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Material eco-replacement: correlating product lifespan and material durability when evaluating the substitution of plastic with novel circular materials

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Abstract: Synthetic polymers surround us, being used in almost every field of application. In the last century, plastic has been covering a starring role in production processes thanks to attractive qualities: it is an economic, versatile, flexible, lightweight, moisture resistant, strong and durable material. Despite this, plastics represent one of the most widespread environmental pollutant. The transition to the Circular Economy model has led to the development of Circular materials characterized for staying within a closed-circuit system by using natural and renewable resources. Circular materials are taking small steps into consumer sectors, starting with disposable and single use products but are rapidly emerging in medium and long lifespan consumer sector as green solutions. This study represents a good practice for designers who operate eco-replacement activities or want to develop new product concepts from innovative circular materials. In order to conceive a sustainable application from material replacement, the work highlights that it is necessary to take into consideration different aspects: product lifespan, lifetime product expectancy, material aesthetic and technical durability.

Introduction

There are more and more concerns about irreversible processes into climate changes due to human activity (Burton, 2018). In the past years, starting from concerns regarding bio-accumulation inside e.g. oceans and concerns for wildlife, research and public opinion focused on the implications of polymers and additives for human health, having as an outcome legislative measures to reduce risks linked to these substances (Thompson, Swan, Moore, & Vom Saal, 2009). Numerous legislative proposals (e.g., EU Plastics Strategy[1]) are seeking to address this issue by limiting the production and use of synthetic polymers, asking producers for product redesign and material replacement measures. In particular, some plastic product categories, characterized by a short life-time, have been highlighted as critical from an environmental point of view: packaging, personal care consumables and toys (Ellen MacArthur Foundation, 2016). Materials are one of the factors that most influence the sustainable nature of the final product, due to its technical and aesthetic aspects (Ljungberg, 2007). Material science research is currently focusing in finding alternative design approaches and non-fossil based materials for these products. Circular materials are those staying within a closed-circuit system with the aim of allowing the use of natural sources, reducing pollution or avoiding the use of non-renewable resources and supporting economic growth.

Novel "circular" material (Pellizzari & Genovesi, 2017), developed from biomass, waste, scraps or recycled resources, are increasingly recognised as "sustainable" alternatives to traditional synthetic polymers (Asdrubali, D'Alessandro, & Schiavoni, 2015; Karana, 2012; Sauerwein, Karana, & Rognoli, 2017). Although, in selecting the most suitable

[1] European strategy for plastics. Available at: http://ec.europa.eu/environment/waste/plastic_waste.htm

"circular" alternative for a specific product application, technical and aesthetic properties of materials must be carefully evaluated (Piselli, Baxter, Simonato, Del Curto, & Aurisicchio, 2018). These novel materials, characterized by expressive-sensorial properties (smell, touch …) that drive unconventional material experiences, must ensure an appropriate performance and durability according to the specific product lifetime expectation (Bridgens & Lilley, 2017; Gnanapragasam, Cole, Cooper, & Oguchi, 2017; Wieser, 2015).

Materials durability vs product lifespan

A crucial moment when designing in a circular perspective is the materials selection. For this reason, during the selection are to be considered selection criteria that contribute to optimize all the phases of the product life cycle. Allione, De Giorgi, Lerma, & Petruccelli, 2012 have divided these parameters into 3 categories:

- Use of materials with low environmental impacts: promote eco-efficiency, short distribution chain, non-toxicity and the involvement of renewable resources.
- Material lifetime extension: aiming to postpone waste disposal while targeting alternate approaches to the materials and life;
- Ethics: looking at the creation of comfort between manufacturers about their environmental responsibilities.

These guidelines, if used together can improve the environmental performance of the product.
In accordance with their point of view, the topics of materials durability and product lifespan have been studied in depth, with a view to following a top-down approach to actively consider the end of life in the selection and replacement process of materials.
The durability of a material is defined as the ability of a material to maintain its functional properties without significant deterioration by mechanical and chemical stresses, wetting, heating, freezing, corrosion, oxidation, etc., for a long time[2]. Materials durability depends not only on the physical and mechanical properties over time, but also on aesthetic ones (Celadyn, 2014). To get a comprehensive view of these properties, specific accelerated aging tests can be carried out to simulate to simulate the decay of technical properties and the looming aesthetic obsolescence (Bridgens & Lilley, 2017). This creates a fundamental perception for the user about the overall quality of the product to which the material it is applied. Materials quality perception is strongly correlated to the absence of surficial defects and to durability property in time (Bridgens & Lilley, 2017; Lilley, Smalley, Bridgens, Wilson, & Balasundaram, 2016). Users often associate surface material qualities with an indirect measure based on contextual conditions where material is applied, to conform to expectations or consumer experience with similar materials in product application (Crosby, 1979; Garvin, 1987; Parasuraman, Zeithaml, & Berry, 1985). There are also aging behaviors of the material that the user knows, for example products made of natural materials e.g. paper, wood, leather, are expected to acquire antiquity and preciousness during their aging period (Rognoli & Karana, 2013). Product Lifetime or Product Lifespan is the time interval since a product is sold to when it is discarded. This is a designed life, known by the designer, who also designs the obsolescence of the product. It represents an important area of enquiry with regards to product design, the Circular Economy and sustainable development.

Durability of bioplastics

The introduction of bioplastics in consumer sectors was first focused on biodegradable and/ or compostable characteristics, directed to the single-use packaging sector (Rognoli, Karana, & Pedgley, 2011). For example, in the case of Polylactic acid (PLA), these applications take advantage of its fast degradation in an industrial compositing environment. But the sensitivity to heat and temperature still lack the long-term durability required for durable applications (Harris & Lee, 2010). Because of this, many material suppliers of PLA have developed injection-molding grades of PLA blended with petroleum-based resins such as polycarbonate (PC) or bio composites (Harris & Lee, 2013). These multiphase system, where plant-derived fiber or mineral / synthetic filler is dispersed in the biopolymer matrix have a far greater

[2] The Business Dictionary, Available from: http://www.businessdictionary.com/definition/durability.html

potential for minimizing the limitations of PLA (Nagarajan, Mohanty, & Misra, 2016).
However, the introduction of a new material into consumer products represents a critical issue for both producers and consumers. The producer aims at establishing a market and refine the technical feasibility, while the material is faced with the public assessment for the first time (Bahrudin & Aurisicchio, 2018).
Consumers can perceived new materials in different ways: appreciate them or feel them unattractive also through their previous perceptual knowledge.
Evaluating the application of circular materials instead of commodity plastics, two fundamental parameters must be taken into consideration: their durability / quality perceived by the consumer and their technical performances and aesthetic aging over time. The goal is to map the applications of circular materials in the different consumption sectors finding correlations and trade offs basing of the lifespan of the sectors they have been applied. These may lead to the outcome of strategies and guidelines to be adopted to apply circular materials to durable consumer sectors. By mapping the current state of circular materials already marketed and placed in consumer sectors, the aim is also look for application sectors for a composite material (biopolymer matrix and natural filler) developed within Making Materials Lab. of the Department of Chemistry, Materials and Chemical Engineering "Giulio Natta" of Politecnico di Milano. The material is called Poly-Paper and brings together the production versatility of plastics and the virtuous end of life of cellulose fibers based materials.
RQ1: In what consumer sectors were circular materials introduced? What is the lifespan of products in these sectors?
RQ2: How can circular materials be incorporated into high-lifespan consumer sectors?
RQ3: Which consumer sectors can be directed to a new circular material still in development?

Methods

This research analyses 26 "circular" materials, both traditional and innovative, taking into consideration their distinctive features and properties, typical applications and production processes and which materials are they substituting candidates.
Following Ashby's method and charts (Ashby & Johnson, 2014), the materials were initially filed, defining them eco-properties (bio-based content, biodegradability, compostability, durability over time). For each material, all of them on the market, were researched the products to which they were applied, and then grouped by commodity sectors. For each sector of application, thanks to the studies of Wieser, 2015 it was then reported the estimated life period and finally the materials that the new solution has gone to replace on the market.

Results

The case studies of circular materials have been categorized according to their "Material biography" (Bahrudin & Aurisicchio, 2018; Wilkes et al., 2014), based therefore on their composition and source of resources as shown in Table 1.

Material	Materials' Biography
Cellulose Acetate CA (Tenite®)[3]	Bio-based bioplastic
Polyhydroxyalkanoate PHA - Mirel®[3]	
Poly Lactide Acid PLA - Nature Works®[3]	
Thermoplastic Elastomer (TPE-E) Apinat Bioplastic®[4]	
Thermoplastic Starch (TPS) Materbi®[3]	
Arboform®[5]	Bio-based bioplastic / Natural filler
Fluidsolid®[6]	
Jelu-Plast® Green composite[7]	
Natureplast®[8]	
Orange Peel[9]	
The salt pup®[10]	
Timberfill®[11]	
Carton board[3]	Cellulose fibers

[3] Cambridge Engineering Selector (CES2018) Software
[4] https://www.apiplastic.com/prodotti/ bioplastics/
[5] https://dornob.com/liquid-wood-fantastic-100-organic-bio-plastic-material/
[6] https://www.fluidsolids.com/en/about/media/
[7] https://www.jeluplast.com/en/
[8] http://natureplast.eu/it/fornitore-di-bioplastiche/fibre-biocomposite-e-co-prodotti-commercialisation/
[9] Lefteri, C. 2014. Materials for Design. Laurence King Publishing. https://books.google.it/books?id=g59LnwEACAAJ.
[10] http://buildingwithseawater.com/#insta http://www.newmaterialaward.nl/en/nominations/the-salt-pup
[11] https://fillamentum.com/products/ fillamentum-timberfill-cinnamon

Chipboard[3]	
Corrugated board[3]	
Honeycomb cardboard[3]	
Paper[3]	
Paper board[3]	
Paper pulp[12]	
Acrodur®[13]	Formaldehyde-free acrylic binders
Bayonix bottle®[14]	Fossil-based polymer
IKEA Patented "Odge chair"[15]	Fossil-based polymer / Natural filler
Jelu-Plast® biocomposite[6]	
S.Cafè®[16]	
Accoya wood®[17]	High performances wood
Qmilk®[18]	Natural fibres

Table 1: Circular materials selected as case studies classified basing on their composition.

Starting from the 26 selected materials, a sampling of products to which these materials were applied was done and 107 products were found. Most of them are included in the general furnishing sector and progressively in the disposable and Single-use products sectors as shown in Figure 1. Afterwards, the Figure 1 represents the product lifespan and the replaced materials in product application. It can be observed that the majority of products made of circular material have a life span of less than six months. Despite this result, which was to be expected, it's possible to notice how the other commodity sectors and their related lifespans resulted also populated.
The replacement of fossil-based polymers with circular ones have touched all the commodity sectors represented. Cellulose-based materials

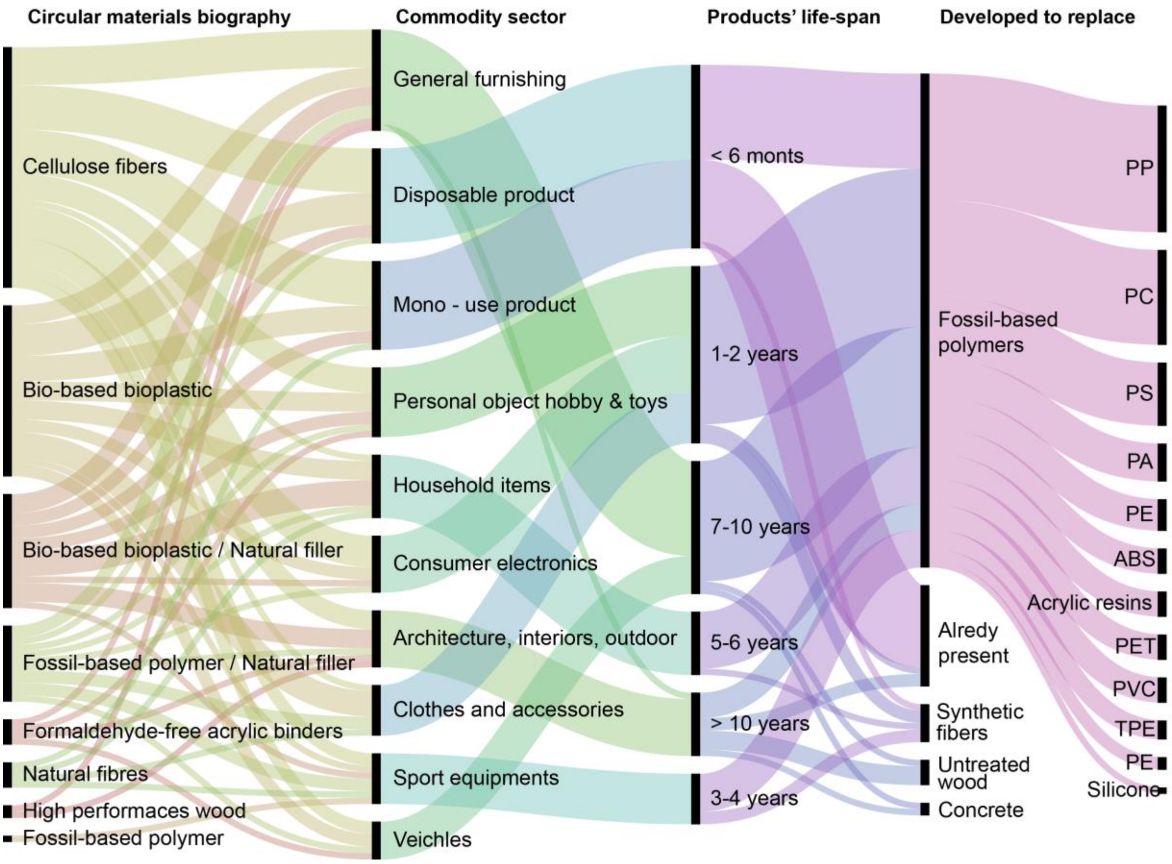

Figure 1. Analysis of the data collected from the application of circular materials in the commodity sectors translated into data visualization by the authors via the site https://rawgraphs.io/.

[12] http://www.davidgardener.co.uk/?p=70
https://www.kadltd.jp/project-14-mould
https://paperwaterbottle.com/
[13] https://www.basf.com/us/en/products/General-Business-Topics/dispersions/Products/Acrodur-acrylic-resins.html
[14] https://bayonix.com/
[15] https://www.dezeen.com/2017/11/13/ikea-form-us-with-love-odger-recycled-wood-plastic-sustainable-chair/
[16] http://www.scafefabrics.com/ en-global/about/development
[17] https://www.accoya.com/sustainability/
[18] https://www.qmilkfiber.eu/?lang=en

are equally averagely inserted in the various commodity sectors i.e. also those > 10 years of lifespan, however, in some of this cases the material will not ensure the same durability of the replaced one, but the eco-replacement has to be properly evaluated.

Cellulose fibers based materials have been taken in evaluation since they represent a forerunner of that of bioplastics or bioplastic composites. In fact, cellulose fibers materials had mostly been destined for short-lived sectors but, in recent years, they have also been included in more durable commodity sectors as “green” alternatives.

Materials that aim to replace the synthetic fibers are constantly increasing their presence on the market, as sustainable textile materials in relation to growing environmental issues i.e. micro plastics dispersion. The analysis carried out represents a state of the art of how circular materials are entering consumer sectors, but are they always preferable to fossil-based plastics? Based on this open debate, in the discussion of the results two indexes will be proposed to better argue materials eco-replacement.

Poly-Paper (Santi et al., 2018) is a material developed to respond to the problems of disposal of multi-material packaging, therefore initially directed towards low-lifespan consumption sectors. Thanks to this study, it was possible to elevate the material to design for sectors such as personal objects, hobbies and toys and the consumer electronics. Following the materials substitution design strategies for sustainability (material eco-replacement) (Bontempi, 2017; Vezzoli, 2013), design concepts and prototypes (Figure 2) have been elaborated as part of a Master's Degree in Design Engineering (Testa, 2018) .

Discussion

The selection of case studies was decisive for the results. For this reason, the research was carried out on circular materials already applied in the most diverse consumer sectors. This section will go into detail on how to use the new materials for the circular economy along the selection or replacement of commodity plastics. Therefore, evaluation indices are suggested for an effective eco-replacement material.

As first consideration, the perception of durability of the material has to be greater than the life expectancy of the product.

According to the studies of Wieser, 2015, the consumer lifetime expectancy of a product is greater than its lifespan. The material applied to the product must satisfy this consumer expectation, appearing more aesthetically durable and of higher quality. Its finishes and soft skills have to be designed in this sense, so that its aesthetic appearance resulted ennobled. How many times do people think: "I'd better buy a top with satin finish for my kitchen so I won't see scratches over the years". However did happen to do the same reasoning with a product with a short life expectancy such as packaging, personal care products or toys.

A relationship can therefore be envisaged:

$$\frac{Materials\ perceptual\ durability}{Product\ lifetime\ expectation} > 1$$

As an example, the “Miss Sissi” lamp made in PHA produced by Flos and designed by

Figure 2. Product design concepts for the application of Poly-Paper into medium-lifespan commodity sectors designed by Testa, 2018.

Philippe Starck responds to the aesthetic requirements of perceived durability thanks to the wise use of materials and has been included in the general furnishing sector which has a life expectancy of 5-7 years (Wieser, 2015) according to consumers perception. On the other hand, based on the properties of technical and aesthetic durability, the material must ensure the performances throughout the lifespan of the product:

$$\frac{Materials\ durability}{Product\ lifetime} \sim 1$$

By-passing this parameter and therefore designing with materials with lower aesthetic and technical durability, the product will be decommissioned and replaced earlier than expected (for aesthetic or functional reasons) producing a waste of resources and energy. In case of short lifespan products made by fossil polymers, which have a durability of over 450 years in contact with the soil or dispersed in the environment, this ratio will skyrocket. This comparison can be made by designing durability in different environments and / or substances and relating them to the lifespan that the product to be designed must ensure.
Based on the criteria, requirements and constraints of the product on carrying out a materials selection, it is possible to select the relative durability parameters or perform aging tests (Manley, Lilley, Hurn, & Lofthouse, 2017) in order to relate them to the product lifetime.

Conclusions

New circular materials are complex systems.
Equally complex is the definition of their parameters, because in addition to the primary source, they rely heavily on their life cycle, energy used and issued for their transformation, emissions and their recovery at the end of life. The criticality is to find a right application, which justifies their inclusion in the market as truly sustainable resources.
In relation to the sectors of application, however, the consequences of their introduction on consumer behaviour are also to be considered. Brand owners and transformers cannot be limited to an "eco- material replacement" because the new circular materials are stand-alone systems and the related product of application needs a complete redesign.
Circulars materials have to be ennobled for their expressive-sensorial characteristics and for their meaning such the transmission of ethical values. By enhancing their aesthetic quality, the related products could also pre-choose them in the case of applications in durable sectors. Despite this, circular materials must be closely linked to the application product ensuring its performances throughout its life period neither more (which would be a divestment of resources still active), nor less (which would result in an early disposal of the product). This paper aims to provide critical exploration for eco-replacement addressed to designers and technician in providing investigative tools. Both designers and producers must be aware that the product development by the selection of circular materials involves the management of a complex system. In order to make the circular material effective, the work highlights that it is necessary to relate different aspects:

- The expressive dimension of the materials quality and expected durability has to be greater than the life expectancy of the product
- The ratio between the aesthetic/technical durability of the material and product lifespan have to approach to one.

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