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Decision Making for Rapid Prototyping Technologies of Sustainable Products

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The prototyping of products by additive and subtractive technology can vary in: quality, time and costs, depending on the characteristics of the products. The selection of technology often is conditioned the decision of the designer/engineer or operator because of the type of material, size and accuracy. Furthermore, the need to incorporate environmental and sustainable attribute has been addressed by important factors that can facilitate the different approaches that act on sustainable product diversity. This paper presents a decision making model to assist the selection of rapid prototyping technology more adequate on sustainable product conception. This proposes focus to improve all aspects of the triangle called "cost-quality-time" and provides an effective design of sustainable product, process and its manufacturing. We used the concepts of Design for Manufacturing, Computer Aided Design, Rapid Product Development and Sustainable Development for one sustainable product of relevant structure and material (lightweight dual) to evaluate and validate the proposed model. In the lightweight dual product from the additive process (SLS technology) has been most successful in view of the purpose of the product and its functions, lower cost, shorter execution time, good surface finish, dimensional accuracy and product formation in the injected. The results show comparisons between the prototyping technologies based on decision making criteria to select the technology for designing sustainable products.

1. Introduction

The Rapid Prototyping (RP) is a manufacturing process widely used in companies, mainly in the areas of new product development. This technology can also be used in other areas, such as, health, aerospace, chemical, industrial and others.

The concept RP defines a set of technologies used to manufacturing physical objects directly from the sources of information or data generated by computer-aided design (CAD) systems. The methods are very special since they bind materials, layer by layer, in order to form the desired object. They offer several advantages in many applications compared to traditional manufacturing processes based on material removal, such as, milling or turning. The most advantages are relative for cooking time and especially complex geometries, where manufacturing by machining process becomes practically impossible.

The product design was heavily influenced by technological revolution in recent years, as new technologies and new processes have emerged, simultaneity, new design methodologies adapted to this sustainable practices. Furthermore, the development of these sustainable products is entered into a technological complex and competitive world, where quality and efficiency are request of equality for economic and social practices (Noorani, 2006).

The first techniques for rapid prototyping became available in 1987 and they were used to produce moulds and prototype parts. In fact, it is estimated that the savings of time and costs provided. This moment, the development of new materials for prototyping with sustainable aspects is now used to produce products where the amount is relatively small, faster and more cheaply.

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The product development emerged in the 90s, seeking to provide the competitive advantage businesses, varieties of products and market segmentation. The main feature of product development is the integration of different areas during phases of new product development. Thus, to identify the needs and expectations of customers aligned to market new materials and technological innovation. Fernandes and Canciglieri Jr (2014) argues that, the sustainable products development requires simultaneous activities between product characteristics and the technologies involved. However, the main focus is to convert the relevant information about the products specifications that can be produced with quality and meet the requirements of sustainable development.

Petrie et al. (2007) demonstrate that the sustainable metrics can be used to support decision making and created framework to aid mineral and metals sectors. Moreno-Benito and Espuña (2011) asserts that sustainability factors and energy resources allow orientating the production of the new products in bath process. While, Porzio et al. (2013) applied a decision support model in the process gas for reduction of CO_2 emissions and costs in steel plan. Smith and Mercado (2013) present a decision making method to assist users in exploring sustainable aspects, placing them into a logical structure for analyzing and evaluating alternatives in chemical process. Vinodh et al. (2014) develop a sustainability model using fuzzy logic for sustainable manufacturing production, utilizing minimum natural resources and productivity safer, cleaner, and environment-friendly products at an affordable cost.

This paper presents a decision making model to assist the selection of rapid prototyping technology more adequate on sustainable product conception. The intent is to provide a support tool in the decision making between the prototyping technologies for rapid and subtractive materials used in the design and sustainable products development. This proposes focus to improve all aspects of the triangle called "cost-quality-time" and provides an effective design of sustainable product, process and its manufacturing.

2. Sustainable Development

The concept of sustainable development is actually interesting and attained relevant importance because of the growing thinking and increasing economical and social aspects for the adoption of sustainable practices (Mattioda et al., 2013). The sustainable development is defined as the future generations must be taken in consideration since they are entitled to aid from the same resources as the previous generations, allowing begins responsible for natural resources as well as for the community. The *Common Future* (WCED, 1987) describes a set of measures should be taken by worldwide to promote sustainable development and among them, stand out: limiting population growth; guarantee of basic source; biodiversity preservation; reduction of energy source. Therefore, the concept of sustainable development is a process of change in the exploitation of resources and social, economic, environmental and human practices.

This structure of sustainable development emerged in an international context of bringing sustainability in a very unequal world, structuring decisions to techno, socio-economic and environmental goals. Vinodh et al. (2014) discuss that the sustainability aspects and dimensions used are economic, environmental and social sustainability. The modern industrials are encouraged to adopt sustainable manufacturing principles due to international rules by Government policies. The issue about sustainable development with focus for ecological well-being is not considered secondary, but equally to human welfare, is the basis upon which the principles of sustainable development need to be reformulated (Imran et al., 2011).

For companies, the sustainable development has become a dominant and essential principle. Orecchini et al. (2012) affirm that since the 1990s, companies began to adopt the sustainability principles in their organizations. The first activities are related to the implementing of the eco-efficient activities and green innovations and subsequently the adoption of social responsibility practices and reporting.

3. Prototyping Technology in Sustainable Product

The emergence of rapid prototyping technology was in 1987 with stereolithography process, initially by 3D Systems American Company, after by Fockele & Schuartz German Company and Ushio Japanese Company. This process builds three-dimensional moulds from liquid polymers sensitive to light, which solidify when exposed to ultraviolet radiation. In 1991, the fused deposition modelling (FDM) process was developed by Stratasys American Company and objects in blade manufacturing (LOM) process developed by Michel Fygin.

The FDM process builds filaments of thermoplastic resin which are heated and extruded from a die-shaped tip that moves in the XY plane. The extrusion deposits fillets extremely thin on the platform to form the layer and parts of the products. The LOM process builds prototype from reels of laminate paper with glue activated by laser beam of high precision for cutting the layers of paper and then raster area of the prototype. In 1992, the selective laser sintering (SLS) process developed by DTM American Company and Teijin Seiki Japanese Company. In this process, the moulds are built on a platform that focuses laser beam to melt, selectively, powdered materials, such as, nylon, elastomers and metals to form the solid object. Since the 2000s emerges other processes from appeared earlier, adding the use of different materials, such as metallic and polyethylene.

The 3D printing process is initiating a kind of Fourth Industrial Revolution (Barnatt, 2013). This process began as a method for rapid prototyping and now, it's called flexible additive manufacturing, which enables fabrication of large parts such as, small aircraft, artificial blood vessels, and this currently entering an era of nanotechnology. The 3D printing process has the possibility of several implementation and application due to have high-speed equipment, lower cost and also the use of nanotechnology material. Table 1 summarizes some characteristics of prototyping technologies available in Brazil.

Wholers (2003) describes that the use prototyping technology in product development can be: (*i*) in the construction of prototypes for evaluation of functionality, geometric shape and applicability. This analysis derive important mechanisms to quantify and type of raw material to be used and provide the dimensions and precision involved in the product; (*ii*) the prototypes are built as physical models of the external appearance of products or intuitive proposals (showcase), being the speed and cost of prototype are critical factors; (iii) the rapid prototyping is used to satisfy the requirement of some processes, such as, casting under pressure, requiring special moulds. In such cases, the prototype generated is the mould that must have high dimensional accuracy, excellent surface finish, adequate heat resistance and satisfactory hardness. Mathaisel et al. (2012) suggest that, the use of prototyping technology is innovative in sustainable product design, but also in general in other production areas, such as the reverse engineering, healthcare, biotechnology and nanotechnology. Furthermore, it require the use of different materials (e.g., polymer, plaster, ceramics and biocompatible composites) and hence the use of different prototyping technologies. Figure 1 shows the acquired volume of rapid prototyping equipment in some Countries and Brazil is still very small. However, the percentage of sustainable materials used for prototyping technology is increasing worldwide, e.g., China 89 % (910/1,023), Japan 46 % (1,050/2,278) and Brazil 43 % (22/51).

Table 1: Characteristics of prototyping technology in Brazil

Important Factors	Technologies			
	FDM	LOM	SLS	3Dprint
Diversity of materials	medium	low	medium	high
Surface finish	medium	medium	high	high
Accuracy	medium	low	high	high
Flexural strength	high	low	medium	high
Post-finishing	medium	low	high	high
Cost (in Brazil)	medium	high	medium	medium

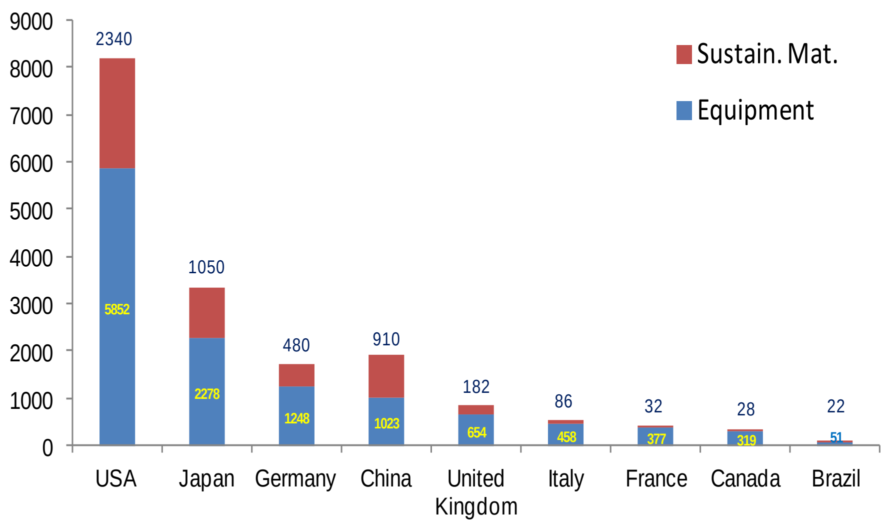


Figure 1: Volume of equipment and sustainable materials for prototyping technology.

4. Decision Making Model

The selection of the best prototyping technology is usually associated with time available for implementation of prototype, however, we must analyze the purpose and value in sustainable product development. Select which technology to use to build prototypes goes far beyond a more opinion on, or requires knowledge of the available technologies and decision criteria so you can choose the most suitable alternative. The potential of prototyping technology is achieved when setting the relevant priori elements of the product to be prototyped, such as accuracy, speed, functionality and cost (Sun et al., 2013). This study evaluated the existing features in rapid prototyping to define the most important characteristics which provided the basis for the decision criteria of prototyping technologies.
The proposed decision model in this research to determine the most prototyping technology for manufacturing of a sustainable prototype is divided into 4 phases:

[1]. Description of product characteristics;
[2]. Application of criteria decision;
[3]. Analysis and decision making;

4.1 Description of product characteristics
The main relevant characteristics to be considered in the proposed decision model are described below: (i) *purpose* - is an aspect that defines the purpose of the prototype will be built, (ii) *material* - is one aspect that defines the type of material that can be used to design the prototype; (iii) *surface finish* - is an aspect that defines the aesthetics of the product and is related to the purpose of the prototype; (iv) *accuracy* - is an aspect that defines the geometry dimensions of the prototype being developed; (v) *time* - is one aspect that sets the time required to perform each prototype in each technology including the setup time, execution and post-finishing; (vi) *costs* - is a key aspect that sets the value for the development and design of the prototype.

4.2 Application of criteria decision
In this phase we evaluate carefully the most relevant characteristics of the prototype and prototyping technologies available to design the sustainable products. The weights in the proposed decision model defining the relevance level which have characteristics analyzed in relation to the product. These attributes allow the material to convert the customer specifications relevant for the sustainable products development.
The decision criteria have the following classification: (i) high relevance - features of the sustainable product is a high priority for prototyping technology, with weight 9; (ii) medium relevance - features of the sustainable product has medium priority for prototyping technology, with weight 3; and finally (iii) low relevance - features of the sustainable product is a low priority for prototyping technology, with weight 1. The prioritization prototyping technology is based on the weighted average of the weights of sustainable product features for technologies. These weights are defined based on the information to Equation (1).

$$\boldsymbol{Q_j} = \frac{\sum_{i=1}^{I} \boldsymbol{d_i} \cdot \boldsymbol{c_i}}{\sum_{i=1}^{I} \boldsymbol{d_i}} \tag{1}$$

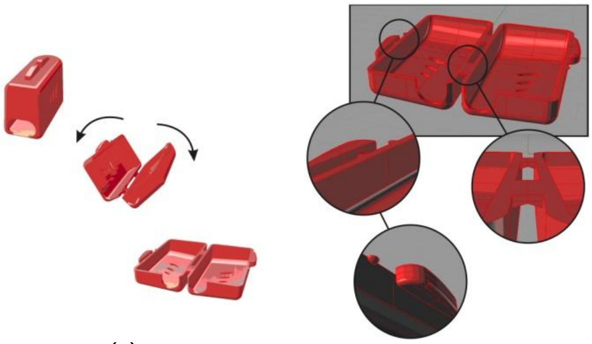
where Q_j is the result of weighted average of i prioritization of sustainable product features for each j prototyping technology; d_i is the weight of priority for the i product features studied; and c_i is the weight of priority for the characteristics of the i prototyping technology.

4.3 Analysis and decision making
The third phase we analyze comparatively the prototyping technology available for sustainable product design, based on the results obtained in phase 2 of the proposed model by providing an aid in decision making. Thus, the design of the sustainable product is based on the decision criteria providing product reliability, time savings and accuracy of dimensions and geometric shapes.

5. Application Study

The application of proposed decision-making model for the prototyping technology was selected a sustainable product, e.g., protector of bristles for toothbrushes (lightweight composite product), shown in Figure 2(a). The product has passed the creation, analysis and dimensional modelling process in the CAD system. The choice of this product was based on the final products characteristics because, such as: different degrees of complexity and geometry, functions and mass that were produced in sustainable material.

The protector of bristles has the function of protecting the toothbrushes in contact with soiled surfaces and dust (see Figure 2b). Their average thickness is 1.00 mm polypropylene random being injected to ensure the flexibility of two plastic hinges of 0.50 mm thickness. Moreover, it has a closing system with clicks, with 1.50 mm in diameter, which allows the shield to be closed around the bristles of toothbrushes.
Based on the description of characteristics, components and product functionality the weights were established for the most relevant characteristics of the sustainable in accord with customers' requirements (see Table 2). The Table 3 shows the result of application for decision making model of the sustainable product in study, suggesting that, this product should be built using SLS prototyping technology (additive material) to the (Q_1 = 5.57).
The analysis of the prototype (protector of bristles) for characteristic *Time* showed a 50 % reduction in execution time, however high production cost. The SLS technology could form the elements that made the product, and kept the hinge and click working (*Purpose*) as designed in the CAD system. The prototyping of products corroborate the analysis of the decision criteria of the proposed decision making in phase 2. One highlighting is that the SLS technology is more suitable for the new product development.



(a) (b)

Figure 2: Images of the sustainable product for prototyping technology

Table 2: Description of characteristics of sustainable products

Characteristics	Specifications	Relevance	Weight
Purpose	Function test	high	9
Material	polypropylene	high	9
Surface finish	hinges	low	1
Accuracy	47.70 x 37.50 x 8.90 mm	medium	3
Time	hours	medium	3
Costs (in Brazil)	high	medium	3

Table 3: Description of characteristics of sustainable products

Characteristics	Product	Technologies	
	weight	LOM	SLS
Purpose	9	1	9
Material	9	1	3
Surface finish	1	3	9
Accuracy	3	1	3
Time	3	9	1
Costs (in Brazil)	3	9	9
Total	-	2.79	5.57

6. Conclusions

Prototyping technology is increasingly used in the manufacture of more several and complex geometries. This technology allows the use of different materials in their applications. The manufacture of customized prototypes is a reality. However, each type of technology used for making models through prototyping technology, can generate different dimensional and visual results. The sustainable products development

is a great innovation for rapid prototyping technologies, both in the use of sustainable materials and production. This paper presents a model decision making to assist the selection of rapid prototyping technology more adequate on sustainable product conception.
The results illustrate that the protector of bristles built on the SLS prototyping technology has been better successful in view of the characteristics: purpose of the product and its functions hinges and clicks, lower cost, shorter execution time, good surface finish and dimensional accuracy.
Finally, we emphasize that the aim is not to establish the best prototyping technology itself, but to establish what the most appropriate technology to build a sustainable product based on the relevant product characteristics: purpose, cost, time, dimensional accuracy and surface quality, aiming at a prototype more efficient, and highlighting the integration between the concepts of Design for Manufacturing (DFM), Computer Aided Design (CAD), Rapid Product Development (RPD) and Sustainable Development (SD).

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