Material Selection and Design for Assembly Applied in the Development of an Energy Generating Device

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Abstract: This study used the Design for Assembly (DFA) and material selection methods as tools to aid the development of a conceptual design of a functional device to transform alternate movement into rotational movement on the axis of a microgenerator. Also, material selection software was used to define the most suitable thermoplastic materials for some components of the projected device, focusing both on performance and low cost. There was a considerable reduction in the number of parts in the set from the basic device (prototype), which had 47 parts, to the conceptual design I, with 34 parts, and the conceptual design II, with 14 parts. The total mass of the set was also considerably reduced, from 160 grams for the basic device to 57.01 grams in the conceptual design I and, finally, 18.30 grams in the conceptual design II. Of thermoplastic materials analysed, considering a selection focused only on performance the most promising candidate, with an ideal set of properties is PEEK. But for a selection that considers the price, that is one of the key variables in the materials selection for most products, PEEK shows is prohibitively price.

Keywords: Design for Assembly, Material selection, Product development, Industrial design.

1. INTRODUCTION

In the last years, companies have seen themselves immersed in a scenario of high demand for quality, lower prices, shorter deadlines to launch new products in the market, and less tolerance for mistakes. The economic competition imposed by globalization has increased considerably worldwide. In general, products today are researched, designed, manufactured, and tested so that they can be rapidly launched in the market, and their life cycle is increasingly shorter. Thus, tools like Design for Manufacturing (DFM) and Design for Assembly (DFA) gain each time more importance [1, 2]. According to Boothroyd*et al*. (2002), Design for Manufacture and Assembly (DFMA) is the combination of DFM and DFA [3]. Both DFM and DFA have basically the same objective, which is to increase the efficiency of product production processes. Some authors often refer to the term DFMA using the expression Manufacture and Assembly-Oriented Design. The use of DFMA includes three main activities:

a) As a basis for Simultaneous Engineering studies to organize groups of projects by simplifying product structure, lowering manufacture and assembly costs and measuring improvements.

b) As a support tool to study competing products and assess manufacture and assembly difficulties.

c) As a cost-based tool to negotiate contracts with suppliers.

The purpose of DFM, also known as "manufacture-oriented design", is to ensure that the individual product parts, which will be grouped and assembled to form the final product, are easily manufactured. DFM aims at eliminating unwanted and unnecessary characteristics that may complicate manufacture. An example is the waste of time and resources in the manufacture of products with finishing and dimensional tolerance better than necessary.

The purpose of DFA, also known as "assembly-oriented design", is to ensure that product assembly is easy and fast. This method will be discussed in detail below.

Still, according to those authors, designers working in product design used to be kept too distant from

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manufacturing activities. In sum, designers used to design procedures that did not promote teamwork. Such behaviour was the origin of the expression “we design it, you make it.” Work was conducted according to the paradigm according to which designers should conceive and design products according to their way of doing things, without external interferences, and then, later on, deliver them to engineers, who would have the difficult task of finding feasible solutions to manufacturing those products. That is, specialists in the area of manufacturing processes often had to adapt their productive processes and change their factory layout to make it possible to manufacture a product, because specialists had not been involved in the designing process. In the literature, this has been called the “over the wall” approach, in which designers are on one side of the wall and throw designs over the wall to manufacture engineers, who are on the other side.

The negative result of such attitudes is that the complexity of the product, resulting from the characteristics defined during the designing phase, often makes product manufacture very difficult or even impossible. Therefore, the solution would be to re-design the product, which led to delays in market launching time and to all the extra costs associated with reworking.

One of the possible ways to overcome this problem is to increase the level of communication between designers and manufacturing engineers in the initial phase of a project. The effective interaction between these professionals may lead to the formation of teams, called simultaneous engineering teams. Designers do not have to specialize in processes, because specialists in production and processes, who know difficulties and limitations, provide support for the development of products by evaluating them and making suggestions for improvement. Such teams are responsible for studying and analyzing project plans from the manufacture and assembly perspective, that is, they analyze project plans using the knowledge generated by DFMA. Still, according to those authors, the capacity to estimate part assembly and manufacture costs in the initial phases of product design is the essence of DFMA. The main objective of several programs to investigate DFMA conducted over the last two decades was to develop economic models of manufacturing processes based on information about product design.

According to Boothroyd*et al.* (2002) [3], when the designing process is approached using the DFMA, design analysis and application should take place after the definition of the first product concept. After DFA protocol is applied, suggestions are made to simplify product structure, so that each evaluation results in improvements and advances in product characteristics. Possible materials and processes are previously evaluated, together with an initial cost estimate. As these steps are followed, an optimal or ideal project concept is defined. After that step, materials and processes that can be used in the process are fully analysed, after which a detailed design of the parts involved is produced. At the time when the designer has the detailed designs of all parts, the prototype can be constructed and, after the prototype has been approved, product manufacture can begin.

DFMA describes a systematic procedure to analyse a concept from an assembly and manufacture perspective and has a series of advantages. It results in simpler and more reliable products and, consequently, products with lower manufacture and assembly costs. Moreover, any reduction in the number of parts in any assembly has an exponential effect on cost reduction because it means fewer designs and specifications, less inventory, less labour, etc. All these factors have an important effect on expenses in general, which often represent the largest share of total product cost. It is important to remember that in product projects, cost is often not necessarily the most important factor to be taken into consideration by companies. Figure **1** shows the results of a survey about the positive effect of DFMA application.

The example in Figure **1** shows that, in this case of redesign, reductions of time to market (39%) and improvements in quality and reliability (22%) were the most important factors for companies. The DFMA tools also promote the dialogue between designers and manufacturing engineers, as well as with any other individuals who have a role in determining final product cost during the initial phases of the project. This means that teamwork is important and, consequently, increases cost savings in the manufacturing sector.

According to Salustri and Chan (2005) [4], the purpose of design for assembly (DFA) is to simplify a product so that assembly costs are reduced. However, as a consequence of DFA application, better quality and reliability are achieved, as well as a reduction of inventory in the production of parts and equipment. DFA includes the need to analyse all parts of the project and the entire product for each assembly

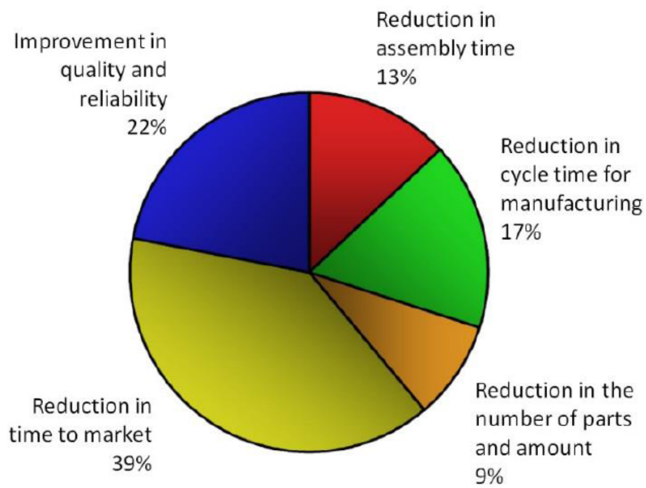


Figure 1: Survey about the importance of reductions due to DFMA.

Source: Adapted from Boothroyd*et al*. (2002) [3].

problem in the beginning of product development. Salustri and Chan (2005, p.1) [4] defined DFA as "a process for improving product design for easy and low-cost assembly, focusing on functionality and on assemblability concurrently."

The adoption of DFA as a distinct design characteristic is recent, but several companies have used it for some time now. For example, in 1960, General Electric published an internal manual of productivity and manufacture as a set of guidelines and data to help designers in their design tasks. The analysis of that manual reveals that those guidelines followed much of what is now part of the DFA principles. Around 1970, some of the first studies and books about DFA were published; the most important publication at that time was the one by Geoffrey Boothroyd, which promoted the use of DFA in manufacturing [5].

According to Salustri and Chan (2005) [4], industrial assembly activities may be divided into three large groups according to their degree of automation:

a) Manual assembly: parts are moved to workbenches, where workers manually assemble products or product components. In this case, assemblers generally use hand tools as an aid. Although it is the most flexible and adaptable assembly method, it usually raises some concerns about worker safety and labour costs.

b) Hard automation assembly: automated machines for customized assembly produce specific products in large volumes. This type of machinery usually demands a high volume of investment capital. As production increases, the capital investment as a fraction of total manufacturing cost decreases. In this type of assembly, indexing tables and parts feeders are used, which makes it a rigid production system.

c) Robotic assembly: the use of robotic production systems is incorporated. This system uses only one robot or a multi-station robotic assembly cell, and all activities are simultaneously controlled and coordinated by a programmable logic controller (PLC) or a computer. This assembly method is extremely flexible. Initial investments are usually offset due to its flexibility to be used in the assembly of several different products.

Figure **2** shows a comparison of the different assembly methods according to annual production volume and product assembly cost. The non-linear cost of robotic production reflects the non-linear cost of robots.

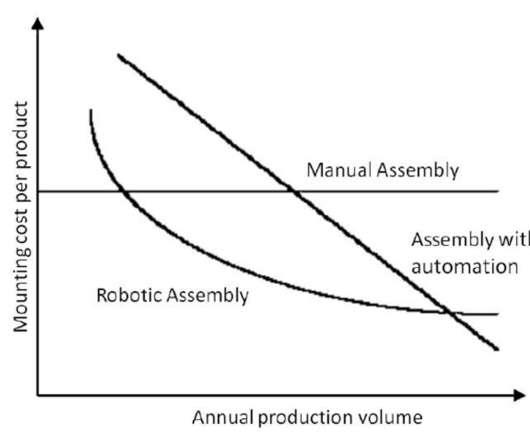


Figure 2: Comparison of assembly methods.

Source: Adapted from Salustri and Chan (2005) [4].

According to Costa *et al*. (2005) [6], DFA is based on the premise that the ideal product has only one part. Therefore, number of parts is the major factor in the efficiency of an assembly line. According to Boothroyd*et al*. (2002) [3], DFA should be efficient to analyse the ease of assembly of products or subset of products that designers design, and should provide quick results, be simple and easy to use, ensure consistency and completeness in the evaluation of product assembly and suggest alternative approaches to simplify product structure and thus reduce manufacture and assembly costs.

Those authors also claim that the use of a DFA tool in the conceptualization stage, during which changes are simple and inexpensive, brings considerable improvement to the communication between the manufacturing and designing sectors and, consequently, the ideas generated and the logical conception led to a reduction in the number of errors in decision making.

1.1. Product Design for Manual Assembly

The results of the use of DFA indicate that some general guidelines should be followed to consolidate manufacture knowledge and present it to designers as a set of simple rules to be followed when designing a product. In this sense, manual assembly may be divided into two areas: one refers to handling (grasping, orienting and moving parts), and the other, to insertion and fastening (one part into another part or group of parts).

1.1.1. Design Guidelines for Part Handling

Boothroyd*et al*. (2002) [3] claimed that, in general, a designer should try to follow the guidelines below to facilitate part handling:

a) design parts that are symmetrical along their length and rotationally symmetrical around their insertion axis. If that is not feasible, designers should attempt to design parts that have the most symmetry possible.

b) design parts that are clearly asymmetrical when it is not possible to have a symmetrical design. The purpose of this rule is to make it easy for the assembler to identify the lack of symmetry;

c) provide elements that prevent jamming of parts that tend to stack when stored in bulk;

d) avoid features that might promote tangling of parts when stored in bulk.

e) avoid parts that, when together, tangle unnecessarily or are slippery, flexible, too small or too large, or that are hazardous to the handler (parts that are sharp, that splinter easily, etc.).

1.1.2. Design Guidelines for Parts Insertion and Fastening During Assembly

According to Boothroyd*et al*. (2002) [3], under specific assembly conditions and for ease of part insertion, a designer should:

a) design so that there is little or no resistance to insertion and, for that purpose, provide chamfers to guide part insertion and an accurate dimensional adjustment to prevent nonstandard play or interference.

b) standardize parts, processes and methods in all models and all product line, which usually reduces final product cost.

c) use stacked assembly – assembly on one axis of reference. Assembling from above is usually better.

d) avoid, whenever possible, the need to hold parts down to ensure that they keep their orientation during handling of the subassembly or placement of another part.

If holding down cannot be avoided, try to design so that the part is fastened as soon as possible after insertion;

e) design so that the part is located before it is released for final positioning. Any elements that may work as guides (holes, grooves, etc) will add safety to assembly;

f) choose adequate securing processes for assembly according to physical and economic factors in agreement with design requisites. For manual assembly, the most common fastening methods are snap fitting, plastic bending, riveting and screw fastening. The snap-fitting method is the least expensive, and screw fastening, the most expensive.

g) avoid the need to reposition assembly.

Still, according to the authors, these design guidelines are a set of rules that, when analysed as a whole, provide adequate information to be used by designers to develop a design that will be easier to assemble than one developed not in accordance with these rules. They are useful and help designers to optimize and develop their projects, but do not provide means to evaluate designs quantitatively in terms of ease of assembly. Also, there is no relative classification of all guidelines that may be used by designers to define which guidelines lead to greater improvement in handling, insertion and fastening. When designers aim at quantifying assembly difficulty, they should use the DFA software developed by Boothroyd and Dewhurst to optimize the calculation of the DFA index, which provides information about assembly efficiency.

1.2. Materials Selection in Product Design

Based on structure-property correlations, the synergy between material selection and product design, in general, is essential to improve and innovate the industrial sector [7]. According Malloy (1994) [8], since the end use of product requirements have been specified, designers can begin looking for materials suitable for the intended application. The material selection is usually made by comparing the properties of each material with a "property" profile derived from the product end use requirements.

Since there are differences in the properties of each type of material, there will also be differences in the products geometry related to each other. If a designer is considering high density polyethylene (HDPE), polypropylene (PP) and polyamide 6/6 (PA 6.6) or nylon 6,6 as materials suitable for an application involving static loading. The polyamide 6/6 is a more expensive material per unit mass or volume, but reductions in wall thickness can overcome this disadvantage.

Since many materials have been preselected, the parts can be designed according to the properties of each material, ie, the wall thickness will be influenced by the stiffness of the material. The geometries of the parts shown in Figure **3** have equivalent stiffness values because the moments of inertia have been adjusted to compensate different Young’s modules of each material. In practice, many other features associated with the performance during assembly or use of the product may vary according to the specific properties of each material.

According to Ashby and Johnson (2002) [9, 10], information about materials enter at all stages of creation. In the project design phase, the information is fluid and all materials are candidates. As the design and requirements become advanced, the need is information on less material, but in a higher level of accuracy. The engineering and design projects are based on a vast number of materials and processes to shape, join, and finish them. Thus, an aspect of the optimized design of any products or systems is to select, from this large group, the materials and processes that best meet the needs of that planning, maximizing their per-formance and minimizing their cost [11].

This study investigated the theoretical basis for DFA and its associations with product development. Its main objective was to define a conceptual design using DFA concepts in the development of a special device to transform alternate movement into rotational movement on the axis of a micro generator. Besides a computerized material selection was used as a tool to analyse the best choice in thermoplastic materials for some components and thus help the DFA in this design of a functional energy generating device development.

Therefore, this study was defined by the need to restructure and modernize companies to use the method called Design for Assembly in the conceptual phase of the project to develop a product.

2. MATERIAL AND METHODS

2.1. Development of Conceptual Design I – First Model

The development of conceptual design I was based on a literature review and analysis and evaluation of a basic device (prototype), which was a reference for the

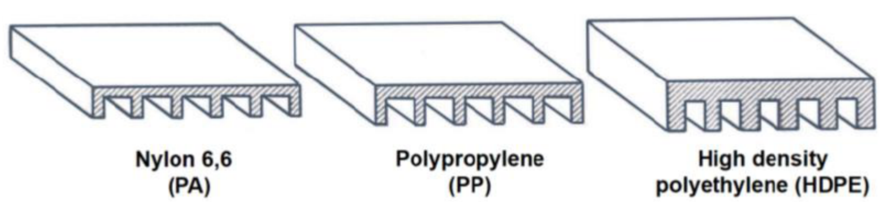


Figure 3: Parts of different polymeric materials with equivalent stiffness values due to the adjustment of the geometries designed to compensate for the different Young's modulus of each material.

Source: adapted from Malloy (1994) [8].

development of this study. Initially, the objective of this study was to develop the conceptual model of a device that would be able to replace the existing device (basic device) at an economic advantage and with a good functional structure.

The basic device (prototype) used as a starting point for the development of this study was a prototype built with parts that were practically all reused from other devices. Such device was manufactured and assembled to transform alternate movement into rotational movement on the axis of a micro generator and to test the possibility of generating energy. However, no scientific method was used for design or manufacture, as our purpose was only to gather components that might facilitate movement transmission. Figure **4** shows this device in its current conception (prototype).

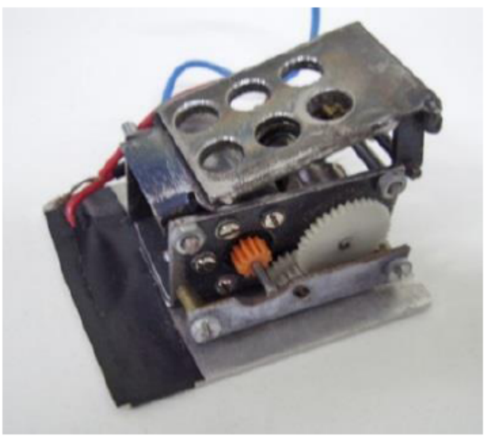


Figure 4: Basic device (prototype).

2.1.1. List of Parts of the Basic Device

1 frame (1 part)

2 mechanical drive (1 part)

3 micro generator (1 part)

4 lateral supports (3 parts)

5 front arms (2 parts)

6 rotation axis (5 parts)

7 separating bushing (2 parts)

8 straight-toothed gear (4 parts)

9 coil spring (1 part)

10 guiding pulleys (6 parts)

11 washers (8 parts)

12 nuts (2 parts)

13 screws (11 parts)

A total of 47 parts make up the basic device, at a total mass of 160 grams.

The analysis and evaluation of the basic device were based on the literature reviewed and conducted at two time points: first, product function was evaluated; second, a checklist with the main product characteristics was used.

2.1.2. Analysis of Product Function

Baxter (2000) [12, 13] defines that function is the object of an action and not the action itself. In general, it is not associated with means (physical components) used for its performance, but only with its objective. Function is generally defined by a verb (action upon something) and a noun (object acted upon). Product functions may be classified as: principal, basic and secondary. For the product under study, we have:

a) Principal function: Transform alternate movement into rotational movement on the axis of a micro generator;

b) Basic function: to produce rotation on the axis of a micro generator (dynamo);

c) Secondary functions: produce rotation on the driven gear 2 joint to the micro generator axis; produce rotation in the drive gear 2; produce rotation in the driven gear 1; produce rotation in the drive gear 1; produce alternate movement of ascending and descending translation in the mechanical drive.

2.1.3. Product Checklist and Evaluation of Basic Device

According to Pahl & Beitz *et al*. (2005) [14], technological and economic characteristics should be incorporated as early as possible for evaluation in the conception phase. Therefore, technological and economic criteria, as well as those that refer to safety, should be taken into consideration simultaneously. Because of that, a checklist model for the original prototype (basic device) was used as an aid for analysis. The evaluation conducted is shown in Table **1**.

A markedly negative finding in the evaluation of the use of the basic device was that it produced rotational

Table 1: Checklist and principal characteristics to evaluate product

Source: Adapted from Pahl & Beitz *et al*. (2005) [14]

Principal Characteristic	Basic Device Evaluation	
	Existing Situation	Desired Situation
Principal function	Transform alternate movement into rotational movement on the axis of micro generator	Transform alternate movement into rotational movement on the axis of micro generator
Working principle	Mechanical - Transform alternate movement into rotation to drive micro generator	Mechanical - Transform alternate movement into rotation to drive micro generator
Base form	Cartesian form:, Dimensional excess and complex configuration	Organic form:, Reduced dimensions and simplification of configuration
Design	No design	Product rendering
Safety	No risks or noxious effects to user or society	No risks or noxious effects to user or society
Ergonomics	High mass and elevated effort to produce movement	Reduction of mass and effort necessary to produce movement
Production	Elevated number of components and production processes that are expensive for current configuration Difficult assembly due to structural complexity	Reduction of components, use of less expensive production processes and simplification of structure to make assembly easier
Control	Structural complexity makes quality control difficult	Simplification of structure to make product quality control easier
Assembly	Assembly complexity due to the large number of parts and use of coil spring and screw fastening elements	Reduction of number of components, elimination and substitution of fastening and movement transmission components, which makes assembly easier
Transport	Difficult stacking, difficult transportation, volume loss at packaging due to frame dimensions	Reduce external size to make stacking easier and have volume gains in product transportation
Use	High noise level. Conversion of alternate movement of the drive lever into rotation on the axis of the micro generator only in the ascending position	Reduce noise level. Conversion of alternate movement of the drive lever into rotation on the axis of the micro generator in the ascending and descending positions
Maintenance	**Preventive:** Difficult to reach components that should receive maintenance **Corrective:** Difficult to reach components. Several parts have to be disassembled for replacement of most components	**Preventive:** Make it easier to reach components that should receive maintenance **Corrective:** Simplification of structure to make access and disassembly easier without interfering with other already assembled parts
Recycling	Except for the gears, made up of polymers; all the other materials are easily recycled.	Use of materials that can be recycled to cause as lower an environmental impact as possible.
Costs	High manufacture and assembly costs due to high number of components	Reduce number of components to lower manufacture and assembly costs

movement on the micro generator axis only when the mechanical drive was in its ascending vertical movement. The descending vertical movement, in this case, was used only to store mechanical energy by means of the coil spring.

For the development of conceptual design I, we used an intuitive method to generate product concepts, the method of question instigation, described by Back *et al*.(2008) [15] and Mike Baxter (2000) [12], and called MESCRAI, an acronym formed by the initials of the following keywords: modify; eliminate; substitute; combine; rearrange; adapt; and invert.

When using this method, the association between the critical characteristics defined in the analysis of the basic device, shown in Table **1**, was analyzed in an attempt to solve problems or improve design elements, such as elevated mass, elevated effort to produce movement, dimensional excess, elevated number of components, difficulty in assembling, complex functional structure, elevated noise level, difficult maintenance and elevated manufacture and assembly costs.

To justify the development of a new concept, the problem of a basic device design that resulted in the production of rotation on the axis of the micro generator only using the return movement (ascending movement) of the drive lever was chosen as a priority and an indispensable goal. The solution of this problem as early as in the development of the first model would result in the use of the full cycle of the mechanical movement. The items associated with the reduction of the number of components, of external dimensions and total product mass were also listed as important in this phase of project development.

2.2. Development of Conceptual Design II – Second Model

The purpose of the development of the conceptual design II – second model was to apply the DFA method using the results of the development of the conceptual design I – first model, conceived according to the MESCRAI method. The use of the DFA method remained to be confirmed, and the significant improvements of the final product had to be demonstrated.

To respond to those needs, the conceptual design I was analyzed according to assembly in this phase of the study. For that purpose, it was important to evaluate the need to use or not use tools, the difficulty in assembling small parts, the possibility of using several types of fastening elements, as well as the possibility of uniting and integrating parts.

According to Beall (1997) [16], several parts and components (plastic or not) may be consolidated in a single injected part, which is much more complex, but has more advantages because of the number of assemblies that it may eliminate. Considering that it is possible, even if not easy or inexpensive, to use injection molding in plastic for practically any part, even those of extremely complex and detailed geometry, an initial analysis pointed to advantages in replacing groups of parts with a single part, which would contribute to the reduction of the number of parts.

Therefore, the conceptual design I – first model was reviewed to evaluate ease of assembly according to the method described by Boothroyd and Dewhurst. According to Boothroyd *et al*. (2002) [3], the method used by Boothroyd and Dewhurst lists three questions to be used to evaluate whether a part is necessary or not in a group of parts – the criterion of minimum number of parts.

a) Does the part or component under analysis during operation in normal mode have movements in relation to other recently assembled parts, that is, in relation to their interfaces?

b) Does the part or component under analysis need to be made of a different material from its interface, or should it be isolated to perform or have its function?

c) Does the part or component under analysis need to be disassembled or removed for the repair of any other part or component?

During the analysis of the first model (conceptual design I) using the three questions of the method described above, questions were made about the relative movements of the parts in relation to each other and each one with its surroundings. This analysis revealed that:

a) parts numbers 01, 05, 06, 07, 10, 11, 12, 14, 15, 16, 17, 20, 21 and 22 moved in relation to the other already assembled parts.

b) for the set to perform its function fully, it is not necessary that all parts listed above move in relation to the other already assembled parts. This is the case of parts 05, 06 and 07, as well as parts 15 and 20.

Our initial conclusion showed that parts 01, 10, 11,12,14,15,16,17,21 and 22 should first be kept as individual units and possibly be used in conceptual design II, except if a technological change might improve design, in which case there should be the replacement of the gear movement transmission systems with a friction movement transmission system, which would facilitate the integration, substitution or addition of other elements.

To answer the second question, materials that might be used in the projects were analyzed and revealed that different materials should be used for some parts, that is, materials with specific characteristics, but not for all parts. Part number 16 is a good example of part for the use of a different material, because this part should resist torsion. The set of parts numbers 17, 21 and 22 may be made of the same material as long as the friction criteria were respected. Parts numbers 01, 04, 06, 07, 10, 11, 12, 14, 15 and 20 might be made of the same material, as long as the minimal criteria of mechanical resistance were respected. Part number 21 may be included in the group of parts mentioned above with the same material, but it would certainly require some change of its size.

Finally, to answer the third question, the possibility or need to reach the set for repairs was analyzed, and results revealed that any type of maintenance in parts number 05 would require the removal of other parts. According to the same line of reasoning, repairs of parts numbers 10 and 11 would require that part number 12 be disassembled.

The function of parts numbers 03, 08, 09, 13, 18 and 19 is to join or fasten other parts and, therefore, they are good candidates for exclusion or substitution.

Part number 2 may be classified as a subset because of its small size and the difficulty to manufacture it. It is purchased ready from a supplier, and for this reason, it has to be kept in the final project.

As seen above, none of the three questions applied to each individual part had a negative answer for all the parts included in the assembly. This fact generated an evaluation that made exclusion, substitution and integration of parts possible.

Considering the individual answers of the analysis of the first model (conceptual model I) for the three questions of the method, as well as exclusion, substitution and integration of parts, and the real needs to make the conceptual design of the functional device (conceptual design II – second model) perform its function, we reached the conclusion that the minimum number of parts would be 14.

2.3. Material Selection for the Energy Generating Device

The material selection criteria for the device were determined by the structural function and the constraints to resist both vibrations, mechanical shock and withstand the operating temperature of the generator combined with the ambient temperature. These design requirements are translated into specifications given by properties combinations such as mechanical strength, tenacity, Young's modulus (relates to the stiffness of the materials), maximum service temperature and price [10].

In order to analyze various materials with potential to be used in the main polymeric components of the energy generating device, as the pulleys and the base, a computerized materials selection with Cambridge Engineering Selector® software [17] was made to verify thermoplastic materials that may present the best properties front the requirements for the analyzed components. This software enables to perform, in a virtual way, the intersection of material properties, where, from a database, a sorting of materials matching can be made for the requested requirements, eliminating those that do not meet the requirements in question. Thermoplastic polymers were considered because these are the ones most suitable materials for the injection molding process [18].

For the material selection of these components some requirements were taken into account. To perform well their functions within the mechanical device, they need to have properties such as: high mechanical strength to avoid the possibility of exceed the yield strength with the mechanical stresses arising the service conditions, high structural stiffness so that it can be used without excessive strain within the elastic range, high toughness so that it can absorb energy arising from mechanical shock possible and high maximum working temperature to support the temperatures attained in the energy generating device operation.

On the other hand, the thermal expansion and price should have low values, since in the first case due to the temperature variation and the polymeric components coupling with metallic components of lower thermal expansion coefficient would result in thermal stresses that could harm the correct functioning of the device. But the price is a variable that, as a rule, the materials selections seeks to reduce wherever possible. Thus, three graphs were drawn by comparing some of the most common thermoplastics materials, one in terms of yield strength versus price, another in terms of maximum working temperature versus the coefficient of thermal expansion and the third graph in terms of fracture toughness versus Young's modulus. The materials analyzed were: LDPE (low density polyethylene), HDPE (high density polyethylene), PP (polypropylene), ABS (acrylonitrile butadiene styrene), PA (polyamide), POM (polyacetal), PET (polyethylene terephthalate), PMMA (polymethyl methacrylate), PC (polycarbonate), PS (polystyrene), PVC (polyvinyl chloride), PEEK (polyether ether ketone), Epoxy resin, PF (phenol formaldehyde resin).

3. RESULTS

3.1. Presentation of Conceptual Design I – First Model

Figures **5** and **6** shows the results of the development of the first concept more clearly.

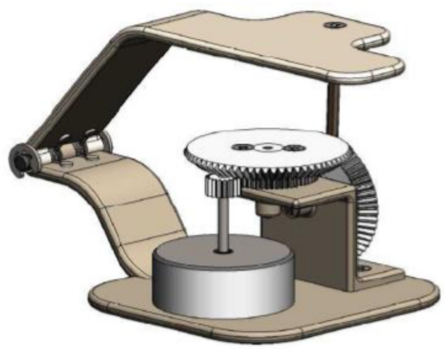


Figure 5: Isometric perspective of the functional device – conceptual design I.

In the first evaluation, the use of the MESCRAI method revealed that the first device model (conceptual design I) had part of the critical items of the design identified in the analysis of the existing basic device. Of the items approached and the improvements made, the following may be mentioned:

a) the number of parts was reduced from 47 to 34, which is a reduction of 27.65% (13 parts).

b) the total mass of the set was reduced from 160 to 57.11 grams, which corresponds to a mass reduction of 84.36% (102.89 grams).

c) there was no significant gain in external dimensions at this first time point;

d) the objective of the project, that is, to produce continuous and unidirectional movement on the axis of the micro generator by means of the alternate movement of the drive lever (descending and ascending) was achieved using an articulate arm with eccentric movement and joining the mechanical drive to the drive gear (conical gear 01), item 14, Figure **6**;

e) the functional structure was simplified, which improved ease of maintenance and the possible replacement of parts, as well as the assembly and disassembly of the set.

f) the gear transmission system was kept in the conceptual design I, but the straight-toothed gears (basic device) were replaced with conical gears (conceptual design I) due to movement transmission at 90 degrees.

3.2. Materials Selection for Plastic Components

Three graphs were drawn by comparing some of the most common thermoplastics materials. One shown in Figure **7** in terms of yield strength versus price, another shown in Figure **8** in terms of maximum working temperature versus the coefficient of thermal

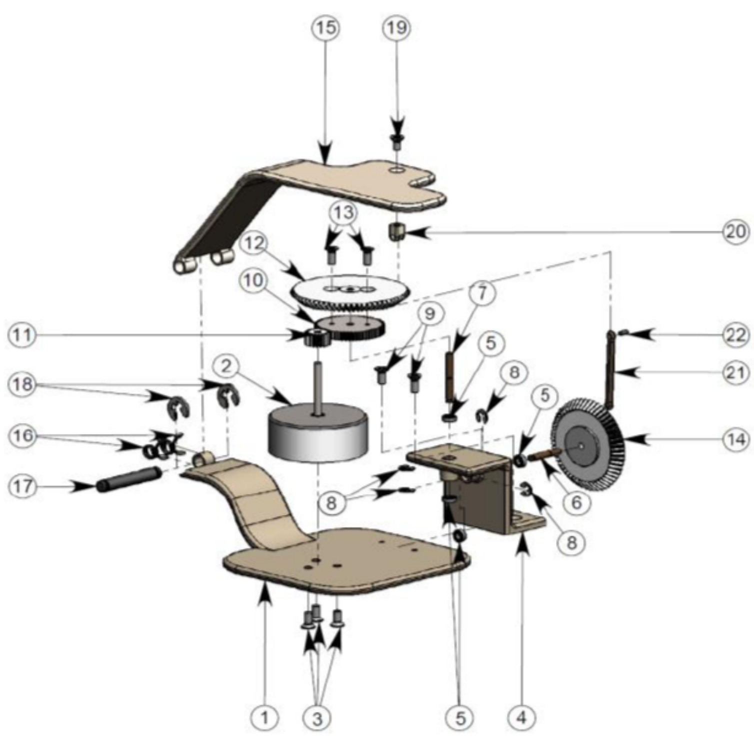


Figure 6: Enlarged perspective of the functional device – conceptual design I.

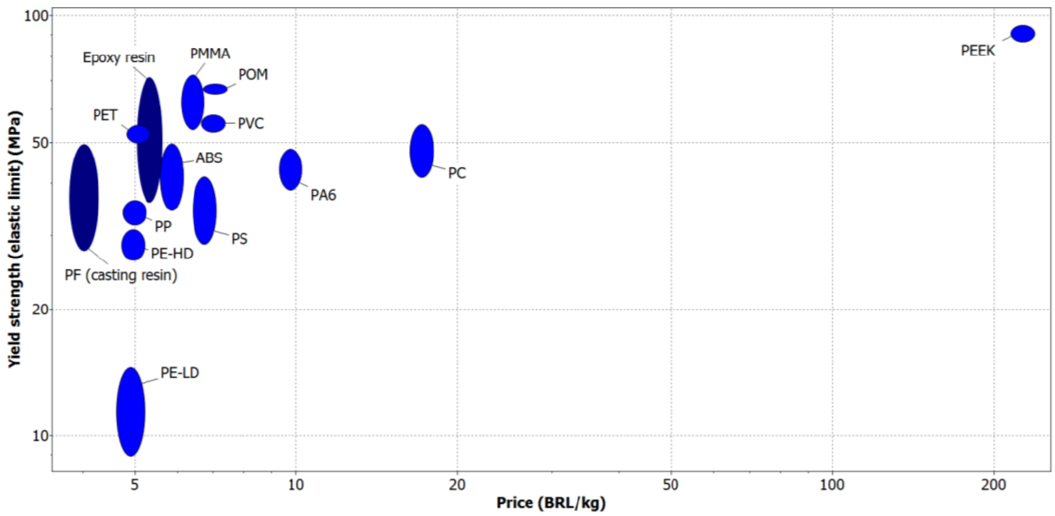


Figure 7: Material selection graphic comparing yield strength and price.

Source: Prepared by the author with the software CES Selector ®.

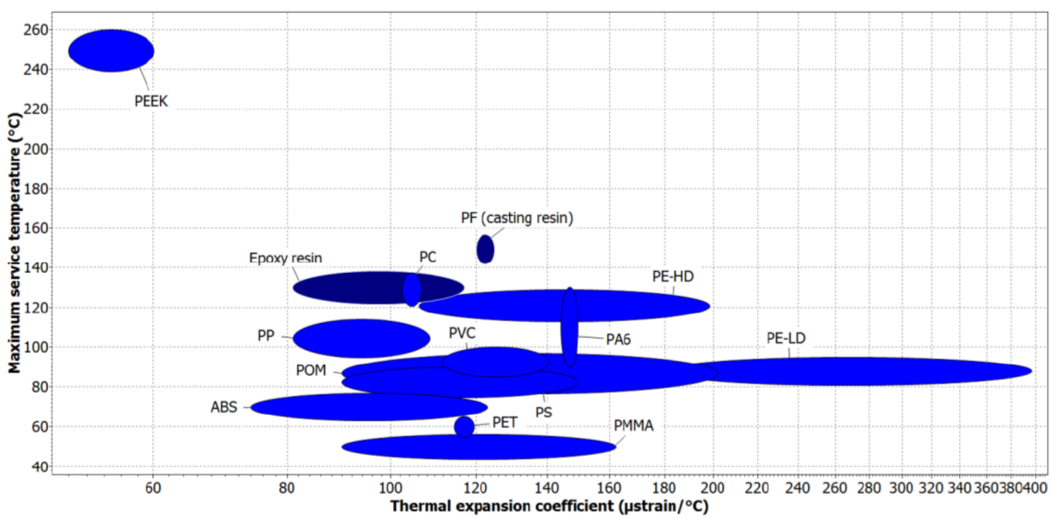


Figure 8: Material selection graph comparing the maximum working temperature and thermal expansion coefficient.

Source: Prepared by the author with the software CES Selector ®.

expansion and the third graph in Figure **9** in terms of fracture toughness versus Young's modulus.

Considering the data presented by the CES software in Figure **7**, it is possible to see that PEEK has the highest elastic limit, but its price is considerably higher than the others materials. The epoxy resin, PMMA and POM are shown as quite interesting alternatives according to these criteria. On the other hand, materials with very low values of yield strength are mainly HDPE and LDPE. Regarding the price used in the horizontal axis scale, was adopted the ISO 4217 standard that defines three-letter codes for currencies worldwide. In Brazil, it was assigned the code as BRL Brazilian Real.

Considering the data shown in the Figure **8** chart, it can be observed that PEEK has a very good performance, with considerably higher value of the maximum working temperature and with considerably lower thermal expansion coefficient.

Other interesting candidates with maximum temperature work high values are PF, Epoxi, PC, HDPE, PA, PP, PVC and POM. On the other hand, PMMA, PET and ABS have low values in this criterion. As the thermal expansion must be low, in addition to the PEEK highlighted earlier, ABS, PP, POM, PET and PVC are promising candidates, while LDPE again is rejected in the selection due it's too high values.

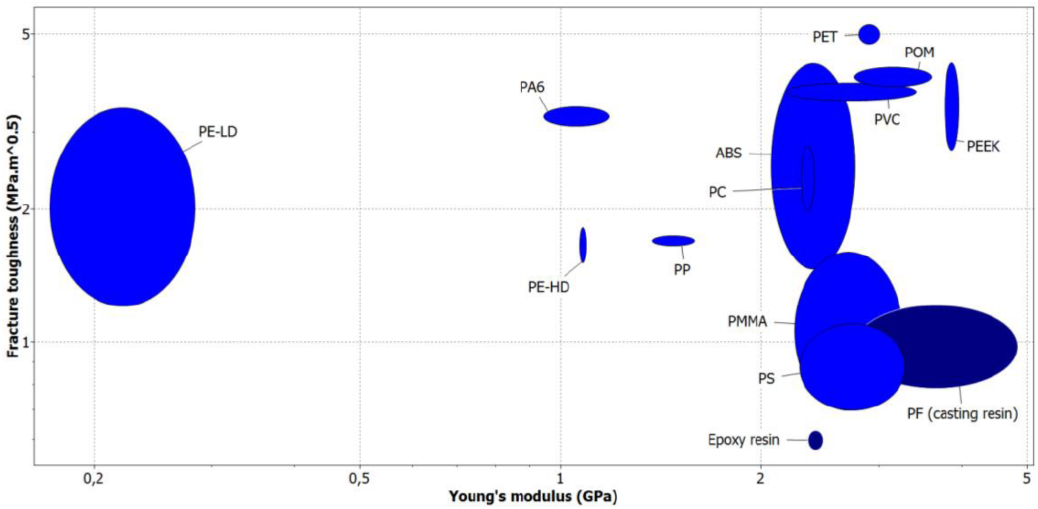


Figure 9: Material selection graphic comparing fracture toughness and Young's modulus.

Source: Prepared by the author with the software CES Selector ®.

Based on the data presented in Figure **9** graph, it can be seen that PET, POM and PEEK have an optimal combination of both analyzed properties with high values of both (fracture toughness and Young's modulus). It should be noted that the Young's modulus relates the stiffness of the material and the higher the value, greater is the difficulty of elastically strain the material. Other little favorable materials according these criteria are LDPE, due to the low Young's modulus and PS, PMMA and epoxy and phenolic resins, because of their low fracture toughness values.

3.3. Presentation of Conceptual Design II – Second Model

Figures **10** and Table **2** shows that there were significant changes in the geometrical configuration from the conceptual design I to the conceptual design II, and the principal items responsible for this change should be described:

a) the choice to replace the gear movement transmission system (parts numbers 10, 11, 12 and 14 – conceptual design II) with the friction movement transmission system (parts numbers 3, 4, 5, 6 and 7 –

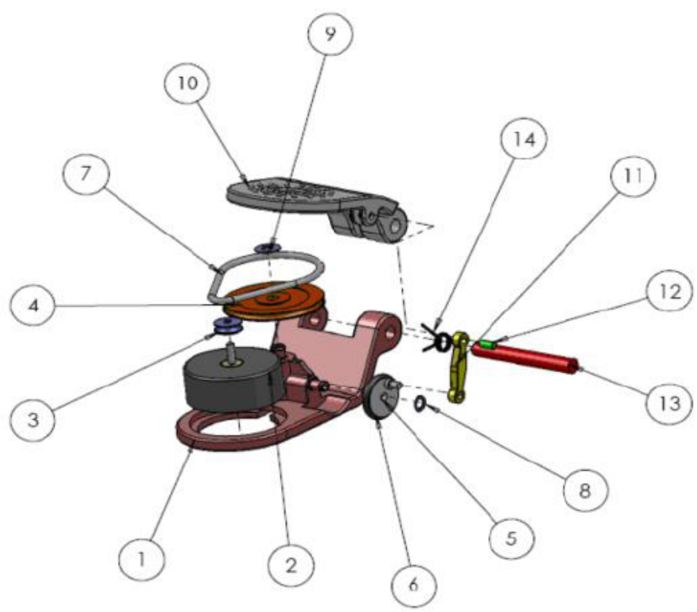
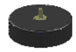
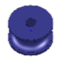
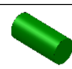


Figure 10: Exploded view of the functional device – conceptual design II.

Table 2: List of Parts that Make up the Functional Device – Conceptual Design II

Part	Name	Image	Quant.	Specification	Material
01	Base		01	28x19,5x56,5mm	POM
02	Microgenerator		01	Ø22x15,5mm	Steel
03	Pulley 3		01	Ø6,25x2mm	POM
04	Pulley 2		01	Ø22,5x2mm	POM
05	Pulley de Atrito		01	Ø10x2mm	POM
06	Ring Friction Wheel		01	Ø11,5xØ1,5mm	POM
07	Main belt		01	Ø10x2mm	NBR
08	Washer 01		01	2.5X4X0.1mm	Steel
09	Washer 02		01	2.5X6X0.1mm	Steel
10	Mechanical trigger		01	28x47x15mm	POM
11	Arm		01	17,5x3,5x2mm	POM
12	Arm pin		01	Ø1,8x4mm	Steel
13	Mechanical trigger pin		01	Ø3.5x28mm	Steel
14	Torsion spring		01	Ø3,6x1,75mm	Steel

conceptual design II) resulted in benefits for both manufacture and assembly. The process of matrix fabrication and, consequently, the plastic injection process, was less complex for pulleys than for gears.

b) the number of parts for manufacture and to be used in the friction movement transmission system (parts numbers 3, 4 and 5 – conceptual design II) was smaller than the number of parts used in the gear movement transmission system (parts numbers 10, 11, 12 and 14 – conceptual design I), which also made manufacture easier. Parts numbers 6 and 7 (friction ring and the main belt), were bought from a supplier and only had to be assembled.

c) the geometry of the base coupling (part 01) and of the mechanical drive (part 15) of conceptual design II was changed, which resulted in the exclusion of two elastic rings (part 18), responsible for limiting the axial movement of the mechanical drive pin and of a torsion spring (part 16), responsible for the memory effect and which enabled the alternate movement of the mechanical drive. The axial movement of the mechanical drive pin in the conceptual design II may be limited by interference adjustments.

d) the combination of parts numbers 01, 04, 06 and 07 (conceptual design I) into a single part numbered 01 (conceptual design II) enabled the coupling of pulley 3 (part 04 – conceptual design II) and the friction pulley (part 05 – conceptual design II) using snap fitting, which made assembly considerably easier. Standard steel washers (parts numbers 08 and 09 – conceptual design II) were used for safety and to block the axial movement of the pulleys mentioned above;

e) fixation of pulley 3 (part number 03 – conceptual design II) on the axis of the micro generator (part number 02 – conceptual design II) was achieved by interference and use of a movement blocking adhesive of the pin-lock-shaft type.

f) combination of parts numbers 15 and 20 (conceptual design I) in a single part of number 10 (conceptual design II) resulted in the exclusion of the fastening screw number 19 of conceptual design I, which, consequently, reduced assembly time.

Table **3** shows the summary of final results of the development of conceptual designs I and II. The variables used in obtaining the results were defined according to the literature reviewed, the objectives defined and the figures, as demonstrated by the authors of this study. Values in the Table were rounded to the second decimal place for convenience.

There was a considerable reduction in the number of parts in the set from the basic device (prototype), which had 47 parts, to the conceptual design I, with 34 parts, and the conceptual design II, with 14 parts.

The total mass of the set was also considerably reduced, from 160 grams for the basic device (prototype) to 57.01 grams in the conceptual design I and, finally, 18.30 grams in the conceptual design II.

The maximum dimensions of the set, according to Table **3**, had a small reduction in width, followed by a small increase in length and in height of the set (conceptual design I). In contrast, the conceptual design II, for which DFA was used, had a marked reduction in length, width and height.

4. CONCLUSIONS

This study analysed the application of the design for assembly (DFA) method as a tool to support product development. The project of a functional device was developed according to the generation of alternatives conceived to respond to a functional structure. The application of the DFA method in the conceptual design phase contributed to select the alternative that best responded to the needs of the functional structure, with significant advantages in number of parts and devices used, which confirms the efficacy of the design process and the reduction of costs in product development.

An intuitive method was used to generate product conceptions, called the method of questions instigation, or MESCRAI, which proved to be very useful to raise ideas in the initial generation of solutions. In the conceptual design phase, we obtained alternative solutions by changing, eliminating, substituting, combining, rearranging, adapting or even inverting parts of the basic device (prototype), which was the reference for the development of the conceptual design I – first model.

Our results, which confirmed this study objectives, were directly associated with the reduction of number of parts in the basic device (prototype) compared with the development of the conceptual design I (first model) and the development of the conceptual design II (second model), while its functional objective was preserved. There was also an important reduction in mass along the development of the conceptual design I (first model) and the conceptual design II (second model), as well as in width, length and height of the devices.

A computerized material selection method was used as tools to aid DFA in the development of a conceptual design of a functional device through thermoplastic materials analysis for some components in terms of better properties front the demands of the device focusing on performance and aiming a lower cost. Of thermoplastic materials analyzed, considering a

Table 3: Summary of Final Results of the Development of Conceptual Designs I and II

Variables	Base Device (Prototype)	Conceptual Model (I)	Conceptual Model (II) using DFA
Number of pieces	**(47)** (100%)	**(34)** (reduction 27.66%)	**(14)** (reduction 70.21%)
Total mass (g)	**(160)** (100%)	**(57.01)** (reduction 64.37%)	**(18.30)** (reduction 88.56%)
Dimensions (mm) Length (C) Width (W) Height (H)	**(65x55x40)** **(C=65)** (100%) **(W=55)** (100%) **(H=40)** (100%)	**(72.19x46x43.35)** **(C=72.19)** increase 11.06% **(W=46)** reduction -16.36% **(H=43.35)** increase 8.38%	**(56.54x28x22.47)** **(C=56.54)** reduction -13.02% **(W=28)** reduction -49.09% **(H=22.47)** reduction -43.83%

selection focused only on performance the most promising candidate, with an ideal set of properties is PEEK. But for a selection that considers the price, that is one of the key variables in the materials selection for most products, PEEK shows is prohibitively price, especially if the product is to be used in mass consumer products. Thus, a compromise between these properties and price is inevitable and POM is the most interesting alternative.

The application of the DFA method to the conceptual design I (first model) resulted in technical solutions that simplified the product in its final conception (conceptual design II - second model) and, consequently, improved assembly conditions. Other solutions may be evaluated to eliminate the restriction to the shape of the micro generator (part 02 of conceptual design II), therefore increasing the number of options of materials for the concept generated.

CONFLICTS OF INTEREST

The authors declared no potential conflicts of interest.

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