/10.1016/j.ijinfomgt.2019.03.002.

10 Schischke, K., Proske, M., Nissen, N.F., Lang, K.D., 2017, Modular Products: Smartphone Design From a Circular Economy Perspective. 2016 Electronics Goes Green 2016+. EGG, 2016:1–8. http://dx.doi.org/10.1109/EGG.2016.7829810.

11 Esmaeilian, B., Behdad, S., Wang, B., 2016, The Evolution and Future of Manufacturing: A Review. Journal of Manufacturing Systems, 39:79–100. http://dx.doi.org/10.1016/j.jmsy.2016.03.001.

12 Seliger, G., Zettl, M., 2008, Modularization as an Enabler for Cycle Economy. CIRP Annals Manufacturing Technology, 57/1: 133–136. http://dx.doi.org/10.1016/j.cirp.2008.03.031.

13 Mihelcic, J.R., Crittenden, J.C., Small, M.J., Shonnard, D.R., Hokanson, D.R., Zhang, Q., Chen, H., Sorby, S.A., James, V.U., Sutherland, J.W., Schnoor, J.L., 2003, Sustainability Science and Engineering: The Emergence of a New Metadiscipline. Environmental Science & Technology, 37/23: 5314–5324. http://dx.doi.org/10.1021/es034605h.

14 Mutingi, M., Dube, P., Mbohwa, C., 2017, A Modular Product Design Approach for Sustainable Manufacturing in A Fuzzy Environment. Procedia Manufacturing, 8/October 2016: 471–478. http://dx.doi.org/10.1016/j.promfg.2017.02.060.

15 Yang, M.G., Hong, P., Modi, S.B., 2011, Impact of Lean Manufacturing and Environmental Management on Business Performance: An Empirical Study of Manufacturing Firms. International Journal of Production Economics, 129/2: 251–261. http://dx.doi.org/10.1016/j.ijpe.2010.10.017.

16 Tan, A.R., Matzen, D., McAloone, T.C., Evans, S., 2010, Strategies for Designing and Developing Services for Manufacturing Firms. CIRP Journal of Manufacturing Science and Technology, 3/2: 90–97. http://dx.doi.org/10.1016/j.cirpj.2010.01.001.

17 Yan, J., Feng, C., 2014, Sustainable Design-Oriented Product Modularity Combined with 6R Concept: A Case Study of Rotor Laboratory Bench. Clean Technologies and Environmental Policy, 16/1: 95–109. http://dx.doi.org/10.1007/s10098-013-0597-3.

18 Mesa, J., Maury, H., Arrieta, R., Bula, A., Riba, C., 2015, Characterization of Modular Architecture Principles Towards Reconfiguration: A First Approach in its Selection Process. The International Journal of Advanced Manufacturing Technology, 80/1–4. http://dx.doi.org/10.1007/s00170-015-6951-3.

19 Bataglin, M., Ferreira, J.C.E., 2020, A Modularization Method Based on the Triple Bottom Line and Product Desirability: A Case Study of a Hydraulic Product. Journal of Cleaner Production, 271122198. http://dx.doi.org/10.1016/j.jclepro.2020.122198.

20 Massimi, E., Khezri, A., Benderbal, H.H., Benyoucef, L., 2020, A Heuristic-Based Non-Linear Mixed Integer Approach for Optimizing Modularity and Integrability in a Sustainable Reconfigurable Manufacturing Environment. The International Journal of Advanced Manufacturing Technology, 108/7–8: 1997–2020. http://dx.doi.org/10.1007/s00170-020-05366-y.

21 Kim, S., Moon, S.K., 2019, Eco-modular Product Architecture Identification and Assessment for Product Recovery. Journal of Intelligent Manufacturing, 30/1: 383–403. http://dx.doi.org/10.1007/s10845-016-1253-7.

22 Miyajima, S., Yamada, S., Yamada, T., Inoue, M., 2019, Proposal of a Modular Design Method Considering Supply Chain: Comprehensive Evaluation by Environmental Load, Cost, Quality and Lead Time. Journal of Advanced Manufacturing Technology, 13/1: 119–132.

23 Ma, J., Kremer, G.E.O., 2016, A Sustainable Modular Product Design Approach With Key Components and Uncertain End-of-Life Strategy Consideration. The International Journal of Advanced Manufacturing Technology, 85/1–4: 741–763. http://dx.doi.org/10.1007/s00170-015-7979-0.

24 Sheng, Z., Li, Y., Wu, L., Xie, H., 2017, Lifecycle-oriented Product Modular Design of CNC Machine Tools. Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science, 231/11: 1981–1994. http://dx.doi.org/10.1177/0954406215625679.

25 Wang, W., Tseng, M.M., 2011, Design for Sustainable Manufacturing: Applying Modular Design Methodology to Manage Product End-of-life Strategy. Interna-

tional Journal of Product Lifecycle Management, 5/2–4: 164–182. http://dx.doi.org/10.1504/IJPLM.2011.043186.

26 Zuniga, J., Katsavelis, D., Peck, J., Stollberg, J., Petrykowski, M., Carson, A., Fernandez, C., 2015, Cyborg Beast: A Low-cost 3D-printed Prosthetic Hand for Children With Upper-Limb Differences. BMC Research Notes, 8/1. http://dx.doi.org/10.1186/s13104-015-0971-9.

27 Zuniga, J.M., Peck, J.L., Srivastava, R., Pierce, J.E., Dudley, D.R., Than, N.A., Stergiou, N., 2019, Functional Changes Through the Usage Of 3D-Printed Transitional Prostheses in Children. Disability and Rehabilitation Assistive Technology, 14/1: 68–74. http://dx.doi.org/10.1080/17483107.2017.1398279.

28 Nair, S.B., Mukundan, G., Thomas, R., Gopinathan, K.K., 2011, Ectrodactyly and Prenatal Diagnosis. The Journal of Obstetrics and Gynecology of India, 61/6: 683–685. http://dx.doi.org/10.1007/s13224-012-0120-5.

29 Ashby, M., 2005, Material Selection in Mechanical Design. 3rd ed. Butterworth-Heinemann.

30 Zuniga, J.M., Young, K.J., Peck, J.L., Srivastava, R., Pierce, J.E., Dudley, D.R., Salazar, D.A., Bergmann, J., 2019, Remote Fitting Procedures for Upper Limb 3D Printed Prostheses. Expert Review of Medical Devices, 16/3: 257–266. http://dx.doi.org/10.1080/17434440.2019.1572506.