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SCHOOL OF DESIGN
MASTEROF SCIENCE IN
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Designing with novel materials for the Circular Economy: the case study of Poly-Paper

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Abstract

The transition to the Circular Economy model has led to the creation of materials that make sustainability and recyclability their strong point. The objectives of the research aim to identify possible design strategies that apply these new materials in consumer products, to promote their dissemination and suggest new development paths. Today, designers propose these new materials with great enthusiasm to the industry, even though there are still many issues to be solved to integrate them in the product development process.

As a starting point, the Circular Economy approach provides numerous hints to improve the design process.
It helps taking into consideration the reduction of the exploitation of primary resources, the improvement of products' efficiency, the extension of their lifespan, or the change of consumption patterns, in order to increase products' sustainability. In designing possible application of novel materials for the circular economy, raw materials procurement and production was considered, but great commitment has been given to the end of life phase of product (and so material). To better describe the context around the development of new polymeric materials in a "circular" perspective, the main categories of biopolymers, their uses and peculiarities have been identified. To complete the bulk analysis framework, paper materials were also investigated in relation to their use in consumer products. The research of materials and products has been carried throughout case studies organised in three sections, which include new circular materials, biobased materials and paper and cardboard. Each profile provides information on its main properties, applications, production processes and sustainability issues.

The values and properties of the different materials for the Circular Economy identified have been compared through the tool of matrixes, that helped also in identifying the potential fields for their application. Focusing on the aspects of sustainability and recyclability, one material has been selected for the concepting phase: Poly-Paper. This material, developed in the Making materials Lab of Politecnico di Milano, is obtained by combining recycled cellulose fibers and a polymeric matrix.

Thanks to its characteristics, the material is workable like a thermoplastic, but it can be transferred to the paper and board recycling cycle. The use of the identified strategies in this study makes the Poly-Paper the link between biopolymers and cellulosic materials, enhancing the characteristics of both, reducing the quantity of bioplastics destined to deterioration due to composting and expanding the application scenarios of cellulose-based materials. Starting from selected product categories, many concepts have been developed considering the aesthetic, functional and end-of-life properties of Poly-Paper.

Circular materials will provide new fields of investigation for applications in consumer products, increasing the scenarios on the design of their end of life, looking for sustainable solutions. This study represents a good practice for designers who want to approach the concepts development starting from innovative materials for the circular economy. The work highlights how it is necessary to start from a research that takes into consideration the different types of new materials, the applications already on the market, the aspects related to the end-life, to achieve sustainable application solutions.

Sommario

Il passaggio ad un modello di Economia Circolare ha portato alla creazione di materiali che fanno della sostenibilità e riciclabilità il loro punto di forza. Gli obiettivi della ricerca mirano a identificare possibili strategie di progettazione che applicano questi nuovi materiali nei prodotti di consumo, a promuoverne la diffusione e suggerire nuovi percorsi di sviluppo. Oggi i designer propongono questi nuovi materiali con grande entusiasmo per l'industria, anche se ci sono ancora molti problemi da risolvere per integrarli nel processo di sviluppo del prodotto.

Come punto di partenza, l'approccio dell'Economia Circolare offre numerosi spunti per migliorare il processo di progettazione. Prende in considerazione la riduzione dello sfruttamento delle risorse primarie, il miglioramento dell'efficienza dei prodotti, l'estensione della loro durata di vita o il cambiamento dei modelli di consumo, al fine di aumentare la sostenibilità dei prodotti. Nel progettare possibili applicazione di nuovi materiali per l'economia circolare, sono stati considerati l'approvvigionamento e la produzione di materie prime, ma ci si è concentrati soprattutto verso la fase di fine vita del prodotto (e quindi del materiale). Per meglio descrivere il contesto intorno allo sviluppo di nuovi materiali polimerici in una prospettiva "circolare", sono state identificate le principali categorie di biopolimeri, i loro usi e peculiarità. Per completare il quadro di analisi, sono stati studiati anche i materiali cartacei in relazione al loro utilizzo nei prodotti di consumo. La ricerca di materiali e prodotti è stata condotta attraverso casi studio organizzati in tre sezioni, che comprendono nuovi materiali circolari, materiali biobased e carta e cartone. Ogni profilo fornisce informazioni sulle sue principali proprietà, applicazioni, processi di produzione e problemi di sostenibilità.

I valori e le proprietà dei diversi materiali per l'economia circolare che sono stati identificati, sono stati confrontati attraverso lo strumento delle matrici, questo confronto ha aiutato anche a identificare i potenziali campi per la loro applicazione. Concentrandosi sugli aspetti della sostenibilità e della riciclabilità, un materiale è stato selezionato per la fase di concept: Poly-Paper. Questo materiale, sviluppato nel Laboratorio Making Materials del Politecnico di Milano, è ottenuto combinando fibre di cellulosa riciclata e una matrice polimerica.

Grazie alle sue caratteristiche, il materiale è lavorabile come un termoplastico ma può essere trasferito al ciclo di riciclaggio della carta e del cartone. L'uso delle strategie identificate in questo studio fa di esso un anello di congiunzione tra biopolimeri e materiali cellulosici, potenziando le caratteristiche di entrambi, riducendo il la quantità delle bioplastiche destinate al deterioramento dovuto al compostaggio ed espandendo gli scenari applicativi dei materiali a base di cellulosa. Partendo da categorie di prodotti selezionate, sono stati sviluppati diversi concept, considerando le proprietà estetiche, funzionali e di fine vita di Poly-Paper.

I materiali circolari forniranno nuovi campi di indagine per le applicazioni in prodotti di consumo, aumentando gli scenari sulla progettazione del loro fine vita, alla ricerca di soluzioni sostenibili. Questo studio rappresenta una buona pratica per i progettisti che vogliono avvicinarsi allo sviluppo di concept a partire da materiali innovativi per l'economia circolare. Il lavoro mette in evidenza come sia necessario partire da una ricerca che prende in considerazione i diversi tipi di nuovi materiali, le applicazioni già presenti sul mercato e gli aspetti legati al loro fine vita, per arrivare a soluzioni applicative sostenibili.

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Circular Economy

Fig.1.1 Take, make, waste lifestyle

1.1 Introduction to the Circular Economy

To better understand the new type of design approaches it is necessary to become aware of the variation that is occurring in economic models, not only at European level, but also worldwide. There are indeed more and more attentions that aim to transform the linear economy, which has remained the dominant model since the onset of the Industrial Revolution, into a circular one.

Today's model of social and economic progress, the Linear Economy, commonly referred to as "take, make, waste.", is based on a continuous increase of the consumption of goods and services (Kluczkowski and Wyrostkiewicz 2018). Resources like minerals, fossil fuels, timber, and the like are extracted from the environment and used to make a commodity; the commodity is sold, used and then deposited as trash at the end of its life. Linear economies have increased our quality of life, reduced mortality rates in the last 200 years but depends on two basic assumptions: one, that there will always be resources that can be extracted and two, that there will always be an "away" to send our discarded materials. While this seemed to be true at the dawn of the industrial revolution, we're realizing today that it is not. The world's population has grown from one billion people in the early 1800s to nearly 7.4 billion today and we are using natural resources faster than they can regenerate. In particular, fossil fuels – which were created over millions of years - cannot be replaced.

Such a radical change entails a major transformation of our current production and consumption patterns, which in turn will have a significant impact on the economy, the environment and society (Rizos, Tuokko, and Behrens 2017). Among the many points and aspects that affect the CE it is possible to find policy instruments and approaches about value chains, material flows, products and technologies, organizational aspects, and social innovation (Winans, Kendall, and Deng 2017). Furthermore, we must also consider that globally there are economies able to sustain a transformation, aiming at modifying technologies and material flows, while others, are weaker or developing, try to orient themselves towards different types of organization of markets and society. In fact, historically, the idea that 'waste equals food (for the planet)' was very much part of all aspects of daily life. While Western countries have largely abandoned such systems and habits, much of consumption in the developing world still functions using a more circular model, with far more active cycling of discarded materials, especially food waste, much higher penetration of reusable packaging and products (Ellen MacArthur Foundation 2013). For this reason, it appears that the CE concept evolved differently in light of diverse cultural and social and political systems (Winans, Kendall, and Deng 2017). Just because the topic is not limited to being part of a single scientific and/or social discipline, it has generated a great deal of attention worldwide, even outside the research area. The concept has been taken up by several governments and businesses around the world that consider the Circular Economy as a solution for reconciling what at first sight seem to be the conflicting objectives of economic growth and environmental sustainability (Lieder et al. 2017; Preston 2012).

According to the data provided by the statistics of the European Union, there are many countries that invest resources in the development of the Circular Economy. As far as concern the economic investments and the employed people for the growth of the CE in the 2015, UK, Germany, France, Italy and Spain are the five leading countries that are most committed to making a change (http://ec.europa.eu/eurostat/web/circular-economy/indicators/main-tables – June 2018).

The CE is also applied in many countries for waste management primarily, although there are also business models that apply material circular use (or reuse) concepts. Some CE-related initiatives aim to increase consumers' responsibility for material use and waste, which is evident in some parts of Korea and Japan. In North America and Europe, corporations apply the CE concept with the aim to enhance reduce, reuse, and recycle programs, and to conduct product-level life cycle studies (Winans, Kendall, and Deng 2017).

1.1.1 From Linear to Circular Economy

The Circular Economy concept has its roots in several schools of thought and theories that challenge the prevailing economic system based on overconsumption of natural resources.

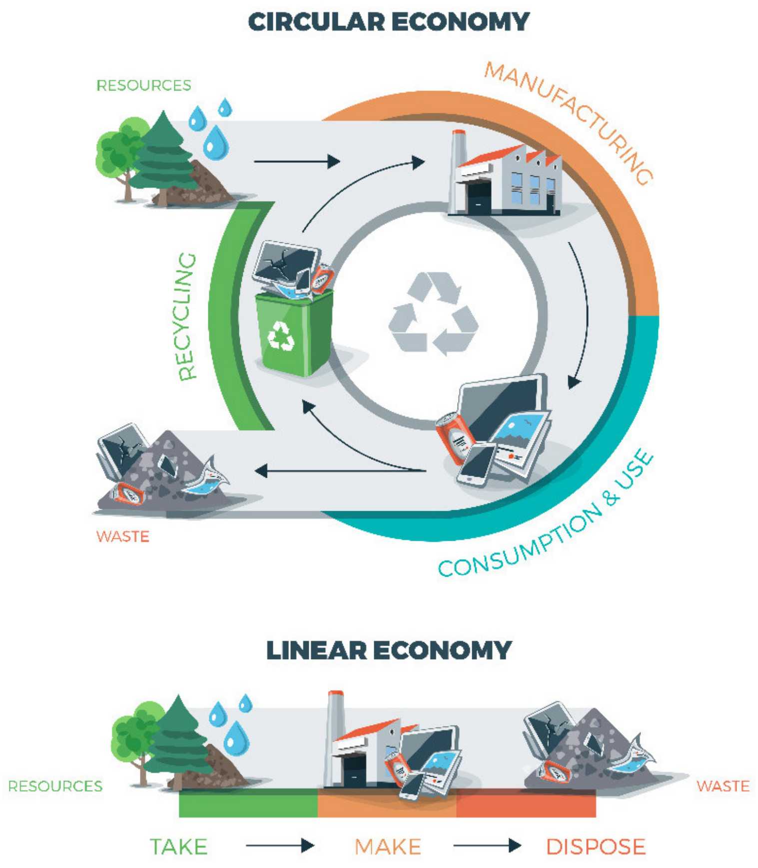


Fig.1.2 From linear to circoular economy

There are many difficulties to face for this change, also if it has been highlighted that the Linear Economy has many limits, like the consumption of raw materials and energy that is not contextualized in a global perspective, and above all, does not consider its long-term effects for the planet sustainability.

1.1.2 The Limit of Linear Consumption

A Linear Economy works according to the ‘take-make-dispose’ step plan. Resources are extracted, and products are produced. Products are used until they are discarded and disposed as waste in landfills or elsewhere. Value is created by maximizing the amount of products produced and sold (https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/how-is-a-circular-economy-different-from-a-linear-economy/ - June 2018).
A Linear Economy flows like a river, turning natural resources into base materials and products for sale through a series of value adding steps. At the point of sale, ownership and liability for risks and waste pass to the buyer (who is now owner and user). The owner decides whether old tyres will be reused, recycled or dumped. The Linear Economy is driven by ‘bigger-better-faster-safer’ syndrome - in other words, fashion, emotion and progress. It is efficient at overcoming scarcity, but excessive at using resources in often-saturated markets (Stahel 2016).

The decrease of real resource prices (especially fossil fuels) have been the engine of economic growth in advanced economies throughout most of the last century. This fact created the current wasteful system of resource use, where the easiness to obtain raw material took waste as an economical loss on every front.

For this reason, the fast-moving consumer goods industry is a force to reckon with in the global economy. While expenditure levels for such goods are vastly different across the globe, they represent a significant share of household budgets in both developed and emerging markets.

In the global economy, materials can easily cross the national borders. Therefore, our responsibility to use the world’s scarce and finite resources sustainably must now be extended to entire global product chains.
Thanks to the continuous increase of the life quality there will be far more consumers. The OECD (Organization for Economic Cooperation and Development) estimates that the global middle class will increase from 1.9 billion in 2009 to 4.9 billion in 2030 with almost 90% of the growth coming from the Asia-Pacific region. These new consumers will switch from loose, unbranded products to manufactured goods. As a result, consumer demand from emerging economies has the potential to exponentially increase the use of material, bring about dramatic rises in input costs, and result in hard-to-manage commodity volatility. In the face of unprecedented resource demands, radical resource efficiency will no longer suffice (Ellen MacArthur Foundation 2013). In the development of the processes for the Linear Economy the biggest economic efficiency gains have resulted from using more resources, especially energy, to reduce labor costs.

The system analysis, however, reveals that waste as part of the linear system results in economic losses on all fronts throughout the value chain, form the extraction to the end of life, passing through processing use and design. Furthermore, another limit of the Linear Economy lies in not having a global vision of a sustainable development. In fact, in his vision of “take, make and dispose” it

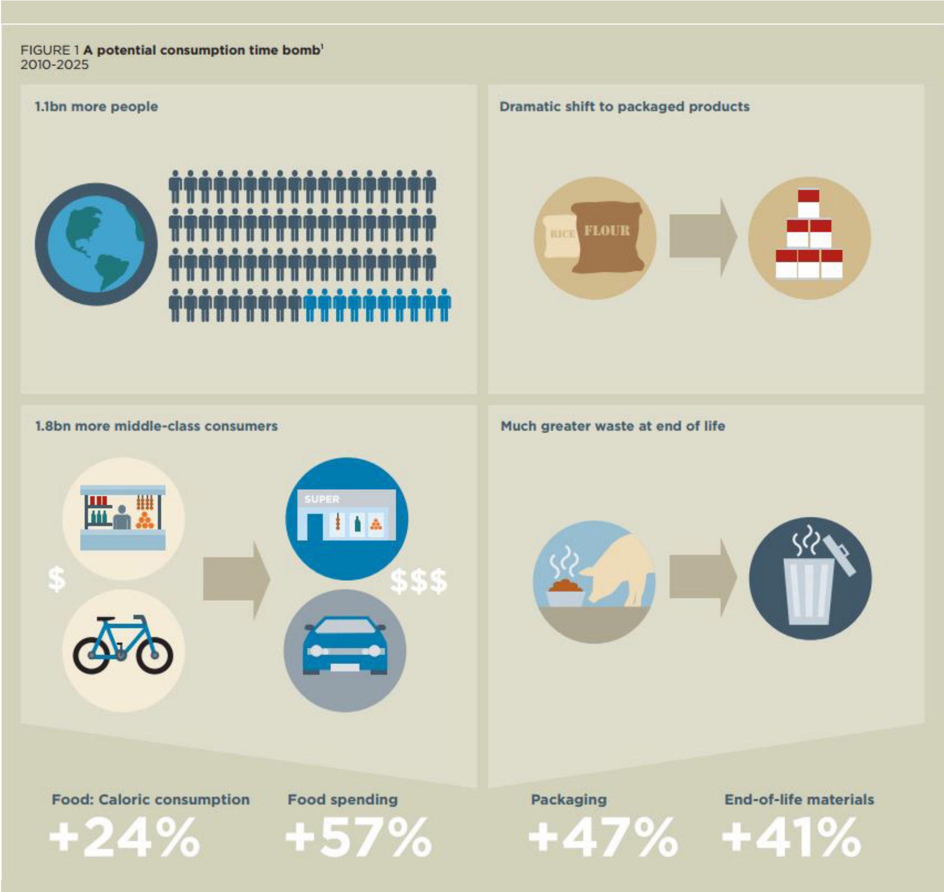


Fig.1.3 Towards the circular economy - a potential consumption time bomb, Ellen McArthur Foundation

was assumed that the first (take) but also the last part (waste) were carried out elsewhere. This situation, however, with the development of a global economy is becoming less and less applicable because of an increasing awareness of the limits that our planet has in terms of resources from an ever-increasing percentage of the world's population.

1.1.3 The Origin of the Circular Economy

Change the linear economic model, that has remained dominant since the onset of the Industrial Revolution, is by no means an easy task and would entail a transformation of our current production and consumption patterns.

The term Circular Economy appears to be formally used in an economic model for the first time by Pearce & Turner (1990). It creates a parallelism with the first and the second principle of thermodynamics between energy and products approaching the principle that "everything is able to feed all the rest".

- First Principle of thermodynamic

Energy is neither created nor destroyed, but is transformed from one form to another

- Second principle of thermodynamic

It is impossible to make a thermal machine whose efficiency is 100%

Their work and line of thought were inspired by the work of Kenneth Boulding and others who discussed a few decades earlier the biophysical limits of the present economic system built on overconsumption and a growing ecological deficit. In recent decades, the development of scientific literature on the circular economy has introduced disciplines and lines of thought such as Industrial Economics and cradle-to-cradle design.

1.1.4 Definition of the Circular Economy [CE]

There is a substantial agreement on what the Circular Economy is, but a univocal definition of Circular Economy is an activity in progress. In fact, according to the approach and the discipline in which the definition of CE deal with, it presents many facets. Research on the Circular Economy appears to be fragmented across various disciplines and there are often different perspectives about the interpretation of the concept and the related aspects that need to be assessed.
While some definitions and interpretations focus on physical and material resource aspects, others go further and discuss a major transformation of the economic system involving various sectors and issues that go beyond material resources and waste (Rizos, Tuokko, and Behrens 2017).

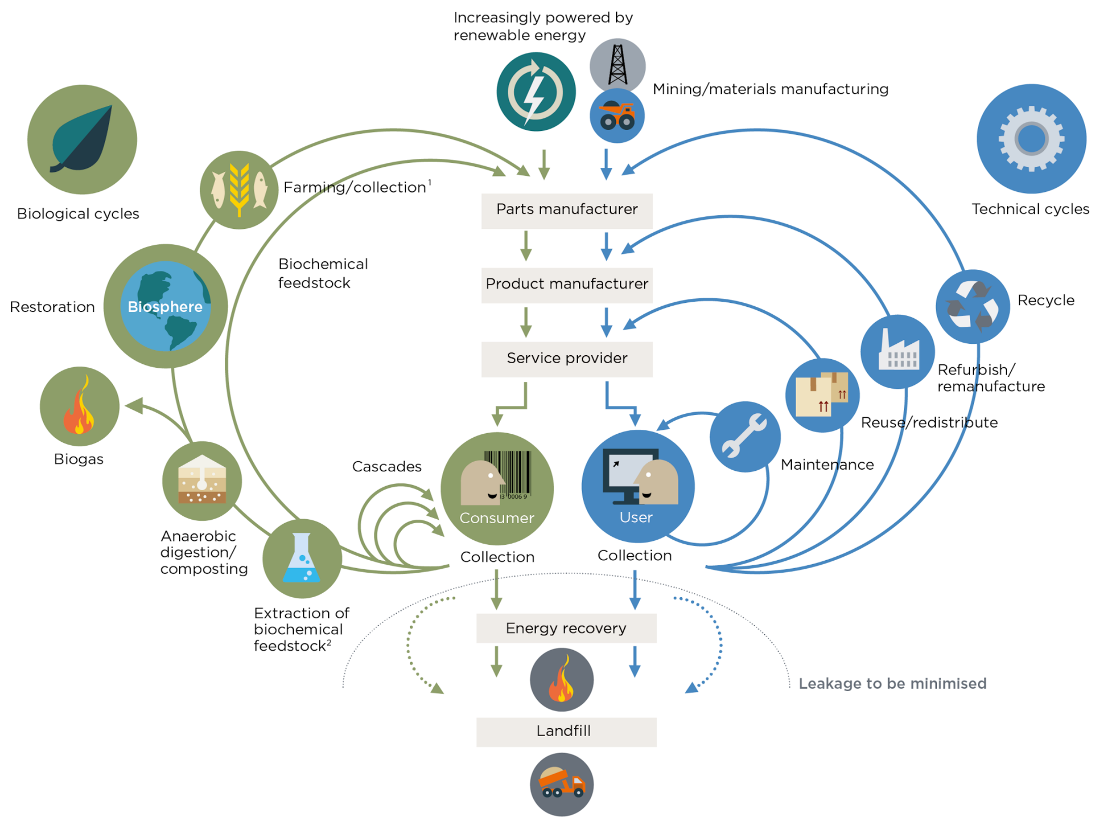


Fig.1.4 Outline of the circular economy - Ellen McArthur Foundation

One of the most frequently cited definitions that tends to incorporate elements from different disciplines is that provided by the Ellen MacArthur Foundation (2013a, p.7) which describes the Circular Economy as "**an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models". The overall objective is to "enable effective flows of materials, energy, labor and information so that natural and social capital can be rebuilt"** (Ellen MacArthur Foundation 2017).

This means that throughout the entire product lifecycle, from product design, production, consumption, to waste management, a comprehensive approach to products and services can provide raw material efficiency (Kluczkowski and Wyrostkiewicz 2018).

From the point of view of the physical resources present and exploitable on the planet, it is evident that there is a need to think about circular materials with a viewpoint of increasing value rather than decreasing it. This is the copernican revolution that is already partially pursued with increasing conviction by planning the re-immission practices in production cycles. It is part of an industrial dynamic, where large quantities of waste material and end-of-life products are processed to make them go back into the value chain, obtaining high performance materials and products (Pellizzari and Genovesi 2018).

1.2 Main Processes of the Circular Economy

In the review article of Rizos et al. "The circular economy -A review of definitions, processes and impacts" there is an interpretation of this topic that attempt to move beyond the notion of management of material resource and incorporate additional dimension. It identifies eight Circular Economy processes, intended as a set of activities that create value by transforming resources into a final product with added value. Those are further classified into three different categories focused on less using primary resources, maintaining the highest value of materials and products and changing utilization patterns.

1.2.1 Less Use of Primary Resources

As far as the lower use of resource concern, the first circular process is recycling. It has been defined by United Nations et al. as "the re-introduction of residual materials into production processes so that they may be re-formulated into new products" (United Nations, European Commission, and International Monetary Fund World Bank 2003). It should not be confused with reuse as the latter does not require the reprocessing of materials into new products, materials or substances.
It has been the most traditional way of implementing Circular Economy principles by capturing the value of existing products and materials and decreasing the use of raw materials, reduce the greenhouse gases emission linked to material resource use and being also cost effective for the industries.

Fig.1.5 Plastic recycling

Fig.1.6 Glass recycling

Fig.1.7 Paper recycling

Focus for recycling - vac from the sea

Electrolux has unveiled five vacuum cleaners made with plastic waste collected from the world's seas and oceans. All the material was sorted and documented, and Electrolux's research and design studios set to work creating the five unique vacuum cleaners each representing the ocean from which the plastic originates: The Pacific, North Sea, Mediterranean Sea, Indian Ocean and the Baltic Sea. The models are fully functional and have been built using the same core structure as the new Electrolux Ultra One Green-model. (http://theinspirationroom.com/daily/2010/electrolux-vac-from-the-sea/)

From left to right: The North Sea Edition, The Indian Ocean Edition, The Mediterranean Sea Edition, The Pacific Ocean Edition, The Baltic Sea Edition.

Fig.1.8 The products of the "vac from the sea project"

The second category of processes are about the efficient use of resources and cleaner production, that refers to improvements to both industrial production processes and products. In the case of the former, it can refer to raw material conservation, reduced material inputs, reductions in consumption of energy and water, avoidance of toxic substances in processes and reduction of toxic emissions and waste. In the case of the latter, it can refer to the reduction of impacts (environmental, health and safety) along the whole life chain (from raw material extraction to the final disposal) (Hinterberger and Schneider 2001). The forest industry presents an interesting example of using biological resources to generate new value that are often not used to their fullest potential. Circular practices may be applied to produce products from these side streams. (https://media.sitra.fi/2017/02/28142644/Selvityksia121.pdf). Typically, they've been used for energy recovery, while for example sawdust can be used in the manufacture of fiberboard or renewable packaging material.
Finally, taking in consideration energy as a primary resource, the use of renewable energy in substitution of the fossil ones is a fundamental requirement for the transition to a circular economy (Rizos, Tuokko, and Behrens 2017).

1.2.2 Maintain the Highest Value of Materials and Products

The second category of processes, being about to maintain the value of the materials and products high, see at the forefront the activities of remanufacturing, refurbishment and re-use of products and components aiming to restore the product into an "as new" condition. In refurbishment and remanufacturing, the products' 'core' parts are restored to maintain the added value of the materials. Reuse of a product is direct re-usage and/or e-sale of either the whole product or a part of it. All these processes have the potential to change the revenue streams for business since they can allow them to earn a second or third (or more) income from selling the product. Another focal point for the sustainability of a product about the materials value can be found in the Product Lifespan Extension. It requires a greater emphasis on its life cycle planning phase, trying to standardize components in terms of dimensions and materials using a modularity criterion (Rizos, Tuokko, and Behrens 2017).

1.2.3 Change Utilization Patterns

A third type of processes sees a significant paradigm shift in the design of goods, focusing on the development of products as services, sharing models and consumption patterns, based on the dematerialization of products in form of information.
The product as a service challenges the traditional commercial approach aimed at selling tangible products, replacing it with leasing, rental, pay-per-use or performance-based business models. In this case the company retains ownership of the product and offers to the customer access to the product thus maintaining the material resources at its disposal. This practice can bring environmental benefits because the model motivates society to repair and maintain the product in use for a longer period of time through recycling and restructuring practices, thus reducing the waste produced.
Sharing models are inextricably linked to the Circular Economy concept since they seek to reduce underutilization of products

On the left

Fig.1.9 Sawdust - a potential resource for circular practices

Below

Fig.1.10 Use of renewable energy source like wind and solar energy

and thereby support the more efficient use of resources. These typologies of service are becoming increasingly common, especially in the transport, entertainment and services sectors.
Finally, a Shift in Consumption Patterns is occurring. Technological advances can bring about a change in market demands. For example, many consumers choose products or services that provide the utility virtually instead of materially. Examples include digital books, smartphones, music and online stores. At the same time, companies can virtually deliver their products using virtual channels (for example, selling digital products through online stores). These changes can in turn lead to resource savings, but it must be kept in mind, however, that there are also concerns about scope of the sustainability benefits that these products and services could allow due to the rebound effects and high-power consumption of data centers (Rizos, Tuokko, and Behrens 2017).

	Circoular process	Examples of sectors where circular process can be applied
USE OF LESS PRIMARY RESOURCES	Recycling	Automobile industry, Textile industry, Building sector, Packaging sector, Critical raw material, Forest sector, Chemical industry
	Efficent use of resources	Building sector, Plastic industry, Mining and metals industry, Food sector
	Utilization of renewable energy sources	Chemical industry, Food industry, Forest sector
MANTAIN THE HIGHEST VALUE OF MATERIAL AND PRODUCTS	Remanufacturing, refurbishment and reuse of products and components	Automobile industry,Manufacture of computer, Electronic and optical products, Building sector, Furniture sector, Transport
	Product life extention	Automobile industry, Manufacture of computer, Electronic and optical products, Household appliances, Building sector, Food industry, Defence industry
CHANGE UTILIZATION PATTERN	Product as service	Household appliances, Transport, Building sector, Printing industry
	Sharing models	Automobile industry, Transport, Accomodation, Clothing
	Shift in consumption patterns	Food sector, Publishing sector, E-commerce sector

Tab.1.1 Mapping of application of circular economy processes in various sectors

1.3 The Approaches of the Circular Economy

In recent decades the development of scientific literature on the Circular Economy has introduced approaches and lines of thought such as industrial economics, Cradle-to-Cradle designs and product Re-upcycling. All these approaches aim to reconcile the ecological, economic and social reasons in new economic/cultural models that appear as a necessary condition for a sustainable future development. Sustainability is one of the greatest challenges facing the 21st century society and industry, and only the radical metamorphosis of existing systems can provide the opportunity for future generations (Kluczkowski and Wyrostkiewicz 2018).

1.3.1 Industrial Ecology [IE]

Industrial Ecology is an interdisciplinary field that focuses on the sustainable combination of Business, Environment & Technology. The word industrial' represents how humans use natural resources in the production of goods and services (http://www.industrial-ecology.com/ - June 2018).
This research discipline studies how the natural ecosystem and man-made industrial system operate in a similar way and are characterized by flows of materials, energy and information. Structural and technological changes combined with economic and cultural evolution in order to achieve energy and materials optimization that minimize the generation of unrecyclable wastes.

In 1989, Scientific American published what would prove to be a seminal article for the field of Industrial Ecology. The article by Robert Frosch and Nicholas Gallopoulos was titled "Strategies for Manufacturing" and suggested the need for "an industrial ecosystem" in which "the use of energies and materials is optimized, wastes and pollution are minimized, and there is an economically viable role for every product of a manufacturing process"(https://is4ie.org/about/history - June 2018).
Since then, the scientific field of the Industrial Ecology has grown quickly. The Journal of Industrial Ecology (since 1997), the International Society for Industrial Ecology (since 2001), and the journal Progress in Industrial Ecology (since 2004) give to the topic a strong and dynamic position in the international scientific community.

Nowadays, it is aimed at understanding the circulation of materials and energy flows; therefore, IE must first understand how the industrial ecosystem works, how it is regulated and its interactions with the biosphere in order to determine how the industrial ecosystem can be restructured to resemble how natural ecosystems function (Erkman 1997).

Industrial Ecolog with its tools can assist in the transition to CE, especially with tools such as Industrial Symbiosis (IS) and Eco Industrial Parks (EIPs).

The Contribution of IE for the CE

To better understand the contribution of IE to CE has been identified three levels, such as: conceptual, technical and policy aspects.

The Conceptual Contribution concerns the development of the knowledge about synergy networks, such as material energy and water flows, in order to implement CE from the application of symbiosis in industrial and/or urban environments.

The Technical Contribution, on the other hand, concerns the use of IE tools to fully or completely support CE. In this case, the tools most used to support the CE, such as Material Flow Analysis (MFA), Ecodesign that is an effective strategy to advance the eco-efficiency of enterprises and can be a useful eco-innovation practice for CE, and Cleaner Production, relevant to reduce emissions, wastes and risks for humans and the environment, are related to the application of IS and implementation of EIPs. In most cases, when applying these tools, different energy and material flows and common infrastructures and services are shared (Saavedra et al. 2018).

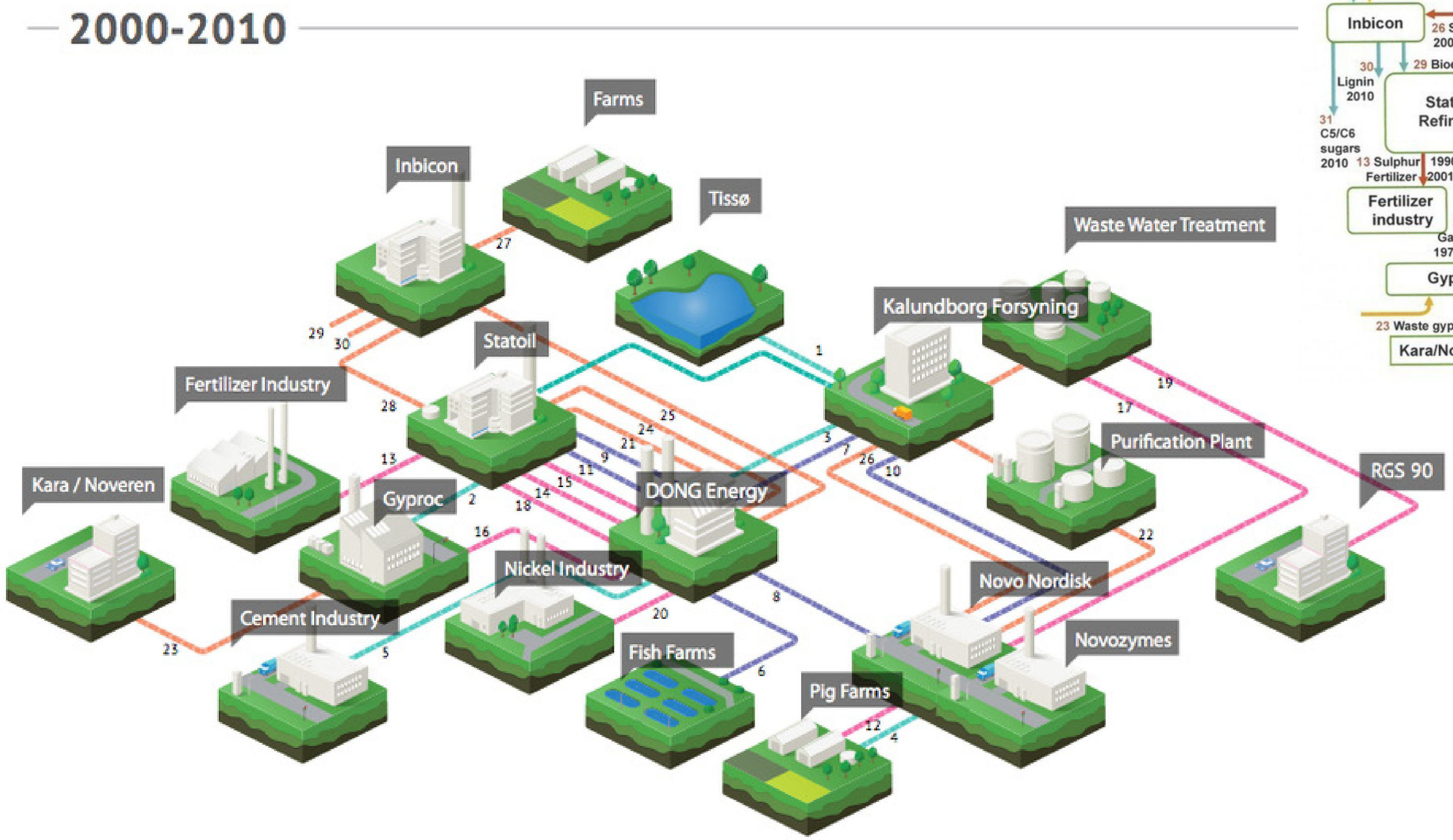
Industrial Symbiosis (IS)

Industrial Symbiosis (IS) is vital for the IE field. It is originated from biology and the existing biological symbiotic relationships in nature, in which two or more unrelated species exchange materials, energy or information in a mutually beneficial manner.

Industrial Symbiosis is characterized mainly by the reuse of waste from one company by another company as raw material. This concept has advanced in the sense that companies seek to develop this type of relationship (Chertow 2000). One of the next steps will be to consider industrial symbiosis in the product development.

Design for X (DFX), also called design for excellence, is an approach used in product development that aims to improve or maximize aspects of the product being developed, or of its life cycle, where the aspects to be improved or maximized are with respect to X. These aspects could concern the product scope or the system scope, from the manufacturing or the usability to the logistic. An example is the Design for Environment (DFE), which aims to support the designers in the development of products that have a reduced environmental impact. The guidelines for this principle are about "Use by-products or waste from other companies as raw material" in the principle " and "Generate by-products or waste that can be reused as raw material by other companies" in the principle "maximize healthy inputs and outputs", or "Take advantage of other companies' utilities in the production process" in the principle "minimize consumption of resources during operation".

On the stream of this approach it's also been supposed a Design for Industrial Symbiosis (DFIS). The first step in the DFIS application is to identify the by-products and wastes generated by nearby companies as well as surplus utilities. Then, for the solution options identification (second step) a morphological matrix should be used to visualize the product functions, different solution principles for these functions and by-products and/or waste that can be used in the product development. Finally, the solution options are evaluated to find the best choice in terms of industrial symbiosis (Mantese, Bianchi, and Amaral 2018).



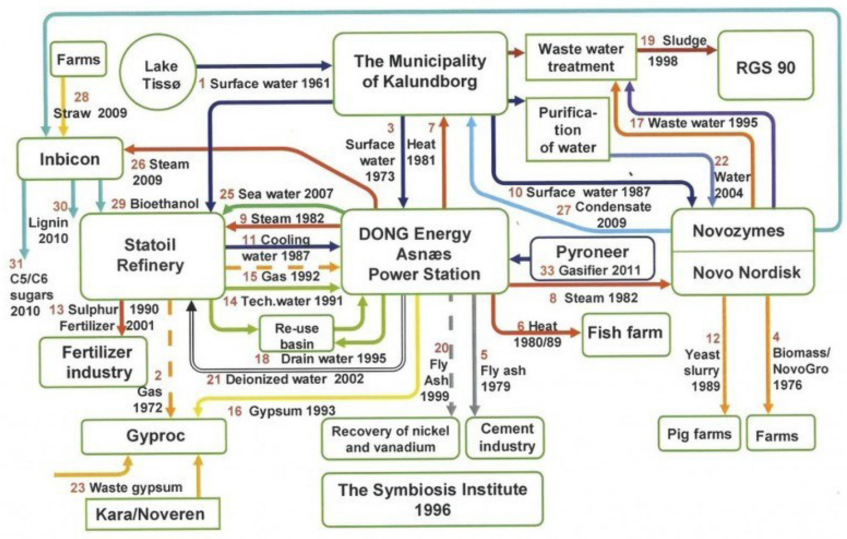


Fig.1.11 Scheme of an Eco Industrial park example of companies that apply industrial symbiosis

Eco Industrial Parks (EIPs)

Eco-industrial park and eco-industrial network initiatives include the exchange of water, energy, information, and or materials "to minimize energy and raw materials use, reduce waste, and build sustainable economic, ecological, and social relationships".

Eco-industrial park developments are the first manifestation of industrial symbiosis, occurring for the first time in the 1960's in the eco-industrial park in Kalundborg, Denmark. Today, there are several examples of eco-industrial parks around the world– in India, Australia, Korea, Japan, Canada, the United States, and Europe– that build upon existing and potential linkages within a region (Winans, Kendall, and Deng 2017). Based on the collaborative strategies, not only include by-product synergy ("waste-to-feed" exchanges), but can also take the form of wastewater cascading, shared logistics and shipping & receiving facilities, shared parking, green technology purchasing blocks, multi-partner green building retrofit, district energy systems, and local education and resource centers. This is an application of a systems approach, in which designs and processes/activities are integrated to address multiple objectives. (https://en.wikipedia.org/wiki/Eco-industrial_park - June 2018)

An example could be found at Kalundborg Symbiosis where public and private companies buy and sell waste from each other in a closed cycle of industrial production. Driven by increased costs of materials and energy for businesses, exchanges between companies are initially assessed on the basis of economic gains in saving of resources or money. Kalundborg Symbiosis is the world's first well-functioning example of industrial symbiosis and, within the academic discipline of Industrial Ecology, has become a textbook example of effective resource saving and cycling of materials in industrial production (https://www.ellenmacarthurfoundation.org/case-studies/effective-industrial-symbiosis - June 2018).

1.3.2 Cradle-to-Cradle Design [C2C]

Cradle-to-cradle design (also referred to as Cradle to Cradle, C2C, cradle 2 cradle, or regenerative design) is a biomimetic approach to the design of products and systems that models human industry on nature's processes viewing materials as nutrients circulating in healthy, safe metabolisms (https://en.wikipedia.org/wiki/Cradle-to-cradle_design#Structure). The term itself is a play on the popular corporate phrase "Cradle to Grave" used in several different contexts in business, most commonly as a description of a product's life cycle, but in marketing and advertising, the term refers to the practice of specifically marketing to children with the hope that they will become loyal consumers of that company's products for life (http://smallbusiness.chron.com/cradle-grave-mean-advertising-23834.html).
The term was used for the first time by William McDonough and Dr. Michael Braungart in the homonymous book "Cradle to Cradle: Remaking the Way We Make Things" in the 2002, implying that the C2C model is sustainable and considerate of life and future generations (i.e. from the birth, or "cradle," of one generation to the next versus from birth to death, or "grave," within the same generation). This book is a manifesto that call for the transformation of human industry through ecologically intelligent design (http://www.c2c-centre.com/library-item/cradle-cradle%C2%AE-english-edition).

Fig.1.12 Cradle to Cradle Logo

Cradle-to-cradle design is an approach of adjacent systems aimed at transforming the industrial material flows to maintain and even enhance the value, quality and productivity of material resources in order to have a net positive environmental effect (Braungart, Mcdonough, and Bollinger 2006).
A basic principle of cradle-to cradle is that there are two types of materials that can be optimized through the design of products, manufacturing processes and supply chains: biological materials and technical materials. The formers are biodegradable and can be safely returned to the environment after their use, while the latter are durable materials that can be reprocessed after their use and continue flowing within a closed-loop system.

The Cradle to Cradle Certified™ Product Standard guides designers and manufacturers through a continual improvement process that looks at a product through five quality categories — material health, material reutilization, renewable energy and carbon management, water stewardship, and social fairness (https://www.c2ccertified.org/get-certified/product-certification).

Quality Categories of Cradle-to-Cradle Design

The first quality principle of C2C is the **Material Health**. It is on the knowledge of the chemical ingredients of every material in a product and optimizing towards safer materials. Through it, is also possible to identify materials as either biological or technical nutrients and understand how chemical hazards combine with likely exposures determines a potential negative impact to human health and the environment.
The second one is on the **Material Reutilization** which aims to maximize the percentage of rapidly renewable materials or recycled content used in a product and the percentage of materials that can be safely reused, recycled, or composted at the product's end of use. It also designates products as technical, so it can safely return to industry and/or biological, where it can safely return to nature.
The third is about the **Renewable Energy & Carbon Management** that takes into consideration if there are source of renewable energy that offset carbon emissions for the product's final manufacturing stage Envisioning a future in which all manufacturing is powered by 100% clean renewable energy.
Water Stewardship is the fourth quality principle co the Cradle-to-Cradle Design that take in consideration the management of clean water as a precious resource and an essential human right. It Identify, assess, and optimize any industrial chemicals in a facility's effluent addressing local geographic and industry water impacts at each manufacturing facility.
The last quality principle is about **Social Fairness**. It aims to design operations to honor all people and natural systems affected by the creation, use, disposal or reuse of a product. (https://www.c2ccertified.org/get-certified/product-certification - June 2018)

Fig.1.13 Cradle to Cradle Quality Categories

Material and products certificate C2C

In 2010, after 20 years of working with companies, the association scaled up the transformation. The founders gifted the license to the certification system and methodology to the public through the creation of the Cradle to Cradle Products Innovation Institute. The non-profit Institute is nowadays an agent of change through open source information. It educates and empowers manufacturers of consumer products to become a positive force for society and the environment, helping to bring about a new industrial revolution.

Many companies, to date, try to follow the guidelines of the quality criteria of C2C by studying and creating finished or semi-finished products that impact less on the environment, making them virtuous examples of sustainable products.

Fig.1.14 Accoya products in architecture

Accoya® - Reducing Environmental Impact, Improving Performance.

Accoya® wood is the result of decades of research and development that has brought together a long-established wood modification technique and patented technology – acetylation – to create a high-performance wood designed for outdoor use and challenging applications. It has properties designed to match or exceed those of the best tropical hardwoods and treated woods and can be used for virtually anything from windows to doors, decking to cladding, and bridges to boats. (https://www.c2ccertified.org/products/scorecard/accoya_wood_radiata_pine_alder - May 2018)
The acetylation process that is used to manufacture the product fits perfectly in the bio-cycle of the C2C concept. Through the acetylation process, the part of wood that readily bonds with water is replaced by acetyl groups which are naturally occurring especially in the more durable wood species. Thus, the acetylation process mimics nature, and without adding any toxic substances, it ensures performance and material health to the highest level possible under C2C standards (https://www.accoya.com/sustainability/ - June 2018)

Fig.1.15 Accoya products in interior design

BAYONIX® bottle - The drinking bottle of the future

The BAYONIX® bottle is a drinking bottle constructed exclusively from a special polymer, designed to be safe for biological cycles, humans, animals and the environment free of harmful substances. Additional materials such as seals, coatings and imprints were deliberately dispensed with (https://www.c2ccertified.org/products/scorecard/bayonix-bottle-food-contact-articles-bayonix-stefan-hunger - june 2018).
The BAYONIX® Bottle producers designed it to be 100% biodegradable and 100% recyclable, safe for humans, society, water and the environment. The recyclable sports bottle was born from the idea of offering people a durable and environmentally friendly alternative to disposable plastic with the aim of freeing the environment as well as humans and animals from disposable products. In fact, to produce commercially available disposable plastic bottles, approximately 3 liters of water are needed to produce each bottle and approximately as much oil as one million cars consume per year.
For this reason, the BAYONIX® bottle is made of a petroleum-based polymer, in which all the materials, chemicals and dyes used are completely environmentally friendly. This means that the entire bottle can be safely returned to biological or technical cycles, either by industrial composting or by decomposing the product into its individual parts, which can then be recycled, using a Cradle to Cradle principles (https://bayonix.com/ - june2018).

Fig.1.16 Bayonix bottle

Wasted bottles are the material source for the Bayonix

1.3.3 Re-Upcycling

In the book "Neomaterial in the circular economy" of Pellizzari and Genovesi, it is very interesting the approach to the valorization of materials, that is not just for re-cycle, but which aims to increase its value, and therefore re-upcycle, precisely because it leads to a second life. With Re-upcycling is meant the change of perspective that aims to reuse discarded objects or materials not only recycling but in a way that creates a product of higher quality or value than the sources that originated it. In this logic, the materials, coming from crops or waste, are divided into three families according to the supply chains that follow during their life cycle and their use and reuse (Pellizzari and Genovesi 2018).
These three families of materials are defined as Bio Based, Neo-Classical Materials and Ex Novo Materials.

Bio Based

Biobased materials are a vast family of materials, many of which are traditional, based on natural cycles of development in the plant and animal kingdom as well as the world of microorganisms.
These materials are sometimes referred to as biomaterials, but this word also has another meaning. Strictly to the definition, where they are material intentionally made from substances derived from living or once living organism. To this area belong all those classic materials derived from tall trees, such as timber and cellulose, basic component of paper, bamboo, cotton, hemp, flax etc. and from animal derivation such as wool, leathers, horn until wax produced by bees. The unprocessed materials may be called biotic material to distinguish them from those processed (https://en.wikipedia.org/wiki/Bio-based_material - June - 2018). To date, as biomaterials it typically refers to modern materials that have undergone more extensive processing, they are renewed and improved in performance thanks to increasingly advanced processes and technologies that have extended their application to new or more efficient sectors.

Among them, moreover, are all those materials that come from radical modifications of the starting product such as polymers obtained from natural raw materials (Pellizzari and Genovesi 2018). Many of the biobased materials have in fact characteristics of durability and preciousness, so it is more advisable that once a first life cycle has been completed, they are reused and recycled rather than biodegradation, such as wood and paper and recently also some biopolymers. The PLA, for example, has acquired over the years high technical properties for which it is aiming to develop technologies and supply chains for the recycling of products and packaging made with this biopolymer instead of closing the cycle immediately sending it composting (Pellizzari and Genovesi 2018).

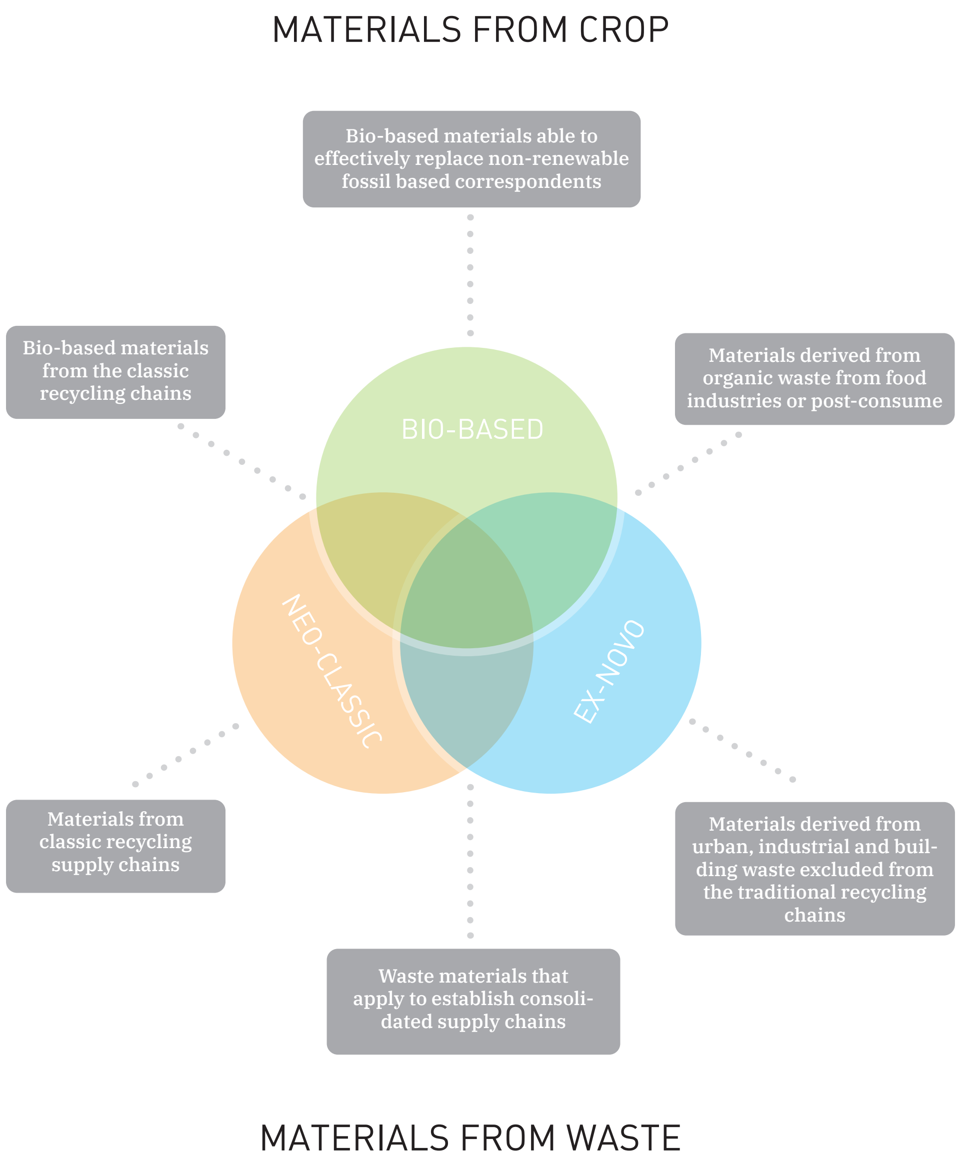


Fig.1.17 Re-Upcycling scheme (Pellizzari and Genovesi)

*One of the companies that develops biomaterials is API, that starting from APINAT has developed a **complete range of polymers and compounds with a high content of renewable sources**. In response to the growing market and consumer needs for sustainable products, API is focused on the development of a wide range of biomaterials designed to reproduce its current products with a **biobased version**. These products are based on raw materials from renewable natural sources and will contribute to a reduction in CO_2 and greenhouse gas emissions (https://www.apiplastic.com/en/bioplastics/).*

On the right

Fig.1.18 Smartphone cover in Apinat TPE-E
with aesthetic characterisic comparable to petrochemicals polymers

Below

Fig.1.19 Supports for bed slats in Apinat TPE-E
that demonstrate that have mechanical characterisic
comparable to petrochemicals polymers

Among the examples of what are today defined as biobased materials, we can find the Timberfill, a WPC (Wood Polymer Composite) developed for additive Manufacturing technologies (FDM) completely biodegradable, composed by a PLA matrix reinforced with about 25-30% of fibre wood powder. The objects printed with this material have the appearance, the consistency and the acoustic properties of the wood and can be worked and finished like the wood itself.

Despite this, it is in the disposable sector that biobased materials find their natural use for their biodegradability characteristics, they are short-lived products usually made of plastic or cardboard and can be recycled if the necessary supply chains are available. (Anna Pellizzari 2018, p.46) One of the most famous material is the MATER-BI. A versatile and innovative bioplastic created by Novamont which is being used to provide low environmental impact solutions for everyday products: carrier bags, organic waste bags, nets for fresh fruit and vegetables, paper wrappings, cups and napkins, plates, cutlery, cups and spoons for ice cream and a range of flexible packaging applications, but above all, the characteristics of MATER-BI are designed to enable processing through normal production plants (http://materbi.com/en/about/?noredirect=en_US).

On the top - left

Fig.1.20 3D printed Timberfill - precision in 3D pinting

On the top - right

Fig.1.21 3D printed Timberfill - Toughness in 3D printing

Below - left

Fig.1.22 Common Mater-bi (TPS) plastic bag

Below - right

Fig.1.23 Common Mater-bi (TPS) disposable forks

Neo-Classic

Neoclassical materials are all those materials that are now permanently recycled, entered into various production processes both in the form of secondary raw materials, and in the form of semi-finished products obtained from used materials, and therefore become waste. Depending on the types of materials, specific recycling chains have been developed. Each material to be recycled can have loop-to-loop applications in which they can be re-used for infinite cycles, such as glass or metals, while others have applications with degradation levels, for example the paper can be reused 7 times, fabrics 5, wood 3 such as tires and thermoplastics (Pellizzari and Genovesi 2018).

Paper can be recycled around 7 times before the fibers in the paper become too short and weak to be reused. Old newspapers are commonly used to make tissue and cardboard, while magazines are often recycled into newsprint. Interestingly, the clay originally added to the paper to make it glossy will help to separate the ink from the paper during recycling (http://www.ipst.gatech.edu/amp/collection/museum_recycling.htm).

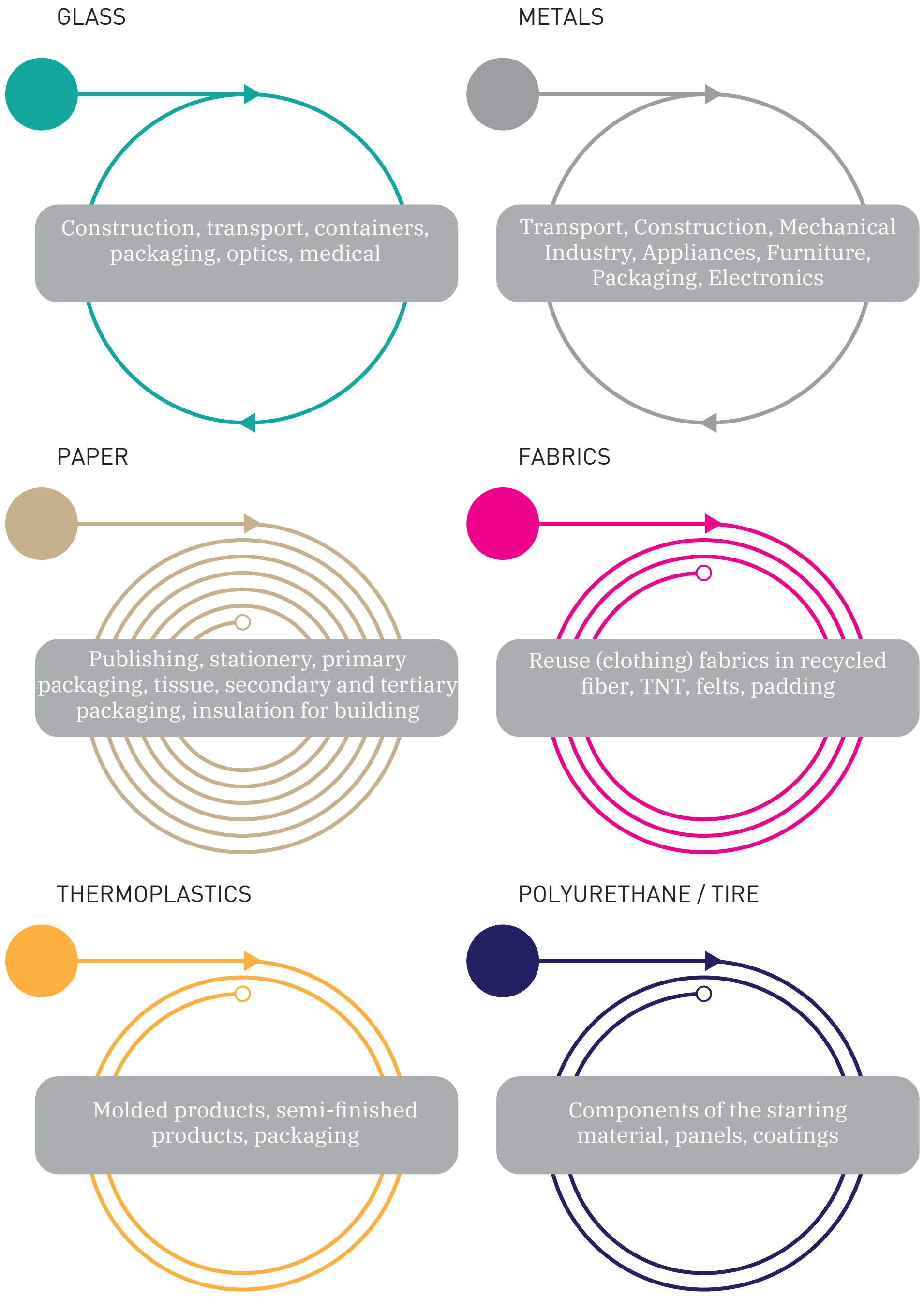


Fig.1.24 Neo classic material cycles

Ex Novo

Ex novo materials are derived from materials such as urban, industrial and construction waste that are excluded from the traditional recycling chains. They are an extremely heterogeneous family because they use waste coming from numerous sources and very different from each other as waste deriving from the processing of raw food or bio-based materials, waste from industrial processes or purification plants, sludge resulting from recycling processes, materials demolition, post-incineration dust or road sweeping lands, to the creation of materials starting directly from CO_2.

These materials give life to interesting reuse projects in addition to the development of new technologies related to transformation processes, they also create the development of a logistics necessary for the establishment of systems for collecting and recovering starting substances that could generate new and virtuous recycling chains.

Fig.1.25 Milk overproduction

On the right - top

Fig.1.26 Q-Milk yarns

On the right - bottom

Fig.1.27 Q-Milk Production Steps

Qmilk

Qmilk, for example, is a biopolymer produced from casein, a substance from milk that can no longer be used for food, which is mainly used to produce yarns through a production process that takes place at temperatures below 100 ° C and uses less than 2 liters of water for the production of 5 kilograms of polymer.

S.Cafè®

It is a polyester fiber for the production of clothing additivated with coffee grounds that are used as a sanitizing additive with anti-odor properties. Born from an experimental chain of recycling that sees the upstream collection of roasted coffee grounds, especially at businesses such as bars and restaurants where it concentrates a relatively high production of this specific waste, provides a specific processing that eliminate substances such as phenols, esters and oils and convert the material into active carbons which are added to the molten polymer mixture to create the yarn with the anti-odor properties.

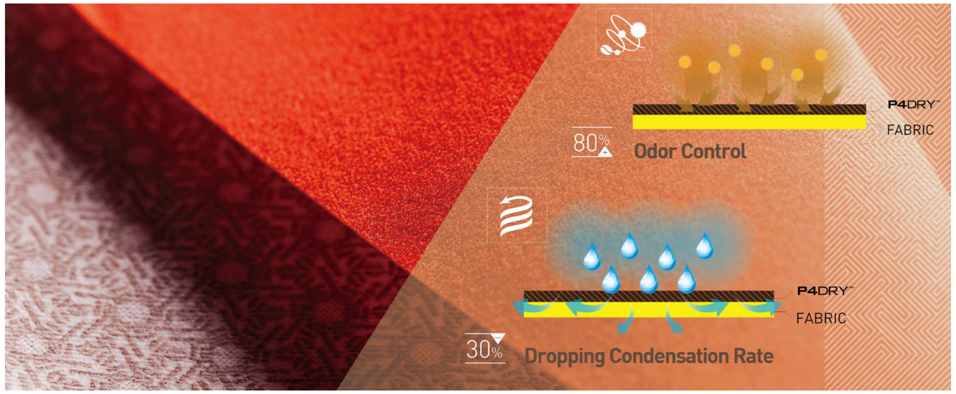


Fig.1.28 Coffee grounds

Fig.1.29 SCafè characteristic

Fig.1.30 Scafè fabric of different colors

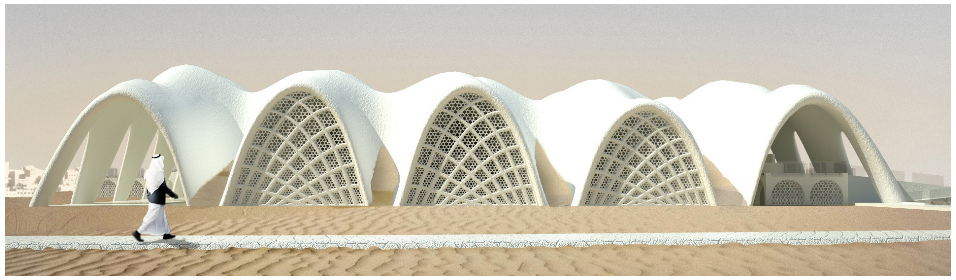
The Salt Pup by Eric Geboers

The Salt Project is a biomimetic attempt to create architecture using seawater in the desert. By using locally available resources we can grow plants and create architecture without producing waste (http://buildingwithseawater.com/#insta – June 2018).

A mixture of almost 90 percent sea salt, a small about of starch and water is heated and dried, leaving a white, hard, translucent material. The material is strong under compression force and weak under tensile force. The logical shape that follows from this is an arch or dome. Because there is a great shortage of fresh water in the world, salt water is desalinated in dry areas. The waste created – brine – is pumped back into the sea, with all the ecological consequences this entails. The Salt Pup is a prototype. The ultimate goal is to use the composite in architecture. (http://www.newmaterialaward.nl/en/nominations/the-salt-pup/)

Fig.1.31 Salt Pup stool for interior design

Fig.1.32 Salt Pup in architecture



The analysis of the current context has brought to light the importance that the values of the Circular Economy have today. The sustainability criteria, the main point of this new economic system, can be treated according to different points of view. Regarding the exploitation of resources, the role of circular materials is visible.

Polymers derived from fossil resources are the symbol of the economic development of the second half of the twentieth century and of the linear economy. In light of the economic model change, new materials derived from biomass are being introduced on the market replacing petroleum derivatives, the biopolymers.

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Biopolymers

Looking at the annual production of petroleum-based plastics, it exceeded 300 million tons in 2015, and 34 million tons of plastic wastes are generated each year throughout the world and 93% of them are disposed of in landfills and oceans (Pathak, Sneha, and Mathew 2014).
Although the technologies for recovering the plastics wastes have been improved, an increase in the world population to about 9 billion in 2050 requires a higher demand for plastic production and eventually, an increase in the amount of plastic wastes (Emadian, Onay, and Demirel 2017).
One of the central themes within the Circular Economy concept, which is based on the efficient use of resources, is the evaluation of materials 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. For this reason, the bioplastics development and technologies related to them, plays a key role within the CE. The materials are part of the collective and individual experience, of the imaginary and of taste. They are indicative of techniques and the technological level of a company and its values (Fiorani 2000).

2.1 Definitions

Biobased

With the term Biobased is meant a man-made or man processed macromolecules derived from biological resources with no specification about derivation (vegetal, animal, mineral, etc..) and degradation (recyclable, biodegradable, compostable, etc..) used for non-food purposes for plastic application (Shen, Haufe, and Patel 2009).

Biodegradable

The term biodegradable refers to the property of those substances that once released into the environment are degraded or decomposed and assimilated as a result of the biological activity of saprophytic bacteria, naturally present in a specific natural ecosystem, which feed on the organic substances derived from residues from other organisms, naturally present in a given natural ecosystem. Therefore, in order for a compound, to be considered biodegradable it is necessary that it be made using substances of natural (mainly vegetable) origin in order to be easily degraded (http://www.chimicare.org/curiosita/la-chimica-dei-materiali/le-nuove-frontiere-applicative-delle-bioplastiche-dalla-nostra-tavola-al-risanamento-ambientale/ - July 2018).
According to European standards EN 13432 and EN 14995 a material is considered to be biodegradable if it degrades by at least 90% within 6 months (180 days). UNI EN 14046 and ISO 14855-1 standards regulate testing for ultimate aerobic biodegradability under controlled composting conditions (https://www.apiplastic.com/en/bioplastics/).

Compostable

The term compostable refers to a substance that could be deteriorate into CO_2 and a soil-like material (humus) by activity of a mixed group of microorganisms in a compost environment within six month as indicated by the CEN standards (Soroudi and Jakubowicz 2013).

Bioplastic

The term 'biomaterials' includes products that are synthesized by renewable biomass sources, such as vegetable oil, corn starch, pea starch or microbiota, under different conditions. One important family of biomaterials is bioplastics that have physic-chemical properties resembling petrochemical plastics (Luengo et al. 2003). A bioplastic or biopolymer is a plastic that is entirely or at least 20 percent composed of renewable biomass sources, such as starch, cellulose or sugar. Because of its biological origin, it is inherently biodegradable and biocompatible, which means that it can easily be broken down into CO_2, water, energy and cell mass with the aid of microbes, rendering it largely carbon neutral, making them extremely interesting from the biotechnological point of view (http://materiability.com/portfolio/bioplastics/ - June 2018).

Biocomposite

Biocomposites are defined as biocompatible and/or eco-friendly composites. They consist of a large variety of organic and/or inorganic components, such as natural and synthetic polymers, polysaccharides, proteins, sugars, ceramics, metals, and nanocarbons. Biocomposites are present in various forms, such as films, membranes, moldings, coatings, particles, fibers, and foams. In addition to the studies aimed at improving basic mechanical properties and functionalities of the materials, a large number of studies have been conducted to develop eco-friendly composite and/or biomedical materials for use in the fields of sensors, tissue engineering, implants, and scaffolds (Haraguchi 2011).

Green Composite

Green composites are defined as a biocomposite combination of natural fibers with biodegradable resins. They are called green composites mainly because of their degradable and sustainable properties, which can be easily disposed without harming the environment. Because of their durability, green composites are mainly used to increase the life cycle of products with short life.

2.2 History

Bioplastics are not new. Since in the biblical Book of Exodus, Moses' built his ark from rushes, pitch and slime, a composite that might now be called a fibre-reinforced bioplastic. Natural resin – like amber, shellac and gutta percha – have been mentioned throughout history, including during Roman times and the Middle Ages.
But the significant commercialization of bioplastic, as we nowadays know, began to be developed in the nineteenth century with the production of goods in Ebonite - a black vulcanized form of natural rubber - or the use of the Gutta percha – rubber like, extract from tropical trees – where a screw extruder was developed for its processing becoming an early precursor of modern extrusion machines (Stevens 2002).

Interestingly the first man-made plastics were derived from biological cellulose. In 1845 Christian Friedrich Schönbein prepared a strong, transparent and waterproof cellulose derivative from paper. At the 1862 building exhibition in London the English inventor Alexander Parkes presented a pressure-molded plastic that he called Parkesine and which he brought to the market in 1866. Three years later the Hyatt brothers patented a process for plasticizing cellulose nitrate with camphor and consequently opened their first factory to mass-produce celluloid.
In the 1910s Henry Ford began experimenting with converting soybeans into plastic for the use of automobile parts. In 1941 he exhibited a prototype car, whose body consisted of fourteen pressure molded panels made from soybean plastic. Further developments were however stopped with the beginning of World War II.

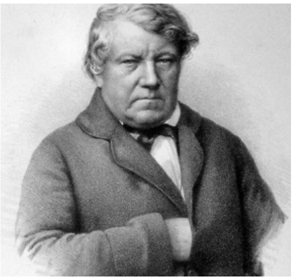


Fig.2.1 1845: Christian Friedrich Schönbein prepares waterproof cellulose.

In 1923 the industrial production of cellophane began, the only bioplastic that until today survived the growth of the synthetic plastics industry, which emerged during the same time. Research into organic chemistry soon led to a shift towards the use of fossil fuels and in turn the discovery of Bakelite (1907), Acrylic, polystyrene, Nylon and Teflon in the 1930s and the industrialization of polyethylene and polypropylene in the 1950s. Since the 1980s research and development into bioplastics has resumed and is again constantly increasing (http://materiability.com/portfolio/bioplastics/ - June 201,8). Another interesting bio-polymer, the PHB, was first discovered in 1925 by Maurice Lemoigne who concluded that bacteria could produce polyesters, and in 1932 Wallace Carothers discovered the PLA at DuPont by heating lactic acid under vacuum while removing condensed water (Jamshidian et al. 2010). However, Maurice's discovery was not officially recognized as PHB until its rediscovery in 1957 in the UK and the U.S.A, 32 years after being first discovered causing much interest in the future of biopolymers (https://www.ukessays.com/essays/chemistry/synthesised-by-living-organisms.php -_August 2018). In fact, the development of biopolymeric materials began in the 1970s. At the time the World had seen two oil crises and Imperial Chemical Industries (ICI) decided to look at biological routes for chemical manufacture in an attempt to insulate themselves from the shock of possible future crises developing the "Biopol" program trying to develop the production in a commercial scale in 1998 claiming that the cost were uneconomical.(Tucker, Johnson, and Limited 2004) The perfect example could be found in the starch-based plastics area, that have claimed melted or "destructurized" starch as a new type of material

Fig.2.2 1941: Henry Ford's soybean plastic prototype car.

prepared exactly in the 1970's (https://onlinelibrary.wiley.com/doi/abs/10.1002/star.19930450806 - September 2018).
Today, the renewable nature of biopolymers leads them to a renaissance and a new interest. In the last 20 years, this interest in sustainable products has driven the development of new biopolymers from renewable feedstocks. Biopolymers have to compete with polymers derived from fossil fuel not only because of their functional properties but also in terms of cost (Chassenieux et al. 2013).

At the base of these materials there are matrices derived mainly from sugars and their polymers. Thanks to this derivation (in fact they are made of the same compounds as a plant or a living being in general) they can be easily and quickly degraded.
Historically, the bioplastics developed from the 1990s were primarily known for being biodegradable. The issue of managing the end-of-life of plastic waste material was becoming increasingly important while the issue of exhaustion of fossil fuels was just taking form. The raw materials arriving on the market (primarily starch-based compounds and PLA) were then predominantly intended for disposable applications for which it made sense to use biodegradable and compostable polymers. It is for this reason that the markets of flexible packaging (films, bags, etc.) and rigid packaging (packaging tray, bottles, glasses, etc.) were initially integrated. Although bioplastics are considered to be environmentally friendly materials, they also have some limitations such as high production cost and poor mechanical properties. The main biopolymer families on the market today derive from renewable sources and include polymers derived from starch, like blends of thermoplastic starch (TPS), aliphatic/aromatic polyester derived from polylactic acid (PLA) and that derived from Poly-hydroxyalkanoates (PHA) and cellulose polymers. In 2012, PLA and starch-based were the most utilized bioplastics by 47 and 41% of total consumption, respectively. Moreover, Polyhydroxybutyrate (PHB) bioplastics got the attention of the scientific community due to their low CO_2 emission (Mostafa et al., 2015).
The different applications of bioplastics are segmented in a significant manner, biodegradable and compostable polymers are predominantly used in sectors where this property may be a technical advantage during their use or their end-of-life, like agriculture, horticulture, and flexible packaging (biodegradable bags). Contrarily, they are almost absent from transportation and building markets (http://natureplast.eu/en/industrial-applications-of-bioplastics/).
There are many industrial sectors that are trying to change their production of goods to a more sustainable one. In particular, the automotive industry is doing a great effort to shift from thermosetting composites to thermoplastic natural-fibre reinforced composites. Despite these great efforts brought by the industry to achieve greater product sustainability, the perception of the end user regarding products made of bioplastics is still very little aware. From a recent study presented as "Perception and challenges - bioplastic at their turning point to consumer communications" carried out on a large

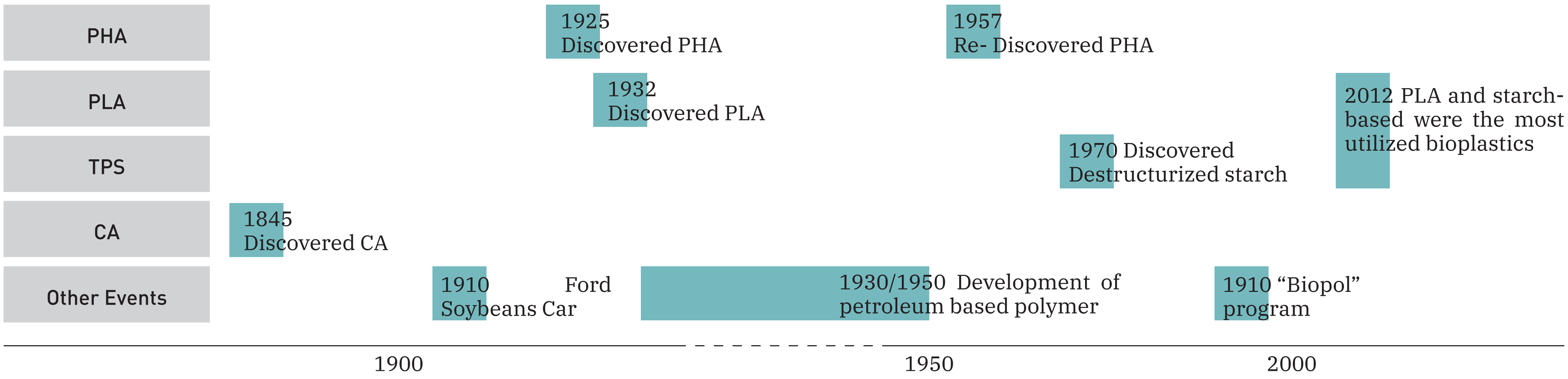


Fig.2.3 Timeline of main events of principal biopolymers

sample of German population concerning the perception and communication of biopolymers in the product, it emerged how about 2/3 of the population results uninformed or poorly informed and only 10% are aware about it. Furthermore, the low level of knowledge and the use of incorrect terms to reach a broader public, creates in the user a confusing perception about materials, but a high expectations regarding their sustainability and disposability (Blesin et al. 2017).
From the worldwide institutions' point of view, they are trying to direct the markets to a lower use of fossil-based plastic materials by promoting those produced from renewable sources. In fact, between these steps, after having banned plastic bags in 2015, Europe is now trying to pursue a strategy of the circular economy package recently approved by the Council and Parliament and the proposal for a plastic tax. Thanks to the proposed new directive, the emission of 3.4 million tons of CO2, environmental damage equal to 22 billion euros by 2030 would be avoided and a saving of 6.5 billion euros will be produced for consumers. In the presence of easily available and economically accessible alternatives, single-use plastic products will be excluded from the market. Will be banned: cotton swabs, cutlery, plates, straws, drink mixers and balloon rods. All these products must be manufactured only with sustainable materials. Single-use beverage containers will only be allowed if the caps and lids remain attached to the container (https://www.greenme.it/informarsi/rifiuti-e-riciclaggio/27803-plastica-monouso-divieto-europa#.Wzyj5X4_c1S.facebook – July 2018).

2.3 Role of Biopolymers in the Circular Economy

Bioplastics are not just one single material. They comprise of a whole family of materials with different properties and applications. According to European Bioplastics, a plastic material is defined as a bioplastic if it is either biobased, biodegradable, or features both properties. These materials are driving the evolution of plastics. There are two major advantages of biobased plastic products compared to their conventional versions: they save fossil resources by using biomass which regenerates (annually) and provides the unique potential of carbon neutrality. Furthermore, biodegradability is an add-on property of certain types of bioplastics. It offers additional means of recovery at the end of a product's life (https://www.european-bioplastics.org/bioplastics/ - June 2018).

Biodegradable plastics were introduced in the 1980s to find ways to produce non-petroleum-based plastics, as well as to reduce the environmental effects because of the increased landfill. All plastics (bio and petroleum-based) are theoretically biodegradable; however, most materials degrade at such slow rates that they are considered non-biodegradable or durable (Soroudi and Jakubowicz 2013). The property of biodegradation does not depend on the resource basis of a material but is rather linked to its chemical structure. In other words, 100 percent biobased plastics may be non-biodegradable, and 100 percent fossil-based plastics can biodegrade.
Bioplastics are an essential part of the bio economy and a fast-growing, innovative industry that has the potential to decouple economic growth from resource depletion and environmental impact. Technological innovation has made it possible to create biopolymers, their industrial scalability, the prospect of the system that has allowed the mass production and therefore the diffusion of the circular material that intends to limit waste or eliminate it altogether, going to impact on the analysis of the material life cycle (LCA) (Pellizzari and Genovesi 2018).

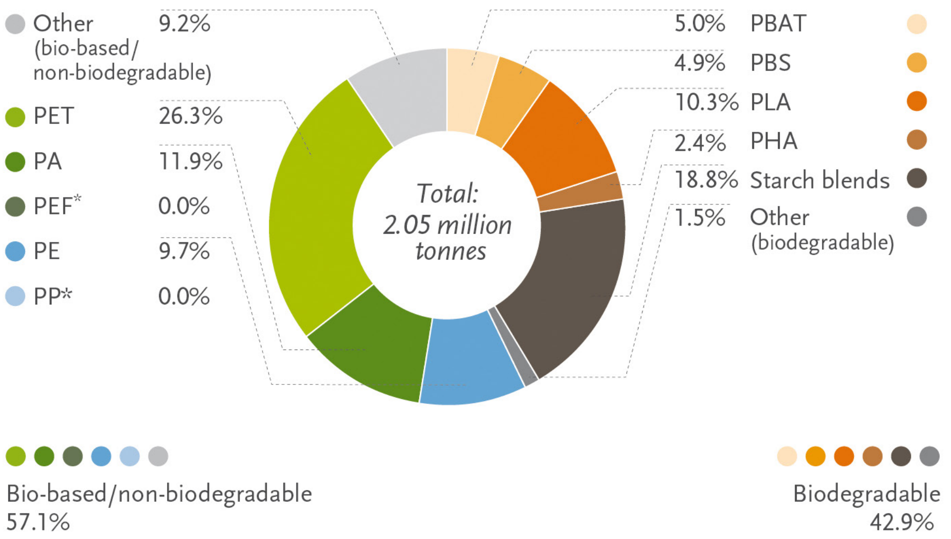
2.3.1 Global Bioplastic Production Overview

At the state of art, there is a bioplastic alternative for almost every conventional plastic material and corresponding application. Bioplastics – plastics that are biobased, biodegradable, or both – have the same properties as conventional plastics and offer additional advantages, such as a reduced carbon footprint or additional waste management options such as composting.
There are three main groups of bioplastics

Fig.2.4 European Bioplastic for the definition of bio-plastic

with different properties. The first ones are the biobased or partially biobased non-biodegradable plastics such as biobased PE, PP, or PET (so-called drop-ins) and biobased technical performance polymers such as PTT or TPC-ET; the second ones, and probably the most known and identified as bioplastic, are both biobased and biodegradable, such as PLA and PHA or PBS; the last ones are biodegradable plastics that are fossil-based, such as PBAT (https://www.european-bioplastics.org/bioplastics/materials/ - June2018).

With a growing number of materials, applications, and products, the number of manufacturers that converters and end-users also increases steadily. Significant financial investments have been made into production and marketing to guide and accompany this development. Bioplastics are used in an increasing number of markets, from packaging, catering products, consumer electronics, automotive, agriculture/horticulture and toys to textiles and several other segments. Packaging remains the largest field of application for bioplastics with almost 60 percent (1.2 million tons) of the total bioplastics market in 2017. Legal framework conditions provide



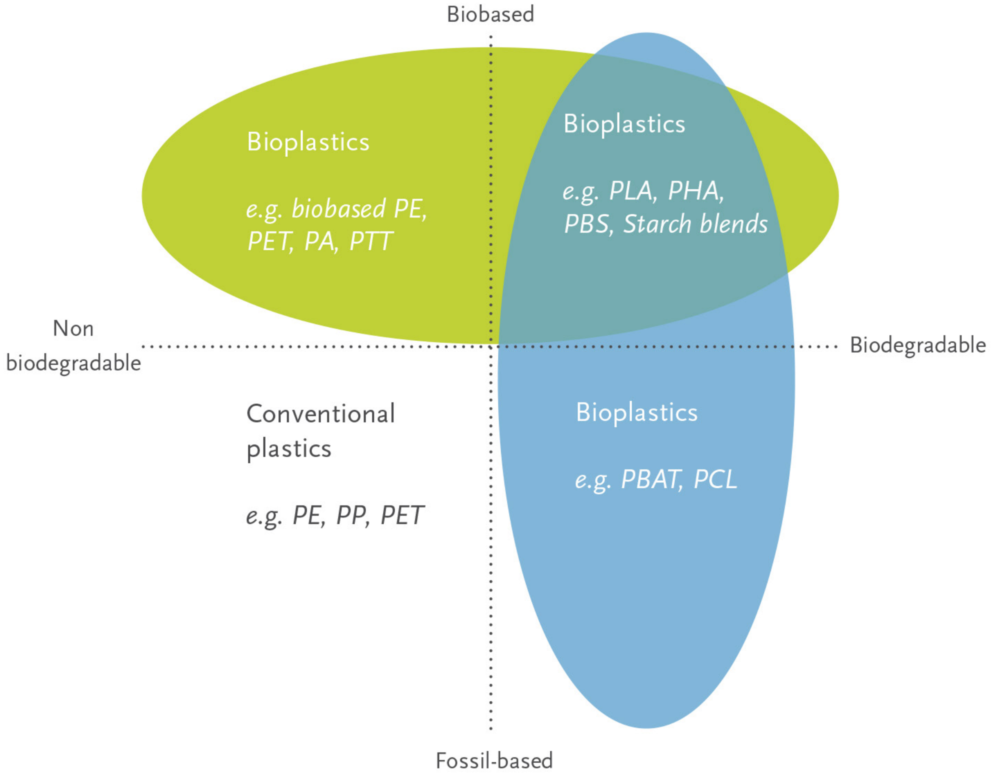
*Bio-based PP and PEF are currently in development and predicted to be available in commercial scale in 2020.

Source: European Bioplastics, nova-Institute (2017).
More information: **www.bio-based.eu/markets** and **www.european-bioplastics.org/market**

Fig.2.5 Global Production Capacities of Bioplastic 2017 (by material type)

incentives for the use of bioplastics in several countries worldwide, including some European Member States, providing stimulus to the market (European Bioplastics 2017).

The characteristics of many bioplastics allow their processing through normal production facilities. They are increasingly appreciated in agriculture by creating objects that do not have to be recovered and disposed of at the end of the crop cycle but are processed in the soil where they biodegrade (e.g. mulch sheets). As already



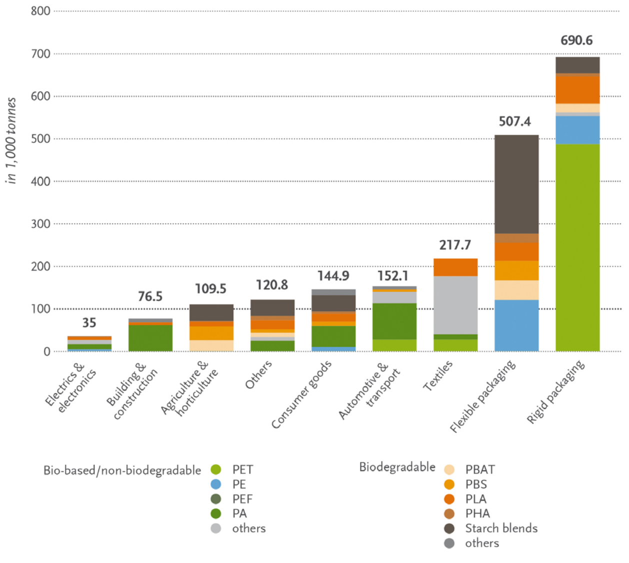
said, another important sector of bioplastics use is that of shoppers. In the Food segment, for example, Mater-bi still prevails offering a complete line for food service dishes glasses cutlery bowls single-portion container for finger food straws cups and ice-cream scoops lids for glasses (Pellizzari and Genovesi 2018).

Fig.2.6 Map of Bio-Plastic Materials

2.4 Biopolymer Research Trends

Regarding the development of these new materials, there are many research directions both at an academic and industrial level. These include various spheres of interest, from the enhancement in mechanical performance, the improvement of recycling cycles and / or increase in the speed with which the material degrades, up to themes with a more communicative character about transmitted values by the products made with biopolymers and their materiality itself. Among the studies related to the increase of the biopolymer's mechanical performances, there can be found those related to additives and modifiers. As commonly used in the plastics compounding industry, different additives and modifiers are generally blended with the virgin bioresin to obtain useful performance properties that are similar to those of conventional polymers. Some of the other benefits of using additives are to enhance melt strength or thermal stability of a biopolymer during processing. Other additives improve the performance, especially impact strength, heat resistance, flame resistance, gas barrier properties, and antifogging properties. Additives are also used to modify the appearance or to reduce the cost of the final product (Ashter and Ashter 2016).

Technical biopolymers are becoming increasingly attractive as both sustainable and good-performing polymeric materials. As far as the mechanical recyclability of the technical biopolymers concern, due to the fact that to date biopolymers have not been methodically integrated into the waste management system yet, was evaluated the effect of repeated polymer processing (extrusion without further compounding with virgin material or additives) on the materials structure and mechanical properties. It is important to note that mechanical recycling – in contrast to energy recovery, chemical recycling, and composting – allows for preserving the polymeric structure and the material value in terms of feedstock and polymerization energy. Consequently, mechanical recycling of biopolymers is crucial to ensure their sustainability in the long term. For this reason, the choice of the polymer mostly analyzed fell on biobased material, not necessarily biodegradable, with high biobased carbon content. Moreover, as mechanical recycling in an individual (single stream) recycling system is only feasible if the mass flow is high enough, biopolymers with an emergent production capacity were nominated. For example, the analyzed polymer in a study of the K. Resch et al. were polytrimethylene terephthalate (PTT), cellulose acetate butyrate (CAB), polybutylene succinate (PBS) and polyhydroxy alkanoate blend (PHBV/PBAT). The results showed that the performance characteristics differed strongly between the biopolymer types. To that effect, PTT and CAB exhibit a high potential for mechanical recycling. By taking advantage of appropriate additivation, the mechanical recyclability of PBS and PHBV/PBAT is also assumed to be high (Resch-Fauster et al. 2017).



Source: European Bioplastics, nova-Institute (2017). More information: **www.bio-based.eu/markets** and **www.european-bioplastics.org/market**

Fig.2.7 Global Production Capacities of Bioplastic 2017 (by market segment)

Other studies have been conducted on how the composition can affect the degradative behavior of a polymer blend and can differ from the degradation routes of the pure components since the interactions among different species in the blends during degradation, and among the degradation products, can occur. These reactions can lead either to an acceleration of the degradation rate or to a stabilizing effect in comparison with the pure components. Thus, the additive rule cannot be often applied in case of degradation of polymer blends and, therefore, it is difficult to predict the degradative behavior on the base of the properties of pure components (La Mantia et al. 2017).

Other important aspects are the studies relating to communication and perception of biopolymers. They are trying to find the right balance between the natural part from the bio-based concept and the high-quality expectations linked to the polymer-based technologies of most products. Published literature has explored the environmental performance and their suitability as an alternative for regular plastics. However, the user perception of these materials applied in consumer products has not been very explored yet.

Fig.2.8 Products made of Apinat™Bio a Biodegradable TPC compound

Fig.2.9 Products made of bioplastic with an high quality appearance

2.5 Biopolymers Classification

Bio-based Plastics, as man-made organic macromolecules, derive from biological resources and are used for non-edible purposes. Biopolymers are roughly divided into two sections: polymers with natural origin and polymers produced by chemical synthesis. Natural biopolymers are obtained from renewable resources, biomass like living organisms as structural components of tissues. These include mainly proteins and polysaccharides obtained from biomass by fractionation. Synthetic biopolymers classification emphasizes the fact, that plastics are more or less susceptible to active biological environment. They are divided in degradable and non-degradable biopolymers. The degradable families are polyesters, obtained, respectively by fermentation from biomass or from genetically modified plants (e.g. PHA, polyhydroxyalkanoate) and by synthesis from monomers obtained from biomass (e.g. PLA, polylactic acid). Those of them which are highly resistant to this activity are called non-degradable biopolymers. The most popular are: silicones, polyethylene (PE), polypropylene (PP), polyamide (PA), polyurethane (PU), polymethacrylates (PMA), polytetrafluoroethylene (PTFE), polycarbonates (PC), acrylic resins and polyvinyl chloride (PVC) (Ekiert, Mlyniec, and Uhl 2015; John and Thomas 2008). A very comprehensive overview of these materials is provided in the publication “Product overview and market projection of emerging bio-based plastics” written in 2009 by L. Shen, J. Haufe and M.K. Patel. The selection of listed biopolymers is due to the replacement of bulk petrochemical plastics by the bio-based ones, that can also be produced at large scale. Since the upscaling of production technology and the development of the market takes time, we include also materials which will first serve higher value applications but could be used for bulk applications from the medium to the long term.

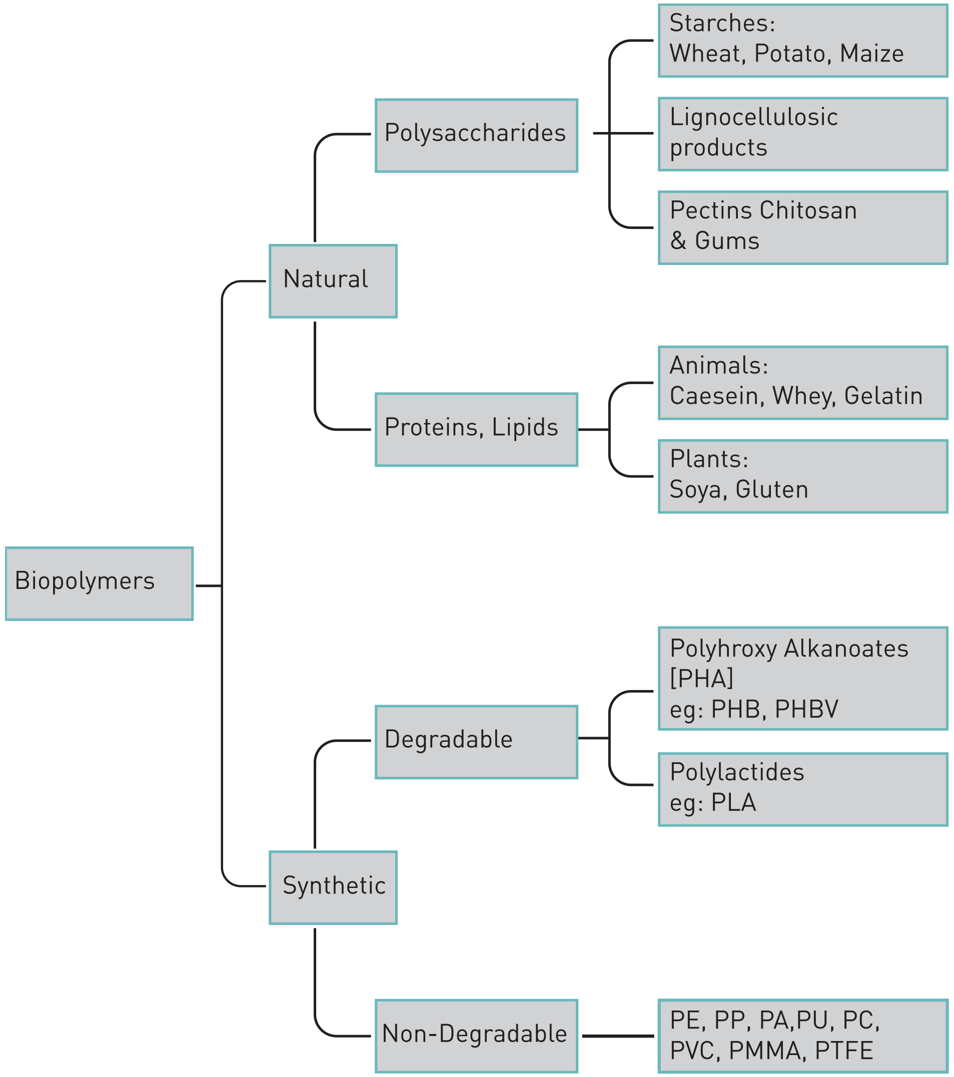


Fig.2.10 Classification of Biodegradable polymers

Fig.2.11 Corn and starch extract

Fig.2.12 Mater-bi plastic bag

Fig.2.13 Disposable TPS products

2.5.1 Thermoplastic Starch (TPS)

From biomass products

Starch is the major storage carbohydrate (polysaccharide) in plants. It is available in abundance surpassed only by cellulose as a naturally occurring organic compound. Starch plastics have been the frontrunners of the renaissance of bio-based polymers on the plastics market over the last 20 years. They have been used in packaging and short-lived consumer goods. This new class of materials has experienced very substantial growth and technology innovation.

Over years, starch plastics have been designed to potentially replace petrochemical plastics. Thermoplastic starch is biodegradable, combustible and can be fabricated into finished products such as mulch film and loose fills through existing technology. Because of the relatively low cost, polymers based on starch can be an attractive alternative to polymers based on petrochemicals. By blending with other co-polymers, a wide range of material grades with diverse properties (e.g. regarding rigidity versus flexibility) is obtained, allowing application in a broad scale of applications.

However, native starch by itself is unsuitable for most applications due to various disadvantages, with the most important ones being its brittleness and hydrophilicity. Moreover, the melting point of starch is higher than the thermal decomposition temperature, resulting in poor thermal processability. In order to overcome these disadvantages (at least partially) native starch is processed chemically, thermally and/or mechanically. To improve its characteristic starch blends are produced by processing destructurized starch (TPS), chemically modified starch or sometimes even native starch in combination with petrochemical, bio-based or inorganic compounds into a (microscopically) homogenous material. The starch content in a blend varies from 30% to 80% by mass depending on the end application.

The potential for starch plastics to substitute for other polymers, is seen to be greatest for the polyolefins, namely low-density polyethylene (LDPE), high density polyethylene (HDPE) and polypropylene (PP). Blends of thermoplastic starch with synthetic polymers come closest to achieving the mechanical properties of LDPE and HDPE, as well as polystyrene (PS) (Shen, Haufe, and Patel 2009).

Fig.2.14 TPS Mulch Film

2.5.2 Cellulose Acetate (CA)

From biomass products

Cellulose is one of the main cell wall constituents of all major plants and constitutes as such the major portion of all chemical cell components. Cellulose is found both in non-lignified plants (such as cotton), lignified plants (such as wood), in green algae and the membranes of most fungi. Chemically, cellulose is similar to starch and has a long history of use in plastic and non-plastic applications. In general, both application areas are in a mature stage and experience a moderate growth.

Cellulosic polymers are produced primarily from wood or agricultural wastes and sometimes also from short cotton fibres, called linters. Linters contain up to 95% pure cellulose together with small amounts of proteins, waxes, pectins, and inorganic impurities. In a relatively recent work, it was reported that the biodegradation of CA bioplastics from low cost fibre flax and cotton linters was 44 and 35%, respectively, after 14 days of composting (Mostafa et al. 2015). Cellulose acetate, being soluble in organic solvent such as acetone, is also suitable for spinning into fibres or forming into other shapes. the term “acetate fibre” is used to describe fibres made from cellulose acetate. The untreated cellulose acetate, cellulose butyrate and cellulose propionate, are crystal clear, tough, hard, scratch-resistant, insensitive to stress cracking, readily dyeable with brilliant colors, but are not permanently weather resistant (Shen, Haufe, and Patel 2009).

Cellulose polymers are produced by extraction or chemical modification of natural cellulose. There are three main groups of cellulosic polymers, I.e. Cellulose esters, that could be organic or inorganic, Cellulose ethers and Regenerated cellulose.
During 1920s and 1930s, intensive research was carried out on organic cellulose esters in order to replace cellulose nitrate (in those days used as lacquers, explosives) due to its flammability. Ultimately, a few processes were proven to be industrially useful and most of them are still used today. Important industrial products over the last 70 years have been cellulose acetates (CA), cellulose acetate propionate (CAP) and cellulose acetate butyrate (CAB). Today, about 20% (approx. 840 kt p.a.) of the global total chemical grade pulp is used to produce organic cellulose esters.

Rigid cellulose acetate plastics refers to thermoformed (injection moulding and extrusion) products made from cellulose esters with plasticizers, including acetate (CA), cellulose acetate propionate (CAP) and cellulose acetate butyrate (CAB). Cellulose acetates can be used to make consumer products ranging from screw driver handles, ink pen reservoirs, x-ray films to radios,

Fig.2.15 Glass frames in CA

telephones, toothbrushes and toys. Cellulose is known for its appealing haptic properties which are used by the producers of more expensive consumer products (with a nice "touch") and high-quality tools (due to their good "grip"). But given their relatively high price compared to petrochemical polymer replacements, rigid cellulose acetate plastics were relegated to comparatively low volumes.

In the fibre sector, regenerated cellulose and cellulose derivatives compete with conventional natural cellulose fibres (e.g. cotton) and synthetic fibres: Cellulosic can technically partially replace cotton, polyester, nylon, and polypropylene. In general, various types of fibres are blended in order to achieve desired properties (e.g. viscose fibres blended with PET).
For all the other sectors, cellulose acetate, cellulose acetate butyrate and cellulose acetate propinate are among the derivatives used to make a wide range of products including knobs, appliance housings, handles, toys and automotive parts (Shen, Haufe, and Patel 2009).

Fig.2.16 Example of food contact PLA

2.5.3 Poly Lactide Acid (PLA)

From biotechnology

The physical and mechanical properties of PLA make it a good candidate as replacement for petrochemical thermoplastics in several application areas. While the high price of PLA long restricted its use to medical and specialty applications, recent breakthroughs in lactide and polymerization technology opened up possibilities for the production of PLA in bulk volumes.

PLA was first synthesized over 150 years ago but due to economic and technological reasons, no immediate application was found, and it was not until the 1960s that its usefulness in medical applications became apparent. Efforts to develop PLA as a commodity plastic were first made in the late 1980s and early 1990s by Dupont, Coors Brewing (Chronopol) and Cargill than after a few years formed NatureWorks', one of the main players in the development and production of this polymer.

PLA has good mechanical properties, performing well compared to standard thermoplastics. The hardness, stiffness, impact strength and elasticity of PLA, important for applications such as beverage flasks, are similar to PET values. On the other hand, it has low impact strength, comparable to non-plasticized PVC. Like other bio-polymer, PLA has high odor and flavor barrier properties. It also has high resistance to grease and oil, thus finding application in the

packaging of viscous oily liquids. It is also suitable for dry-products packaging and short shelf-life products.

Blending of PLA with natural fibres such as flax and kenaf leads to interesting composite materials with high rigidity and heat resistance. Blends of PLA and natural fibres have increased durability and heat resistance and have a lower cost-to-weight ratio compared to unblended PLA. The development of nanotechnology offers new opportunities to improve PLA's properties. For example, the usage of PLA nanocomposite can improve the gas barrier of PLA films.

Studying the biodegradation of PLA under home composting conditions for eleven months, showed a very slow biodegradation. For this reason, mechanical recycling is seen as a favorable recycling method. For LCAs, cradle-to-gate and cradle-to-grave, for PLA bioplastics, using four different recycling methods, compared with the mechanical recycling process, the other methods like incineration, composting and anaerobic digestion processes, are clearly underperforming from the environmental point of view (Castro-aguirre et al. 2016).

The PLA potential is to partially replace LDPE, HDPE, PP, PA and PET as well as seeing possibilities to substitute also PMMA and PUR. No possibility is seen for substitution for PBT and POM. There was no clear consensus on the other polymers. Little or no substitution potential exists for PVC, PC and POM. PVC has already lost its importance in packaging, while it is still an important polymer for the building sector and electrical devices. POM has extreme abrasion resistance for moving parts. Compared to PS crystal clear, PLA is less transparent while elongation & breakage are comparable. HI-PS is very tough, so only impact-modified PLA could compete. PMMA has super clarity and transparency combined with good weatherability that are important features where in some applications PLA cannot match.

Since the first large-scale PLA production facility become reality in 2002, PLA has gradually gained market importance. Examples of major end products are extruded sheet for thermoformed products, biaxially oriented film, blow molded bottles, injection-molded products and fibres for apparel and nonwovens. PLA has been used for a wide range of application areas, such as packaging (cups, bottles, films, trays), textiles (shirts, furniture), nonwovens (diapers), electronics (mobile phone housing), agriculture (usually blended with TPS) and cutlery (Shen, Haufe, and Patel 2009).

2.5.4 Polyhydroxyalkanoates (PHAs)

From microorganism (PHA/PHB/PHBH/PHBV/PHx)

Polyhydroxyalkanoates (PHAs), constituting a class of bio-based polyesters with highly attractive qualities for thermo-processing applications, is on the edge of mass production. Like PLA, PHAs are aliphatic polyesters produced via fermentation of renewable feedstocks. Whereas PLA production is a two-stage process (fermentation to monomer followed by a conventional polymerization step), PHAs are produced directly via fermentation of carbon substrate within the microorganism.
Between 2000 and 2003, the first production plants of PHA (PHBV) were realized in Brazil and China both with a huge perspective of growth that started from a capacity of 50 t.p.a. that in a few years increased up to 2.000. In the meantime, the previous PHA frontrunner P&G sold its intellectual property of PHA to Meridian Inc. that announced in 2007 to build a production facility with an annual capacity of 270.000 tonnes underlining the growing interest regarding this category of bio-polymer.

Currently, the feedstock type varies greatly depending on the product grade desired and the microorganism used in the fermentation. PHAs can consist of chains of

Fig.2.17 Mylos Etik cover frame from ABB Relized with a technopolimer from Maip called "IamNature" [PHB]

identical components such as is the case with polyhydroxybutyrate (PHB), a polymer which consists of several hydroxybutyrate monomers. However, other types of PHAs can be polymerized from different monomers, resulting in material characteristics change. Thus, the PHA with the simplest structure, polyhydroxybutyrate, PHB, has similarities with the mass plastic polypropylene, but PHB has a considerably reduced tear strength (Bächtle 2009).
Polyhydroxyalkanoates (PHAs) have useful mechanical properties and excellent biodegradability. However, they are still expensive and polyhydroxybutyrate (PHB) in particular is quite brittle, so using them in polymer blends is a better option. To improve stiffness and strength, to enhance the barrier properties and increase the opacity, PHA base (co)polymer may be blended with inorganics such as $CaCO_3$, talc and mica. Bio-based polymers including thermoplastic starch, chitin and PLA may be added to control the rate of degradation and/or disintegration.

Fig.2.18 "Miss Sissi" biopolymer lamp produced by Flos designed by Philippe Starck

Fig.2.19 MINERV-PHA™ the "Miss Sissi" biopolymer produced by Bio-On

Today, the commercially available types of PHAs, can be used for injection moulding, extrusion and paper coating and can be converted to a range of finished products including films and sheets, molded articles, fibres, elastics, laminates and coated articles, nonwoven fabrics, synthetic paper products and foams.
The greatest potential for PHB copolymers lies with substituting for PVC, PE-HD, PE-LD and PP. To a lesser extent, substitution for PET, PBT, PUR and ABS could take place. Non-polymers, specifically wood and paper, could also be substituted in niche applications (Shen, Haufe, and Patel 2009).

Mirel™, a trade name for a PHA made by the Metabolix, can be used for the production of many everyday plastics products. According to the manufacturer, there are already numerous clients interested in using the bioplastic. The polymer chemistry seems to be in place, the plastic is suitable for the production of device casings, tins, dishes and other items used for packaging consumer goods. However, it remains to be seen whether the chemistry between the bioplastic and the consumers is also the right one. (www.metabolix.com/Products/Biobased-Chemicals/Chemical-Products/Bio-Based-Acrylic-Acid | www.tianan-enmat.com)

Fig.2.20 Mirel™ products made of PHA

2.5.5 Natural Fibres Compound (NFC)

In these last years, there has been a rapid growth in research and innovation in the Natural Fibres Composite (NFC) area. Interest is warranted due to the advantages of these materials compared to others, such as synthetic fibre composites, including low environmental impact and low cost and support their potential across a wide range of applications.

The advantages of the NFC are the low density and high specific strength and stiffness due to the fibres, a renewable resource, for which production requires little energy, involves CO_2 absorption whilst return oxygen to the environment. Economically they have a low cost of production and environmentally a low hazard of the manufacturing process and emission of toxic fumes. On the other hand, the disadvantages are in a lower durability, a greater variability of properties often due to a higher moisture absorption.

Fibre type is categorized based on its origin: plant, animal or mineral. All plant fibres contain cellulose as their major structural component, whereas animal fibres mainly consist of protein. Although mineral-based natural fibres exist within the asbestos group of minerals and were once used extensively in composites, these are now avoided due to associated health issues (carcinogenic through inhalation/ingestion) and are banned in many countries. Commonly, geography relating to fibre availability plays a major role in fibre selection, where often a much higher strengths and stiffnesses are obtainable with the higher performance plant fibres than the readily available animal ones.

Fig.2.21 Hemp Chair by Werner Asslinger produced by Leibal, it use hemp fiber reinforced with Acrodur® (BASF) acrilic resin

Among the factors that influence the properties of a composite material there are the fibers dispersion inside the matrix, where the better performances are obtained by a constancy of fibers dispersed in the matrix, and the interfacial bonding between matrix and fibers themselves which transfers the stresses inside the material. The best mechanical properties for composites are obtained when the fibre are aligned parallel to the direction of the applied load. Some alignment is achieved during injection moulding, dependent on matrix viscosity and mould design but, to get to higher degrees of fibre alignment, long natural fibre can be carded and placed, often manually, in sheets prior to matrix impregnation.

The most common methods used for NFCs are extrusion, injection moulding (IM) and compression moulding (CM). Resin transfer moulding (RTM) is also used with thermoset matrices and pultrusion has been successfully employed for combined flax /PP yarn composites and thermoset matrix composites. Due to the viscosity requirements, IM of such composites is generally limited to composites of less than 40% fibre content.

Fig.2.22 “Orange peel material” products

Over the last thirty years, their application increased, first in Europe encouraged by government legislation and then all of the main international manufactures, above all in the automotive sector have featured natural fibre-reinforced polymers in door panels, package trays, hat racks, instruments panels, internal engine covers, sun visors, boot liners, oil/air filters progressing to more structurally demanding components such as seat backs and exterior underfloor paneling. They have been used in many applications as toys, funeral articles, packaging, marine railings and cases for electronic devices such as laptops and mobile phones as a replacement for synthetic fibre (Pickering, Efendy, and Le 2016).

Wood Polymers Composite (WPC)

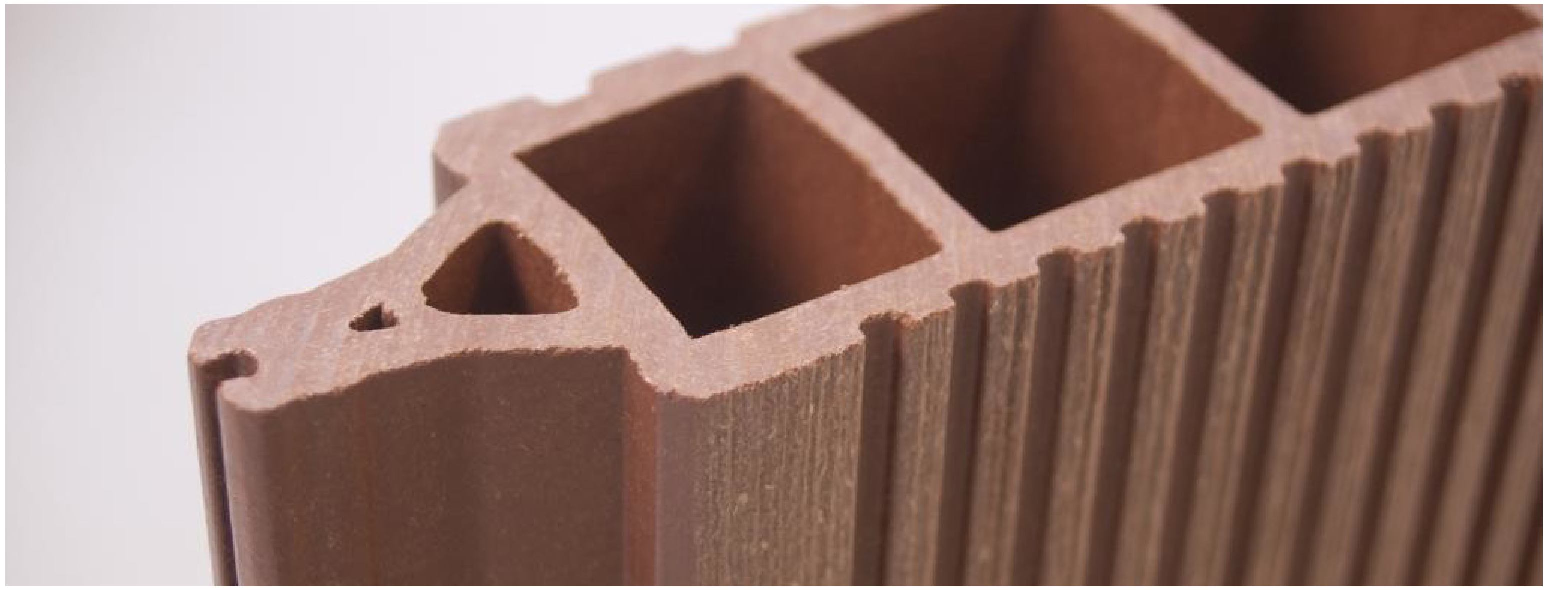
The most common NFC are the Wood-polymer composites (WPC). They are composite materials made of wood fiber/wood flour and thermoplastic(s) (includes PE, PP, PVC, PLA etc.). They are materials in which wood is impregnated with monomers that are then polymerized in the wood to tailor the material for special applications. The resulting properties of these materials, from lightness and enhanced mechanical properties to greater sustainability, has meant a growing number of applications in such areas as building, construction and automotive engineering (Clemons 2008).
In WPCs, a polymer matrix forms the continuous phase surrounding the wood component avoiding swelling corrosion degradation and rot. Polyethylene based WPCs are by far the most common. Additives such as colorants, coupling agents, UV stabilizers, blowing agents, foaming agents, and lubricants help tailor the end product to the target area of application (https://en.wikipedia.org/wiki/Wood-plastic_composite).
Like all the NFC, due to the addition of organic material, WPCs are usually processed at far lower temperatures than traditional plastics during extrusion and injection molding. WPCs tend to process at temperatures about 50 °F (28 °C) lower than the same, unfilled material, for instance. Most will begin to burn at temperatures around 400 °F (204 °C).
The key mechanical properties such as strength and stiffness of the composite materials lie between those for polymer and wood. The excellent moisture resistance of

on the right

Fig.2.23 NFC panels from NewTechWood

below

Fig.2.24 Arboform by TECNARO composed of lignin (ca. 30%) cellulose (ca. 60%) and fillers,p lasticizer, ecc.. (ca.10%)



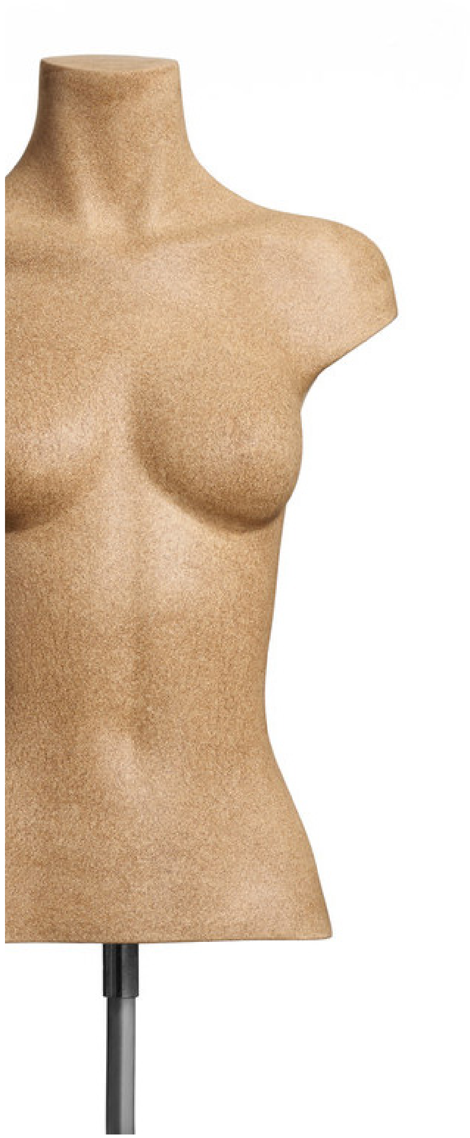


Fig.2.25 FluidSolids® product

polymers compared with wood directly relates to molecular structure of plastic material used, making WPC more durable and attractive. The development of a mechanically durable and maintenance-free WPC can help not only in the economic growth for both the wood and plastic-based industry but also ensures exciting new options for the end user (Sain and Pervaiz 2008).
Wood-Plastic Composites (WPCs) have demonstrated technical and price requirements to become new mass-produced materials, like thermoplastic recycled materials. Bound by durable biopolymers, a 100% natural material can emerge from today's WPC research. Its market chances mainly depend on political frameworks: packaging ordinance, end-of-life vehicle ordinance, and many other regulations, as well as the globally increasing CO_2 discussion must be mentioned as potential "catalysts"(Carus, Gahle, and Korte 2008).

IKEA Odger Chair

Reclaimed wood chips and recycled plastic were both used to create this IKEA chair, designed by Swedish studio Form Us With Love. It is made through injection moulding, using a mixture that is 70% polypropylene and 30% wood chips. The wood chips all come from reclaimed wood, while recycled plastic is favored over so-called "virgin" plastic. (https://www.dezeen.com/2017/11/13/ikea-form-us-with-love-odger-recycled-wood-plastic-sustainable-chair/ - September 2018)

Jelu Plast

The German company JELU has developed WPC bio-composites for industrial processing mainly based on PP, PE, TPS, PLA and other plastic. The new material made from thermoplastic starch (TPS) and wood fibres is a wood plastic composite (WPC), 100% renewable, that fulfils the European Standard for Compostability DIN EN 13432. It can be used for injection moulding and extrusion techniques and is suitable for conventional plastics processing machines. In its basic blend, the compound contains 50% TPS and 50% wood fibres. By means of additives, the characteristics can be varied and adjusted to individual applications. (https://www.jeluplast.com/en/ - September 2018)

Fig.2.26 JELUPLAST® Buttons.
They consist of PP and have a wood fibre content of 50%. They were manufactured using injection moulding.

Fig.2.27 JELUPLAST® cups.
The compostable cups are food-safe and used in catering. The WPC granulate from JELU consists of TPS and 50% wood fibres

2.6 Biopolymers End of Life

After having reported the main categories of biopolymers on the market, their characteristics and market trends, we want to investigate also the end of life of these materials. It is important to understand what are their disposal or recycling possibilities and the present problems that tend to make these virtuous and sustainable cycle complicated.
In fact, approximately 50% of plastics are used for single-use disposable applications, such as packaging, agricultural films and disposable consumer items, between 20 and 25% for long-term infrastructure such as pipes, cable coatings and structural materials, and the remainder for durable consumer applications with intermediate lifespan, such as in electronic goods, furniture, vehicles, etc. Even degradable plastics may persist for a considerable time depending on local environmental factors, as rates of degradation depend on physical factors, such as levels of ultraviolet light exposure, oxygen

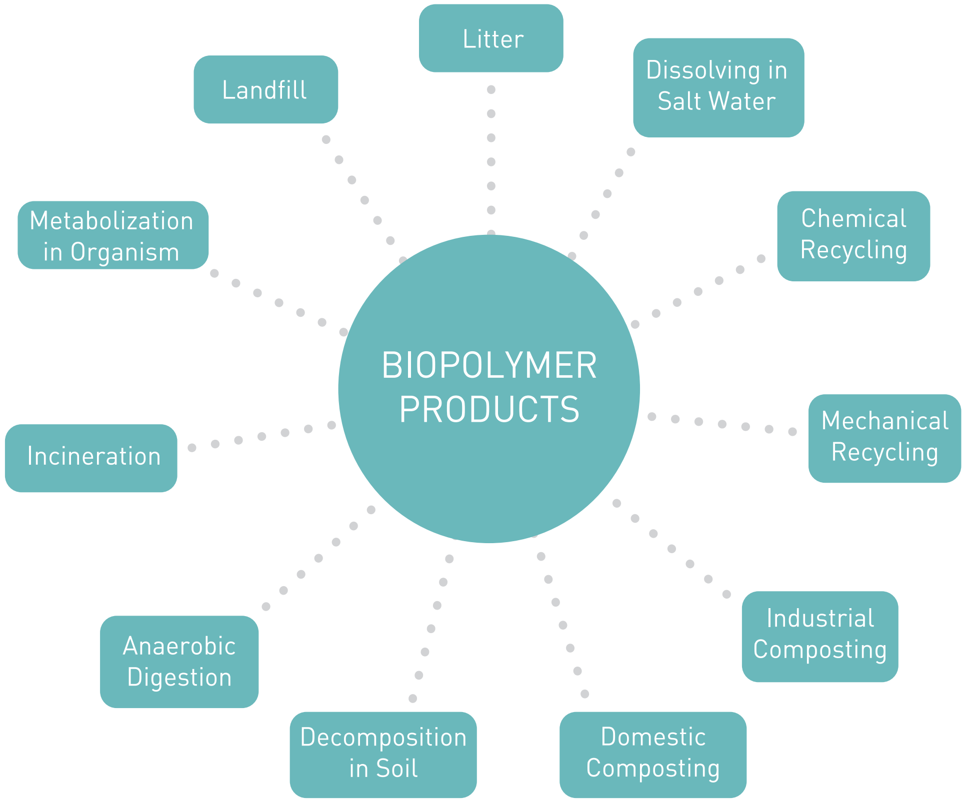


Fig.2.28 End of life options for biopolymer

and temperature. Fortunately the advances in technologies and systems for the collection, sorting and reprocessing of recyclable plastics are creating new opportunities for recycling, and with the combined actions of the public administrations, industry and governments it may be possible to deviate the majority of plastic waste from landfills to recycling over the next decades (Hopewell, Dvorak, and Kosior 2009).

2.6.1 Waste Management and Recovery Options for Bioplastics

Bioplastics are suitable for a broad range of end-of-life options, including reuse, mechanical recycling, organic recycling, and energy recovery. The overwhelming part of the bioplastics volume produced today can easily be recycled alongside their conventional counterparts where separate recycling streams for certain material types exist (e.g. biobased PE in the PE-stream or biobased PET in the PET-stream). This way, bioplastics contribute to higher recycling quotas in the EU and the implementation of the Circular Economy (https://www.european-bioplastics.org/bioplastics/waste-management/ - June 2018). One of the unique elements of compostable bioplastics is the end of life of the products. In fact, who decides the fate of the bioplastic, choosing whether to make it secondary raw material or not, is the consumer. A bioplastic object can end up both processed as plastic and in composting (Pellizzari and Genovesi 2018). Analysis results found that none of the bio-based plastics currently in commercial use or under development is fully sustainable. To maximize the effective use of 'green' plastics, it is important to prepare for their recycling through a suitable labelling system and initiatives to increase public awareness and education about different types of plastics (Soroudi and Jakubowicz 2013).

2.6.2 Recycling

Recycling refers to set of practices aimed at recovering useful materials from waste, in order to reuse them rather than dispose directly in landfills, thus preventing the waste of potentially useful materials.
Recycling is not a new concept. It has a history that dates back to the historic times, as early as 400 BC (and even earlier), people have been recycling. However, it has been affected predominantly by supply and demand, much as it is today. As for the history of recycling prior to the industrial revolution, recycling and general household

re-using was a commonplace practice. Before mass production flooded the market with loads of materials and products, it was generally cheaper to reuse items as opposed to buying new ones, and when materials did become worn beyond further use, recyclable ones (e.g. glass, aluminum) were recycled into new items. The history of recycling took a turn during the times of industrialization. As it became easier and cheaper to produce goods (through technological innovation and mass production), it also became easier and sometimes cheaper to throw used items away. In the 1940s and 1950s, when landfilling became a cheap way to dispose trash, recycling was less popular. The environmental movement had started since 1960s, and there was greater public awareness and rising environmental consciousness. It was in the 1970s that became more popular again and drop-off recycling centers were established.

From there, recycling once again became a mainstream idea. Due to public acceptance, the market for recycled goods increased from year to year. The success of recycling traces a wide public acceptance, bringing to improved economics of recycling that has enforced recycled content in many manufacturing processes (http://www.all-recycling-facts.com/history-of-recycling.html - June 2018).

Among recyclable products, plastic recycling has got to be the easiest and most important, since it doesn't degrade like organic materials. It is possible to find new uses for any existing plastic bags and containers or send these plastic products to a recycling plant to be remade into 'new' material. Plastic solid waste (PSW) presents challenges and opportunities to societies regardless of their sustainability awareness and technological advances. There are four recycling and recovery routes of plastic solid waste: primary (re-extrusion), secondary (mechanical), tertiary (chemical) and quaternary (energy recovery).

Primary recycling, which involves the re-introduction of clean scrap of single polymer to the extrusion cycle in order to produce products of the similar material, is commonly applied in the processing line itself but rarely applied among recyclers, as recycling materials rarely possess the required quality. On the other hand, the fourth route, the Energy recovery, implies burning waste to produce energy in the form of heat, steam and electricity. This is only considered a very sensible way of waste treatment, when material recovery processes fail due to economical constrains.

Plastic materials possess a very high calorific value (when burned); especially when considering that they are derived from crude oil. Since the heating value of plastics is high, they make a convenient energy source. Producing water and carbon-dioxide upon combustion make them similar to other petroleum-based fuels (Lettieri and Baeyens 2009).

Mechanical Recycling

Mechanical recycling, also known as secondary recycling, is still the most preferred and viable recycling method that provides an effective and easy way of reusing the material. The recycled polymers, however, are often contaminated, resulting in inferior mechanical properties to previous feedstock. Mechanical recycling is the process of recovering plastic solid waste (PSW) for the re-use in manufacturing plastic products via mechanical means (Lettieri and Baeyens 2009). It was promoted and commercialized all over the world back in the 1970s, but separation methods are still not efficient. An example is media density as the fundamental for separation and/or preconcentration in the recycling of plastics, but the current use of static media processes limits the capacity and size of material that can be treated commercially. To improve the commercial recovery of recyclable plastics, Gent et al. in 2009 reviewed cylindro-conical and cylindrical cyclone-type media separators (such as those used for processing coal) and suggested their use as a potential substitute (Soroudi and Jakubowicz 2013).

Mechanical recycling of PSW can only be performed on single-polymer plastic, e.g. PE, PP, PS, etc. The more complex and contaminated the waste, the more difficult it is to recycle it mechanically. Separation, washing and preparation of PSW are all essential to produce high quality, clear, clean and homogenous end-products. One of the main issues that face mechanical recyclers is the degradation and heterogeneity of PSW.

The quality is the main issue when dealing with mechanically recycled products. The industrial PSW generated in manufacturing, processing, and distribution of plastic products is well suited for the use as a raw

Fig.2.29 Shredded plastic bottle cup

material for mechanical recycling due to the clear separation of different types of resins. Mechanical recycling of PSW has also become an important issue in R&D, where numerous researchers have devoted their efforts too (Lettieri and Baeyens 2009).

Recycling PSW via mechanical means involves several treatments and preparation steps to be considered:

- **Cutting/shredding**: Large plastic parts are cut by shear or saw for further processing into chopped small flakes.
- **Contaminant separation**: Paper, dust and other forms of impurities are separated from plastic usually in a cyclone.
- **Floating**: Different types of plastic flakes are separated in a floating tank according to their density.
- **Milling**: Separate, single-polymer plastics are milled together. This step is usually taken as a first step with many recyclers around the world.
- **Washing and drying**: This step refers to the pre-washing stage (beginning of the washing line). The actual plastic washing process occurs afterwards if further treatment is required. Both washing stages are executed with water. Chemical washing is also employed in certain cases (mainly for glue removal from plastic), where caustic soda and surfactants are used.
- **Agglutination**: The product is gathered and collected either to be stored and sold later on after the addition of pigments and additives or sent for further processing.
- **Extrusion**: The plastic is extruded to strands and then pelletized to produce a single-polymer plastic.
- **Quenching**: Involves water-cooling the plastic by water to be granulated and sold as a final product.

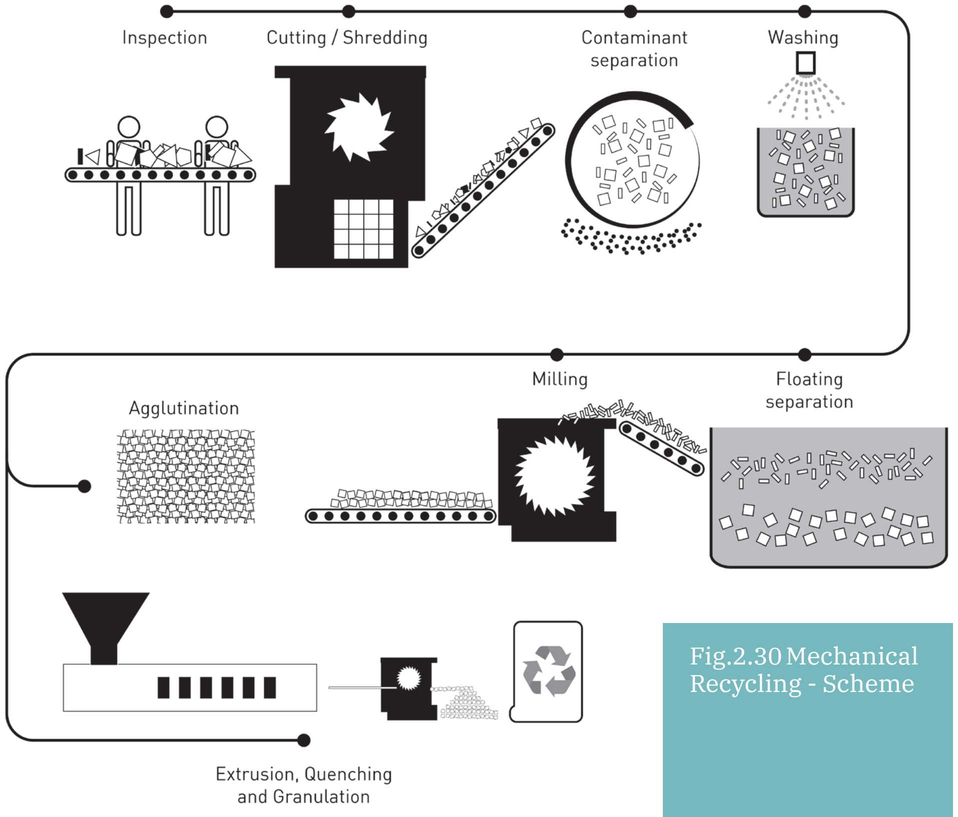


Fig.2.30 Mechanical Recycling - Scheme

Chemical Recycling

Chemical (tertiary) recycling is a term used to refer to advanced technology processes which convert plastic materials into smaller molecules, usually liquids or gases, which are suitable for use as a feedstock to produce new petrochemicals and plastics. The term chemical is used because an alteration is bound to occur to the chemical structure of the polymer. Products of chemical recycling have proven to be useful as fuel. The technology behind its success is the depolymerization processes, that can result in a very profitable and sustainable industrial scheme, providing a high product yield and minimum waste.

By their nature, several polymers are advantageous for such treatment. Polyethylene terephthalate (PET) and certain polyamides (nylon 6 and nylon 66) can be efficiently depolymerized. In particular, polyethylene (PE) has been targeted as a potential feedstock for fuel (gasoline) producing technologies (Lettieri and Baeyens 2009).

2.6.3 The Biodegradation of Polymers

The biodegradability of bioplastics can occur under different environmental conditions, such as soil, compost, marine and other aquatic environments. Generally, form the chemical point of view, polymers with a shorter chain, more amorphous part, and less complex formula are more susceptible to biodegradation by microorganisms. Another important factor to take into consideration regarding biodegradation is the environment in which the material to be degraded is inserted, in fact, soil environments contain a vast biodiversity of microorganisms, which enable the plastic biodegradation to be more feasible with respect to other environments, such as water or air. The biodegradation of polymers consists of three important steps: (1) Biodeterioration, which is the modification of mechanical, chemical, and physical properties of the polymer due to the microorganisms growth on or inside the surface of the polymers. (2) Bio fragmentation, which is the conversion of polymers to oligomers and monomers by the action of microorganisms and (3) Assimilation where microorganisms are supplied by necessary carbon, energy and nutrient sources from the fragmentation of polymers and convert carbon of plastic to CO_2, water and biomass. Generally, polymers with a shorter chain, more amorphous part, and less complex formula are more susceptible to biodegradation by microorganisms (Emadian, Onay, and Demirel 2017). The plastic wastes were found to be largely accumulated evenly in deep marine environment. Due to their semi-permanent stability in a marine ecosystem, the plastic wastes potentially result in marine pollution, which can have impacts on marine animals. In order to understand the biodegradation of bioplastics in marine habitats, the test methodology should include a lot of variables and different conditions like six different habitats (supralittoral, eulittoral, sublittoral benthic, deep sea benthic, pelagic and buried in the sediments). From these tests, for example, it was found out that the degradation in pelagic habitat was more efficient with respect to eutrophic habitat. Other variables of the marine habitat that impact on the biodegradation are the water temperature and the dynamic conditions and, in addition, different sea waters might play a substantial role in biodegradation, depending on the existing bioplastic-degrading microorganisms. Another parameter, which can alter the degree of biodegradation in marine water is the shape of the polymer. In fact, a larger polymer/water interface also facilitated the attachment of microorganisms to the surface of the polymer, condition observed also in tropical soil environments (Emadian, Onay, and Demirel 2017).

2.6.4 Composting

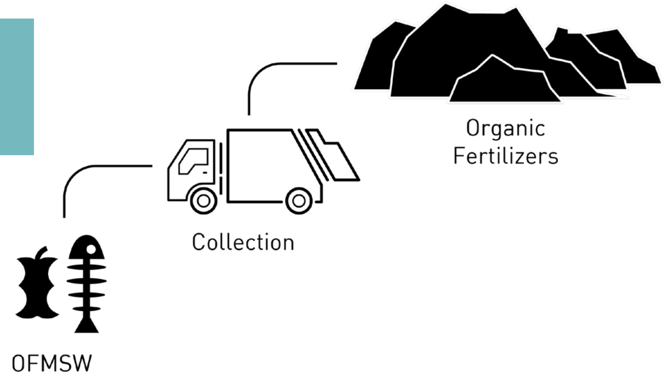
Composting is a process in which the organic matter is converted to CO_2 and a soil-like material (humus) by activity of a mixed group of microorganisms. In the aerobic process are usually distinguished three phases, the first one is the growth of bacteria that start the degradation of carbohydrates, lipids and proteins producing carbon dioxide and water, as well as causing a rapid rise in temperature.
In the next phase (called thermophilic or stabilization) temperatures exceed 50°C: in such an environment only, thermophilic bacteria resist, and the bio-oxidative phenomena are accelerated, during which ammonia is released and the pathogens are killed.
In the last phase (cooling or maturation), fungi and actinomycetes provide to the degradation of cellulose and lignin with the formation of the humus. At the same time the temperature and pH are lowered and the microbial activity decreases.
Environmental conditions such as medium pH, moisture and oxygen contents, and temperature play a significant role in the degree of the bioplastic's biodegradation. Furthermore, the addition of material with a high soluble sugar content, may enhance the bioplastic biodegradability. Soil environments contain a vast biodiversity of microorganisms, which enable the plastic biodegradation to be more feasible with respect to other environments, such as water or air (Emadian, Onay, and Demirel 2017).

Fig.2.31 Compost plastic bag

Aerobic Digestion Process

The first scenario sees the collection of the Organic Fraction of Municipal Solid Waste (OFMSW) and the disposal in landfills where an Aerobic Digestion takes place thanks to the action of a series of microorganisms operating in environments rich in oxygen that lead to the production of a family of compounds known as humus (humic acids and fulvic).

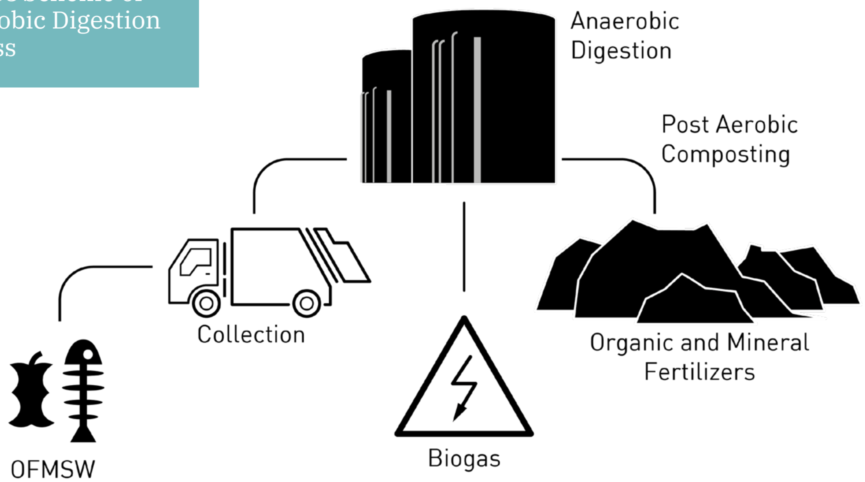
Fig.2.32 Scheme of Arobic Digestion process



Anaerobic Digestion Process

The second scenario, following the collection, involves the treatment of waste in a digestion plant. Here is an Anaerobic Digestion process that unlike composting takes place in the absence of oxygen and is able to produce biogas, or a mixture of methane and carbon dioxide that is then reused to produce thermoelectric energy. The solid part has an aerobic post-composting phase for the formation of organic and mineral fertilizers.

Fig.2.33 Scheme of Anaerobic Digestion process



Development of the Anaerobic Digestion Process - Towards the biorefinery

The third scenario involves the refining of biogas generated by the anaerobic process in biomethane. It is capable of making fuel for waste collection and transport in general, transforming what once were simply landfills into what today can be called biorefineries. Producing fuel from a non-fossil source, but rather, from waste matter, fully embraces the philosophy of Circular Economy.

Unfortunately, however, the quality of the wet fraction, taking as an example the analysis carried out on the Italian territory in 2015 by the CIC, presents a percentage of 4.8% of non-compostable material (MNC). This percentage, due to the presence of non-compostable plastic materials above all, involves 20% of waste for disposal. For the optimization of composting processes and the implementation of these recycling practices, it would therefore be appropriate to increase the quality of organic waste by making the compostability of packaging an essential requirement. This type of scenario, increasingly needs adequate collection systems with proper communication to the consumer.

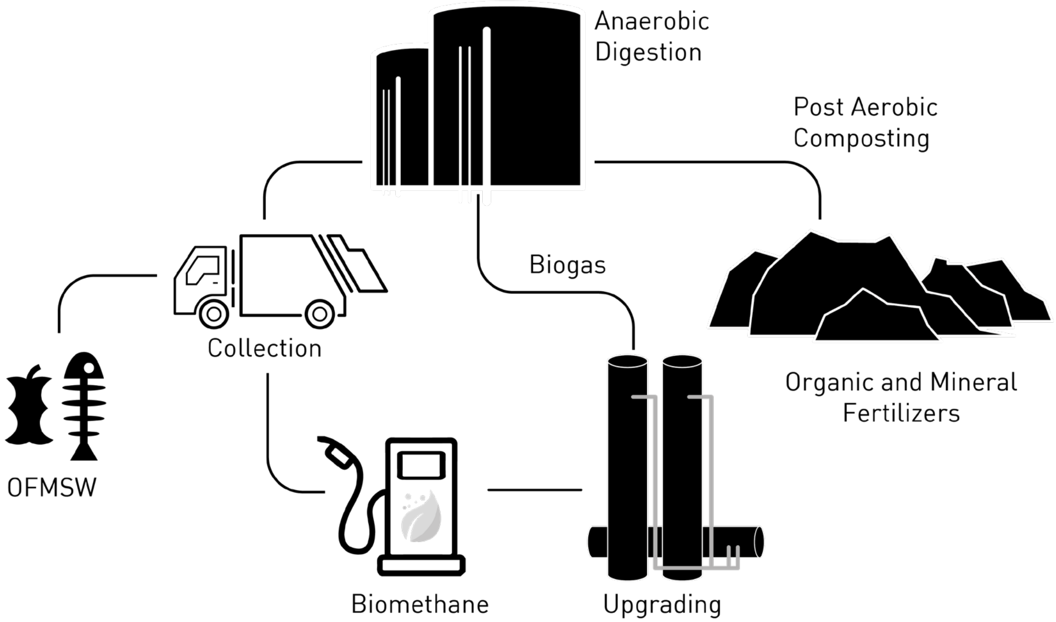


Fig.2.34 Scheme of Anaerobic Digestion process and biorefinery

2.7 The Impacts of Bioplastic in the Plastic Recycling Chain

It can be expected that biodegradable polymers (such as PLA, PBAT) may appear in the flow of petroleum-based polymeric waste. Their impact on recycling processes is not yet known; but the properties of products made with contaminated polymers are not easily predictable.

For this reason, to be recycled mechanically, the biopolymers must be completely fungible with the existing recycled resins or be available in sufficient quantity to reach the necessary critical mass. Adding new materials to the current mix requires to have working technology, satisfied customers, raw material, and investors. Rigid plastic container recycling focuses on high-density polyethylene (HDPE) and polyethylene terephthalate (PET) bottles, the overwhelming percentage of bottles sold in North America and Europe. Bottles of other resins, including polyvinyl chloride (PVC), polypropylene and biopolymers, lack critical mass necessary for independent reclamation.

To be mechanically recycled, biopolymers must be either completely fungible with existing recycled resins or be available in sufficient quantity to achieve the needed critical mass. Biopolymers, like all minor bottle resins, must pay their own way in sorting and processing without subsidy from PET and HDPE recycling. Based on limited data, some biopolymers may have little effect on recycled HDPE performance, but will represent a yields loss and added economic burden at some level of occurrence. In a first period, biopolymers have not been shown to be compatible with PET and likely will represent performance problems and economic burdens at even low levels of occurrence. Biopolymers applications should be carefully selected so as to not interfere with currently recycled materials unless critical mass can be achieved quickly (Cornell 2007)satisfied customers, raw material, and investors. Adding new materials to the current mix requires satisfying all four needs for those materials. Rigid plastic container recycling focuses on high-density polyethylene (HDPE.

An example can be found in the study of different polyethylene compounds mixed from regranulates polyethylene film waste and original polylactic acid (PLA) film for extrusion and injection moulding. The rheological properties of the regranulates and the mechanical properties of the samples changed significantly when PLA was added, the viscosity and specific volume of the mixtures decreased as the mechanical properties (tensile strength, modulus and impact strength). Young's modulus increased, while elongation at rupture and impact strength decreased increasing the weight fraction of PLA (Gere and Czigany 2018).
So far, the projections of the volume of biopolymers are not encouraging for the recycling chain, resulting in an increase in costs for their sorting and reworking, compared to the recycling of PET and HDPE. The introduction of 'green' plastics into the market has created a number of issues that need to be addressed. One important question concerns the potential risk of contamination of the collected conventional plastics (Soroudi and Jakubowicz 2013).

2.7.1 Consumer Education on Biopolymers

The concept of sustainable development offers a qualitatively new form of conscious and responsible life, both individual and social, on the basis of development together with the broadly understood environment and not only confined to the natural environment. In this sense, it appears as an educational concept – that is, the one that can change human thinking. Starting from this point, the Circular Economy should be one of the fundamental issues of contemporary education to give an instrument that leads to an ecological awareness for the improvement and optimization of common practices for the achievement of environmental sustainability.

In fact, throughout the product lifecycle, from product design, production, consumption, to waste management, a comprehensive approach to products and services can provide raw material efficiency. In practice, education for sustainable development means far more than just environmental education. According to UNESCO, education for sustainable development means education that enables the learner to acquire skills, knowledge and characteristic that ensure his/her sustainable development, that's equally accessible at all levels and in all social context and that using a variety of educational methods is based on the principle of lifelong learning concerns local and not just global issues (Kluczkowski and Wyrostkiewicz 2018)

A few groups are working on developing a set of competences that should be central to sustainability education. The United Nations Economic Commission for Europe (UNECE), Strategy for Education for Sustainable Development, for instance, published a report entitled 'Learning for the Future' which details competences that should be seen as a “goal to which all educators should aspire” providing a framework for their professional development.

Another example is the ThreeC project (http://www.threec.eu/) that has identified 10 competences that are important in a circular economy. This European project has the goal to develop a framework for education where circular economics is the fundamental idea. The competences are divided into three dimensions: the **cognitive dimension**, which details how we should change our thought processes; the **affective dimension**, or the attitude we have towards our work; and the **active dimension**, which handles our approach to our work. (https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/is-rol-onderwijs/ - June 2018)

2.7.2 Information on Biopolymers Recycling or Disposal

As bioplastics are not one type of material but a whole family of different kinds, they can be treated in various recycling and recovery streams and offer even more options, such as industrial composting. From the complexity of the topic arises therefore a huge number of possibilities, which translates into great confusion in the communication level of what are the materials’ values and properties. This produce vague or general claims that often produce misunderstanding in the disposal phase or misleading products. When it comes to biobased and potentially biodegradable or potentially compostable polymers, such as PLA, there is an even greater need for a clear end-of-life claim. Depending on the application, composting or recycling might be suitable solutions. The property of biodegradability does not constitute a permit to litter. This property only enables additional means of correct disposal possible for certain materials and products, so a clear message should be communicated to consumers who often misunderstand these properties. A clear end-of-life recommendation on a product is therefore important.

Claims such as “environmentally friendly” are non-specific When it comes to the product level (for manufacturers of bioplastics resins count as products), claims should be more clearly determined. Empty, generalized claims, standing in isolation and without any specification, e.g. “this product is sustainable”, can easily be challenged by consumer protection institutions or NGOs and legally disputed. Claims of biodegradability and compostability are widely used in the bioplastic industry. Biodegradability as a sole claim without a standard specification is misleading, if a material or product is advertised as biodegradable, further information on the timeframe, the level of biodegradation, and the surrounding conditions should be provided (European bioplastic 2012).

“The European Commission considers that the use of clear, truthful and relevant environmental claims should be promoted as a means of facilitating informed decision-making by consumers, to encourage the provisions of goods and services with lower environmental impacts, and to protect honest claimants against unfair competition by ruling out false, unclear and misleading claims”(European Commission 2000).

It is for this reason that, in order to be suitable for recycling, products and materials need to meet the strict criteria of the European norm. The main category of objects that are sensitive by nature to the issue of disposal and recycling are packaging. The criteria indicated in the regulations related to packaging can also be a guide for the design, use and disposal of generic goods.
For the requirements of a recoverable packaging by material recycling the norm EN 13430 indicates the requirements of a pack, or product, to be considered recoverable with the purpose to save resources and minimize waste. It gives indications about all the aspects about design and manufacture, including construction, composition and combination of materials; and use and post-use collection and sorting with the declaration of the recyclable percentage of materials and guidelines to enhance the separability of components and the compatibility with the recycle streams.

As far as the recoverable through composting and biodegradation packaging concern, the EN 13432 is the norm on industrial compostability that gives the evaluation criteria about the acceptance for these processes that includes aerobic composting and anaerobic bio-gasification. The compostability of products, especially those related to packaging, is an essential requirement for their acceptance of composting plants for the recycling of organic waste.

Following successful certification, these products and materials are permitted to be advertised and labelled as ‘compostable’. The Seedling label is a well-known mark for products conforming to EN 13432 (https://www.european-bioplastics.org/bioplastics/waste-management/composting/). The international organization for standardization (ISO) issued the iso 14020 series on “Environmental labels and declaration” in 1999. This series is the main international guideline for relevant "green claims" publications. The standard promotes three different types of environmental labels and declarations:

- Type i environmental labelling (14024),
- Type ii self-declared environmental claims (14021),
- Type iii environmental declaration (14025).

Thanks to observance of these regulations and the communication effectiveness, according to data provided by the CIC (Italian Composting Consortium), 6,516,000 tons of organic waste were composted in 2016 (107.6kg/abs) with a forecast of up to 140 kg/ab/year to 2025. The quality of organic waste is a priority for the organic waste recycling optimization: the presence of non-compostable materials involves significant energy and environmental costs for its removal. Fortunately, the bioplastic products are in large part represented by bags for waste collection and shoppers; and the presence of paper in organic waste is compatible with recycling processes. The processes of recycling paper remain the privileged paths, but we can identify criteria to discriminate within the different categories of packaging products more or less compatible with the organic waste chain (Confalonieri 2018).

It can therefore be said that the development of bioplastics is certainly a strong sign that indicates the willingness to move towards a sustainable exploitation of resources and an environmental impact reduction. The ideas and points to be developed, for these new biological materials, are still many even if their presence is becoming more and more important in the products of common use. Fortunately, there are other types of sustainable materials, which derive from renewable sources and with a consolidated recycling cycle, from which the new world of biopolymers can be inspired, that are the cellulosic materials such as paper and cardboard.

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List of figures

3

Paper & Cardboard

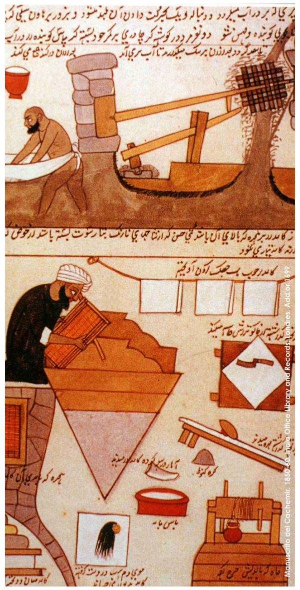
3.1 Paper-based materials in the Circular Economy

Paper is a natural fit for the circular economy model. Paper-based materials are becoming the go-to replacement as companies look for more sustainable ways to produce their products. Paper, and paper-based products, are an illustration of large-scale use of renewables feedstock. For these materials, there are already collection systems and recycling technologies where products made from recycled cellulose fibres have a market and an economic value. Moreover, the raw material for paper is continuously replenished using sustainable forest management also providing as a form of carbon sequestration (Harris et al. 2018).

Like many major manufacturing operations, it is an energy-intensive endeavour. However, for example, roughly two-thirds of the energy used by North American pulp and paper mills is self-generated using renewable, carbon-neutral biomass in combined heat and power (CHP) systems. In fact, the forest products industry produces and uses more renewable energy than any other industrial sector (Two Sides 2018).

Fig.3.1 Common used paper

Fig.3.2 Ancinet Papermaking



Paper is the basic material used for written communication and the dissemination of information. In addition, paper and paperboard provide materials for hundreds of other uses, such as wrapping, packaging, towelling and insulating (https://www.britannica.com/technology/papermaking). Moreover, thanks to its characteristics, paper and cardboard in their various shapes are also used in design and architecture for the creation of products, furnishings and structures often provocative or evocative.

3.1.1 History

Papermaking is the formation of a matted or felted sheet, usually of cellulose fibres, from water suspension on a wire screen. The history of paper dates back almost 2,000 years to when inventors in China first crafted cloth sheets to record their drawings and writings. The main theory indicates as the first creator a Chinese gentleman named T'sai Lun around 105AD, inspired by bees weaving fibers together, which caused him to experiment on his own mixing mulberry bark, hemp and rags with water, mashed it into pulp, pressed out the liquid, and hung the

thin mat to dry in the sun. In the 8th Century, Arabs recognized the value of paper. The major contribution by the Arab world was the first truly industrial paper mill. This facility was capable of producing consistent sheets that were thicker than those produced before it and improved also the consistency of the writing surface with a combination of starch and other additives that allowed ink sit on top of paper fibers, rather than penetrate the paper (https://www.casey-connect.com/blog/whats-the-history-of-paper). By the 13th century, the knowledge and use of paper had traveled to Europe and in 1680, it got its first major upgrade in nearly 500 years. the Dutch invented the *Hollander Beater*, a mechanized way to extract good fibers in an efficient way. It allowed new “virgin” fibers to be included in the paper making process. In 1774 the bleaching characteristics of chlorine was discovered and German jurist Justus Claproth invented paper recycling. Extracting fibers from existing paper was not a problem but removing ink (or “de-inking”) paper that had been previously printed. Around 1845 it became possible to use fibres from wood. The German Friedrich Gottlob developed a process to free the fibres out of wood with a grinding wheel. The development of alternative raw material sources was strengthened by the short supply of rags and at the same time increased demand for paper. Around 1985 a further important development was made in the bleaching technology for fibres. First the bleaching with chlorine was replaced with bleaching with chlorates and chlorine dioxide (Elementary Chlorine Free = ECF) and after that the development of bleaching process without use of chlorine containing agents, like ozone, oxygen and peroxide (Totally Chlorine Free = TCF) (https://en.wikibooks.org/wiki/Papermaking/History_of_paper).
Today, paper is made from trees mostly grown on working forests and from recovered paper. Recycling has always been a part of papermaking. When you recycle your used paper, paper mills will use it to make new newspapers, notebook paper, paper grocery bags, corrugated boxes, envelopes, magazines, cartons, and other paper products (https://www.paperrecycles.org/about/the-history-of-paper).

3.1.2 Characteristic

Used in a wide variety of forms, paper and paperboard are characterized by a wide range of properties regarding mainly mechanical performance and the optical appearance. The characteristic strengths of the paper are above all in terms of weight, cost and availability. Paper is in fact a light and economical material, easily cuttable, foldable and printable, available in a large range of colors, with different coating or it can be translucent.
The fundamental property of paper and paperboard products is the weight or substance per unit area, called Basis Weight determined bringing a sample, constituted of at least ten sheets with a total area of 600cm· to equilibrium in standard condition (24°C).
The paper strength is determined by the combination of many factors. First of all there is the strength of the individual fibres of the stock, then the average length of the fibre, the interfibre bonding ability of the fibre, which is enhanced by the beating and refining action, and in the end the structure and formation of the sheet. The paper resistance to rupture, when subjected to various stresses, is an important property in practically all grades of paper. It is important not only to satisfy the minimum requirement of the product in use, but also it must be strong enough to permit efficient handling in manufacture. Tensile strength is the greatest longitudinal stress a piece of paper can bear without tearing apart. The stress is expressed as the force per unit width of a test specimen (https://www.britannica.com/technology/papermaking/Paper-properties-and-uses).
The paper recycling is easy and widespread, in fact more than twice as much paper is recycled than is sent to landfills, and since 2009 the paper recovery for recycling has reached or exceeded 63% saving more than 3.3 cubic yards of landfill space for every ton of paper recycled (https://www.paperrecycles.org/about/fun-facts).

3.1.3 Paper Products

The paper is a global commodity that, depending on its characteristic, is used for many purposes. It is mainly used for storing information (books, magazines and newspaper), to representing value (paper money, bank note), for personal use or communications (diary, note, scratch paper). Other typical uses are packaging (corrugated box, paper bags) and cleaning (toilet paper, paper towels). Most of these uses, due to the versatility and low cost of paper materials, provide products that have mainly a short life term and that often are disposable. From the end of the twentieth century the use of paper and cardboard began to play an interesting role also as material for medium and long-term life products. The advantage of ease in processing and low cost, allowed the creation of products that meet multiple design requirements. One of the forerunners of the use of paper and cardboard was Frank Gehry who since 1972 wanted to experience the potential of an economic and versatile material to be proposed for furniture in order to realize the Volkswagen of furniture, a true democracy of design with cardboard protagonist. This material use is present in many types of products. The most explored category is certainly that of interior furnishings or temporary set up, that give a transitory character of the objects; not only bookcases and tables made by gluing many layers or the crossing of sections so as to assume a striking three-dimensionality, but also thanks to the sensorial aesthetic properties of translucency of the paper also lamps, jewels or works of art. Among the most particular uses we can find those for “outdoor objects”, often supports that have the purpose of incorporating themselves with nature and architectural experiments that want to relate ecology and nature, and the study of means of transport that end the structural use of cardboard.

3.2 Paper Made Products

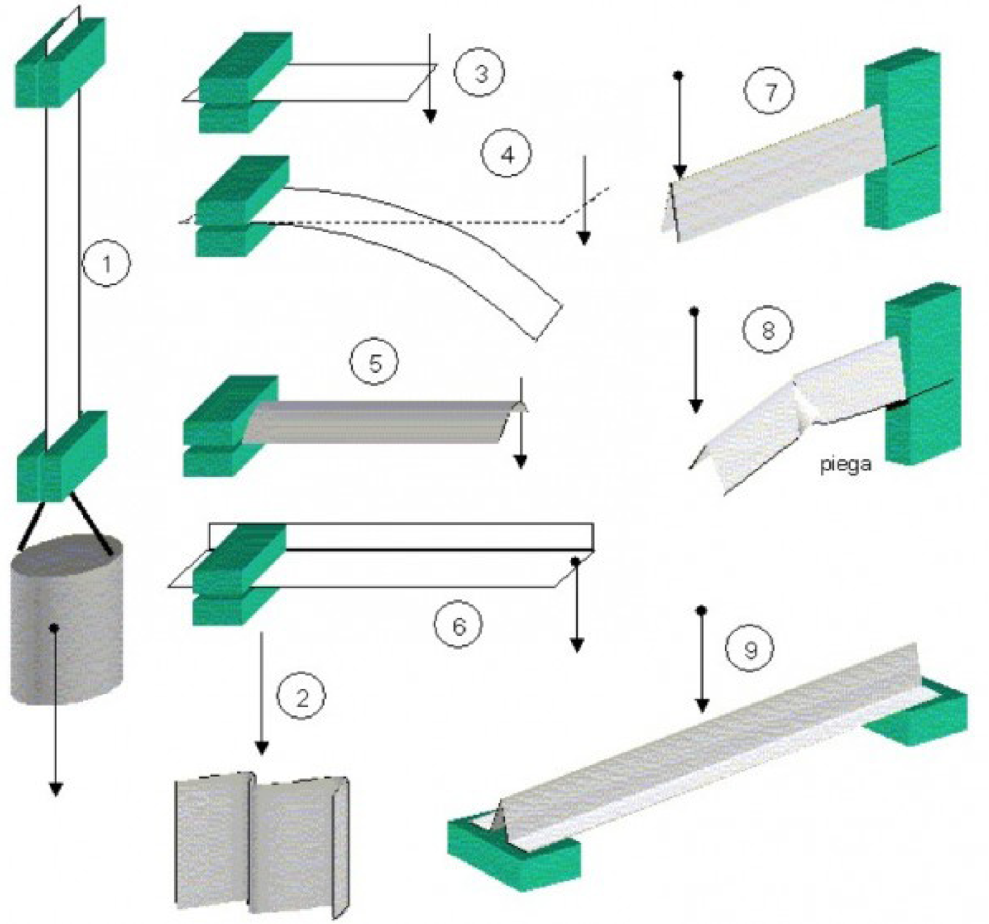
3.2.1 Paper

Fig.3.3 Paper sheets

A homogeneous sheet consisting of fibrous particles almost always of a vegetal nature (cellulosic fibers) of a maximum length of a few millimeters, which are intertwined together and held together by interfibre bonds to form a fibrous context. It is obtained by discharging an aqueous suspension of the fibers, through the meshes of a cloth and then drying the thin layer of material thus obtained. The paper is manufactured from fibrous materials, whose nature determines its basic characteristics with the addition of mineral powder, glues, dyes and various additives. It is distinguished from the cardboard mainly by the weight that is expressed in grams per square meter. The actual paper has a weight of up to 150 g/m^2, usually with a thickness of 0,1mm. Products between 150 and 250 g/m^2 can belong to both paper and cardboard, while those between 400 and 600 g/m^2 are among the cardboards and cartons (http://www.comieco.org/glossario/).

As for the mechanical characteristics, the paper has an excellent tensile strength (1), with a tensile strength range between 23 and 51 MPa, until the stressed surface is twisted or deformed. Shear load (2) still shows good resistance, provided that its fibers remain parallel to the load force. Bending load (3 and 4) the paper does not show great properties, but if the overhang is short and the discrete surface (short sample (2 - 3 cm) and quite wide (1 - 2 cm)), then the resistance can be sufficient for this purpose. For strips with a length to width ratio greater than 5 or 6, the bending strength is almost zero and does not even support the weight of the sample. Over 10 cm overhangs do not even support considerable widths. However, if the surface is only slightly curved (5) in the transverse direction and kept curved, the resistance grows very quickly. The same strengthening effect is obtained with a transverse "L" shape (6) where the vertical wall introduces the necessary resistance. The drawing (7) shows a strip with a "V" section loaded with a rib. The resistance increases a lot, but only if the section is kept at constant aperture. As shown in the drawing (8), in this case the section tends to widen to the unconstrained end and this causes a bend on the sides which destroys its resistance and the strip yields under a rather modest load. One method to counteract this failure is (9) that of providing the edges of the strip of fin as perpendicular to the side surfaces of the "V" as possible, which in turn will have to be rather narrow. In this way a good resistance is obtained. About folds, it can be said that the net ones

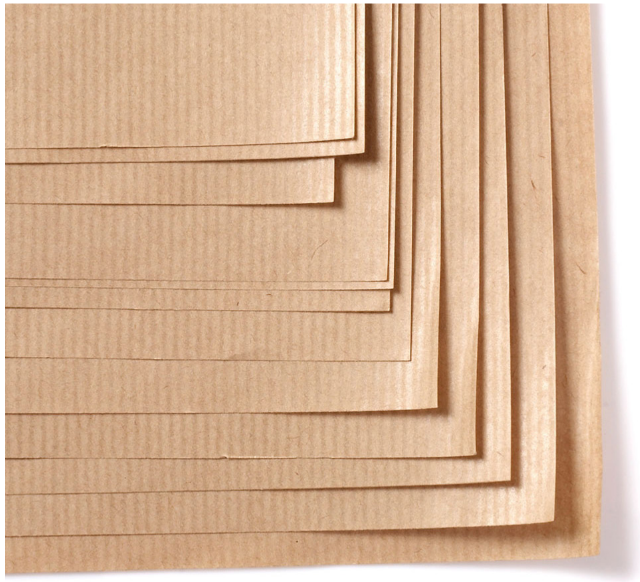
Fig.3.4 Mechanical paper behaviours



help to keep the parallel paper fibers when the load is cutting on the edge of a face and parallel to the folds, while destroying the resistance in an oblique or perpendicular direction, for direct loads on the face. The irregular folds or filming are always weak and almost always harmful (http://educazionetecnica.dantect.it/2013/07/10/la-carta/).

Kraft paper

Kraft paper is a particular kind of paper board with high elasticity and high tear resistance (in German "Kraft" means force), designed for packaging products with high demands for strength and durability. Kraft pulp is darker than other wood pulps, but it can be bleached to make very white pulp. Fully bleached Kraft pulp is used to make high quality paper where strength, whiteness, and resistance to yellowing are important. Normal Kraft paper is strong and relatively coarse with a grammage that is normally 40–135 g/m². (https://en.wikipedia.org/wiki/Kraft_paper).



Cabbage chair

Nendo designed the cabbage chair for 21st Century Man exhibition in Tokyo, to make furniture out of the pleated paper that is produced in mass amounts during the process of making pleated fabric, and usually abandoned as an unwanted by-product. The solution was to transform a roll of pleated paper into a small chair that appears naturally as you peel away its outside layers, one layer at a time. Resins added during the original paper production process adds strength and the ability to remember forms. The chair has no internal structure. It is not finished, and it is assembled without nails or screws. This primitive design responds gently to fabrication and distribution costs and environmental concerns (http://www.nendo.jp/en/works/cabbage-chair-2/).

Author: Nendo
Year: from 2008

Fig.3.5 Kraft paper

Fig.3.6 Cabbage chair - Nendo

3.2.2 Paper board

Paper board is a general term that is descriptive of products which are 0.30 millimetre or more in thickness, made of fibrous materials on paper machines. A heavy weight, thick, rigid and single or multi-layer sheet. What differentiates paperboard from paper is the weight of the sheet (Sekulic 2013). Paper heavier than 150 g/m^2 meter are normally called Paperboard, commonly made from wood pulp, straw, wastepaper, or a combination of these materials. There are three main types of paperboard: (1) boxboards, used for such products as food board, food trays, plates, and paper boxes, (2) container boards, for the manufacture of corrugated and solid fibre shipping containers, and (3) paperboard specialties, including such items as binders board, electrical pressboard, and building boards.

Fig.3.7 Paperboard finishings

Fig.3.8 Eco Amp

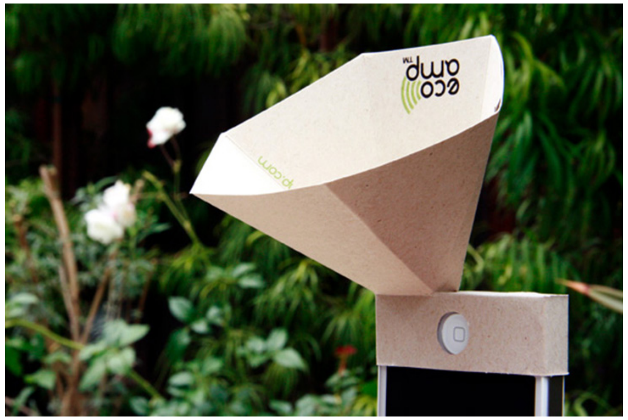
Fig.3.9 Airplane toy

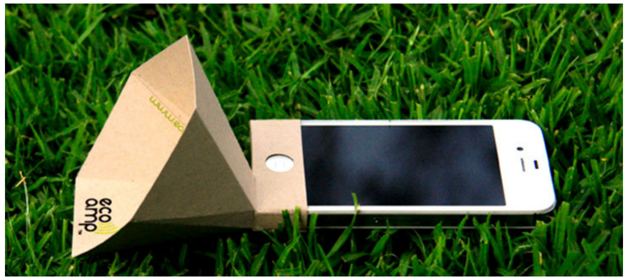
Fig.3.10 Paperboard jewelery

Fig.3.11 Paperboard lamps

Cardboard jewellery

Contemporary jewelry Sandra Di Giacinto, light, durable and sophisticated, using bookbinding materials, canvas panels, metallic or coated with PVC, or recycled cardboard and resin materials for technical and reinterpret traditional Italian contemporary aesthetics, where design configures as an element of innovation (www.sandradigiacinto.it).
Author: Sandra Di Giacinto
Year: from 2008



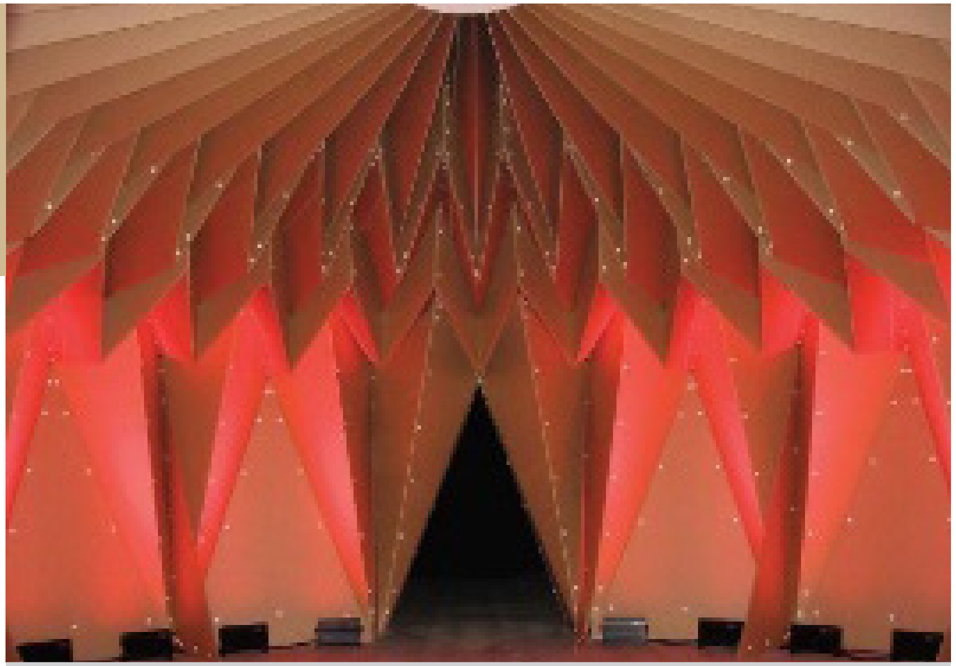


3.2.3 Carton board

Carton board is a paper product with a weight exceeding 600 g/m^2 although the weight can drop to around 450 g/m^2. It can reach 1100 g/m^2. The cartons are always manufactured in several layers, usually coupled to wet, sometimes glued with adhesives (casein, starch, animal glue, etc.) manufactured simultaneously on a multilayer paperboard machine. In some types the different layers have the same fibrous composition, while in others the outer layer - which takes the name of the cover - has a more precious composition that improves the surface qualities, such as degree of whiteness, color, cleanliness, absorbency, printability. Cardboard may be coated with polymers to achieve a material that can be used in ovens, microwaves, and other demanding conditions, or it may be laminated with metal films to enhance appearance and protect the content (http://www.comieco.org/glossario/).

Fig.3.12 Packaged
Miwa Takabayasy

Fig.3.13 Caronboard
disposable bag



Packaged

Packaged is a large scale folded architectural installation, developed through a series of model in collaboration with a cardboard packaging factory, that embodies traditional Japanese paper folding but also underline the modern mass market incarnation and contemporary industrial packaging techniques. The cardboard pieces were cut by a machine and connected by hand with plastic ties. The final form measured six meters in diameter and create a habitable space. Packaged was designed specifically for display within a shopping environment and functioned as a refuge from the simulated scenarios of the consumer world (Yabuka 2010).

Author: Miwa Takabayasy
Year: 2008

3.2.4 Chipboard

A paperboard, thicker than cardboard, used for backing sheets on padded writing paper, partitions within boxes, shoeboxes, etc. An inexpensive and thick one-ply cardboard usually produced from waste paper. It is used for packaging purposes as well as a backing board for notepads etc.(Sekulic 2013). Multilayer chipboard can also be used to manufacture spiral wound paper tubes that are used as a structural element in cardboard architectures due to the good resistance to both tensile and compressive stresses (Schönwälder 2016).

Fig.3.14 Public Farm - Work Architecure Company

Public Farm

Public Farm 1 was designed by professors at Princeton University to focus on the relationship between ecology and urban planning to demonstrate the possibilities of rural engagement in Urban environments and proposed that Cities could function as more integrated System (Yabuka 2010). *PF1's intent is to educate thousands of visitors on sustainable urban farming through the unique medium of contemporary architecture. It is a sustainable construction together with sustainable agriculture, PF1 has been built entirely of recyclable materials, be 100% solar-powered and will utilize rain collection for irrigation. PF1 is formed as a folded plane made from cardboard tubes, designed to hold planters for vegetables, herbs and fruit. While most of the tubes create an elevated canopy for shade, some tubes extend to the ground to become columns (http://www.publicfarm1.org/).*

Author: WORK Architecture Company
Year: 2008

Carta collection

With the Carta Collection the architect Shigeru Ban share the clear and ecological values when it comes to design and production using natural and biodegradable materials as paper and wood. It has been spent almost two years on developing the collection. The seven designs include a stool, a chair, a bench, a lounge chair and a chaise longue, complemented with two sizes of table. Both the seats and the table frames are created from slim cardboard tubes, which are treated to be waterproof and durable. The 'paper tubes' for the Carta Collection come from Japan where they are treated with urethane resin to make them impervious to fluids and other environmental influences. The furniture is manufactured in Italy, using a sophisticated technique to fix the tubes to the simple birch plywood frames of the seats without using metal and with only a few invisible screws (http://www.wbform.com/en/kollektion/Shigeru-Ban-Kopie.php).

Author: Shigeru Ban
Year: 1999

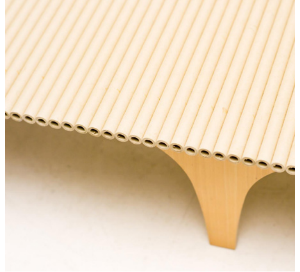


Fig.3.15 Carta Collection - Shigeru Ban

Fig.3.16 Onemi radio - Yanko Design

Onemi - Cardboard Radio

The ONEMI Radio is an example of good design for social impact. Designed for ONEMI, Chile's National Emergency Office, the radio is a way to ensure the safety of civilians during a natural calamity. A cheap, beautiful, portable, and effective radio that can allow the government to communicate with the national population, giving it proper advice during a state of emergency. The radio's cardboard construction allows it to be folded so it can be stored (as well as distributed) easily (https://www.yankodesign.com/2016/05/05/a-revolutionary-radio/).

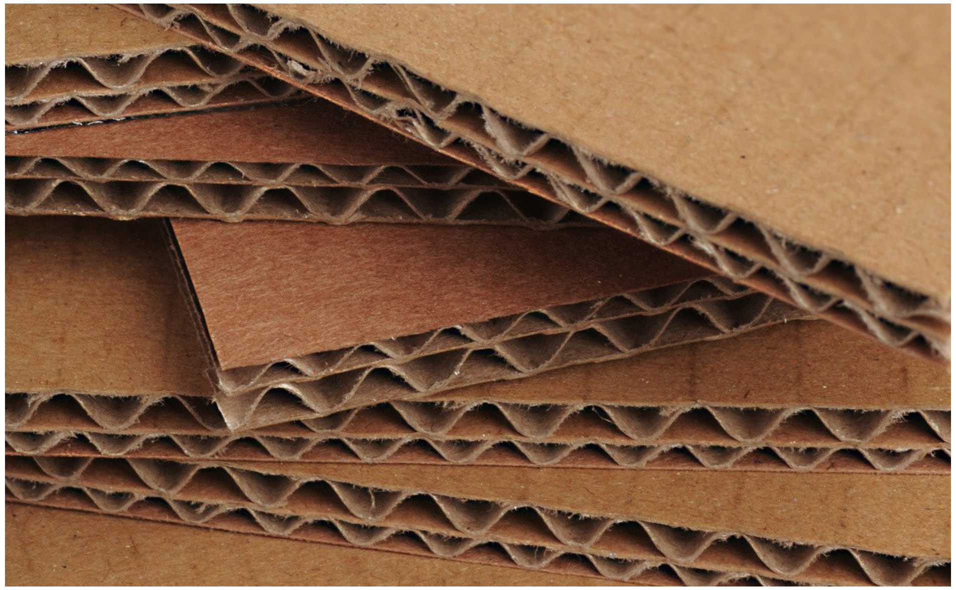
Author: Shakleton group - Yanko Design
Year: from 2008

3.2.5 Corrugated board

Corrugated board is a sandwich construction with a web core and face sheets made from paper. Container board is the common name for the paper materials used to manufacture corrugated board, and includes liner board, used for the facings, and fluting, which is the paper used in the core. The face sheets and core are typically glued together with a starch-based adhesive. The main function of the core is to separate the face sheets in order to achieve a structure with high bending stiffness. The core must also provide shear transfer between the face sheets to minimize sliding deformation during bending (Sekulic 2013).
The corrugated cardboard could have one wave, as described above, but can also be composed of two waves, two sheets of corrugated paper interleaved and joined with a three-sided adhesive sheet (two covers and a central brim), or with three waves, consisting of three sheets of corrugated paper interleaved and joined with a four-sided adhesive tape (two covers and two central braces).

Fig.3.17 Corrugated board Hercules - Nextmade

Fig.3.18 Corrugated board sheets



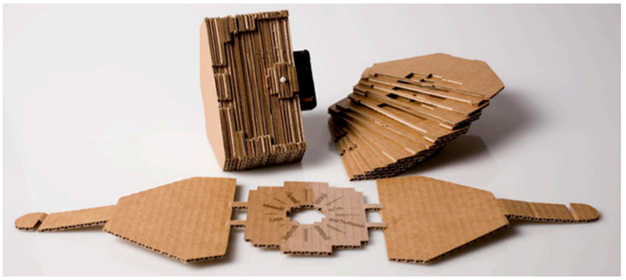


Fig.3.19 Corrugated Board Products

Corrugated cardboard, thanks to its low cost and its good characteristics is often used for many products that can also contain electrical parts.

Terra Armchair

The "Terra" armchair, designed by Studio Nucleo in 2000, is a provocative garden furniture proposal designed to increase the empathic relationship with the user by making the user himself "generate it". It consists of a cardboard framework to be filled with earth on which to plant the seeds supplied with the kit to result in an armchair-shaped lawn that becomes part of your landscape. A surprising project, winner, among others, of the 19th Compasso d'Oro, a prestigious award for Italian design (http://nucleo.to/site/terra/).

Author: Studio Nucleo
Year: 2000

Fig.3.20 Terra Armchair - Studio Nucleo

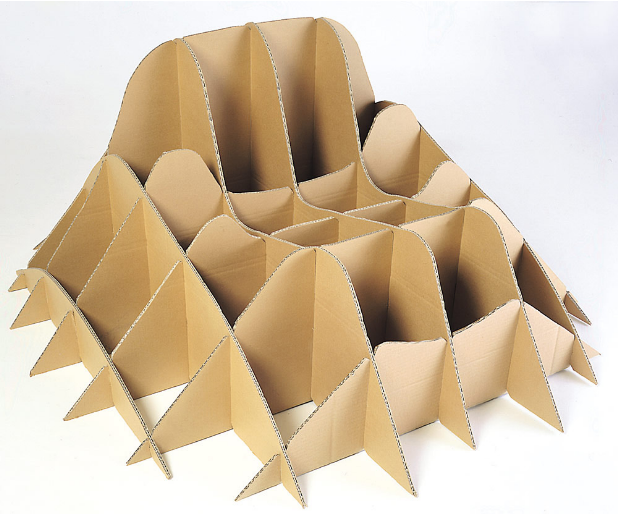


Fig.3.21 Magma Stores

Magma Stores

Magma is a Small British chain of shop selling art and design books and design and design-related products. Owners view shopping as an experience rather than merely transaction, so they look for a new approach for the interior of their first product store. Inspired by packaging design they sought a spatial unity designing the retail entirely in cardboard. It can be altered, added or replaced easily and cheaply (Yabuka 2010).

Author: Julie Blum / Nikki Blustin
Year: 2007

Fig.3.22 Gruff-set - Arno Mathies

Wiggle side chair

In 1972, Gehry was a foresight designer of cardboard products. He designed the Easy Edge collection with unexpected characteristics: the sheets were glued together to take an interesting three-dimensionality. With the furniture series "Easy Edges" he succeeded in lending a new aesthetic dimension to such an everyday material as "cardboard. Although they look surprisingly simple, the "Easy Edges" pieces have been constructed with an architect's skill and are exceedingly robust and stable (https://www.vitra.com/en-us/product/wiggle-side-chair).

Author: Frank O. Gehry
Year: 1972

Fig.3.23 Wiggle Side chair - Frank O. Gehry

Gruff-set

Strong yet dismountable, the gruff range of furniture transforms sheet and honeycomb cardboard into tough furniture that is held together without screws, bolts, or brackets. Swiss designers Real-Made devised a construction system that use fifteen-millimeter thick corrugated cardboard. a housing joint is a type of connection that is typically used in carpentry. It joins two elements that meet at right angles, with one component slotted onto a trench cut across the grain of the other component. The gruff range contains table, bench, and shelving unit and the angles incorporated into each design maximize the decorative quality of sectional cardboard (Yabuka 2010)

In the Gruff-set form it has references to structures made of very thick wood which is resistant, which creates a contradiction with the fleeting nature of cardboard as a building material.

Author: Arno Mathies
Year: 2011

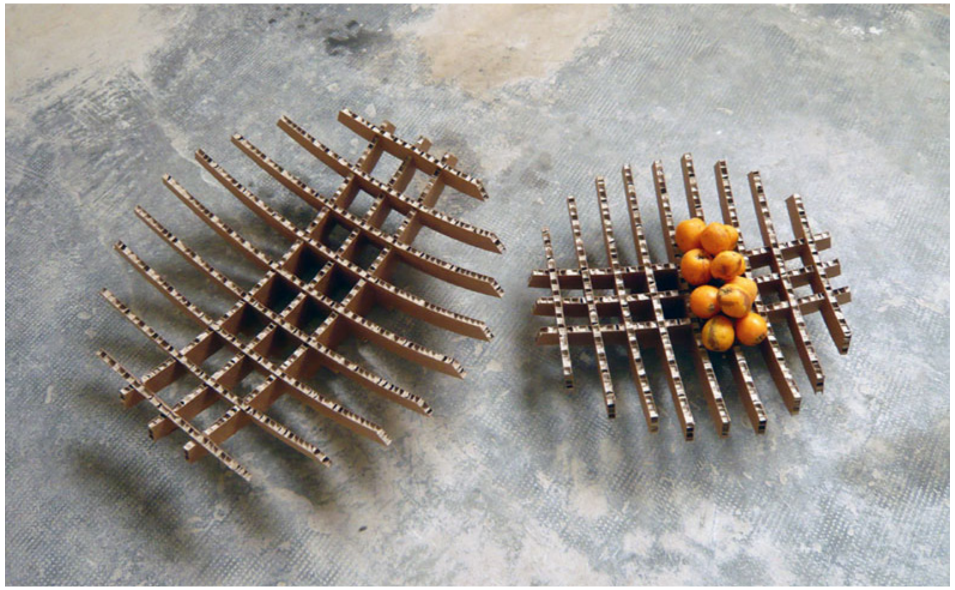


Fig.3.24 Standing Furniture
- A4Design

Standing Furniture

The Standing range of furniture design by A4design explores the potential of recycled honeycomb cardboard as a construction material. Using this material in a variety of manners: in sheet form stacked both horizontally and vertically, in block form, cantilevered, sandwiched and slotted together. The various means of use yield equally numerous expressions of the material's characteristic, but each conveys the strength and lightness of Honeycomb cardboard (Yabuka 2010).
The versatile Multichair for example is a composition of a stratified sheets of multiple thicknesses. It features a cantilever at the ledge that can function as a reclining surface a coffee table or a second seat were laminated board provides durable seating surface (http://www.a4adesign.it/index.php?&lang_id=1).

Author: A4 Design
Year: since 2002

Cardboard Core surfboards

Cardboard was used as a substitute of wood in ribbed hollow surfboard. The cardboard was used as widely available and with a better price-quality ratio than other materials used to make surfboards. The fiberglass cloth gives a translucent effect when the hollow surfboards are held up to the light, their mesmerizing pattern of interlocking internal cardboard ribs are revealed. The structure is a structural grid of triangles and hexagons sealed together with fiberglass cloth and epoxy Resin. The surfboard could be customized as far as the shape of the grid concern (Yabuka 2010)

Author: Mike Sheldrake
Year: 2010

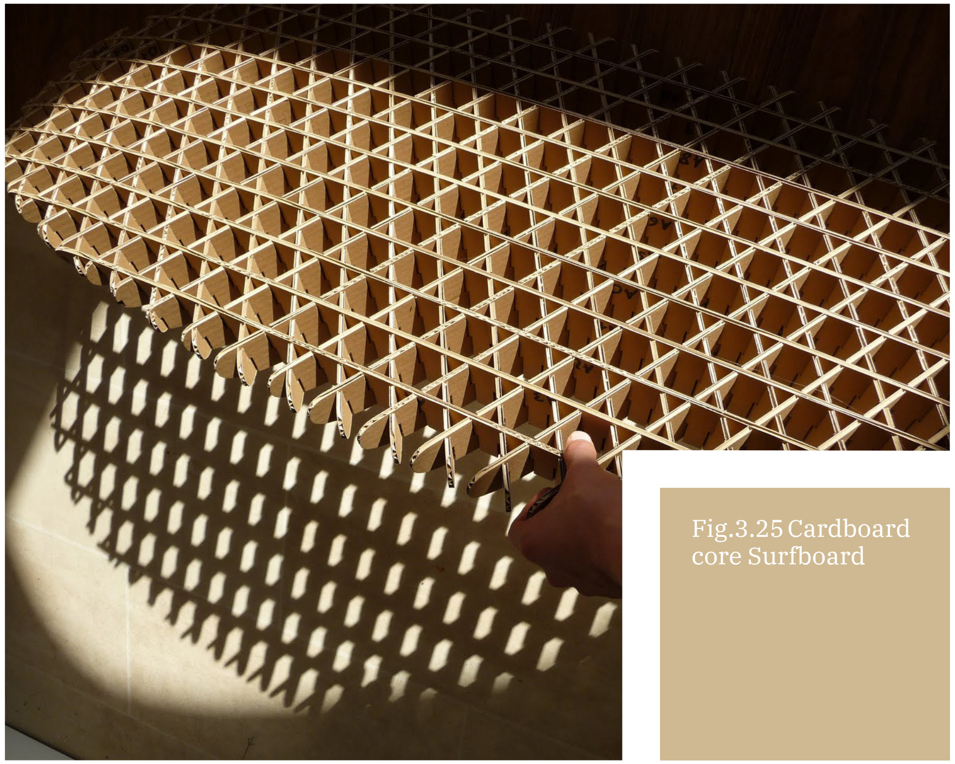


Fig.3.25 Cardboard core Surfboard

Nintendo Labo

Nintendo Labo is a set of DIY accessories dedicated to Nintendo Switch that transforms sheets of cardboard into interactive creations called Toy-Con, designed to work with the Nintendo Switch and Joy-con controllers to interact with virtual objects through the controls in cardboard made by itself. From assembly, guided by the game, to the game and the personalization of Toy-Con, Nintendo LABO is a 360-degree interactive experience (https://labo.nintendo.com/kits/variety-kit/).

Author: Nintendo
Year: from 2018

Fig.3.26 Nintendo Labo Variety Kit

3.2.6 Honeycomb Cardboard

Paper honeycomb sandwich panel is composed of two pieces of face-paper and a piece of core paper which thickness that can be cut to a suitable size in practical application ranging from 8 up to 110 mm. It is widely used in the transporting and packaging process for sophisticated electronic equipment and household appliances. Its mechanical properties depend on the ratio of thickness to length (Dongmei and Ziyou 2015). Tests carried out in certified laboratories attest to the high resistance to compression, which varies from 1.5 to 3.7 kg/cm², depending on the mesh and the weight of the cover used (http://www.tivuplast.it/pannello-in-cartone-alveolare.php).

Fig.3.27 Honeycob Cardboard

Fig.3.28 Cardboard office - Paul Caudamy

Cardboard Office for Elegangz

The aim of the Cardboard Office project is to convert an empty industrial space of 180m² into an office. The conceptualization and realization of the work had to be completed within five weeks and the budget was restricted to minimum. The work was to avoid standard shelves provide a new lighting system, be temporary, and look beautiful and dynamic. It has been used a forty-millimeter-thick water-resistant honeycomb cardboard to create a suite of strong adaptable furniture modules with a system of holding, cutting, stacking, gluing and Taping. The construction takes just seven days obtaining twenty working posts in different spaces, meeting box for fast intern meeting, meeting rooms and a coffee space (http://coudamyarchitectures.com/en/architecture/cardboardoffice/).

Author: Paul Coudamy
Year: 2008

Ecohelmet

Ecohelmet is a foldable bike helmet constructed from waterproofed recycled paper in a radial honeycomb pattern able to absorbs blows from any direction as effectively as traditional polystyrene.
Being made by exploiting only the core structure of the honeycomb cardboard it folds flat for easy storing when not used (https://www.ecohelmet.com/).

Author: Isis Shiffer
Year: 2016

Fig.3.29 Eco helmet

Cardboard Technologies

Cardboard Technologies is a company whose vision is to make the everyday needs such as transportation, more eco-friendly and accessible. Unique in many ways, the Cardboard Bicycle is comprised primarily of recycled cardboard, and supplemented with recycled plastics and car tires. The cardboard itself is highly durable, as well as both fire and water resistant, supporting riders of up to 125Kg.

Designed to address a large global market, the Cardboard Wheelchair will primarily target developing countries. As a durable, low-cost product, it is perfectly suited to areas where medical equipment is scarce and price sensitivity is high. Its price, storage, and disposal make it particularly ideal for patients with short-term disabilities (https://www.cardboardtech.com/).

Author: Cardboard Technologies
Year: from 2020

Fig.3.30 Cardboard Technologies - Bike and wheelchair

3.2.7 Molded pulp

Molded Pulp, also known as paper pulp, is a packaging material, made up of cellulose wood fibres bonded together with lignin typically obtained from recycled paperboard and/or newsprint providing a useful outlet for industrial and post-consumer paper waste. No additional adhesives, binders or other ingredients are added to strengthen this natural composite material (Thompson 2007). It is used mainly for protective packaging or for food service trays and beverage carriers and it is quickly becoming a popular primary and secondary package due to its sustainable qualities.

The molded pulp manufacturing is improving, making it easier for companies to design more developed molded pulp packages (Howe 2010). For many applications, molded pulp is less expensive than expanded polystyrene (EPS), vacuumed formed PET and PVC, corrugation, and foams.

Currently there are four different types of molded pulp based on the manufacturing process and quality of materials put into the process. The first type is called “Thick Wall” referring to the usual 5 to 10 mm thick walls made out of Kraft paper. One surface is relatively smooth, with one side rough. Primarily used for support packaging of non-fragile, heavier items (vehicle parts; furniture, motors etc.). As well as, plant, floral and nursery pots and containers.
The second one is called “Transfer Molding”, this process can obtain slightly thinner walls ranging from 3 to 5mm. Surfaces are relatively smooth on one side. Most common use is for egg cartons and trays. New designs are used for many types of electronic product packaging such as cell phones, DVD players etc. Also, used for hospital disposables, electrical appliances, office equipment, tableware and fruit and drink trays. Object from both these two processes need to be oven dried after forming.
The third type is called “Thermoformed Fiber” or “Thin Wall” where heated molds are utilized. These molds make the products more precise in shape, that closely resemble thermoformed plastic materials, with product wall thickness of about 2 to 4 mm. Due to the hot mold pressing process, the walls are somewhat denser, and it also make unnecessary to have a drying step. The final type is called “Processed Pulp” and takes one of the other three types of molded pulp and “finishes it” adding printing, additives, coatings or further tooling like die-cutting, embossments or perforations (https://www.imfa.org/molded-fiber/).

Fig.3.31 Molded Pulp protective packaging

Thermoformed fiber

This newest form of molded pulp is the highest quality of thin walled products available today. The process uses “Cure-In-The-Mold” technology which produces well defined, smooth surfaced molded pulp products. After being formed, the product is captured in heated forming molds which presses and densifies the molded products. They are accurately formed and have the appearance of plastic material. The products are ejected from the heated molds in their finished state as opposed to being dried in a heated oven. Typical uses for this type are for point-of-purchase packaging and those applications where high definition and appearance are of prime importance (https://en.wikipedia.org/wiki/Molded_pulp).

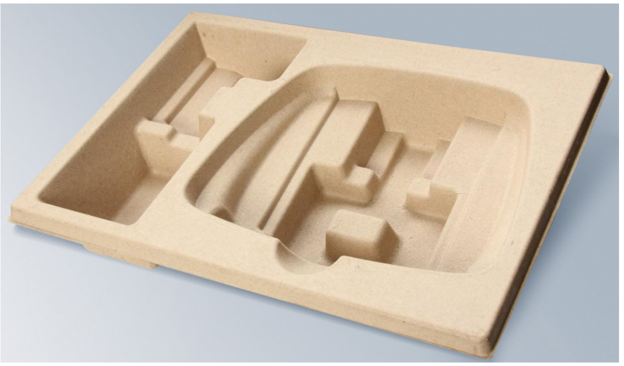


Fig.3.32 Thermo formed fiber products

Packaging Lamp

This lamp is made from paper pulp packaging sourced from recycled newspaper. Its structure contains a compact fluorescent light bulb and a plug. When opened, the packaging becomes the lamp form, saving on waste. It is easy to carry and totally biodegradable (Serrats 2009).

Author: David Gardner
Year: from 2008

Fig.3.33 Packaging Lamp - David Gardner

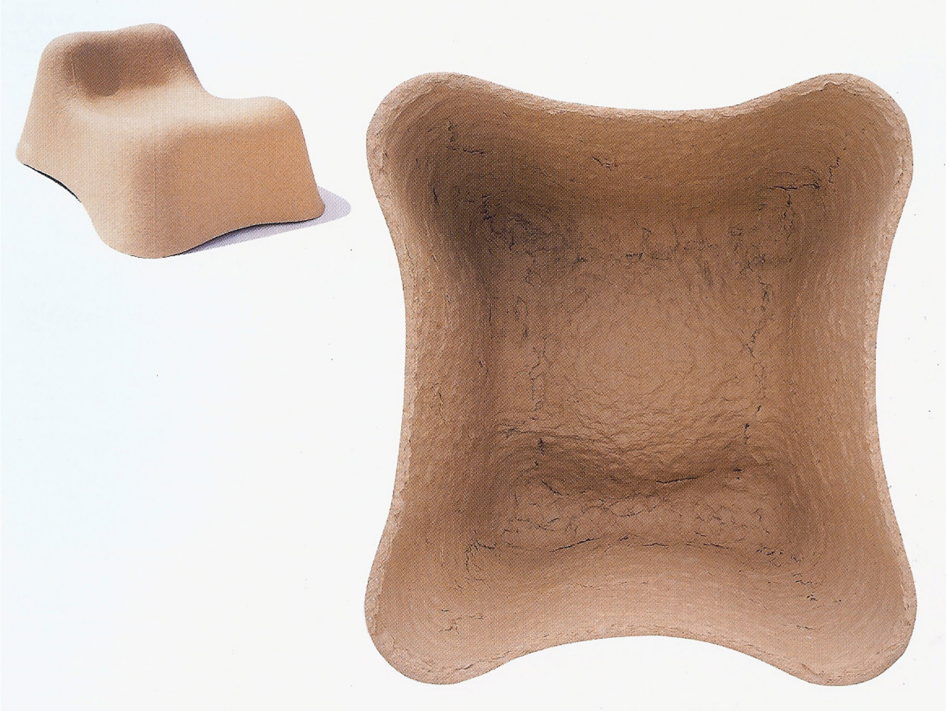
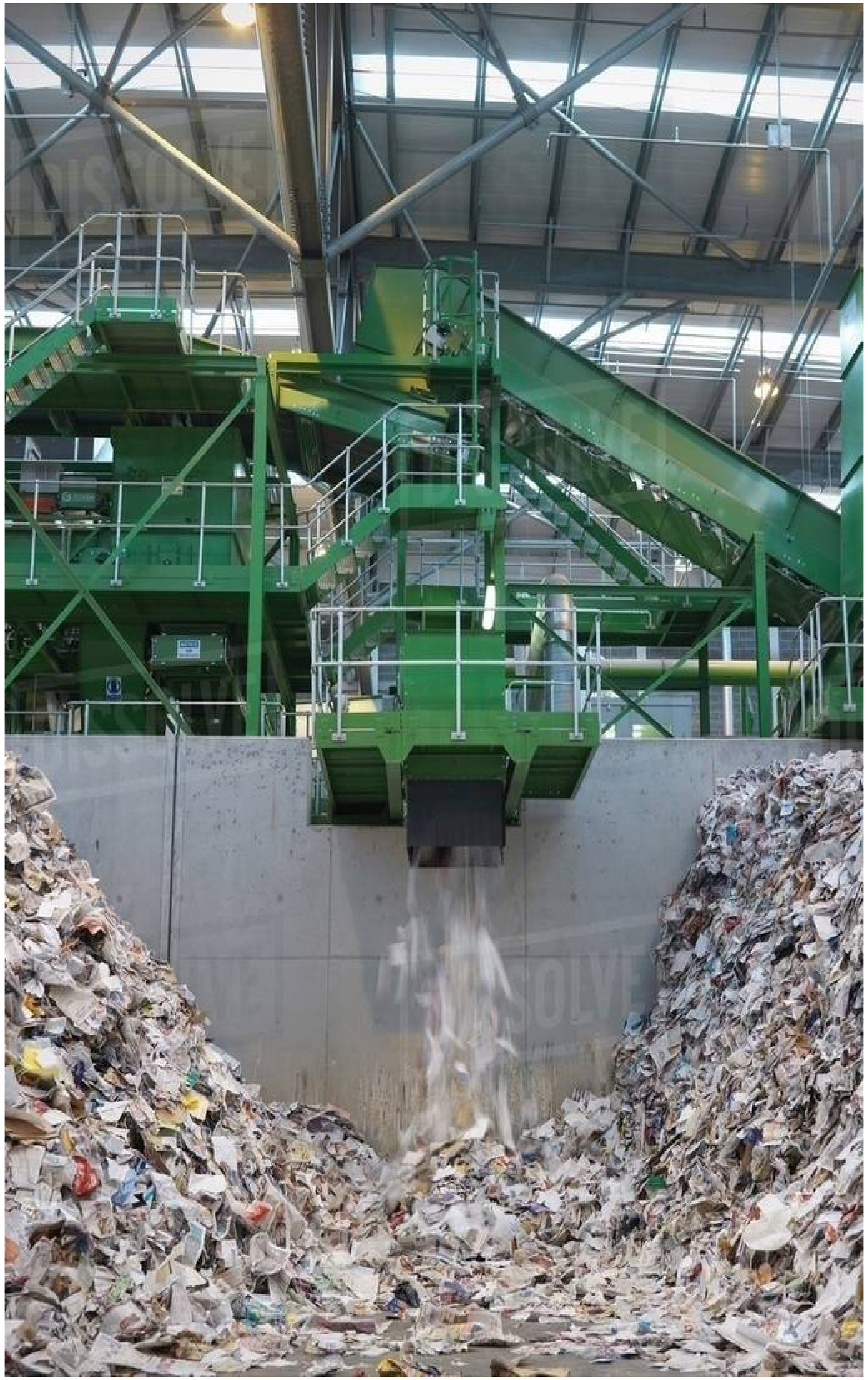


Fig.3.34 Mould Chair - Amano Katsutoshi

https://www.kadltd.jp/project-14-mould



3.3 Paper Recycle Chain

Markets affect how and which materials are collected for recycling, so it is important to consider the market for recovered paper. The paper industry is an example of a field in which recycling plays a key role (http://www.paperforrecycling.eu/publications/). In fact, recovered paper is a global commodity that involves many products, most of all disposable and other with a medium or long-life term.

In 2017 the European paper recovery rate has been of 71,5% while the U.S rose to 65.8%. Industry has already increased recycling rates to high levels. However, different patterns in consumption, new technologies and diversifying application of paper-based solutions make it challenging to maintain recycling rates, which are now starting to reach a theoretical maximum (European Paper Recycling Council 2016).

3.3.1 Paper recycling process

At the beginning of the paper recycling process there is paper waste collection from urban and industrial sources at the recycling facility. At the recycling facility, the paper is separated by type and grade, and then it is wrapped into bundles and sent to paper mills for further processing.

At the first step, the paper is placed in the "pulper", a big vat where is chopped into pieces and damped with water. Pulping has the function of impregnating the fibrous material in order to break the bonds between the fibers without damaging them. The cellulose fibers are then dispersed in water until a proportion of 2 parts of fiber per 100 of water is reached. The mixture is then heated to further break down the paper fibers.

The pulp is put through sieving machines with mesh up to 0.25 mm to remove items such as plastic tape or other incompatible materials. After the screening process the pulp is cleaned eventually using chemical additives or steam.

Fig.3.35 Wasted paper and Pulper

Larger pulp fibers are separated into smaller fibers, and any remaining bulk materials such as staples and paper clips are removed. With the pulp completely cleaned follows the deinking process that removes printing ink and sticky materials such as glue residue and adhesives.

The deinking process involves the “washing” process that removes small particles of ink by rinsing the pulp with water, and the “Flotation” process that removes larger particles and sticky materials by using air bubbles. During flotation, surfactants are added to the pulp that force the remaining ink and sticky materials to the top and allow for easier removal from the clean pulp.

Next, the pulp is refined, beaten and swells it, where larger fibre bundles are separated into individual fibers. Chemicals are added to remove dyes and color-stripping and if white paper is desired, the paper pulp may be bleached with hydrogen peroxide, chlorine dioxide, or oxygen to make it white and to brighten it.

After all these processes the pulp is upcycled, made it into new paper, used alone or additional virgin wood fibers can be added to the pulp to give the paper extra strength or smoothness. The watery pulp is sprayed onto quickly moving screens, where water drains and the recycled fibers bond together into sheets. Press rollers squeeze more water out of the sheets and heated metal rollers dry the paper sheets. If coated paper is desired for smooth printing, a coating mixture may be applied to the paper near the end of the paper-making process or after the process is completed.

The paper sheet is wound into giant rolls, that can be as wide as 10 meters and weigh 20 tons and removed from the paper making machine; shipped to plants where they will be printed or made into new products. Unfortunately, there is a limit to how much recovered paper can be recycled. During the paper recycling process, the individual paper fibers are shortened more and more each time they are recycled, and generally have a maximum limit of 5-7 times that they can be recycled (https://greentumble.com/how-is-paper-recycled-step-by-step/ | https://greenerideal.com/guides/0528-10-step-guide-paper-recycled/).

Recovered paper can be used to make new products composed entirely of recovered fibre or a blend of recovered and virgin fibres. Such “end of the line” paper products include things like cardboard egg cartons, cereal boxes, or Cellulose insulation material that can no longer be recycled. The best way to dispose of these products in an environmentally-friendly way is to compost them at home or in a municipal or commercial facility (http://www.bir.org/industry/paper/).

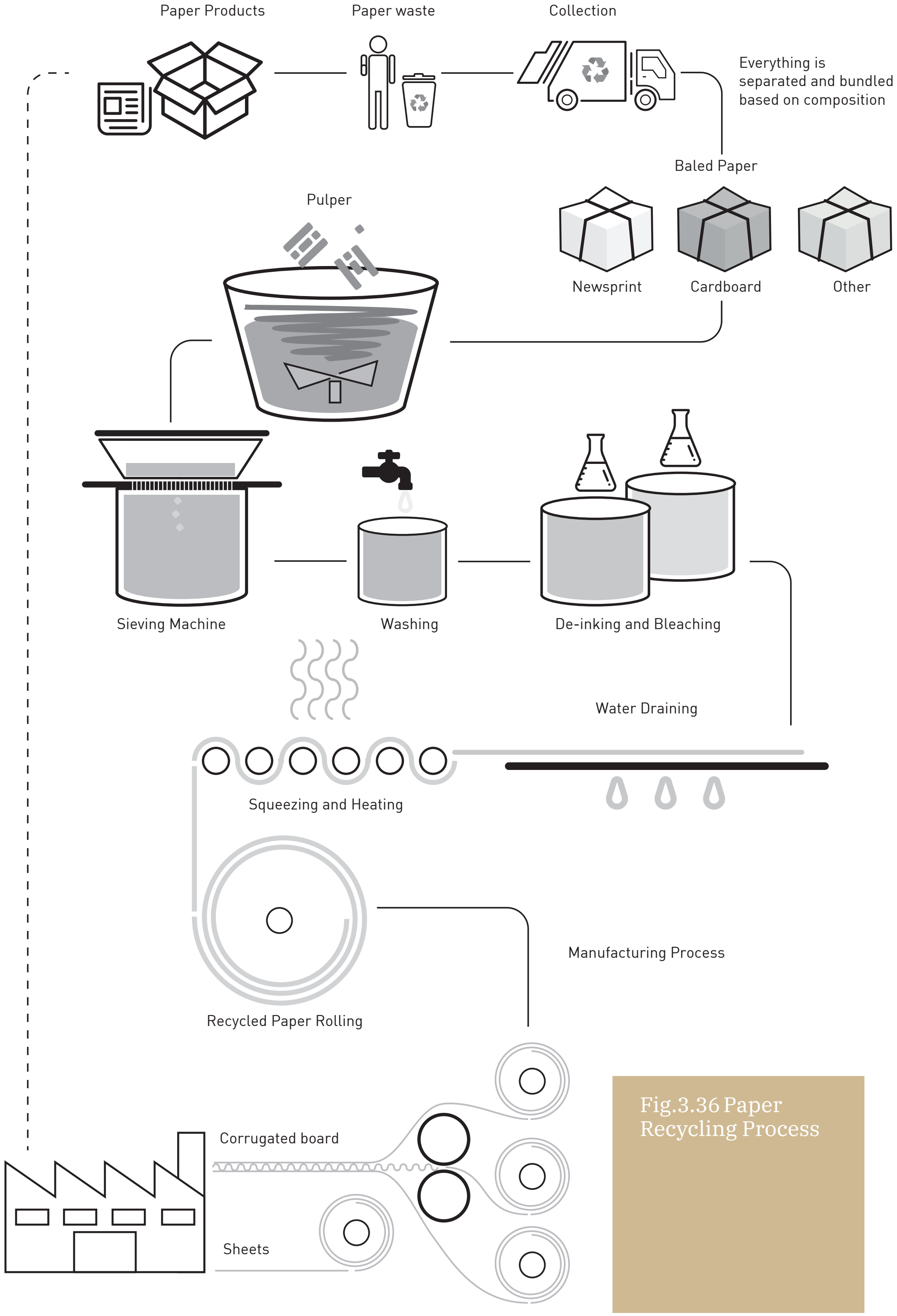


Fig.3.36 Paper Recycling Process

3.3.2 Grades of paper

Since, to date, paper is one of the most recycled materials, it turns out that is made using different recipes, including different types of fibers and chemical requirements, recycling newspaper, old documents or packaging is not a simple as we would like it to be. In fact, the continuous reworking, goes to impact on the quality of the paper every time it is recycled and decreases its quality both in terms of aesthetics and resistance. For this reason, the Environmental Protection Agency (EPA) has defined how the challenge of paper recyclability can be broken down into five different paper grades. The grade of paper is determined by fibers length, which shortens after each trip through the recycling process. After being recycled five to seven times, the fibers become too short to make new paper and will need to be mixed with virgin fibers, according to the EPA (https://earth911.com/business-policy/business/paper-recycling-details-basics/).

The high-grade paper is constituted by the pulp substitutes, often sourced as shavings and clippings from converting operations at paper mills and print shops. Mills can use pulp substitutes in place of virgin materials to make high-grade paper products.

Then is possible to find high-grade de-inked paper, made of high-grade paper such as letterhead, copier paper, envelopes and printer and convertor scrap that has gone through the printing process. It must first be de-inked before it can be reprocessed into high-grade paper products such as printing and writing papers or tissue.

Going towards grades of increasingly lower quality there are old newspapers, used to make new recycled-content newsprint and in recycled paperboard and tissue with other paper grades.

After that there is mixed paper. It is a broader category which includes discarded mail, telephone books, paperboard, magazines and catalogues. Paper mills use mixed paper to produce paperboard and tissue, as a secondary fibers in the production of new paper or as a raw material in nonpaper products such as gypsum wallboard, chipboard roofing felt, cellulose insulation and moulded pulp products such as egg cartons.

At the lowest grade defined by the EPA there are old corrugated containers, also known as corrugated cardboard. Paper mills use these materials to make new recycled-content shipping boxes and recycled paperboard for product packaging like cereal boxes, shoeboxes and more (https://recyclenation.com/2014/08/understanding-recyclability-of-different-paper-grades/).

Other agencies, such as Complete Recycling, a Managed Services Provider (MSP) that provides recycling solutions for large-scale commercial companies, further subdivide the qualitative aspect of the recycled paper product by defining 50 Grades of paper to be used to optimize the material for different products (https://www.completerecycling.com/resources/paper-recycling/stock-grades).

Fig.3.37 Paper and paperboards of different grades

As we could see, the paper is a cellulose-based material with a consolidated presence in our daily life. Paper and cardboard can have different aspects and performances that allow to create many types of products, often characterized by box shapes. It is also among the most recyclable and recycled materials and this makes paper an important Circular Material. The potential of cellulose, however, can also be exploited by using it as reinforcing fibers for new composite materials. One example is the Poly-Paper, a new cellulose-based polymeric material which will be considered as a case study.

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List of figures

4

Case Study: Polypaper

Fig.4.1 Poly-Paper Pellets

4.1 Objectives of the Material

Poly-Paper is a new composite polymer, developed in the Making materials Lab of Politecnico di Milano in collaboration with Nextmaterials. It is a composite material between polymeric and cellulosic material, born from the desire to create a polymeric behavior material with high environmental sustainability (having as a horizon an impact on the world of packaging) that could be inserted into the paper and cardboard recycling chain. In fact, these are materials that respond very well to issues related to sustainability and recyclability, because we are all used to seeing them recycled also before the term "recycling" became commonplace. The recycling of Poly-Paper alongside the "waste paper" collected needs a hydro soluble matrix of PVA (polyvinyl-alcohol), polymeric material produced without subtracting fertile soil for agriculture, able to dissolve in water forming compounds without any risk of toxicity (S.-J. Zhang and Yu 2004; W. Zhang et al. 2011). This feature makes the material interesting for end-of-life aspects because, despite its polymeric nature, it reinserts it into an established and consolidated recycling cycle like that of paper.
To date, the properties and characteristics that have been identified by the Politecnico di Milano and by Nextmaterials, holders of the material patent (Italian patent n. 102015000028276 "Composite material with high environmental sustainability", filed 26/6/2015, granted 30/11/2017), already make it a material with curious future applications (https://www.nextmaterials.it/it/Poly-Paper/). Poly-Paper wants to represent a step forward in the development of products with high environmental

sustainability, allowing to have a very stiff and resistant material, formable even in complex shapes that can be used in an integrated way with paper materials and that can be inserted in their same recycling chain (Del Curto 2016).

The objectives expressed by the initial formulation, focused attention on the development of a material that could be competitive within the vast packaging sector, Poly-Paper has been analysed focusing on its functions, constraints and objectives following the Ashby method (Santi 2016).

Functions

- Be a material that makes the product disposable as a single material
- At the end of its life the material must be quickly perishable and recyclable in the paper and cardboard supply chain

Constrains

- Ensure that the material is recyclable in the paper and cardboard supply chain
- Biocompatibility and water solubility of the matrix for recycling through the pulp of the cellulosic amount
- Comparable mechanical properties respect to the common packaging materials

Objectives

- Weight optimization, workability, disposal ensuring structural technical performance.

4.1.1 Starting Point

Applications were initially directed towards single-use or short-lived packaging types, service items, and coatings for paper and cardboard applications. However, the possible products obtained from bio-resources cover a wider range. Therefore, by imagining Poly-Paper as a hybrid material between plastic and cardboard, as processable as plastics, but recyclable as paper, the analysis of the two materials application sectors is proposed, to highlight areas of growth in the consumer sectors (Del Curto 2016).
The research is therefore aimed at investigating a fair compromise for the use of Poly-Paper finding a balance between feasibility in terms of production and ethical value of the material. Assuming the ease of processing comparable to that of the polymers used today for packaging (PET, PP, PS, PVC), the values of recyclability, sustainability, creativity and innovation of the material must be highly transmitted.
The paper and cardboard recycling chain, in Italy has proven to be constant for years with a percentage of around 80% on entry and a weight value of 3,752 Kt (FISE UNIRE 2017). It had proved to be the most receptive, active and effective in recycling, and was decreed as the best way to manage the end of life, so the new material had to be able to insert itself in it.
The Poly-Paper was initially studied in mixtures with 30% cellulose fiber charge percentages showing an increase in mechanical performance, reaching a breaking stress of about 12 MPa (Santi 2016). Other tests with higher fiber percentages up to 50% have led to an increase in mechanical characteristics. Larger fiber percentages lead to a loss of consistency of the material for which they have not been investigated.

4.1.2 Poly-Paper Components

In a composite material there are at least two constituents with significantly different physical or chemical properties that, when combined, produce a new material with different characteristic from the initial components. In the case of Poly-Paper, the matrix material, that surrounds and supports the reinforcement materials by maintaining their relative positions is represented by Poly vinyl alcohol (PVA), a biodegradable and water-soluble synthetic polymer, but inert to organic solvents such as petrol, white spirit, oily solvents and greases. To date, applications based on the biodegradability of PVA are found in hot water-soluble films, film for wrapping pallets, fertilizer bags, industrial packaging and general consumption. The reinforcement material used in Poly-Paper consists of Micro-Fiber Cellulose (MFC), it is used to give the desired strength and stiffness characteristics in the composite material. It has been selected as a reinforcement material because it is perfectly integrable in the paper recycling cycle.

4.1.3 Poly-Paper in the Circular Economy

From the research on the approaches related to the Circular Economy, it is possible to see how the Poly-Paper has the potential to be applied in scenarios that are aligned to many points dealt with by the new orientation of the CE.
The combination of PVA and Cellulose micro-fibers, therefore, creates a composite material whose objectives are mainly focused on the final disposal of the products. The use Poly-Paper aim to make or treat a product itself as a mono-material, highlighting the recycling chain to which they are intended, and avoiding common errors that the user can create due to a poor or lack of communication, even only on the material level (*Recycling*). Reduce, at a design level, the amount of material needed while ensuring the same function of the product (*Efficient use of resources*). The material must be included in product categories designed according to its overall life cycle, where the recyclability features reinforce the profile (*Lifecycle planning*), further widening the application horizons and enhancing paper and cardboard (*Re-manufacturing hypothesis or re -use*)(Rizos, Tuokko, and Behrens 2017). Trying to frame the Poly-Paper according to the Re-Upcycling approach described in the book "Neomaterials in the circular economy"(Pellizzari and Genovesi 2018), it fits between the Ex-Novo and Neoclassic categories, as it is a composite polymer whose matrix is not conventionally used in industrial products, loaded with natural fibers which, being cellulose, can be part of a consolidated and driving recycling cycle like that of paper.

4.2 Properties

Poly-Paper is an innovative material still undergoing characterization but has already proven to have very interesting technological features. The percentage that has shown the best workability and that is able to find compatibility with the paper recycling cycle, is that which provides a percentage of 55% cellulose and 45% PVA (weight). With a cellulose percentage of more than 50% it would be suitable to be recyclable in the paper / cardboard chain (passed the preliminary Aticelca tests MC 501: 2017 European Standard EN 13430: 2004).

Density

For the estimated density calculation, considering that the percentages indicate the quantity by weight, knowing the density of the individual components and assuming a final quantity of 1 kg of Poly-Paper, first to calculate the volume of the individual components and then, knowing the final weight at the density of the materials based on the mixtures. The density of a generic PVA is 1,19 kg/dm^3 while that of cellulose is 1,5 kg/dm^3.

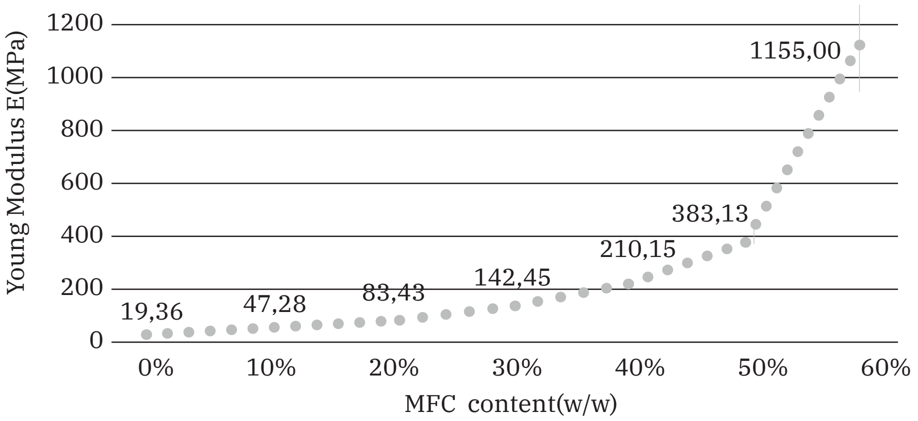
% filler	ρ [kg/dm^3]
30%	1,269
40%	1,297
50%	1,327
60%	1,358

Tab.4.1 Poly-Paper Density

4.2.1 Mechanical Properties

Start to define what are the mechanical characteristics of the material, tensile strength tests were carried out with samples of different composition percentages. The different composites exhibited a good stress-strain behavior as well as a close correlation between MFC content and tensile properties. From 10 to 60% w/w MFC content, there is an increase in Young modulus of ten times. With the increase in the cellulose percentage, an increase of the yield strength stress was observed, with also a significant reduction in the elongation at breakage (Santi et al. 2018).

Mechanical Properties			
% filler	E [MPa]	σ_y [MPa]	Ɛ[%]
0%	19,36 ±0,71	14,59 ±0,54	466,88±24,92
10%	47,28 ±3,22	9,78 ±0,13	276,10 ±17,07
20%	83,43 ±10,34	9,52 ±0,36	96,08 ±13,22
30%	142,45 ±13,88	11,94 ±0,67	57,68 ±2,48
40%	210,15 ±6,99	16,60 ±0,12	27,87 ±1,30
50%	383,13 ±22,57	23,88 ±1,26	18,03 ±0,72
60%	1155,00 ±182,53	46,98 ±2,57	10,50 ±1,53



Tab.4.2 Poly-Paper Mechanical Properties
Fig.4.2 Young Modulus (E) / MFC content Ratio

4.2.2 Technological Properties

Among the technological properties, as the attitude of a material to be subjected to the different processes, characterizing the behaviour of the material subjected to them, has been identified, besides the extrudability and the injection moldability, fundamental for the workability of the Poly-Paper as a common polymer, the most particular Shape memory forming, the Self-Healing or weldability by water and the hand smoothing (https://www.nextmaterials.it/it/Poly-Paper/).

Shape Memory Forming

Artefacts made of Poly-Paper can be put into shape and stabilized by heat treatment taking various configurations.

Self-Healing by water

It has been verified that by simple wetting with water of the Poly-Paper surface it is possible to weld it strongly to itself and to cellulosic materials such as wood, paper and cardboard. The tests were carried out by Nextmaterials and the Milan Polytechnic in part following the ISO 4587 Standard "Adhesives - Determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies". The tests clearly show that the simple wetting with water of an area of 625 mm2 is sufficient to support a force of about 80 kg.

Fig.4.3 Shape Memory Forming of Poly-Paper

Fig.4.4 Surface Smoothing of Poly-Paper

Hand smoothing

The material can be smoothed by simply rubbing an object (a cloth or the hand) wet with water or a mixture of water / alcohol or water / ethanol. Tests were carried out on samples obtained by 3D printing, reducing their surface roughness by about 2/3. Furthermore, the tactile sensation of the material is interesting as a middle way between the plastic and the cardboard touch.

4.2.3 End of life

The end of life of the Poly-Paper is the most characteristic feature of the material, in fact the polymer matrix material can then go to conveying, together with the cellulosic materials, into the pulp. PVA, in fact, even if it is a polymer of chemical origin, is water-soluble, biodegradable and considered non-toxic by the American FDA (Consumer watchdog in America's healthcare system) turning into water, carbon dioxide and cell biomass when it comes into contact with microorganisms present in water. Also factors such as temperature, PH and water turbulence influence the dissolution of the matrix. The tests have shown that as the temperature and turbulence increase, the dissolution of the material is accelerated (Santi 2016). The biodegradability of PVA modified in water is comparable to that of the common biodegradable biopolymers and is certified by the EN / ISO 14852/2004 and UNI EN 24987/2007 regulations that regulate the biodegradability methods in water (Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium). The results of the solubility tests carried out by Santi have shown that the dissolution rate of the material placed in pulp conditions makes it compatible with the paper recycling chain. It is further hypothesized that as the cellulose percentage increases, and therefore less than PVA, the dissolution of the material in water takes place in less time.

4.3 Material Comparison

For a direct properties comparison of the investigated materials in the previous chapters and those of the Poly-Paper, reference was made to the data provided by the CES Selector Granta database 2018. The first comparison was made between the elastic modulus E and the density of the various materials. This chart provides an overall view to relate the characteristics of stiffness and which require the weight minimization or material quantity of a component.

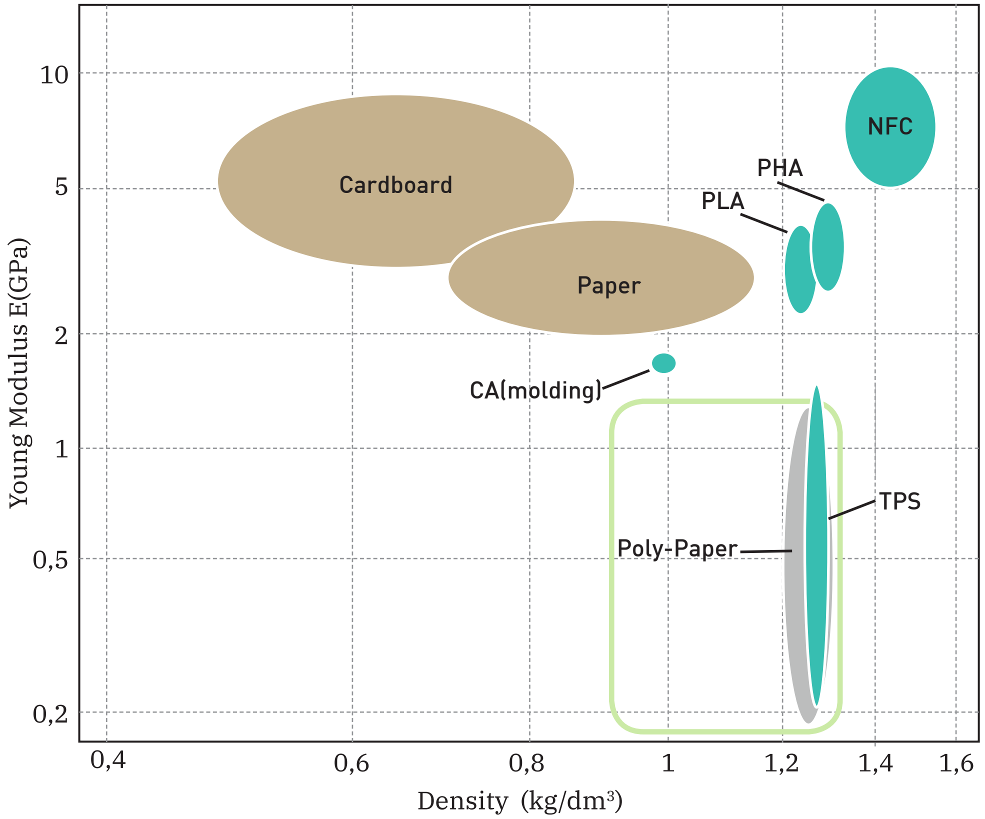


Fig.4.5 Young Modulus (E) / Density Ratio

Subsequently, the materials were compared based on the level of use and adequacy for the main types of processability, relative to the polymers, to which the materials can be submitted. These include extrusion, injection molding and thermoforming, which give general indications on the behavior of the materials for all the associated process sub-categories. The classification used followed that provided by the CES 2018 database which associates four qualitative values: Excellent, Acceptable, Limited Use e Unsuitable. Excellent means that the technology is frequently used and does not present any major problems. The Acceptable value means that it is generally used but may not be an optimized grade. If the material may be used in limited case or requires additional measures to avoid problems the value is Limited use and finally if the material is not used for the technology, it is Unsuitable.

Processing propertis (Polymers Related)			
Material	Extrusion	Injection Molding	Thermoforming
PLA	Acceptable	Acceptable	Acceptable
PHA	Limited Use	Acceptable	Unsuitable
TPS	Acceptable	Acceptable	Unsuitable
CA	Limited Use	Excellent	Limited Use
NFC*	Limited Use	Acceptable	Limited Use
Poly-Paper	Acceptable	Acceptable	Limited Use

*The NFC data are related to a generic PLA+30%natural fiber

Tab.4.3 Processing properties of analyzed polymers

Material	Average price [€/kg]	Average Price [€/dm^3]
PLA	4,25 - 4,49	5,28 - 5,7
PHA	4,23 - 5,92	5,2 - 7,4
TPS	1,86 - 4,23	2,34 - 5,41
CA	3,78 - 3,95	3,70 - 3,95
NFC	3,54 - 3,72	4,58 - 4,87
Paper	0,84 - 1,02	0,586 - 1,18
Cardboard	0,63 - 1,27	0,3 - 1,09
Poly-Paper	6,99 - 4,98	8,87 - 6,77

Tab.4.4 Prices of analyzed polymers

As far as the cost estimate of the Poly-Paper is concerned, the calculation was made considering the cost of the individual elements and the percentage used. Considering that the cost of the modified PVA has a cost of about 8-10 € / kg (considered an average price of 9 €/kg) and the micro-cellulose of 2.30 €/kg (price data has been provided by NextMaterials), the Poly-Paper has a cost, depending on the percentage of cellulose contained in it in a range of 6,99 €/kg, at a percentage of 30% up to 4,98 €/kg at a percentage of 60%. As regards the minimization of the cost and not of the weight of the material, always related to the stiffness of the material, the relative cost per unit of volume has been inserted on the abscissa axis. This chart provides information about the cost of a component that may be subject to a material replacement without any change in morphology.

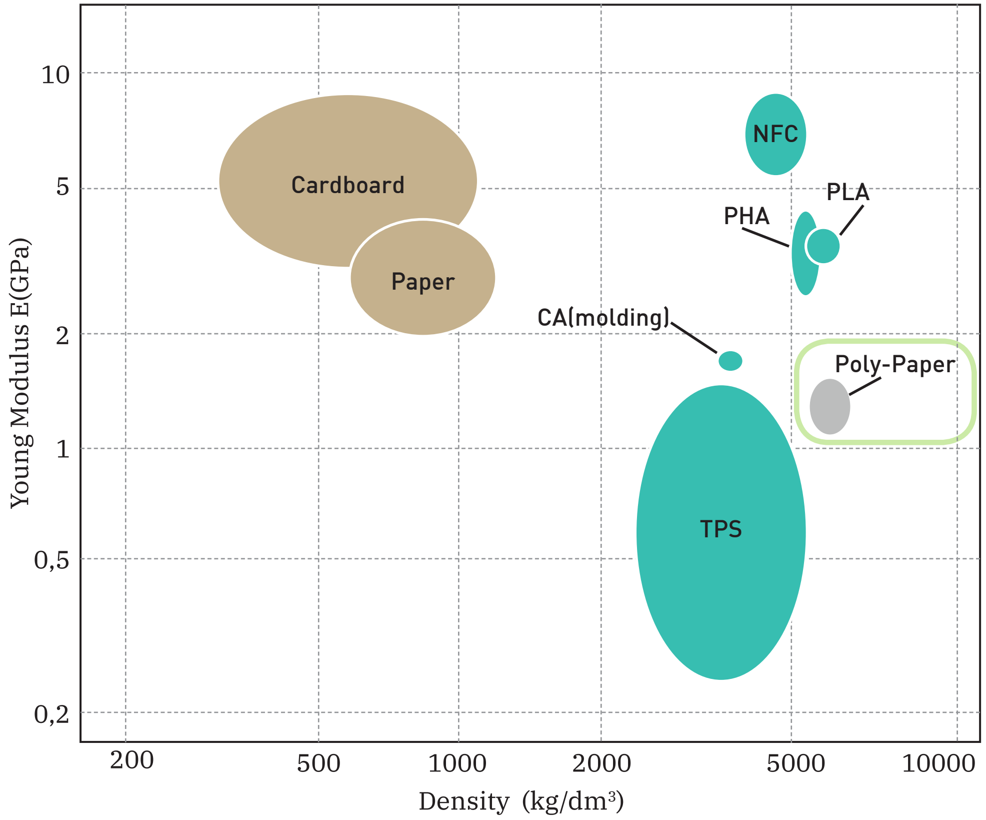


Fig.4.6 Young Modulus (E) / Price per unit volume Ratio

The comparison between the characteristics of Poly-Paper and its direct competitors (biopolymers and cellulose materials) shows how its mechanical properties are comparable to those of TPS. From the graph observation we can see the excellent ratio between elastic modulus and density of cellulose materials, a property limited however by their workability, which does not offer the same range of processability technologies of polymeric materials. This result suggests that the combination of cellulose and Poly-Paper materials can result in products with good mechanical qualities and processability qualities equal to those of polymers. In fact, it can be noted that depending on the polymer the processability may vary. The processability of the Poly-Paper has been investigated as far as extrusion and injection molding is concerned and is acceptable and in line with the values of the majority of biopolymer competitors. Tests on its thermoformability have been carried out and will be discussed in the next paragraph. Addressing the issue of comparing the costs of materials, the values calculated for the Poly-Paper are due to the reference of the purchase of the substances with retail prices, which distort the comparison to its disadvantage. In the hypothesis of a mass production the cost of the material should lower. Moreover, once again, the possibility of combining the Poly-Paper with paper and cardboard would result in a product whose average cost due to materials turns out to be competitive with that of biopolymers.

4.4 Laboratory experiences

4.4.1 Material Production

To perform tests on the material, the first step was the production of extruded material. This was possible thanks to the use of an extruder equipped with a double co-rotating screw (LabCompounder KETSE 20 / 40D EC, Brabender, Duisburg, Germany) able to obtain good mixing, cooling and producibility results. PVA and cellulose, have been provided in the form of powders to optimize mixing inside the extruder. The modified PVA was measured in a weight ratio and combined with the cellulose fiber, and this mixture was introduced into the hopper with a volumetric feeder. The product Poly-Paper was used for the creation of demonstrators and semi-finished products useful to demonstrate the potential of the material.

Wire extrusion

For the wire production a percentage of cellulose of 40% was used following the temperature profiles that allowed to melt the PVA without going to burn the cellulose, compromising its properties. The extrusion head used consisted of three 1.75 mm diameter holes, a standardized measure for the filaments used in FDM 3D printing. To guarantee the continuity of the process, the threads once extruded have been fixed to spools mounted on a winding machine regulated with a rotation speed equal to that of the filament output.

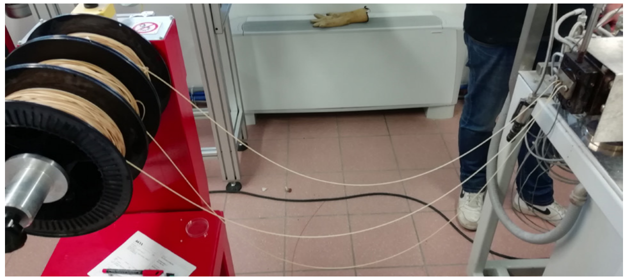


Fig.4.7 Wire Extrusion

Fig.4.8 Spools on winding machines

Tape extrusion

For the tape production has been used a 50% cellulose percentage with an extrusion head 0.5 mm thick and 25mm wide. Due to debris and impurities accumulated near the extrusion head, the tape had a jagged side. Since the extruded material had only one irregular side but a high percentage of useful surface it was adjusted using a disc sander thus obtaining both the regular edges.

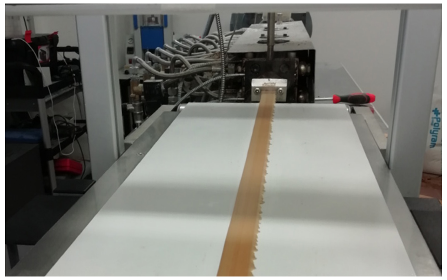
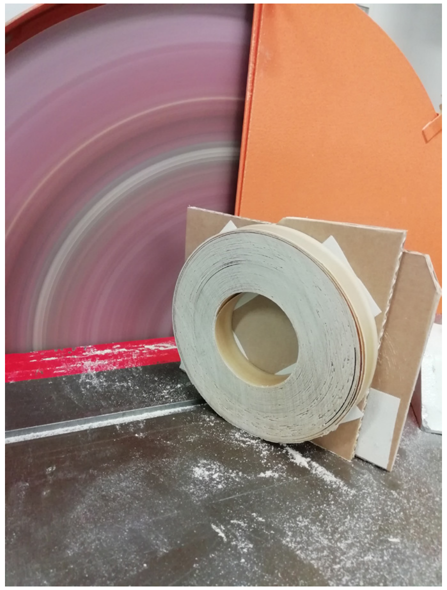


Fig.4.9 Tape Extrusion

Fig.4.10 Tape Correccion

Fig.4.11 Tapes Produced



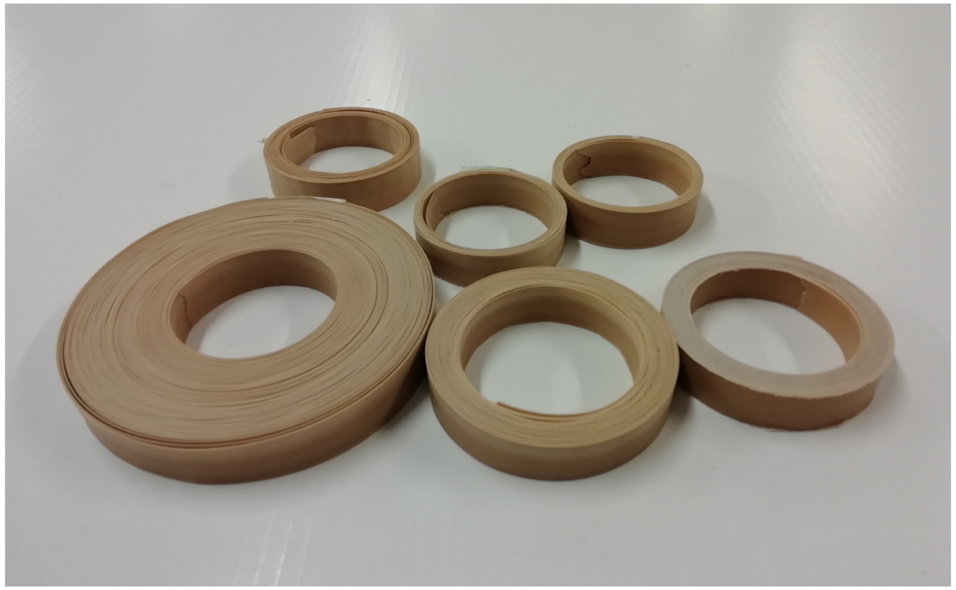
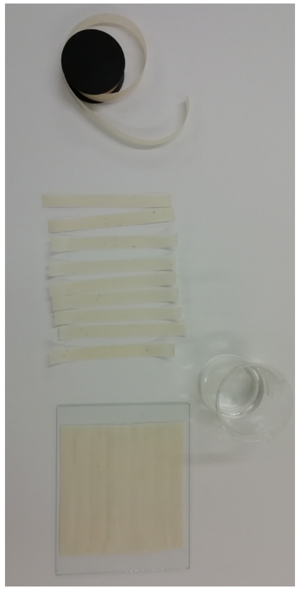


Plate Lay-up

For the plate creation, an extruded 30% cellulose tape with a thickness of 0.5mm was cut into strips of about 20cm in length. The first attempt to assemble a plate was made by wetting the edges of Poly-Paper strips and placing them side by side, trying to obtain a plate with a thickness of 0.5mm. The pairing succeeded but the result presented discontinuities and humps and being very fragile it required a long time for the assembly. In a second moment the surface was uniformly wetted and other strips of Poly-Paper of equal length were applied orthogonally, obtaining a 1mm thick plate. The whole was pressed between two rigid surfaces (glass and forex) to level the resulting slab as much as possible. In the second test, strips of 15cm in length were cut. The edges have been trimmed to favour optimal flanking between the strips. Thanks to the support of paper tape, the first dry strips were placed in such a way that there was no light between them. Subsequently, they were uniformly wetted, and a second layer was applied orthogonally. In a few minutes it was possible to handle the sheet that was passed through rollers to press it evenly. The coupling succeeded without presenting discontinuity and required a very short assembly time.



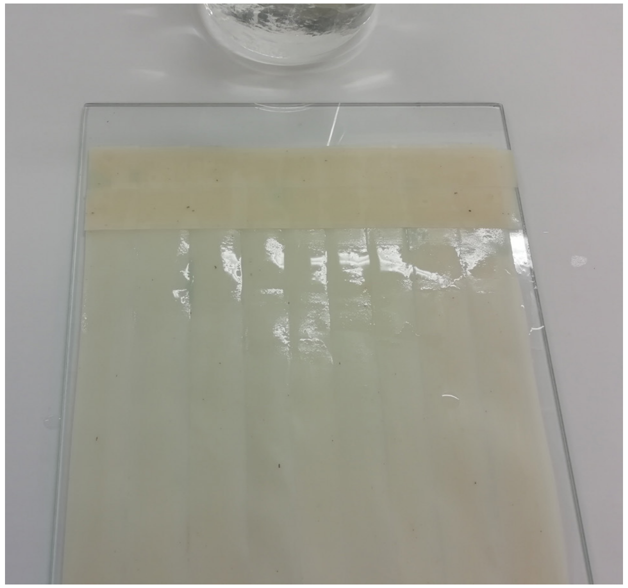
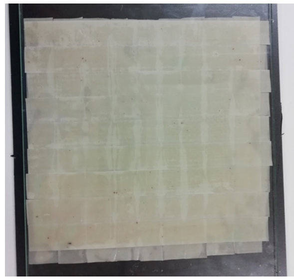
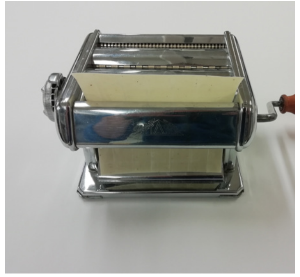
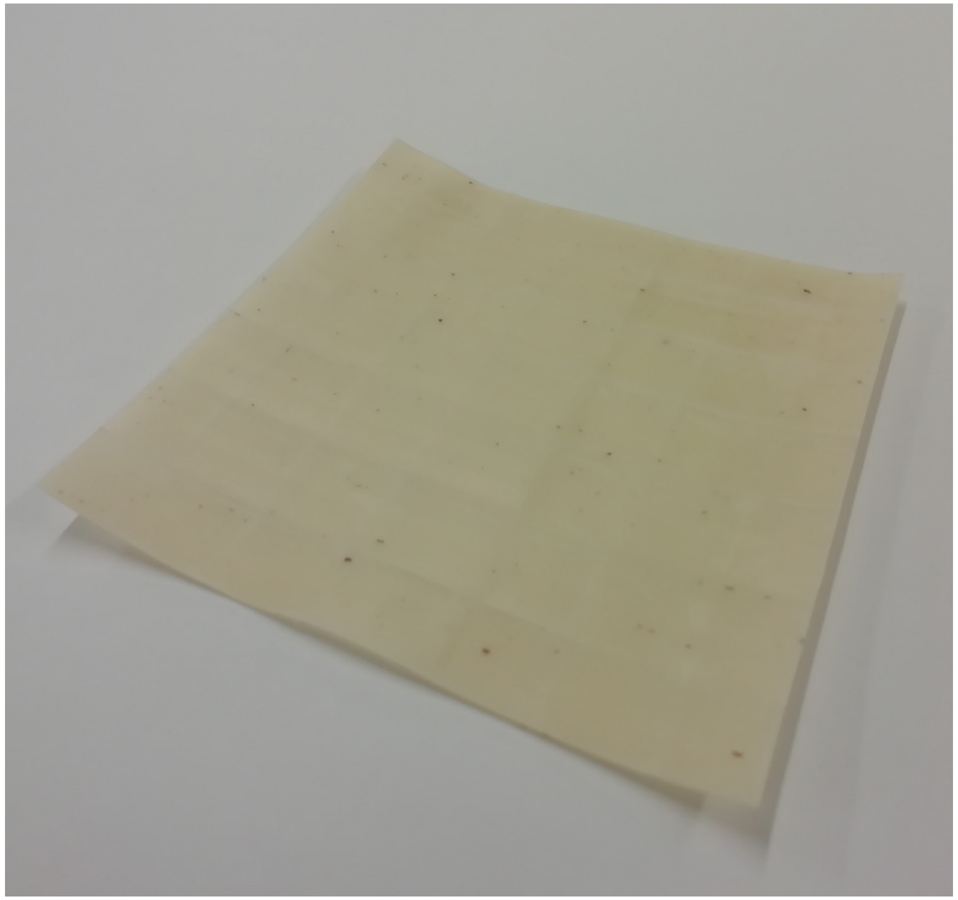


Fig.4.12 Slab Creation Step







4.4.2 3D Printing

3D printing has been used as a technology as it was the one that allowed to simulate other industrial-level technologies at best (injection molding or compression molding machines, plate extruders, etc.). It was decided to use this technology to product demonstrators that will be discussed in Chapter 8. For 3D printing, Sharebot NG1 printers have been used, with special measures to optimize the use of Poly-Paper. In fact, the material, very sensitive to humidity, prefers extruders with transmission wheels with a deeper toothing and little load on the springs of the guide bearing. In case of excessive humidity in the environment, to allow printing, the filament has undergone drying cycles at 40° C for 4/6 hours. As far as the printing speed is concerned, in order to obtain a better adhesion of the material, the printing speed used has been within a range between 25 and 40 mm/s. The design of the demonstrators considered the potential of the material by exploiting its weldability with water and then creating components that minimize the use of support material or with dimensions greater than the printing plane. The material has also been able to withstand overhang angles of up to 90° with overhangs of about 2mm without the need for support material.

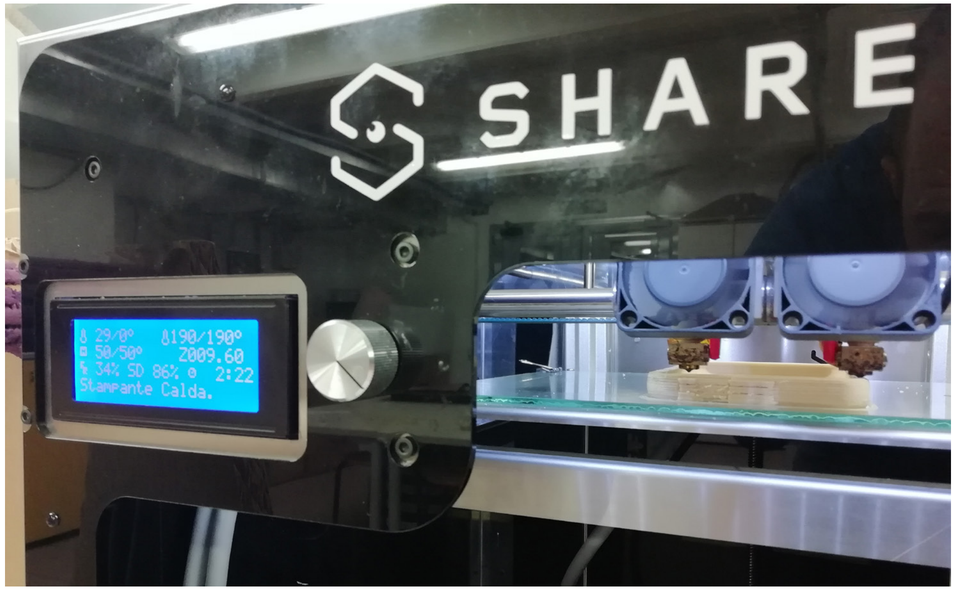
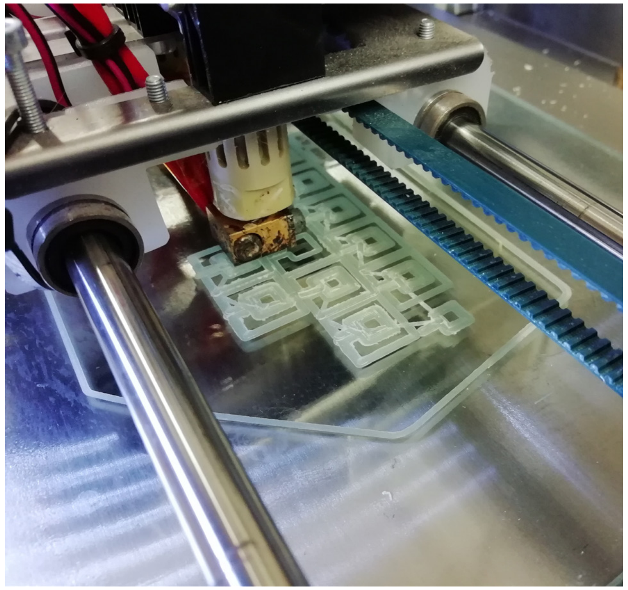
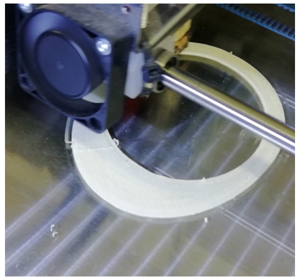
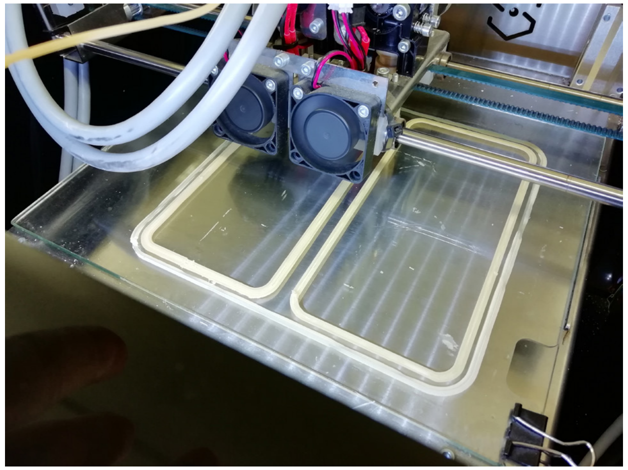
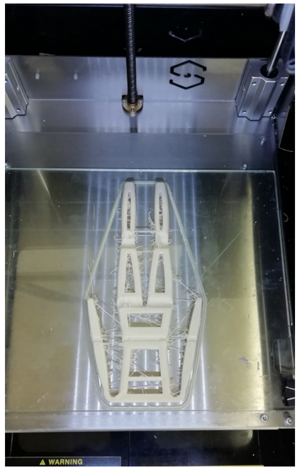


Fig.4.13 3D Printing of Poly-Paper Demonstrator









4.4.3 Thermoforming

Compression Thermoforming Tests - 30% Cellulose Tape

Compression thermoforming tests were carried out on an extruded Poly-Paper tape with 30% cellulose, with a thickness of 0.5mm cut into strips of about 10cm in length. For the test, a molded 3D PLA matrix was created with five shells of 7mm diameter and a height ranging from 1.5mm to 3.5mm. The samples were obtained by heating the material with the heating plate of the Formec 450DT thermoformer present in the Model Laboratory of the Politecnico di Milano. Once heated, the material was compressed into the matrix by applying a uniform pressure within the matrix. The power of all the plate resistors was set to the maximum. The specimens were exposed for periods of 20/30/35/40 sec while one was heated by means of a heat gun.

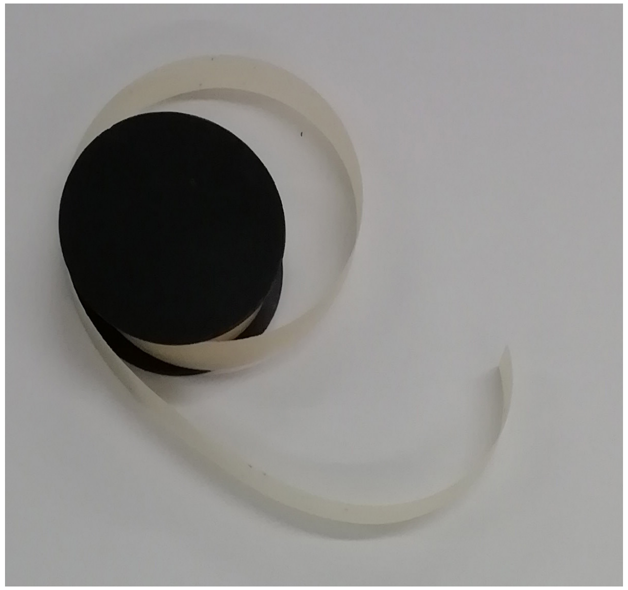


Fig.4.14 Poly-Paper_30% cellulose Tape

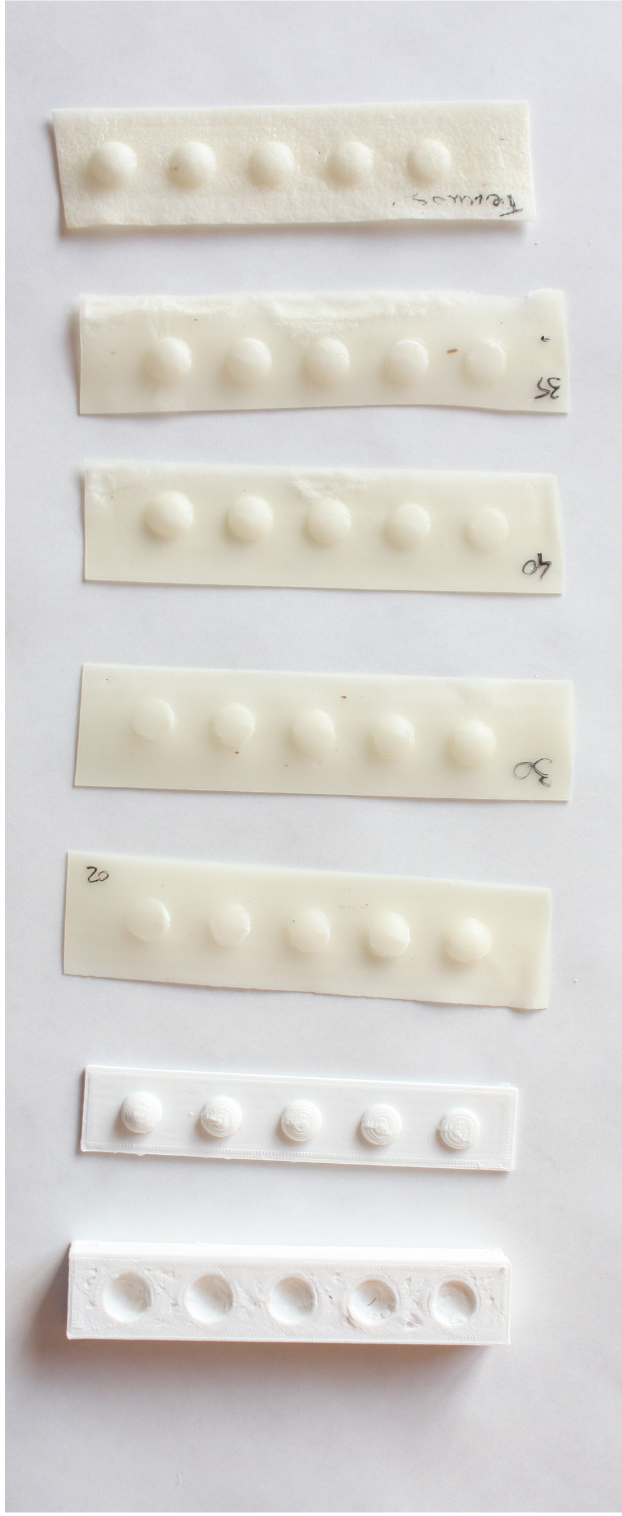


Fig.4.15 Specimens and molding matrix for compression thermoforming tests

Results - 20sec

The material, due to an initial thermal relaxation, was not able to deform and presented fractures along the base diameter of the caps. The surface did not show any variations in finishes.

Results - 30sec

The material, as a result of initial thermal relaxation, was able to deform without presenting fractures or changes in the surface appearance.

Results - 35/40sec

As a result of initial thermal relaxation, the specimen was able to deform, but areas were created in which the material started to present bubbles inside it, deforming the sample surface and expanding. On the 35sec specimen there are also breakages on the base diameter probably due to the cooling of the same during the displacement from the heat source to the matrix.

Results – Heat Gun

The material after being exposed to the jet of the heat gun for about 15/20 seconds presented a sudden expansion that changed the surface finishes of the side exposed to the flow of hot air. However, the forming has presented results with an excellent definition of detail for all the heights of the caps.

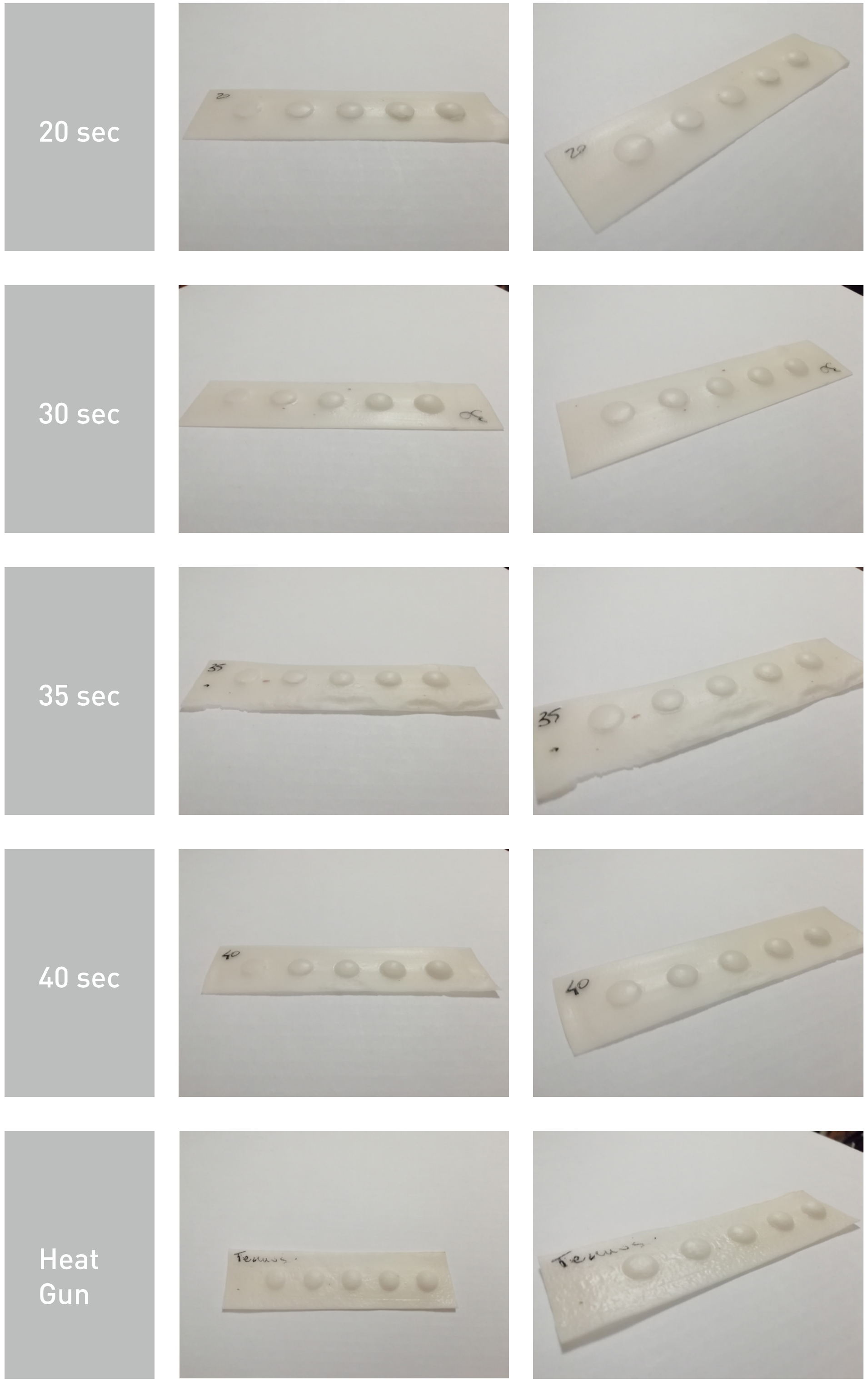
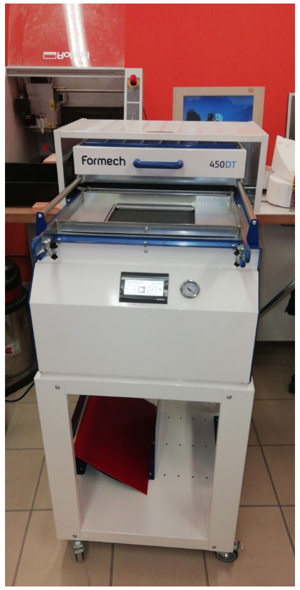


Fig.4.16 Compression Thermoforming Results

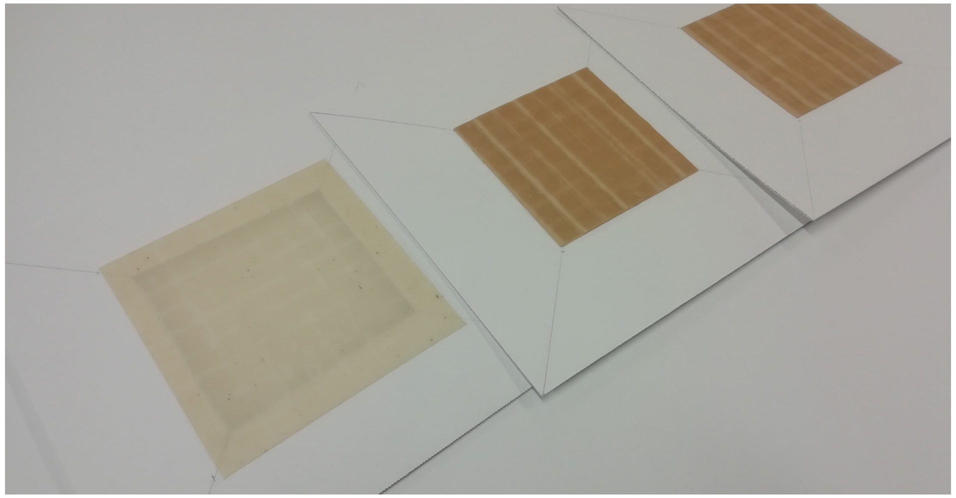


Vacuum Thermoforming Tests - 30% / 50% cellulose sheets

The plates described above have been cut into a dimension suitable to be pressed between the rollers. Subsequently, they were applied on a cardboard frame to reach the minimum area necessary to cover the thermoforming window. Three specimens were created for vacuum thermoforming: one with 30% cellulose Poly-Paper and two with 50% cellulose Poly-Paper. The plates edges applied to the cardboard window have been sealed with the aid of high temperature resistant adhesive tape to guarantee vacuum tightness. The external areas of the thermoforming heating plate have been kept at low power to avoid sagging in the tape or excessive heat on the paper part of the specimen. Hemispherical matrices have been used to ensure uniformity in material deformation and to avoid stress concentration points such as edges or concavities. A support has also been created to raise the support surface of the hemispherical matrix to avoid bending of the edges of the plate or sagging of the cardboard support.

Fig.4.17 Formec 450DT termoformer

Fig.4.18 Poly-Paper Slab Specimen



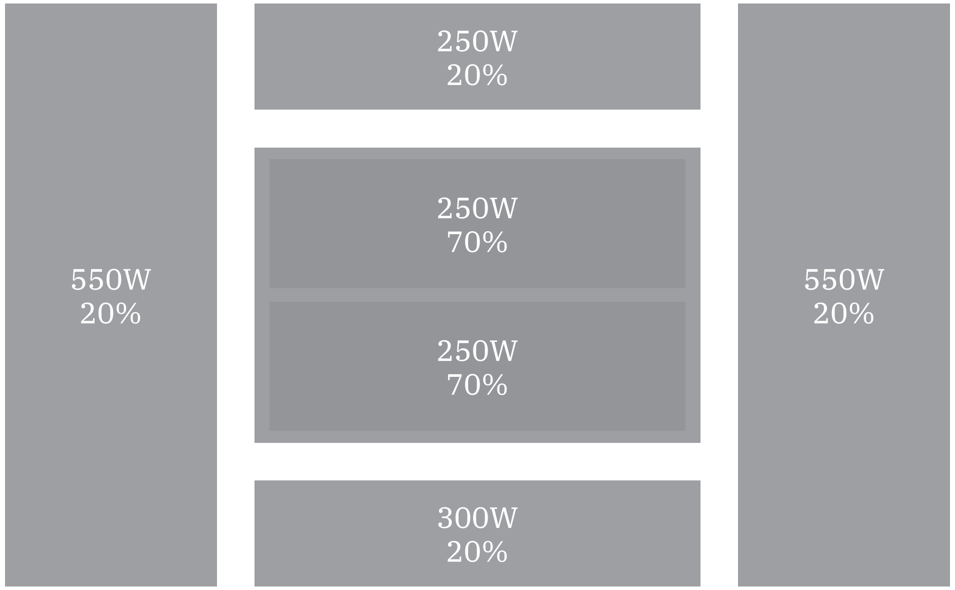


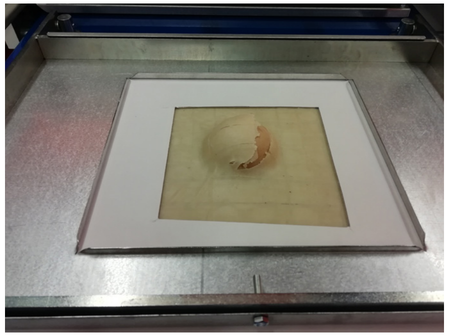
Fig.4.19 Termoformer settings

Nominal power for each zone of the thermoformer plate and percentage of power set during the tests.

Fig.4.20 Termoformer interface and values

First Test

For the first test it has been used Poly-Paper 30% cellulose with a 70mm diameter hemispherical matrix. The specimen has undergone several heating cycles before being able to be deformed. The first heating cycle lasted 35sec but the specimen was not deformable. The second heating cycle lasted 60sec and was subjected to a very short suction (1-2 sec), resulting in little deformation. Finally, for the third heating cycle, which lasted 120sec, the specimen was first moistened due to crevice formation between the joints of the strips. At about 60sec the material showed a slight elastic recovery and at 120 sec it was subjected to a 5-6sec suction until the plate was broken. During the third heating cycle the material showed a good softening state despite previous thermal cycles. The rupture may be due to the non-homogeneity of the plate, to the thermal cycles and to the size of the matrix.



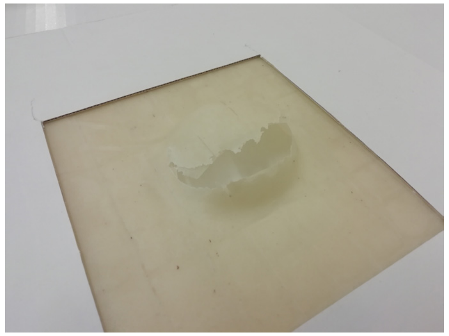
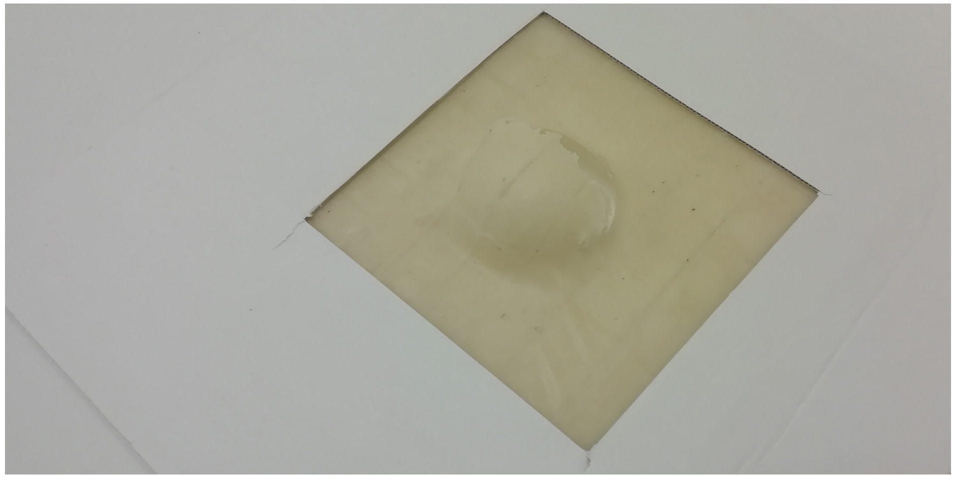


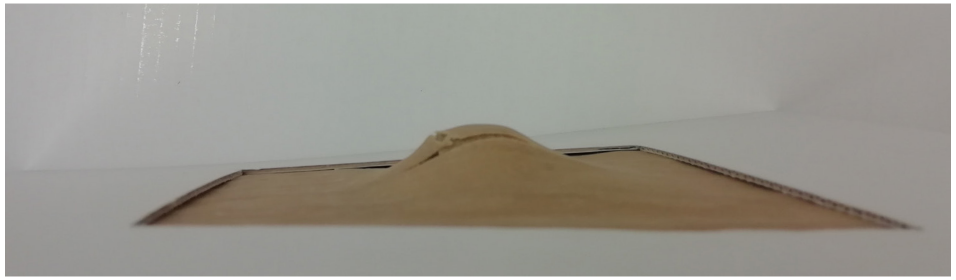
Fig.4.21 Specimen result of first test - Cellulose 30%



Second Test

For the second test it has been used Poly-Paper 50% cellulose with a hemispherical matrix of 40mm in diameter. Following the first test, the size of the die has decreased to avoid incurring the slab's failure. The specimen was subjected to two heating cycles before being able to be deformed. The first heating cycle lasted 80sec but the specimen was not very deformable, and no suction force was applied. The second heating cycle lasted 180sec, even here the specimen was first moistened due to crevice formation between the joints of the strips. At about 60sec the material showed a slight elastic recovery and at 120 sec a slight softening of the slab and finally at three minutes of heating was subjected to a suction of 3-4sec until the plate was broken. The second heating cycle was kept prolonged to soften the plate further. The material, however, presented an embrittlement probably due to the "cooking" of the cellulosic part which led to a brittle fracture of the slab at the top of the shell.

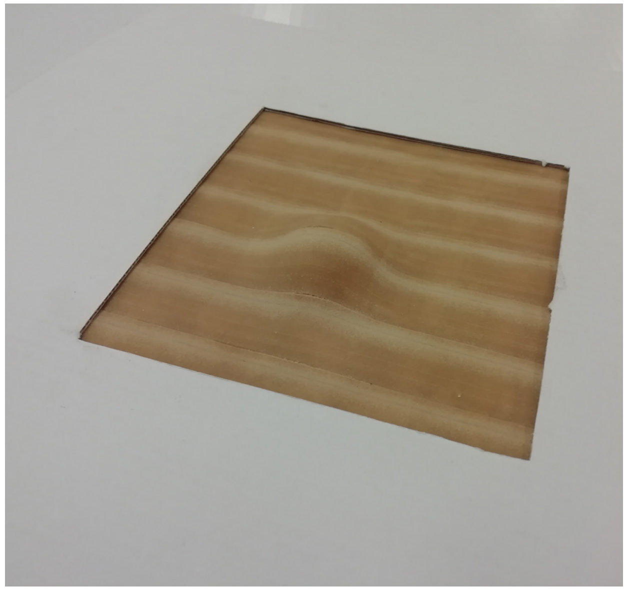
Fig.4.22 Specimen result of second test - Cellulose 50%

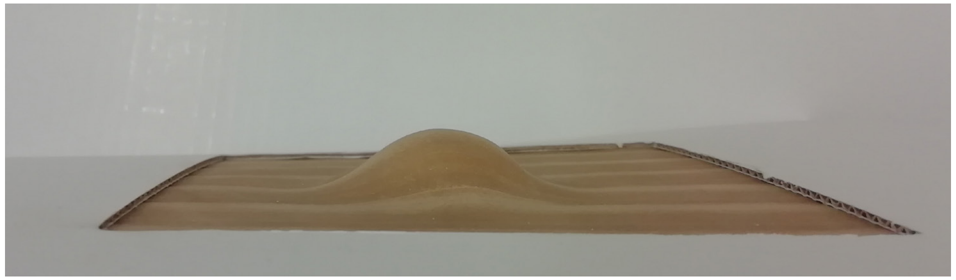


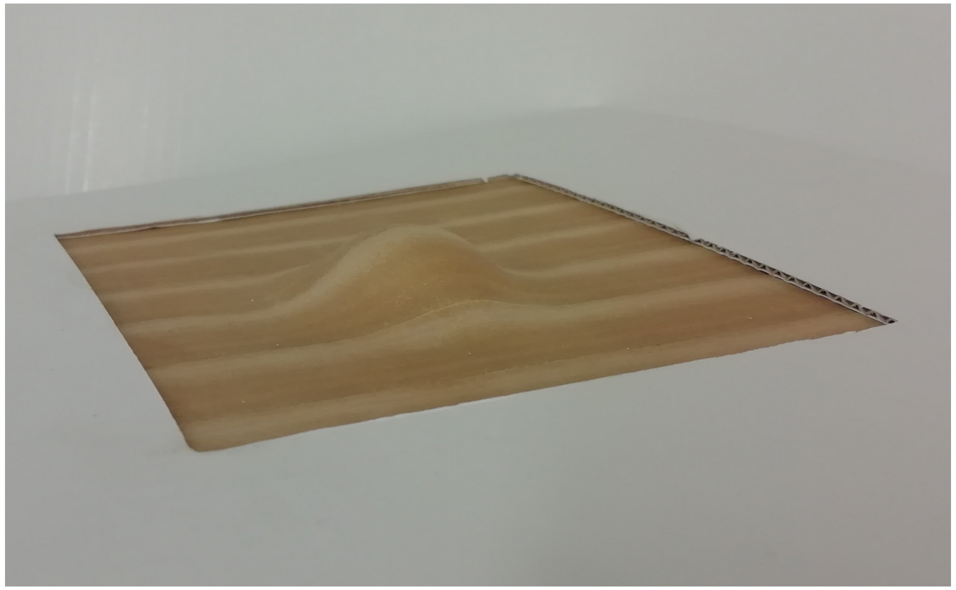
Third Test

For the third test it has been used Poly-Paper 50% cellulose with a hemispherical matrix of 30mm in diameter. Following the second test, the size of the die has been further reduced to prevent the slab from collapsing. The specimen was subjected again to two heating cycles to achieve good deformation. The first heating cycle lasted 90 seconds and was still slightly deformable by pushing with the matrix on the plate but without suction. The second heating cycle lasted 120sec after moistening the specimen due to crevice formation between the joints of the strips. At about 60sec the material showed a slight elastic recovery and at 120sec with the softening of the plate was applied suction for 4-5 s. The third test saw a deformation of the slab that was not forced to prevent failure. Although there is no presence of the detail of the base diameter of the spherical shell, the sheet has maintained the deformation without sagging once removed from the machine.

Fig.4.23 Specimen result of third test - Cellulose 50%







Final Observations

The performed tests gave satisfactory results regarding the material thermoformability. The results obtained suggest the use of the spherical matrix of smaller dimensions to increase the ratio between the useful area and the deformable area. The tests have shown a good result in terms of detail in the plate at 30% which also suggests tests with 40% cellulose slab (optimal percentage used for the 3D printing filament).

Fig.4.24 Thermoformed Poly-Paper 50% cellulose

This new interesting material in the field of novel materials for the circular economy, has been investigated from the point of view of processability and applicable technologies. We now have all the information to compare the Poly-Paper with the materials encountered up to now. The aim is to create a tool that, quantifying characteristics especially on sustainability aspects, helps to identify how this material becomes captivating into the new materials categories driven by the CE, identifying the values on which to push for its development and its possible applications in products.

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Sitography

https://www.nextmaterials.it/it/Poly-Paper/ - September 2018

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Case Studies

Case studies index

5.1 Definitions Guide

Organized into three sections embracing New Circular Materials, Biobased and Paper & Cardboard materials, each profile includes information on key features, typical applications, production processes and sustainability issues. This chapter will allow to understand in simple and visual terms the different qualities, features and applications of materials that define the scenarios in which the Poly-Paper could be inserted.

5.1.1 Materials Classification

To define the scenarios that see the application of the principles of the Circular Economy, case studies have been selected from a variety of materials that are of interest for peculiarities and applications. The materials have been subdivided into three macro-categories to better define the areas of application and development in which they are located.

Biopolymers

In the biopolymer section have been included the major biopolymer families on the market and several green composites and other materials made from biomass sources (Lefteri 2014).

Paper & Cardboards

With regard to the different types of paper and cardboard, macro-families of semi-finished products have been analysed, distinguished by their grammage, structure or production method for paper products (Attoma 2011; Serrats 2009; Yabuka 2010).

Other Circular Materials

In the Other Circular Materials section is possible to find analysed materials or products interesting for characteristics that embrace the various points treated by the Circular Economy approaches, such as lifespan elongation of products or enhancing the waste materials from different production cycles and the use in products with improved characteristics (Pellizzari and Genovesi 2018).

5.1.2 Values Definitions

In order to compare the different materials, characteristics related to the derivation of the materials, their sustainability, use, field of application and their end of life have been identified. The characteristics identified are therefore: how much the material is Biobased, Biodegradable, and what is the average lifetime expectation of the applied material to the products that mostly see it as the protagonist on today's market. These characteristics have been codified with a scale of values to allow them to be framed in a comparison matrix.

Biobased

Percentage of biological resources of which a product/material or polymer is composed.

percent	pt
100%-95%	●●●●●●●
95% - 71%	○●●●●●●
70% - 51%	○○●●●●●
50% - 31%	○○○●●●●
30% - 21%	○○○○●●●
20% - 10%	○○○○○●●
<10%	○○○○○○●

Biodegradability

Capacity of a material to degrade quickly and breaks down into carbon dioxide, water, inorganic compounds and biomass. (https://en.wikipedia.org/wiki/Biodegradation)

time	pt	
Very Fast	●●●●●●●	1 month
Fast	○●●●●●●	6months
Good	○○●●●●●	12 months
Acceptable	○○○●●●●	1-5 years
Slow	○○○○●●●	5-10 years
Very Slow	○○○○○●●	10-50 years
Unsustainable	○○○○○○●	+50 years

Lifetime Expectation

Quality and applications of the material related to the life expectancy of the product for example: mono-use, disposable, not very durable, fashion dependent, durable, very durable, etc. The definition of the time range and the scores is defined in chapter 6.2.4.

	pt
>5 years	●●●●●●●
2-5 years	○●●●●●●
1-2 years	○○●●●●●
6 months	○○○●●●●
1 months	○○○○●●●
disposable	○○○○○●●
mono-use	○○○○○○●

Compostability

Capability of the material to be composted.

yes / no

Material Source

Substances from which the materials are derived, for example: Food, Crops, Waste, Fossil based.

Commodity Sector

Areas of use of the products made by the material.

Production Methods

Common production methods for the evaluation of the sustainability of the processes.

Material Substitution

Common materials, usually fossil based, normally used for the production of products in the commodity sector.

5.1.3 Material Profile Form Definition

In the material profile form are provided information regarding the description of the material and its common applications using reference images and a summary of information provided by the manufacturers. We then assessed and quantified characteristics such as biodegradability, the percentage of biobased material and the lifetime expectation of the material.

Material Profile Form

Material Name / Designation / Trade name

exemplary images of material applications

Material description

Biobased
Biodegradability
Lifetime Expectation
Compostability y/n

Scores

Material Source

Commodity Sector

Production Methods

Material Information

Considerations about pros and cons of the material

+/-

Material Substitution

Images of material substitution

Reference

5.2 Biopolymers

Thermoplastic Starch (TPS) _Mater-bi®

Starch is available in abundance surpassed only by cellulose as a naturally occurring organic compound. Starch plastics have been designed to potentially replace petrochemical plastics. Thermoplastic starch is biodegradable, combustible and can be fabricated into finished products such as mulch film and loose fills through existing technology.
Mater-bi is a family of biodegradable thermoplastic materials made from maize starch. They are water resistent and resembles plymers made from petrol-chemicals. They retain their properties while in use, but when composted in an environment containing bacteria, they biodegrade to carbon dioxide,water and fibrous residue.

Considerations

+

Biodegradable biopolymer

-

Low durability

Biobased	●●●●●●●
Biodegradability	○●●●●●●
Lifetime Expectation	○○○○○●●
Compostability	yes

Material Source
Biomass - (maize) Starch

Commodity Sector
packaging / short-lived consumer goods / hobby and toys / household items

Production Methods
Injection molding / Blow molding / Extrusion

Material Substitution
Fossil based plastic - LDPE -PS

Reference
http://materbi.com/
Cambridge Engineering Selector (CES 2018) Software

Cellulose Acetate (CA) _Tenite®

Cellulose polymers are produced by extraction or chemical modification of natural cellulose. Rigid cellulose acetate plastics refers to thermoformed (injection moulding and extrusion) products made from cellulose esters with plasticizers. It is known for its appealing haptic properties which are used by the producers of more expensive consumer products and high-quality tools.

Biobased	●●●●●●●
Biodegradability	○○○○○●●
Lifetime Expectation	○●●●●●●
Compostability	nd

Material Source
Biomass - cellulose (cotton)

Commodity Sector
Spectacle frames / tool handles / toys / cosmetic packaging / textile

Production Methods
Injection molding / rotational molding / vacuum-forming

Considerations

+

good aesthetic and mechanical properties

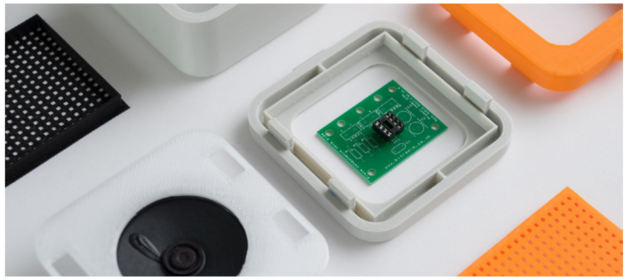
-

very susceptible to environmental stresses

Material Substitution Fossil based plastic - ABS / PC

Reference
Cambridge Engineering Selector (CES 2018) Software

Poly Lactide Acid (PLA) _Natureworks®



PLA has good mechanical properties, performing well compared to standard thermoplastics.
The hardness, stiffness, impact strength and elasticity of PLA, important for varous applications.
PLA has high odor and flavor barrier properties. It also has high resistance to grease and oil, thus finding application in the packaging of viscous oily liquids. It is also suitable for packaging of dry products and short shelf-life products.

Biobased	●●●●●●●
Biodegradability	○○●●●●●
Lifetime Expectation	○○●●●●●
Compostability	yes

Material Source
Biomass - maize / corn / sugar beets / sugar crane

Commodity Sector
Packaging / disposable items / clothes and accessories / consumer electronics / household items / furnishings

Production Methods
Injection molding / extrusion / thermoforming

Considerations

+
appearance of a common plastic

-
sustainability and biodegradability values difficult to communicate

Material Substitution Fossil based plastic - LDPE, HDPE, PP, PA and PET

Reference

Cambridge Engineering Selector (CES2018) Software

Shen, Haufe, and Patel 2009

Polyhydroxyalkanoates (PHA) _Iamnature®

Polyhydroxyalkanoates (PHAs), constituting a class of bio-based polyesters with highly attractive qualities for thermo-processing applications. They have useful mechanical properties and excellent biodegradability.
Recent developments are selling the valorisation of the origin and sustainable destination of the polymer family for uses in durable consumer goods and technical items.

Biobased	●●●●●●●
Biodegradability	○○●●●●●
Lifetime Expectation	○●●●●●●
Compostability	yes

Material Source
Biomass - bacteria fermentation

Commodity Sector
Interior design / automotive/ toys / electric appliances / multi-purpose household items

Production Methods
Injection molding/ Blow molding / Extrusion

Considerations

+

smart biodegradation - like wood in interior design

-

expensive

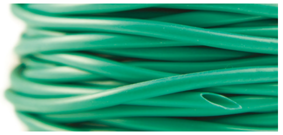
Material Substitution

Fossil based plastic - PVC, PE-HD, PE-LD and PP

Reference

https://www.maipsrl.com/greenhope/biopolimeri/la-bioplastica-iamnature

Thermoplastic Elastomer (TPE-E) _Apinat Bioplastic®



APINAT developed of a wide range of biomaterials designed to reproduce its current products with a biobased version. These products are based on raw materials from renewable natural sources and will contribute to a reduction in CO_2 and greenhouse gas emissions.

INature cover made of Apinat Bio (TPE-E)

Range of materials
Apilon - sunglass / rollers
Apigo - Toothbrush / bed parts
Megol - boot
Apinat bio - capsule / wire

Considerations

+

appearance of a common plastic

-

expensive

Biobased	○○●●●●●
Biodegradability	○○●●●●●
Lifetime Expectation	○○●●●●●
Compostability	yes

Material Source
Biomass

Commodity Sector
Clothing / Sports equipment/ Shoes / Automotive / Toys / Packaging

Production Methods
Injection molding / Extrusion / Blow bolding / Film extrusion

Material Substitution
Fossil based plastic - TPE, Silicone

Reference
https://www.apiplastic.com/prodotti/bioplastics/

Timberfill®

Timberfill filament is made of biodegradable material based on wood. The material exhibits similar mechanical features as ABS or PLA and models printed with this material have a genuine appearance of wood.

Biobased	○●●●●●●
Biodegradability	○○●●●●●
Lifetime Expectation	○○○●●●●
Compostability	nd

Material Source
Biomass (PLA) + wood

Commodity Sector
3D printed objects and gadget

Production Methods
3D printing

Considerations

\+
aesthetic that recalls wood

\-
material only for 3D printing

Material Substitution

Fossil based plastic - ABS
Bio based plastic - pure PLA

Reference

https://fillamentum.com/products/fillamentum-timberfill-cinnamon

Orange Peel®

This by-product of the fruit juice industry is a renewable and compostable material that turn uncommon waste and biomaterials into manufacturable new forms. APeel by Alkesh Parmar is a concept material that use only natural sources and organic binders.

Biobased	●●●●●●●
Biodegradability	●●●●●●●
Lifetime Expectation	○○●●●●●
Compostability	yes

Material Source
Waste - orange peels

Commodity Sector
Household items

Production Methods
Mouldable

Considerations

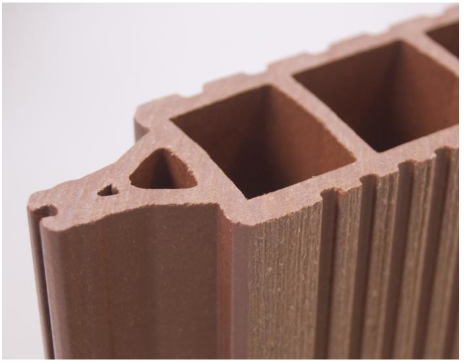
+
100% sustainable

-
concept material

Material Substitution Fossil based plastic

Reference
Lefteri 2014

Arboform® _Liquid Wood



ARBOFORM®, a thermoplastic granule composed of lignin, a compound which makes up 30 % of every wood plant, and natural fibres (e.g. flax and hemp), which can be processed at raised temperatures just like an synthetic thermoplastic material. It is comparable to the standard synthetic thermoplastic materials in terms of tensile stress and impact strength. It also has similar mechanical and thermal properties like natural wood and thus combines the positive properties of natural wood with the processing capabilities of thermoplastic materials.

Biobased	○●●●●●●
Biodegradability	○○○●●●●
Lifetime Expectation	○●●●●●●
Compostability	yes

Material Source
Biomass - Lignin and natural fibers

Commodity Sector
Automotive / Interiors / Toys / personal objects / Sport equipment

Production Methods
Injection moulding / extrusion / deep drawing / pressing.

Considerations

+
high sustainability

-
brittle material

Material Substitution Fossil based plastic

Reference

http://www.spin-project.eu/index.php?node_id=58.43&lang_id=1
https://dornob.com/liquid-wood-fantastic-100-organic-bio-plastic-material/

Fluidsolid®

FluidSolids produce biodegradable composite materials that use residuals and waste materials to reduce the environmental impact. Biocomposites made using the FluidSolids technology feature exceptional mechanical properties, making them suitable for use in countless application areas.

Biobased	○○●●●●●
Biodegradability	○○○●●●●
Lifetime Expectation	○●●●●●●
Compostability	nd

Material Source
Waste - residuals and waste materials + softwood or cellulose

Commodity Sector
Furnishings / household items

Production Methods
Compression molding / injection molding / extrusion

Considerations

\+
biodegradable

\-
currently only available from limited supplyers

Material Substitution Fossil based plastic

Reference

https://www.fluidsolids.com/en/about/media/

https://www.architonic.com/en/project/fluidsolids-products/5104396

Jelu-Plast®

_greencomposite

The Jeluplast green composite consist of mixtures of biobadsed polymers (PLA / TPS) with cellulose or other types of wood fibers contents. These green composites are used in different applications such as disposable products, bottles and cutlery. Some of these objects declare conspicuously their part biologically derived underlining and emphasizing the trend of the sustainability.

The compostable cups are foodsafe and used in catering. The WPC granulate from JELU consists of TPS and 50% wood fibres.

Considerations

+

addition of color to the characteristic finish of WPC products

-

Low durability

Biobased	●●●●●●●
Biodegradability	○○●●●●●
Lifetime Expectation	○○○○○●●
Compostability	yes

Material Source
Biomass - TPS + wood fibres

Commodity Sector
Food and packaging

Production Methods
Compression molding /
Injection molding

Material Substitution Fossil based plastic - PS

Reference
https://www.jeluplast.com/en/

Natureplast®

The objective is to incorporate by-products or local waste material in different biosourced polymers to work on the concept of a circular economy and reclamation of waste material.
These fields were chosen for their industrial viability, in terms of volumes and quality (reproducibility of batches). These by-products are sourced primarily from agro-food industries, like shellfish, algae, fruits and vegetables, etc.; and from the agricultural field, like plant fibres (wood, flax, hemp, miscanthus, reed, bamboo), and grains (wheat, corn, etc.)

Biobased	
Biodegradability	
Lifetime Expectation	
Compostability	yes

Material Source
Waste + biosourced polymer

Commodity Sector
Packaging / household items / stationery

Production Methods
Injection molding

Considerations

+

biobased from waste

-

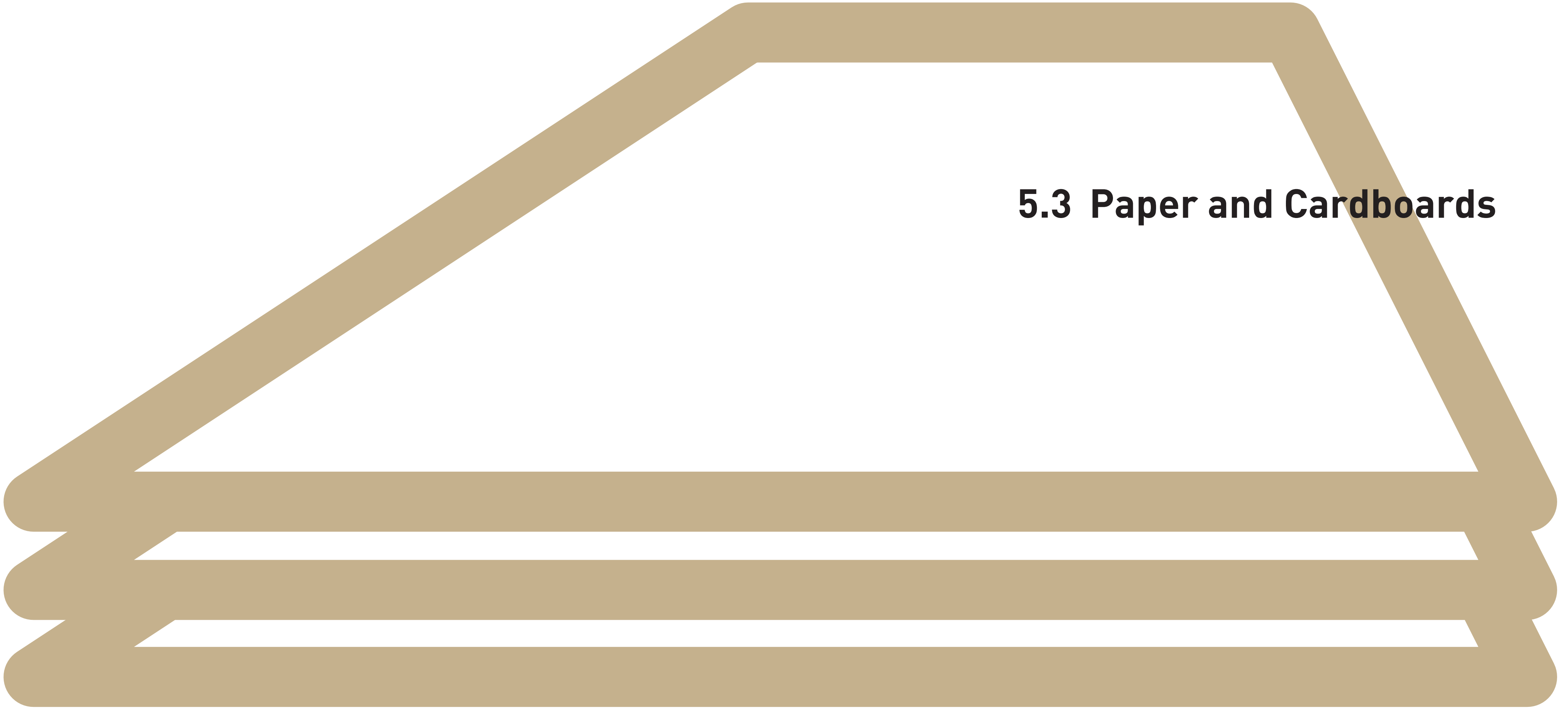
variable characteristics dependent on the reinforcement material

Material Substitution Fossil based plastic

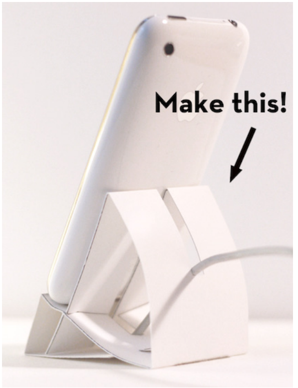
Reference

http://natureplast.eu/it/fornitore-di-bioplastiche/fibre-biocomposite-e-co-prodotti-commercialisation/

5.3 Paper and Cardboards



Paper



The paper is used in products that exploit its aesthetic and material properties as in the case of jewels, providing countless possibilities of colors and workmanship, re-workability as in the case of the Cabbage Chair, which from a waste product of paper processing obtains an object with a strong stylistic connotation up to exploit the optical properties of the material from the low grammage which serves as a lampshade as in the case of Regolit lamp IKEA.
The application of the paper in these objects has in common a not very long life expectancy and do not subject the material to stresses that tend to wear it giving a “delicate” appearance to the object.

Considerations

+

cheap, light and easy available

-

weak, vulnerable to water

Biobased	
Biodegradability	
Lifetime Expectation	
Compostability	yes

Material Source
Virgin paper

Commodity Sector
Packaging / Clothes and accessories / personal objects / Furnishing

Production Methods
cutting / gluing / folding / printing

Reference

www.nendo.jp/en/works/cabbage-chair-2/

www.ikea.com/us/en/catalog/products/70103410/

Paper Board

The paper board, with a slightly higher grammage than the paper, is used in products that, thanks to folds and gluing, they manage to create complex volumes in a very economical way as in the case of the origami lamps or the eco amp. As for the paper another example is given by Sandra di Giacinto that using bookbinding materials, canvas panels, or recycled cardboard has reinterpreted traditional Italian contemporary aesthetics, where design configures as an element of innovation.

Considerations

+

dimension and shape of the artifacts

-

not very resistent

Biobased

Biodegradability

Lifetime Expectation

Compostability yes

Material Source
high quality grades recycled paper

Commodity Sector
Packaging / Disposable product / Clothes and accessories / Consumer electronics / Furnishing

Production Methods
cutting / gluing / folding / printing

Reference

www.sandradigiacinto.it
https://design-milk.com/eco-amp-by-eco-made/

Carton Board

The carton board, thanks to its hig grammage (from 450 to 1100 g/m2) is able to be used for applications that can also respond to structural functions, for installations or objects of small or medium size. Miwa Takabayasy gived an example with Packaged. It is a large scale folded architectural installation that embodies traditional Japanese paper folding but also underline the modern mass market incarnation and contemporary industrial packaging techniques. Another example is given by the samsung cardboard mono laser printer. The product is a cardboard form that is realized using an origami-based assembly method. The 100% recycled material is cut out based on a planar figure, and the subsequently folded in order to shape the exterior of the box in which the mechanics and engine unit of the printer are placed. The employed paper-folding technique offers a structurally sound and durable shell which is comparable to those provided by typical printers made from plastic, as well as uncompromised printer functionality.

Biobased
Biodegradability
Lifetime Expectation
Compostability yes

Material Source
good quality grades paper

Commodity Sector
Packaging / disposable product / hobby / consumer electronicsc / architectural installations

Production Methods
cutting / gluing / folding (origami) / joints

Considerations

+

resistent and recyclable

-

not very durable appearance of the products

Reference

Yabuka 2010

https://www.designboom.com/technology/samsung-eco-conscious-origami-cardboard-mono-laser-printer/

Chipboard

Chipboard is a paperboard, thicker than cardboard, used for backing sheets on padded writing paper, partitions within boxes, shoeboxes, etc. Multilayer chipboard can also be used to manufacture spiral wound paper tubes that are used as a structural element in cardboard architectures like in the Public farm 1 designed by the WORK Architecture Companiy in 2008.

The ONEMI Radio is an example of good design for social impact. Designed by yanko design for ONEMI, Chile's National Emergency Office, the radio is a way to ensure the safety of civilians during a natural calamity. A cheap, portable, and effective radio that can allow the government to communicate with the national population, giving it proper advice during a state of emergency. The radio's cardboard construction allows it to be folded so it can be stored (as well as distributed) easily.

Considerations

+

applications in sectors that tend not to be paper-related

-

little formal variety in products

Biobased

Biodegradability

Lifetime Expectation

Compostability yes

Material Source
Low grade recycled paper

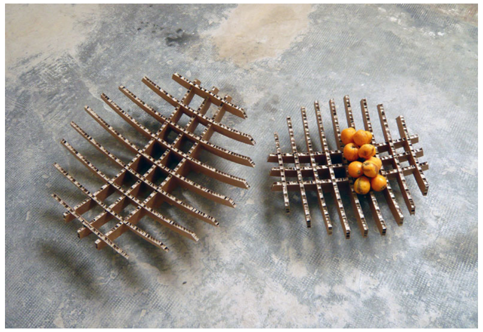
Commodity Sector
Personal objects and toys / consumer electronics / Furnishing / Architecture

Production Methods
Gluing / joints / screwing / pressed, waxed and sealed

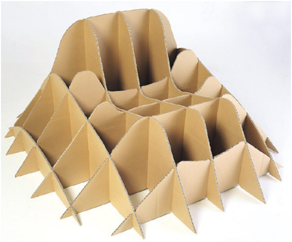
Reference

Yabuka 2010
http://www.publicfarm1.org/
https://www.yankodesign.com/2016/05/05/a-revolutionary-radio/

Corrugated board








The corrugated board for its particular structure result very cheap and resistent. It is employeed in a large variety of products that exploit it in different ways for its characteristics, from the formal material experimentation, as in the case of the wiggle side chair, designed in 1972 by Gehry to the degradability as in the case of the Terra Armchair of the Studio Nucleo. Other examples use it to create furniture and light structures, like gruff set or A4Design, or incorporate electronic components to create objects or games that amplify the product experience, as in the case of the Nintendo Labo.

Considerations

+

_ wide possibilities of applications
_use of architectural techniques for the construction of structures
_much less durable than other materials

-

_overrated lifetime expectation
_often combined with difficult or non-recyclable materials
_low cost aesthetic

Biobased	○●●●●●●
Biodegradability	○○○●●●●
Lifetime Expectation	○○○●●●●
Compostability	nd

Material Source
good quality grades paper

Commodity Sector
Sports equipments / toys / consumer electronics / household items / furnishings / outdoor applications

Production Methods
Gluing / stacking / ribbing / printing

Reference

http://www.a4adesign.it/index.php?&lang_id=1
https://www.arnomathies.com/#gruff-set-2
https://www.vitra.com/en-us/product/wiggle-side-chair
https://labo.nintendo.com/kits/variety-kit/

Honeycomb Cardboard

Paper honeycomb sandwich panel is composed of two pieces of face-paper and a piece of core paper which thickness that can be cut to a suitable size in practical application ranging from 8 up to 110 mm. It finds applications, in addition to the protective packaging sector, in the furnishing sector with excellent results in terms of cost / performance ratio, as in the case of the Cardboard office for Elegangz by Paul Caudamy. Thanks to its sturdy structure and its ability to absorb shocks, projects have been developed or are under development, such as EcoHelmet, cardboard bikes or wheelchairs.

Considerations

\+

_good mechanical properties

\-

_overrated lifetime expectation
_low cost aesthetic

Biobased
Biodegradability
Lifetime Expectation
Compostability yes

Material Source
good quality grades paper

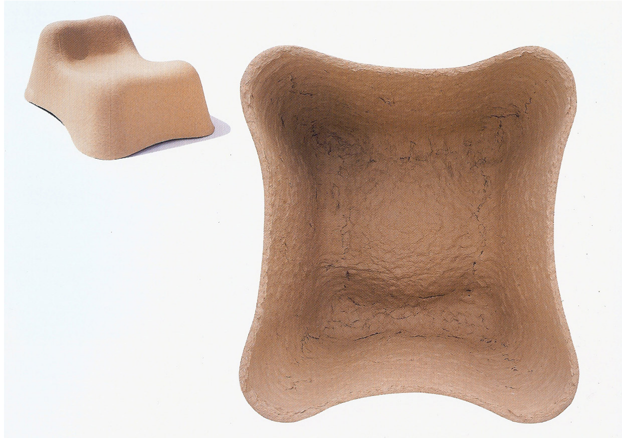
Commodity Sector
sports equipments /
furnishing/ veichles

Production Methods
stacking

Reference

http://coudamyarchitectures.com/en/architecture/cardboardoffice/
https://www.cardboardtech.com/
https://www.ecohelmet.com/

Molded Pulp



Molded Pulp is mostly a packaging material, made up of cellulose typically obtained from recycled paperboard and/or newsprint providing a useful outlet for industrial and post-consumer paper waste. Developments in the quality aspect of the products made of this material, starting from the thick wall molding process (the oldest and rough one) to the thermoformed fiber process (the most recent and fine one), are leading to the creation of increasingly detailed objects that can be inserted into product categories with an higher life expectancy. Examples of these applications include David Gardener's Pakaging Lamp or Kazutoshi's Mold Chair for durable products, and the 360°paper bottle, a premier pulp packaging used as a solution for consumer packaged goods.

Considerations

+

Recyclable Low-Cost Products

-

Coarse appearence

Biobased

Biodegradability

Lifetime Expectation

Compostability yes

Material Source
Low grades quality paper

Commodity Sector
Packaging / Disposable Products / Furnishing

Production Methods
Transfer Molding / Thermoformed Fiber

Reference

http://www.davidgardener.co.uk/?p=70
https://www.kadltd.jp/project-14-mould
https://paperwaterbottle.com/

5.4 Other Circular Materials

Accoya wood®

High performance wood designed for outdoor use and challenging applications. It has properties designed to match or exceed those of the best tropical hardwoods and treated woods. Long-established wood modifcation technique through the acetylation process, where part of wood that readily bonds with water is replaced by acetyl groups which are naturally occurring especially in the more durable wood species. Thus, the acetylation process mimics nature, and without adding any toxic substances, it ensures performance and material health to the highest level possible under C2C standards.

Considerations

+

sustainability linked to the extension of product life

-

Not immediate perception of the qualities of the material

Biobased
Biodegradability
Lifetime Expectation
Compostability yes

Material Source
Radiata Pine & Alder Wood

Commodity Sector
Windows/doors/decking/cladding/bridges/boats

Production Methods
Acetylation

Material Substitution Untreated wood

Reference

https://www.accoya.com/sustainability/
https://www.c2ccertified.org/products/scorecard/accoya_wood_radiata_pine_alder

Bayonix bottle®

Drinking bottle constructed exclusively from a special polymer, designed to be safe for biological cycles. 100% biodegradable and 100% recyclable, safe for humans, society, water and the environment. The recyclable sports bottle was born from the idea of offering people a durable and environmentally friendly alternative to disposable plastic with the aim of freeing the environment as well as humans and animals from disposable products.

Considerations

+

100% biodegradable
100% recyclable

-

Fossil Based polymer

Material Substitution PET

Biobased	
Biodegradability	
Lifetime Expectation	
Compostability	yes

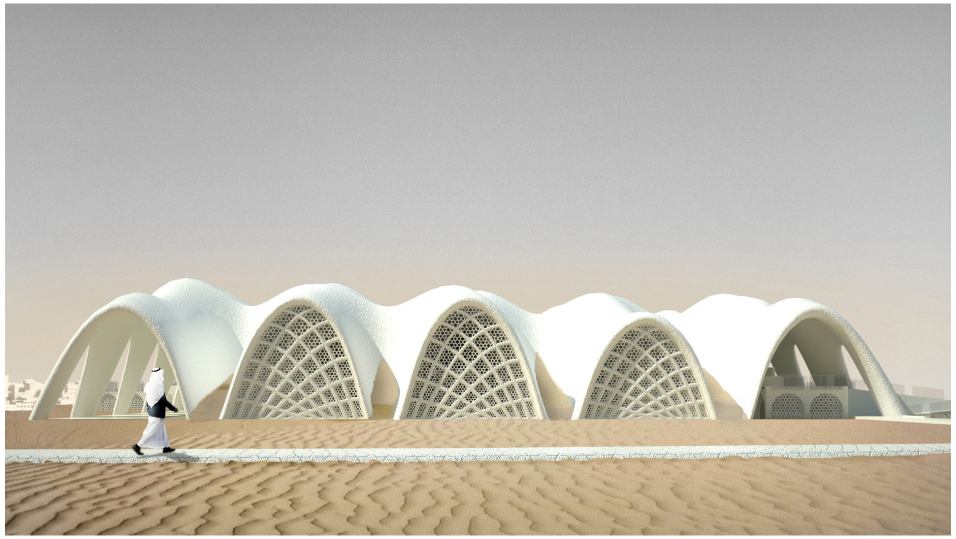
Material Source
Petroleum based polymer

Commodity Sector
Personal / Sport bottles

Production Methods
Injection moulding

Reference
https://bayonix.com/

The salt pup®



The Salt Project use locally available resources to create architecture without producing waste. A mixture of almost 90 percent sea salt, a small about of starch and water is heated and dried, leaving a white, hard, translucent material. The Salt Pup is a prototype. The ultimate goal is to use the composite in architecture.

Biobased
Biodegradability
Lifetime Expectation
Compostability nd

Material Source
Sea salt & TPS

Commodity Sector
Architecture / Furniture

Production Methods
Molding

Considerations

+
100% from natural resources

-
Prototype material

Material Substitution Concrete

Reference

http://buildingwithseawater.com/#insta
http://www.newmaterialaward.nl/en/nominations/the-salt-pup

Qmilk®

Qmilk fibers are 100% natural, soft and smooth as silk and skin friendly. With a natural antibacterial effect and high hydrophilicity, they provide added value of the fiber products in the growth market. Qmilk is the only natural fiber which has thermo-bonding properties. Thus, natural fibers can also be combined without conventional plastics or phenolic resins remaining 100% biobased making it also compostable.

Biobased	●●●●●●●
Biodegradability	○○●●●●●
Lifetime Expectation	○○●●●●●
Compostability	yes

Material Source
Waste - Milk

Commodity Sector
Wearable, household linen, monouse products

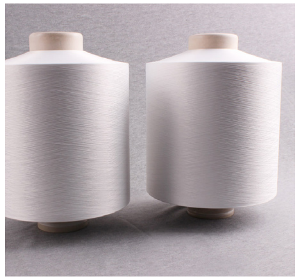
Production Methods
Yarn

Considerations

+
raw material from waste

-
available from limited supplier

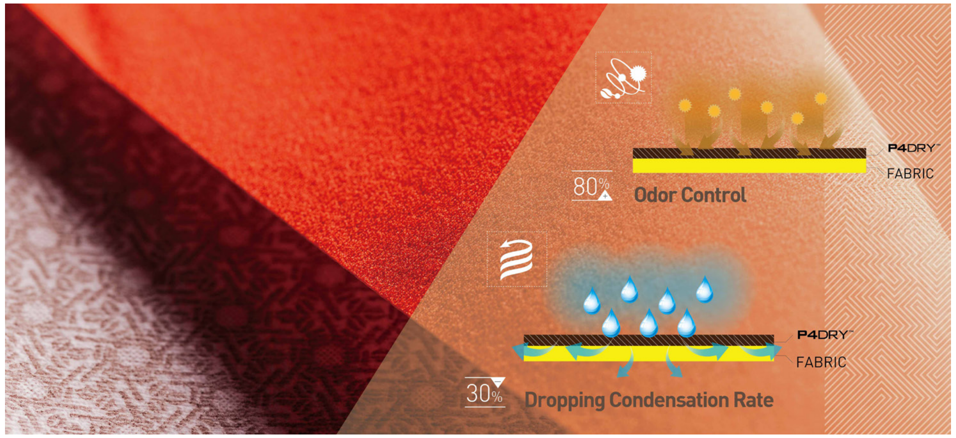
Material Substitution Synthetic fibers



Reference

https://www.qmilkfiber.eu/?lang=en
http://www.qmilkfiber.eu/faser-technische-anwendung?lang=en

S.Cafè®



It is a polyester fiber for the production of clothing additivated with coffee grounds that are used as a sanitizing additive with anti-odor properties. Born from an experimental chain of recycling that sees the upstream collection of roasted coffee grounds, provides a specific processing that eliminate substances such as phenols, esters and oils and convert the material into active carbons which are added to the molten polymer mixture to create the yarn with the anti-odor properties.
A low-temperature, high-pressure and energy saving process, combines coffee grounds onto the yarn surface, changing the characteristics of the filament, and offers up to 200% faster drying time compared to cotton.

Considerations

\+

raw material from waste

\-

additive on a not biodegradable material

Biobased	○○○○○●●
Biodegradability	○○○○●●●
Lifetime Expectation	○○○●●●●
Compostability	no

Material Source
Waste - Coffee ground

Commodity Sector
Outdoor and sports performance apparel / household items

Production Methods
Yarn

Material Substitution
Synthetic fibers

Reference
http://www.scafefabrics.com/en-global/about/development
http://www.scafefabrics.com/en-global/about/particular

Acrodur®

Acrodur® is a binding agent for natural, synthetic and glass fibers. As a water-based system, Acrodur offers an alternative to formaldehyde-containing or solvent-based resins and therefore guarantees safe, simple and ecological handling. this resin is used in driving sectors such as furniture and automotive, with the aim of replacing unsustainable materials

Werner Aisslinger presents with MOROSO the worldwide first natural fibre mono-chair designed with a brand new new technology: Natural fibres like hemp are moulded under heat with a special ecological glue into a new natural and sustainable composite material, developed in cooperation with BASF Acrodur.

Considerations

+
good mechanical properties

-
difficult biodegradability

Biobased	ooooooo
Biodegradability	ooooooo
Lifetime Expectation	ooooooo
Compostability	nd

Material Source
biomass - non wood fibers + bio acrilic resin

Commodity Sector
Personal Object/ Furniture / Veichles / Architecture

Production Methods
Compression / injection molding

Material Substitution Fossil based polymers

Reference

https://www.aisslinger.de/hemp-chair/
https://www.basf.com/us/en/products-and-industries/General-Business-Topics/dispersions/Products/acrodur.html

IKEA Patented Material _Odger chair

Reclaimed wood chips and recycled plastic were both used to create the Odge IKEA chair., using a mixture that is 70 per cent polypropylene and 30 per cent wood chips derived from IKEA wood processing waste.
Initially developed for the production of ikea pallets, it turns out to be a good example of the application of valorization of waste materials

Biobased	○○○○●●●
Biodegradability	○○○○○○●
Lifetime Expectation	●●●●●●●
Compostability	no

Material Source
Waste - wood chips + polypropilene

Commodity Sector
Furniture

Production Methods
Injection molding

Considerations

\+
optimization of production waste as a reinforcement material

\-
misleading materiality

Material Substitution Glass fiber reinforced plastic

Reference

https://www.dezeen.com/2017/11/13/ikea-form-us-with-love-odger-recycled-wood-plastic-sustainable-chair/

Jelu-Plast®
_biocomposite

The Jeluplast biocomposite consist of mixtures of fossil badsed polymers (PP / PE) or biomass debris (PE / PLA / TPS) with cellulose or other types of wood fibers contents. These biocomposites are used in different applications such as household items, toys but also fashion and automotive. Some of these objects declare conspicuously their part biologically derived underlining and emphasizing the trend of the sustainability.

Biobased	○○○○●●●
Biodegradability	○○○○○○●
Lifetime Expectation	○○●●●●●
Compostability	no

Material Source
50% non biodegradable polymers (fossil or biobased) + 50% wood fibre content

Commodity Sector
Household items, fashion, toys, personal objects, automotive, outdoor

Production Methods
Compression molding / Injection molding

Considerations

+
use of biofibres

-
misleading materiality

Material Substitution Nylon, polyester, wood etc.

Reference
https://www.jeluplast.com/en/

5.5 Poly-Paper

Poly-Paper

Polypaper is a hybrid of polymeric and cellulose material created with the aim of introducing a polymeric material, compatible with hot forming technologies. It can be inserted alongside the paper and cardboard recycling chain thanks to the hydro soluble matrix of PVA (polyvinyl-alcohol). The Polypaper presents numerous and curious technological properties like the shape memoy forming, the Self Healing or weldability by water and the hand smoothing.

Considerations

+

processability of a polymer

compatible with paper

-

sensitive to moisture

Biobased

Biodegradability

Lifetime Expectation

Compostability yes

Material Source
Cellulose + PVA (fossil base polymer)

Commodity Sector
- (3D printing)

Production Methods
Extrusion / Injection Molding

Reference
https://www.nextmaterials.it/it/polypaper/

5.6 Tables of materials

In the following pages there are tables summarizing the profiles of the materials to allow a first visual comparison between the materials belonging to each category and compare the results.

Tab.5.1 Biopolymers Properties

BIOPOLYMER	biobased	bio degradability	lifetime expectation	compostability		material source	commodity sector	production methods	material substitution
Thermoplastic Starch - TPS (Materbi®)	●●●●●●●	○●●●●●●	○○○○○●●	yes		biomass - starch (maize starch)	packaging / short-lived consumer goods / hobby and toys / household items	injection molding / Blow molding / extrusion	Fossil based plastic - PS - Fossil based plastic - LDPE
Cellulose Acetate CA (Tenite®)	●●●●●●●	○○○○○●●	○●●●●●●	X		Biomass - cellulose (cotton)	spectacle frames / tool handles / toys / cosmetic packaging / textile	injection molding / rotational molding / vacuum-forming	Fossil based plastic - PE / PC
Poly Lactide Acid PLA (Nature Works®)	●●●●●●●	○○●●●●●	○○●●●●●	yes		Biomass - maize / corn / sugar beets / sugar crane	Packaging / disposable items / clothes and accessories / consumer electronics / household items / furnishings	injection molding / extrusion / thermo-forming	Fossil based plastic - LDPE, HDPE, PP, PA and PET
Polyhydroxy Alkanoates-PHA (Mirel®)	●●●●●●●	○○●●●●●	○●●●●●●	yes		biomass - bacteria fermentation	interior design / automotive / toys / electric appliances / multi-purpose household items	injection molding/ blow molding / extrusion	Fossil based plastic - PVC, PE-HD, PE-LD and PP
TPE-E (Apinat Bioplastic®)	○○●●●●●	○○●●●●●	○○●●●●●	yes		biomass	Clothing / Sports equipment/ Shoes / Automotive / Toys /Packaging	injection molding / extrusion / blow bolding / film extrusion	Fossil based plastic - TPE, Silicone
Timberfill®	○●●●●●●	○○●●●●●	○○○●●●●	X		biomass (PLA) + wood	3D printed objects	3D printing	Fossil based plastic - ABS / Bio based plastic - pure PLA
Orange Peel	●●●●●●●	●●●●●●●	○○●●●●●	yes		waste - orange peels	household items	mouldable	Fossil based plastic
Arboform® Liquid Wood	○●●●●●●	○○○●●●●	○●●●●●●	yes		biomass - Lignin and natural fibers	Sport Equipment / personal object / Interiors / automotive / Toys	injection moulding / extrusion / deep drawing / pressing.	Fossil based plastic
Fluidsolid®	○○●●●●●	○○○●●●●	○●●●●●●	X		waste - residuals and waste materials + softwood or cellulose	household items / furnishings / architectural installations	compression molding / injection molding / extrusion	Fossil based plastic
Jelu-Plast® Green composite	●●●●●●●	○○●●●●●	○○○○○●●	yes		biomass - TPS and wood	disposable products / food	compression molding / injection molding	Fossil based plastic - PS
Natureplast®	○●●●●●●	○○●●●●●	○○○●●●●	X		Waste + biosourced polymer	packaging / household items / stationery	injection molding	Fossil based plastic

PAPER & CARDBOARDS	biobased	bio degradability	lifetime expectation	compostability		material source	commodity sector	production methods	material substitution
Paper	●●●●●●●	●●●●●●●	○○○●●●●	yes		virgin paper	Packaging / Clothes and accessories / personal objects / Furnishing	cutting / gluing / folding / printing	
Paper Board	●●●●●●●	○○●●●●●	○○○●●●●	yes		high quality grades paper	Packaging / Disposable product / Clothes and accessories / Consumer electronics / Furnishing	cutting / gluing / folding / printing	
Carton Board	●●●●●●●	○○●●●●●	○○○○●●●	yes		good quality grades paper	Packaging / disposable product / hobby / consumer electronics / architectural installations	cutting / gluing / folding (origami) / joints	
Chipboard	●●●●●●●	○○○●●●●	○○○●●●●	yes		low grades quality paper	Personal objects / consumer electronics / Furnishing /veichles / architecture	Gluing / joints / screwing / pressed, waxed and sealed	
Corrugated Board	○●●●●●●	○○○●●●●	○○○●●●●	n/d		good quality grades paper	sports equipments / toys / consumer electronics / household items / furnishings / outdoor applications	cutting / gluing / stacking / ribbing / printing	
Honeycomb Cardboard	●●●●●●●	○○●●●●●	○○○●●●●	n/d		good quality grades paper	sports equipments / furnishing / veichles	stacking	
Paper Pulp	●●●●●●●	○●●●●●●	○○○○●●●	yes		low grades quality paper	packaging / disposable products / Furnishing	transfer molding / thermoformed fibres	

Tab.5.2 Paper & Cardboard properties

OTHER CIRCULAR MATERIAL	biobased	bio degradability	lifetime expectation	compostability		material source	commodity sector	production methods	material substitution
Accoya wood®	●●●●●●●	○○○○○●●	○●●●●●●	yes		biomass - wood	furniture / archi-tecture	acetylation	untreated wood
Bayonix bottle®	○○○○○○●	○○●●●●●	○○●●●●●	yes		fossil based	personal / sport bottle	injection molding	fossil based poly-mers - PET
The salt pup®	●●●●●●●	○○●●●●●	●●●●●●●	X		sea salt + TPS	Furnishing / Archi-tecture	molding	concrete
Qmilk®	●●●●●●●	○○●●●●●	○○○○●●●	yes		waste - milk	Wearable	yarn	synthetic fibers
S.Cafè®	○○○○○●●	○○○○●●●	○○○●●●●	no		waste - coffee grounds	Wearable	yarn	synthetic fibers
Acrodur®	○●●●●●●	○○○●●●●	○●●●●●●	X		biomass - non wood fibers + bio acrilic resin	Personal Object/ Furniture / Veichles / Architecture	molding	fossil based poly-mers - PP
IKEA Patented material (Odger chair)	○○○○●●●	○○○○○○●	●●●●●●●	no		fossil based + waste	Furniture	injection molding	glass fiber reinfor-ced plastic
Jelu-Plast® biocomposite	○○○○●●●	○○○○○○●	○○●●●●●	no		fossil bsed + cellu-lose	household items / fashion / hobby and toys / Veicles / outdoor application	compression / injection molding	nylon polyester wood or nacre

Tab.5.3 Other circular materials properties

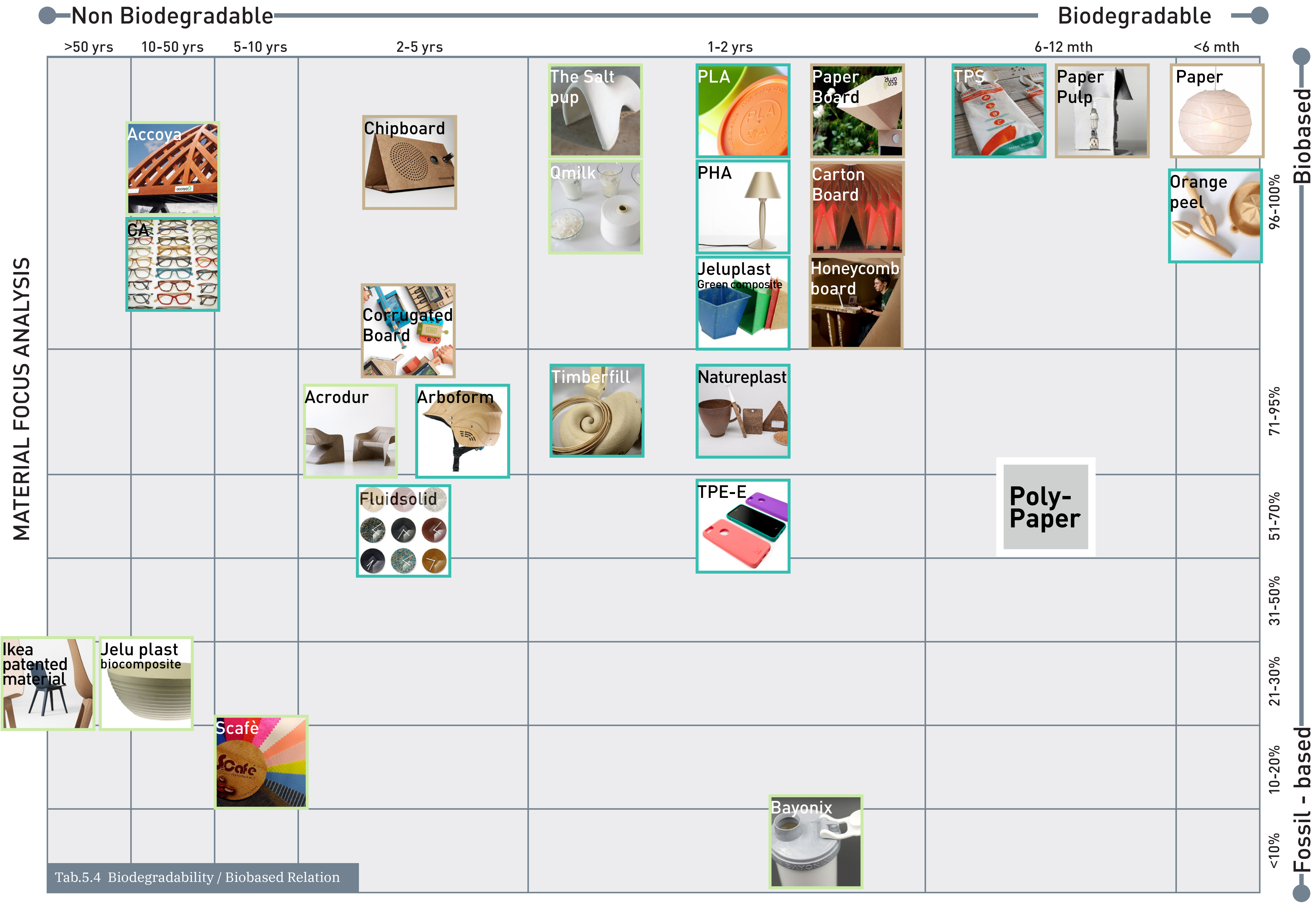
5.7 Materials map

5.7.1 Map Definition

The map is constructed to give a visual result comparison between the materials of the different macro-families. The division of the axes represents the subdivision in values from 1 to 7 of the identified characteristics and is reported in non-uniform scale to favor a better visualization of the results concerning the number of cases present per feature. The map will result in a more dilated scale in the areas where the characteristics of a greater number of case studies are crossed.

Legend Symbols

- Circular material
- Biopolymer
- Paper&Cardboard



Tab.5.4 Biodegradability / Biobased Relation

5.7.2 Materials Map - results

Following the analysis of case studies, the interesting results are focused on the materials that best put in relation the biobased percentage and their biodegradability. The examples of materials with a percentage of biological derivation lower than 50% (score 5) were considered secondary for a direct comparison, since the Poly-Paper for its characteristics has a percentage equal or higher. As far as biodegradability concern, material with a score less than 2-5 years (score 6), maximum duration of degradation of a paper object (considered additive of substances of more difficult degradation as inks, coatings or poly-laminates) they have not been considered as useful examples for the research about new Poly-Paper applications. The materials to be considered less, therefore, are those that, although aligned with the values of the circular economy, focus their strengths on the lifespan elongation, as the example of Accoya woods or that following the principles of re-Upcycling exploit waste materials to enhance non-biomass materials.

This first comparison allowed to filter the materials, which although being circular, respond differently to the guidelines of the circular economy. We can concentrate on the fields of application of the case studies resulted more related. In fact, to find uses to a new material, it is important to consider not only the advantages given by its characteristics, but above all to understand how these can be enhanced through application in a product.

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List of Tables

6

From Material to Products

6.1 Analysis Aim

The durable goods analysis carried out involves materials identified among the case studies of chapter 5, of interest in relation to their "Circular" approach, to their derivation from biomass and paper materials. The analysis purpose is to investigate the types of products currently available on the market made with the analyzed materials to identify a relationship between material lifetime expectancy and product life expectancy. As a result, it is supposed to find the direction to product categories that match with the characteristic of the Poly-Paper.

6.1.1 Product Lifespan Definition

Product Lifetime or Product Lifespan is the time interval since a product is sold to when it is discarded. It represents an important area of enquiry with regards to product design, the Circular Economy and sustainable development. This is because products, with the materials involved in their design, production, distribution, use and disposal (across their life cycle), embody carbon due to the energy involved in these processes. (https://en.wikipedia.org/wiki/Product_lifetime)

6.2 Product Lifespan – Studies

Products and Consumer Attitude

Modern society witnesses an unprecedented acceleration of social life. This can also be observed for contemporary material and consumer culture, which is characterized by increasing product replacement rates and short product life spans. Increasing replacement rates create social pressures to stay up to date and keep pace with the technological development, resulting in harried and exhausted consumers (Wieser 2015). The Product Lifespan is influenced both from the product design and the user's utilization who also takes care of the disposal.

In the article "Public understanding of product lifetimes and durability" is given an indication on how to think of products' lifetimes as being determined by a combination of 'nature' and 'nurture'. A product's nature being the inherent properties it has – its durability, functionality, reliability or overall quality or performance, often defined by the manufacturer. Then, how a product is nurtured, or treated (throughout all stages of the products' lifecycle) will, in conjunction with the nature of the product, determine how long that product lasts in the hands of any given consumer (Lyndhurst 2011). These two concepts lead to a gap between the potential and the real lifetime of a product, setting out the critical points at which that life could be ended. This therefore leads to the search for statistical data related to the Lifetime Expectation of products by users in order to hypothesize an ideal duration of the products that see the use of Poly-Paper.

Tab.6.1 Average duration of products (Lyndhurst 2011, Wieser 2015)

1-2 years	3-4 years	5-6 years	7-10 years	>10 years
Small electrical appliances (e.g. toothbrushes, toys) mobile/smatphones, general clothing, hoes	Portable devices, personal computers, bed items, specific clothing (e.g. sports), bicycles, coats	Cameras, general kitchenware, lighting, power tools, vacuum cleaners, washing machines, curtains	Automotive, TVs, kitchen appliances, general furniture, carpets, beds, refrigerators	Appliances attached to house (boiler, sunroof, etc.), kitchen and bathroom, specific furnishing

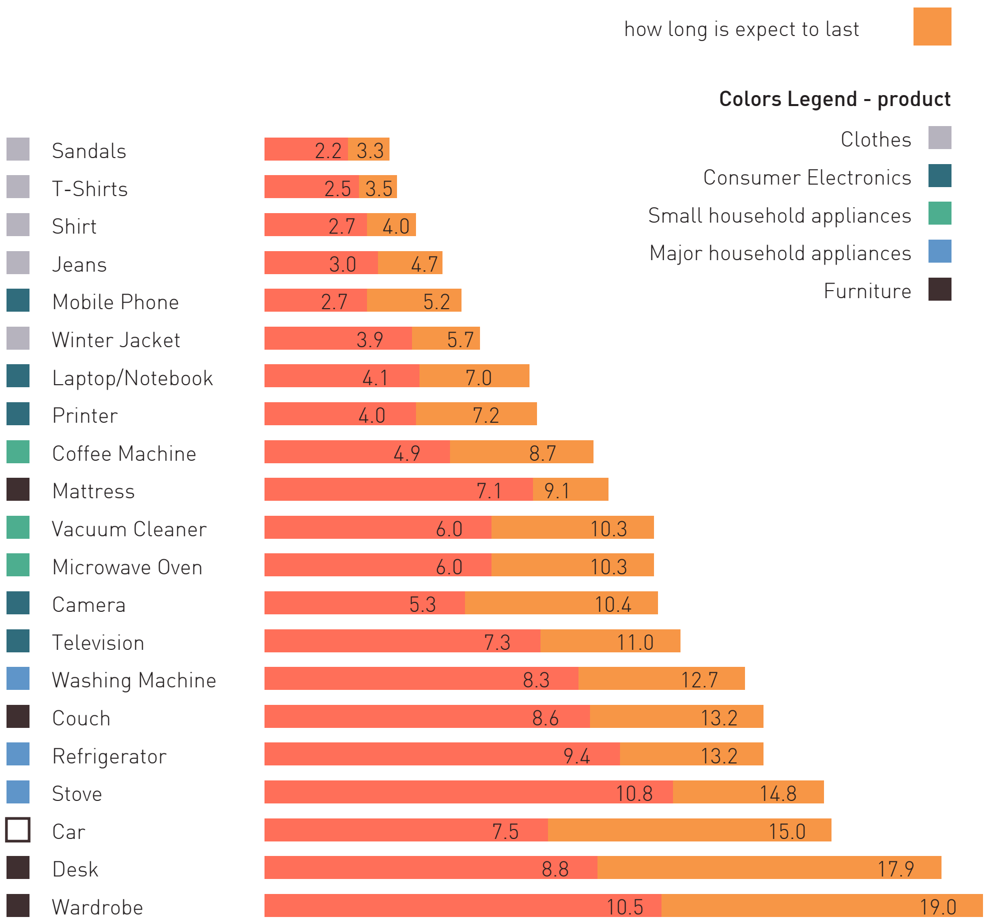
In the article of Lyndhurst et al. are also identified three categories of attitude on products that determine their lifetime: Up-to-date, Workhorse and Investment. The Up-to-date attitude was held on products that were felt to be more important for their look than for their function. Specifically, products treated as ‘up-to-date products’ tended not to be discarded because they had broken down or worn out, but because participants perceived them to be ‘out of date’ and no longer sufficiently fashionable. Most users usually treat clothing, portable electronics and any items in their home that had the potential to affect its look with an ‘up-to-date mindset’. This meant that some furnishing products (particularly smaller, more visible accessories), and some home electronics are also included within the up-to-date category.
Workhorse attitudes placed far more emphasis on the nature of products. Such attitudes focused on product functionality more than appearance, and lifetimes of workhorse products tended to end because the products had broken down.
Finally, there is a range of attitudes and behaviors in which nature and nurture combined in positive ways to prolong product lifetimes. Such a mindset operated in respect of those products by the users indicates how the decide to ‘invest’ in (Lyndhurst 2011).

Tab.6.2 Average expected life of up-to-date products (Lyndhurst 2011)

Average expected lifetimes of up-to-date products		
Under 2 years	**2-5 years**	**5-7 years**
shirt, shoes, mobile, jeans, jumper, coat	suit, mp3 player, cushions, computer	camera, curtains, television, table lamp

These kinds of attitudes, obviously, affect the lifespan of products and the actual amount of time they are used. The “use-time” denotes how long a product is used and includes both the duration in operation and the duration in stand-by. The use-time is thus formulated from the perspective of the user instead of the product. The graph combines the data from the article “the consumers’ desired and expected product lifetime” of Wieser et al. shows how long the cited products are used, in years, and the expectation of the following products to last for the user (i.e. ‘desired lifetimes’). Notably, consumers want products to last considerably longer than they are currently used.

Fig.6.1 Comparison between "use time" expected lifetime (Wieser 2015)



The ratio between desired lifetimes and use-time shows what are the products that are replaced before their desired life expectancy, highlighting product categories that may require a project intervention. The consumers' expectations regarding product lifetimes play a vital role throughout the consumption process. Consumers have to make a decision regarding product quality and costs. The consumer's expectations regarding product lifetimes affect also their decisions on whether to repair or replace a defective product and the low expectations may also be used as justifications for early replacements (Wieser 2015).

Object	Ratios
Materss	1,73
Stove	1,75
Winter Jacket	1,86
Fridge	1,92
Jeans	2,01
T-Shirt	2,02
Shirt / Blouse	2,03
Couch	2,05
Washing Machine	2,11
Sandals	2,14
Laptop	2,19
Tv	2,20
Mobile Phone	2,50
Camera	2,51
Wardrobe	2,55
Printer	2,69
Vacuum Cleaner	2,70
Coffee Machine	2,81
Desk	2,82
Car	3,03
Microwave	3,62

Tab.6.3 Ratio between Expected lifetime and "use time" (Wieser 2015)

Case studies on consumer electronics

Electronic product lifespans are getting shorter

A study of the German environment agency has released results that show how the upgrade cycle is a growing problem in the consumer electronics sector. The results showed that the proportion of large household appliances that needed to be replaced within five years of purchase due to a defect grew from 3.5 percent in 2004 to 8.3 percent in 2012. The agency described that rise as "remarkable". Alongside these findings, another concerning trend showed that a third of all replacement purchases for household appliances were motivated simply by desire for a better unit while the old one still worked fine. That proportion rose to 60 percent when it came to televisions. There was one exception, however. The desire to upgrade a laptop that's working fine seems to have dropped within Germany between 2004 and 2012, suggesting perhaps that the pace of technological change has dropped. A quarter of replacements are now due to defects instead. The EU, too, has taken an interest in regulating the inefficient use of resources in products, particularly with the Ecodesign Directive which sets mandatory standards for energy efficiency in more than 40 types of product. Future changes to the directive are expected to include standards for durability and repairability to combat the issues raised in this study (https://www.wired.co.uk/article/product-lifespans).

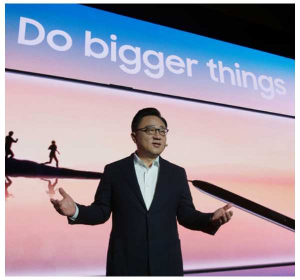


Fig.6.2 Shorter lifespan for electronic products

Case studies on Toys

The Toy Market, with a total revenue of 88.8 bn USD in 2017, is another important player which deals with products of variable duration. This duration is linked to the age of the end user or often dependent on fashions with types ranging from infant toys, action figures and dolls, youth electronics to building sets, powered vehicles or educational toys (https://www.statista.com/topics/1108/toy-industry/). Children and their playthings change rapidly, and so does the market that feeds that change. Once upon a time, toys were something a child held. Then they were something a child played on a screen. Then they were things as likely to be collected by adults as loved by a child. Now they are often all these things all at once (https://www.npd.com/wps/portal/npd/us/industry-expertise/toys/). Maybe even more than consumer electronics, products with the need to be up-to-date are toys. This is another category very subject to obsolescence because often result to be "viral" products with even more faster toy fads. According to the Toys Association the major trends of 2018 will be about the importance to engage with kids on an unplugged level in today's world and are turning to classic toys and old-fashioned imaginative play that inspires children and the "unboxing" products, that grew of the 14% globally in 2017, by introducing a variety of toys across several different categories that focus on the act of unboxing. In terms of tech, on the other hand, it is expected to see more affordable and user-friendly virtual and augmented reality toys, interactive and buildable robots with new features, and RC flyers (like drones) that are easier to handle and fly (https://www.prnewswire.com/news-releases/top-toy-trends-of-2018-announced-at-new-york-toy-fair-300600503.html).

Fig.6.3 Toys - To last or not to last?

Consumer Satisfaction

An important factor in the product lifespan regards the user satisfaction about the product lifetime. In the article "Consumer perspectives on product lifetimes", that studied a lifetime satisfaction and the purchasing factors, are taken into account eighteen product categories, designed to be representative of the entire range of consumer durables, thus achieving a comprehensive consumer survey. The survey results firstly underline that consumers shown limited concern for the environmental impacts of discarded products while continually expecting innovation, and psychologically link products to their identity and success.

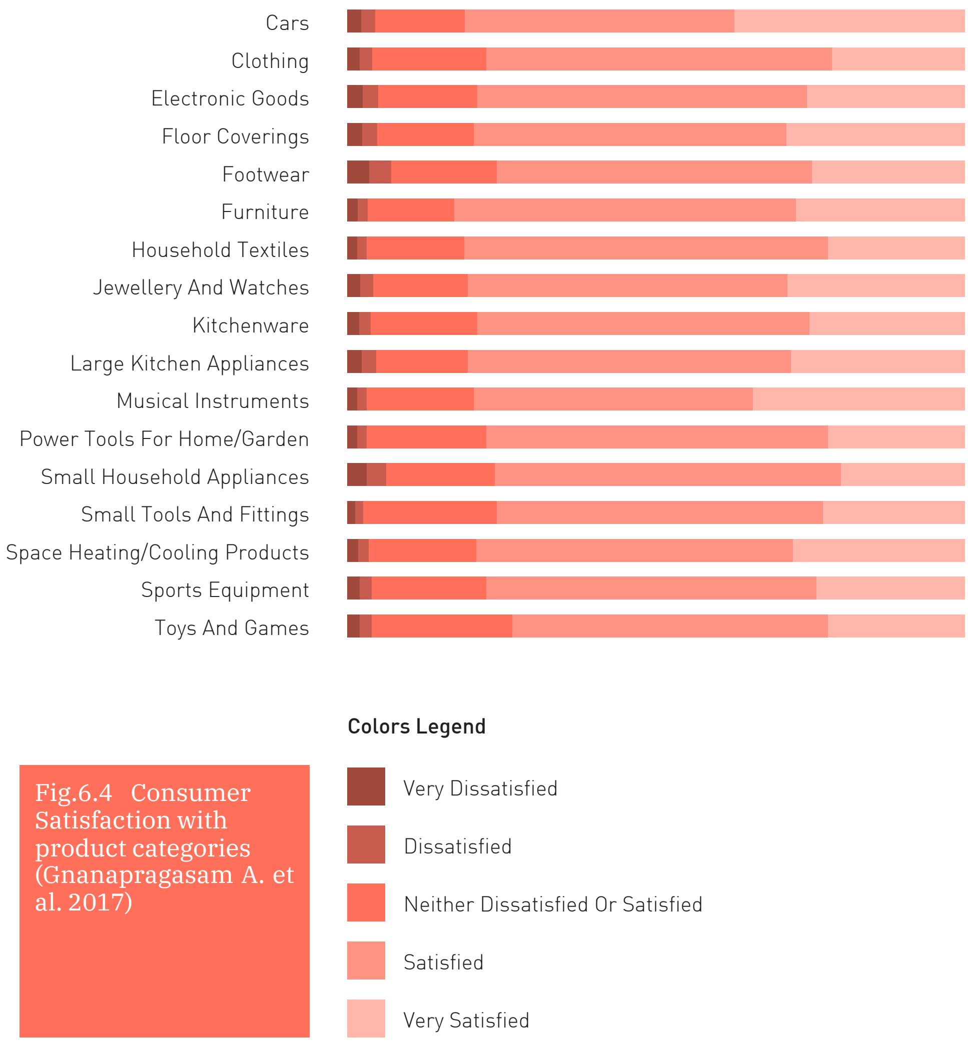


Fig.6.4 Consumer Satisfaction with product categories (Gnanapragasam A. et al. 2017)

All product categories illustrated shown high satisfaction levels, ranging from 77% for toys and games to 85% for furniture. In contrast, only a small proportion of respondents indicated that they were 'dissatisfied' or 'very dissatisfied' with product lifetimes. Aggregating these responses, participants who reported dissatisfaction with product lifetimes ranged from 2% for small tools to 6% for both footwear and small household appliances. The product category with the highest proportion of respondents indicating that they were 'dissatisfied' was small household appliances (5%). A final reflection present in the article, proposes as a Lifetime labelling could enable consumers to consider information on product lifetimes when making purchasing decisions (Gnanapragasam et al. 2017).

Sustainable material use

The environmental impact of a product is mainly determined by its material component, as related to its lifetime. Potential measures for a longer lifetime for products should consider the materials used and how they retain their value (predominantly through recycling when in a state of raw secondary material) (Stahel 1994).
One of the most suitable solutions, which are reflected in the principles of the Circular Economy, would be that remanufacturing and recycling all maximize the value of the material used and minimize environmental burdens (European Parliament 2016). However, the sustainable use of materials often goes against the need and opportunity to be 'up to date'. In fact, it has been argued that possessions can often reflect people's values and contribute to their identity. A rise in disposable incomes, a fall in many product prices in real terms, the increased availability of a widening range of products and an increase in the amount of time and number of opportunities for consumer spending all facilitate the maintenance of an up-to-date identity. These factors together contribute to the premature disposal of products by consumers who wish to satisfy their consumption aspirations (Lyndhurst 2011). This culture of consumerism has been termed the 'throwaway society'. The pace of new product releases is a testament to the dynamism and innovativeness inherent in the consumer electronics industry. One indication of a dynamic and fast-paced industry, complete with a steady stream of new products, is the answer to the question: how long do products last before replacement? And what happens to products once they have reached their life expectancy? (Lyndhurst 2011).

6.3 Identification of the Goods Categories

An evaluation of the United Nations' Statistics Division's, Classification of Individual Consumption According to Purpose (COICOP) and Mintel Academic market research database identified over 400 products that could be classified as durable goods (Gnanapragasam et al. 2017). A consumer durable is a good that may be used for purposes of consumption repeatedly or continuously over a period of a year or more (UN, EC, OECD 2008). For the analysis of the products, however, we proceeded to insert them into macro-categories for better data management.

Survey Products Categories

For the product categories identification has been taken as references, those mentioned in the article "the consumers' desired and expected product lifetime" of Wieser et al., were have been selected at least three durable goods from five product categories: clothes, consumer electronics, small household appliances, major household appliances, and furniture (Wieser 2015). Other references was found in the article "Consumer perspectives on product lifetime" of Gnanapragasam et al. where eighteen product categories were designed to be representative of the entire range of consumer durables (Gnanapragasam et al. 2017). Some of these categories have been grouped together in order to make the crossover of data between different statistics more effective.

Amazon Products Categories

In order to identify the largest number of product categories and to integrate any shortcomings with respect to those considered in the surveys, the categories of one of the largest E-commerce sites in the world as Amazon were observed. From all the categories of the site have been eliminated those that concern non-tangible articles such as services, software, music and movies, etc. but were instead considered all the categories that see or could potentially see the use or application of Poly-Paper.

Short life categories

In addition to the durable products from the case studies of the materials considered, however, uses in mono-use and disposable products have emerged. The term mono-use refers to an object designed for single use (it is used only once and then thrown away). Several mono-use products frequently used belong, for reasons of hygiene, to the health sector or are however goods for strictly personal use. But in this category, we also find other types of objects that can be used only once, like, for example, explosives or some war tools (https://it.wikipedia.org/wiki/Monouso). The term disposable, instead, refers to objects designed for a limited use in time and then is thrown away once its purpose is finished (https://it.wikipedia.org/wiki/Usa_e_getta).

6.3.1 List of defined categories

Therefore, from the crossing of the different sources, eleven macro-categories have been defined.

Category	Sources
Mono-use Products	*Material research*
Disposable products	*Material research*
Clothes and Accessories	*Survey reference*
Sport equipment	*Amazon categories*
Personal Object hobby and toys	*Amazon categories, Survey, material research*
Consumer Electronics	*Amazon categories and Survey reference*
Household Items	*Amazon categories, Survey, material research*
Household Appliances	*Amazon categories and Survey*
Furnishing	*Survey and material research*
Vehicles	*Survey and material research*
Architecture / outdoor application	*Survey and material research*

Tab.6.4 Source of selected product categories

6.3.2 Lifetime Range

When referring to products, many studies has a focus primarily on goods that have a lifetime typically between one and 20 years, but it includes any product with a lifetime between one month and 30 years, to keep the scope consistent. This is based on a product's average expected product lifetime (AEPL). For the definition of the time intervals related to the material categories, as for the product categories, has been considered the values related to the average expected lifetime of up-to-date products, i.e. products with life expectancy greater than years, 2-5 years and less than 2 years to consider durable goods (Lyndhurst 2011). For the completion of the scale for shorter durations, the mono-use products with instant duration were considered, the disposable products and then, 1-6 months ranges for temporary or emergency type, 6-12 months and 1- 2 years for seasonal products or in any case with a limited life expectancy depending on the material used for the product.

The ranges are defined with the following scores:

	pt
>5 years	●●●●●●●
2-5 years	○●●●●●●
1-2 years	○○●●●●●
6-12 months	○○○●●●●
1-6 months	○○○○●●●
Disposable	○○○○○●●
Mono-use	○○○○○○●

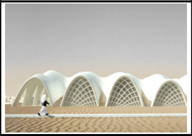
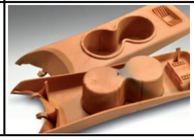
For each product category has been, then, assigned the average value by the scoring ranges for the types of products contained in them. In the table it has been tried to sort the product categories from the one with the shortest lifetime expectation to the longest one.

6.4 Tables of products

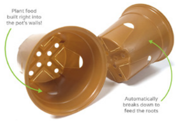
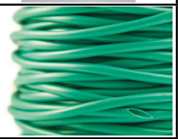
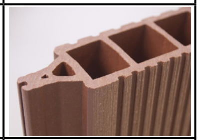
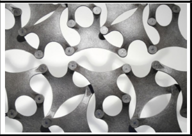
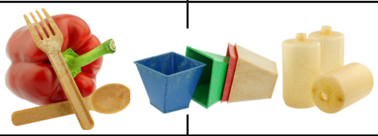
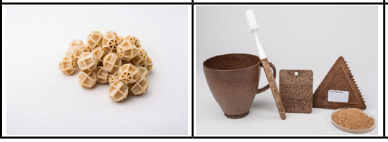
The research has seen an in-depth analysis of the applications of materials in analysis between the different identified product sectors. According to an intersection of data relating to different surveys, to each product category has been assigned the ranges of values relating to the average life expectancy of the products contained therein, in order to estimate the average life expectancy at material level. As far as the Poly-Paper is concern, since material still in the experimental phase has been assigned an expectation value resulting from the average between the average expectation value of the biopolymers and paper materials resulting in a duration of 6 to 12 months (score 4).

Poly-Paper lte = (average lte Biopolymer + average lte Paper & Cardboard)/2

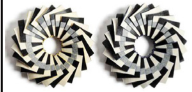
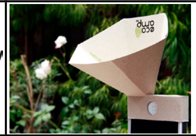
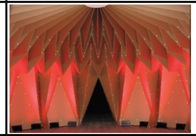
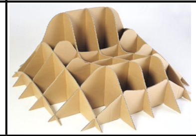
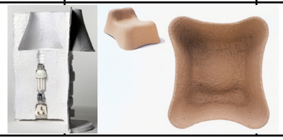
Biocomposite

circular material	mono - use product	disposable pro-duct	clothes and accessories	sport equipments	Personal object hobby & toys	consumer electronics	household items	household appliances	funishings	veichles	architecture and outdoor applica-tions
Accoya wood®											
Bayonix bottle®											
The salt pup®											
Qmilk®											
S.Cafè®											
Acrodur®											
IKEA Patented material (Odger chair)											
Jelu-Plast®											

Tab.6.5 Circular material products categories

	Bio Polymer	mono - use product	disposable pro-duct	clothes and accessories	sport equipments	Personal object hobby & toys	consumer electronics	household items	household applian-ces	funishings	veichles	architecture and outdoor applica-tions
Biopolymer	TPS Thermoplastic Starch (Materbi®)											
Biopolymer	CA Cellulose Acetate (Tenite®)											
Biopolymer	PLA Poly Lactide Acid (Nature Works®)											
Biopolymer	PHA Polyhydroxy Alkanoates (Mirel®)											
Biopolymer	TPE-E (Apinat Bioplastic®)											
Green composite	Timberfill®											
Green composite	Orange Peel											
Green composite	Arboform® Liquid Wood											
Green composite	Fluidsolid®											
Green composite	Jelu-Plast®											
Green composite	Natureplast®											

Tab.6.6 Biopolymer products categories

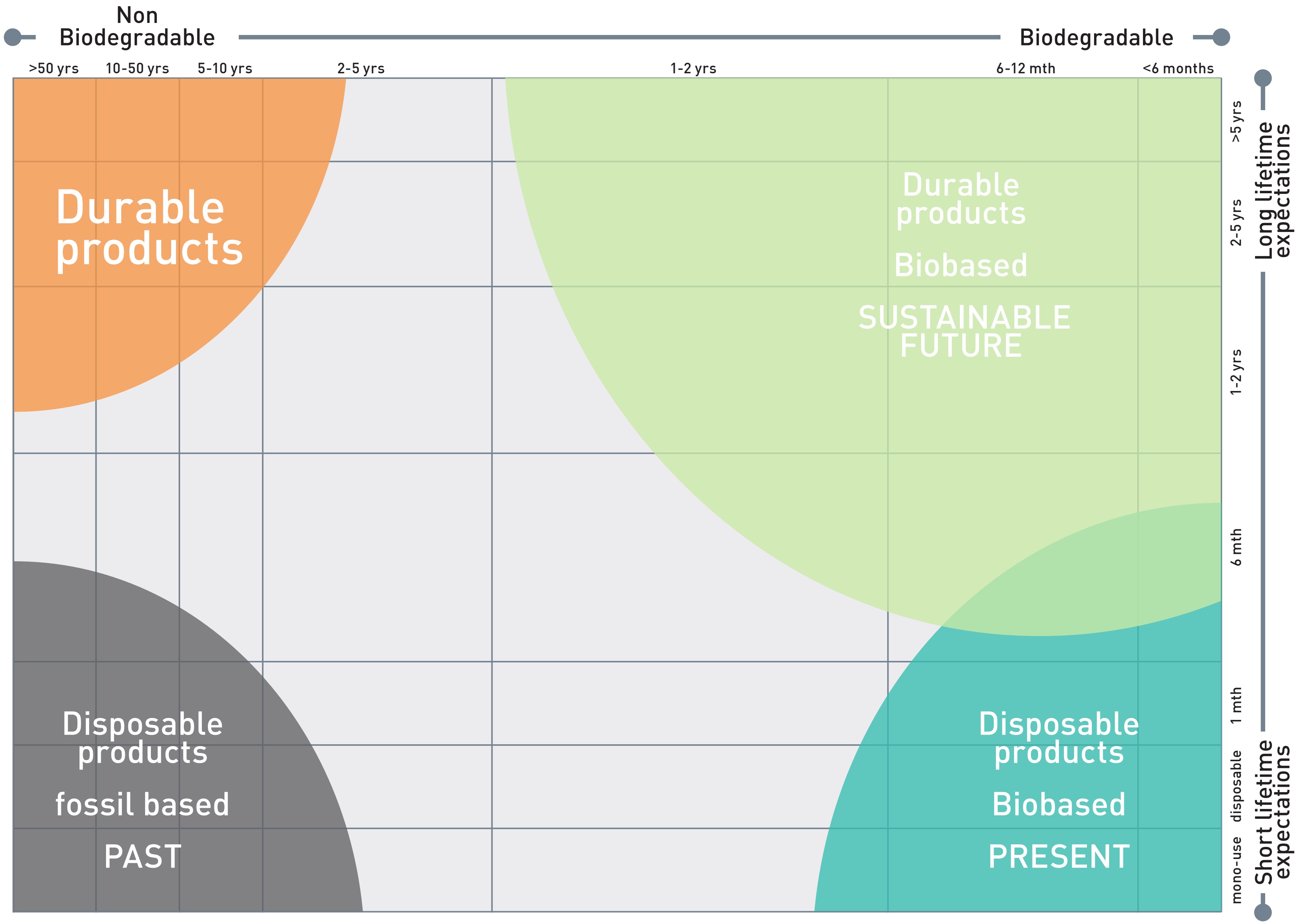
Paper and card-boards	mono - use product	disposable pro-duct	clothes and accessories	sport equipments	Personal object hobby & toys	consumer electronics	household items	household applian-ces	funishings	veichles	architecture and outdoor applica-tions
paper											
paper board											
Carton board	Packaging										
Corrugated Board											
Chipboard											
Honeycomb car-dboard											
paper pulp											

Tab.6.7 Paper & cardboard products categories

6.5 Products map

Once assigned a value to the Poly-Paper, relative to the lte (lifetime expectation), has been determined a score tolerance of 3 points has been given, 2 in positive and 1 in negative; the choice was made because of the desire to investigate more between durable solutions than the disposable ones.

In this map is possible to see the positioning of the various materials, starting also to considering their applications in products. Furthermore, it is useful to identify at its four corners macro-typologies of products, that can be positioned in an “economic approach” level on a timeline. In fact, we find high-quality products in the upper left, with a long life expectancy and that do not fear degradation and that we could define as eternal; in the lower left corner we find objects belonging to the past, that is all those non-biodegradable objects but with a short life expectancy as could be the bags or dishes in fossil based plastic, typical of the Linear economy. In the lower right corner, we find the result of recent developments that are part of the present, thanks to the development of biodegradable materials for disposable objects. Finally, at the top left it is possible to find the direction, hopefully future, towards which the products will have a longer life expectancy but once they have reached their end, they will be easily disposable and biodegradable. From the map we can see that there are already many virtuous examples that, aligning themselves with the principles of Circular Economy, point towards this objective goal.



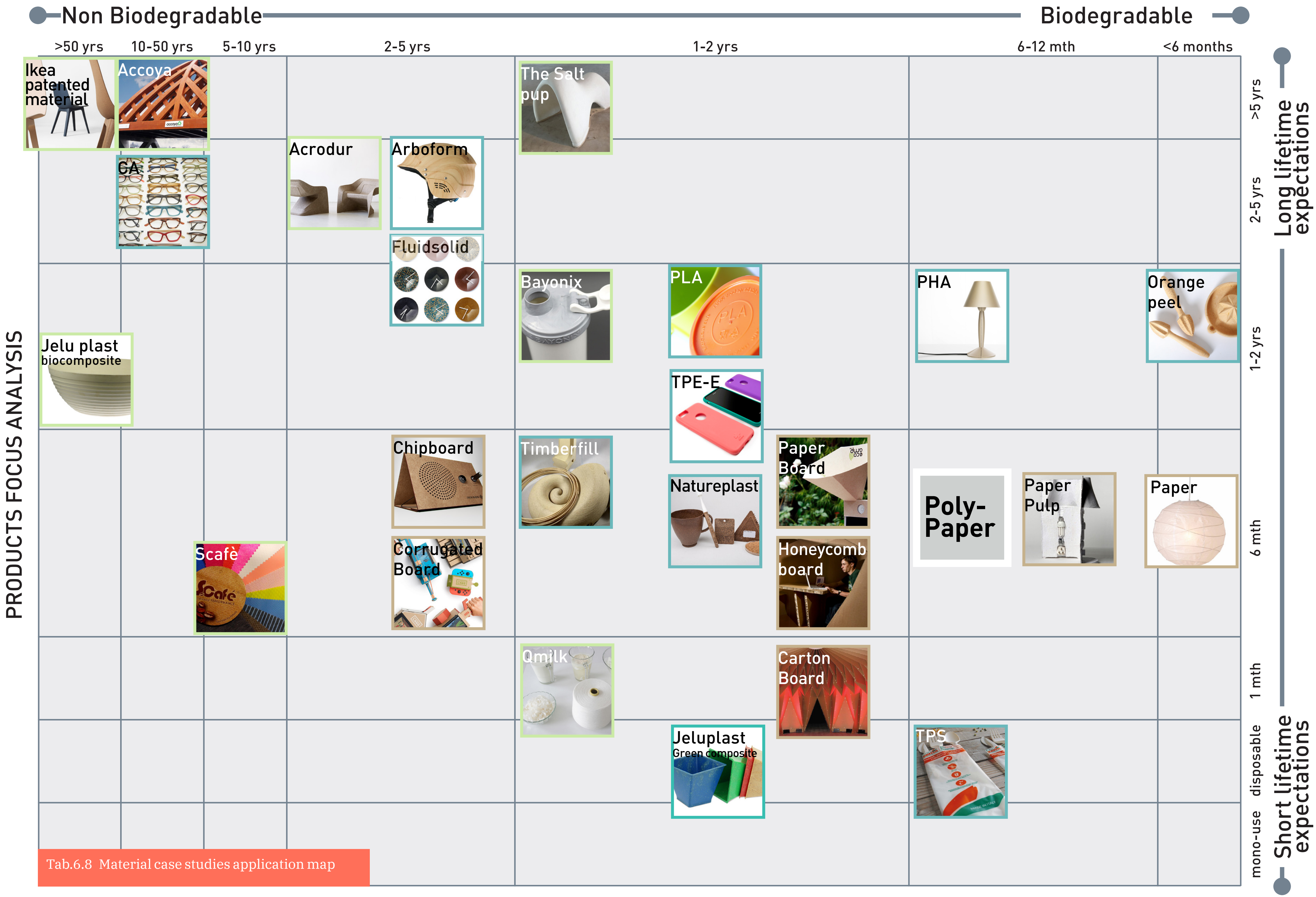
Legend Symbols

Circular material

Biopolymer

Paper&Cardboard

Fig.6.5 Material applications - general map



Tab.6.8 Material case studies application map

6.6 Analysis Considerations

The analysis results and the intersection of data concerning materials and related applications, have made it possible to identify, among the many possibilities that a new material may have, which fields of application could create the right compromise between feasibility in terms of production and transmission of values, typical of Poly-Paper, of recyclability, sustainability, expressiveness and innovation of the material. On the table of products, for each product category have been assigned, according to the data reported in the article “Public understanding of product lifetime” range of values related on the product lifespan (Lyndhurst 2011). This allowed to select hypothesized product categories that are more congruent with the characteristics of the Poly-Paper.
The fields of application that are most interesting for Poly-Paper development, responding in a more congruous way to the percentage of biomass derivation, biodegradability and Lifetime Expectation of the materials are therefore that of Personal Objects, Hobbies and Toys and the Consumer Electronics categories. Sectors such as Household Items, Household Appliances and Furnishing can be interesting too, applying some technical adaptations at the design level. Observing well the average lifetime expectation of the products contained in them, even if some paper products specifically denoted a temporary nature, it was close to or more than 2-5 years. Regarding Household Items, in addition, applications with high humidity are feared when used.
The categories of Mono-use and Disposable objects are those that have pushed the development of this new material, are interesting for the recycling of material also having to deal with a too short life expectancy related to products. The product category relating to Sport Equipment is a bit less attractive because, especially the products that see the use of paper, do not respond to values related to environmental sustainability due to couplings often with non-sustainable materials. Furthermore, for functional reasons they often do not turn out to be mono-materic, inserting a problem of design for disassembly in order to enhance the aspect linked to the simplicity of the recycling of products. The Clothes and Accessories sector is still not very attractive because experiments in the field of textiles have not yet been developed. Finally, sectors related to Vehicles and Architecture are not very congruent with the characteristics of Poly-Paper due to the mechanical performance required, the conditions of application and the long-life expectation related to the products they contain.

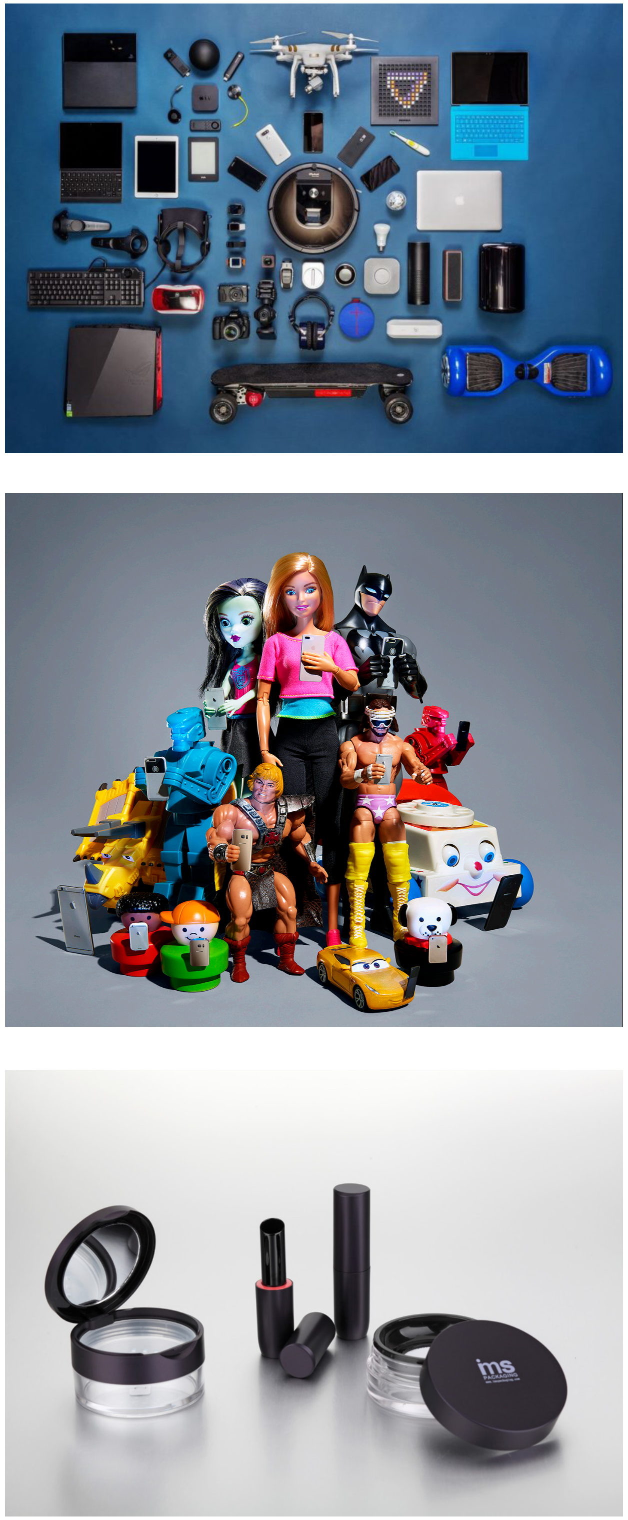


Fig.6.6 Potential field of application for Poly-Paper

The analysis of the relationship that links materials and objects has led to find product categories, not only compatible with the characteristics of the case study, but aimed at enhancing its properties, differentiating it from its competitors. These categories, filtered according to the uses and life expectancy of the products, have very different needs to satisfy. As for the production and use, when the item changes, the requirements and dynamics for disposal also change, which is the key to closing the life circle of a product.
For this reason, it is important to differentiate, according to each product, the design strategies to use, to increase their sustainability using new materials.

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Sitography

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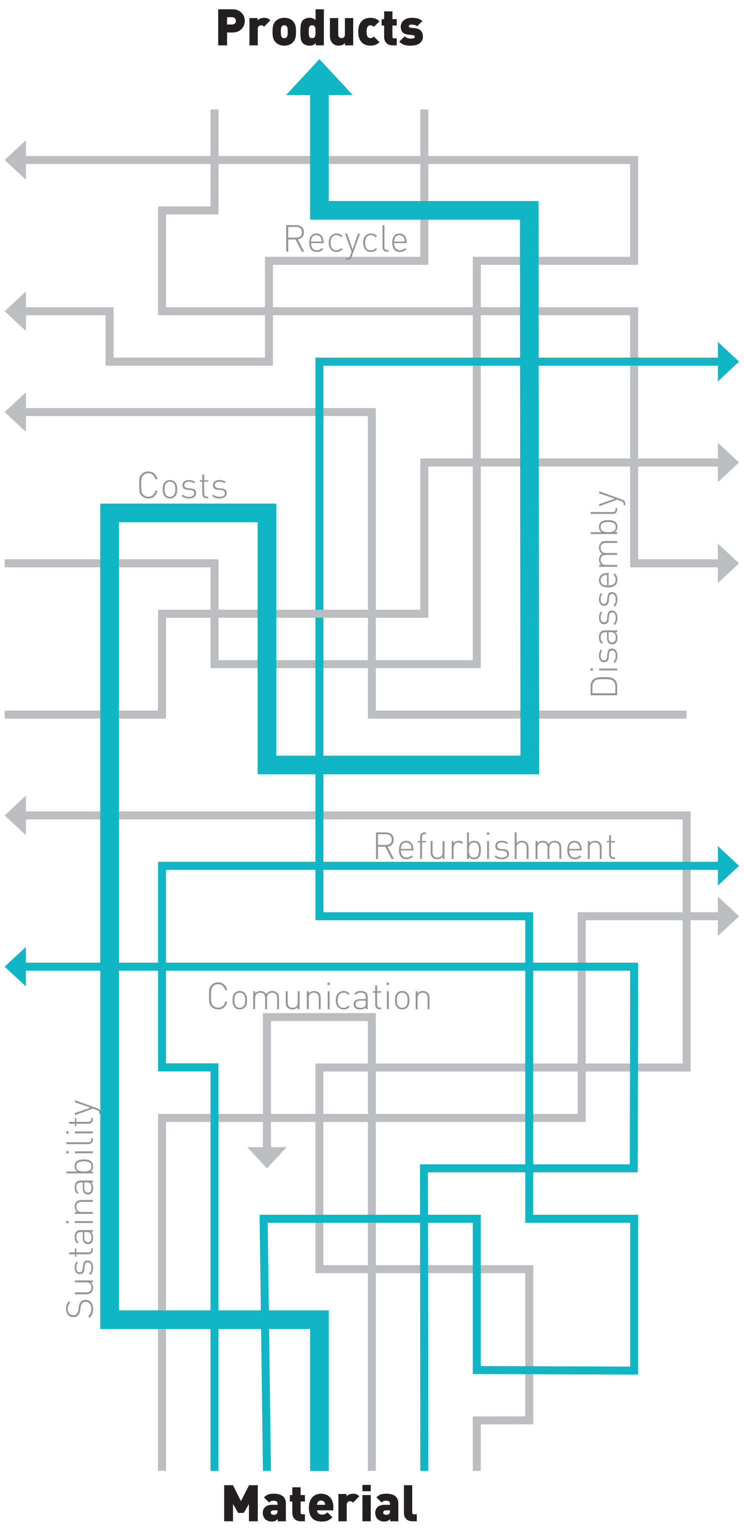
7

Design Strategies for Poly-Paper



7.1 Life Cycle Engineering in Product Development

Besides dematerialization, loop closing of resources is one of the key criteria towards sustainability. The issues of loop-closing, resource efficiency, waste reduction, and life-extension are many facets of the life-cycle engineering concept, developed as an integrated method to design, manufacture, use, and recover materials and products for optimal resources turnover "from cradle to cradle".

After the identification of sectors and product categories, it is now useful to combine the material characteristics with their design requirements, to understand how the Poly-Paper can be used and what are the characteristics which rely on, depending on the product that has to be developed. From the knowledge about the Circular Economy, as seen in chapter 1, the aspects that take better account of the use of materials in products are fundamentally the efficient use of resources in terms of raw material conservation, reduced material inputs, recycling and to maintain the highest value of materials and products thanks to remanufacturing, refurbishment and re-use of products and components. This leads to define what are the most interesting design aspects to consider when designing a product that sees the Poly-Paper as the protagonist and design constraint. There are strategies, in addition of limiting the product costs, that designers are nowadays forced to use to reduce the environmental impact and to optimize possible economic gains over the total product lifecycle focusing on different End-of-Life (EoL) treatment strategies in the early stages of the design process. Life cycle engineering puts priority on prevention principles, which should be activated in the early stages of the design process, leading to improvements in design, material selection, and assembly practices would benefit from incentives to recover individual parts in complex assemblies at all stages of the life cycle of the products (Leterrier 2000). These tools encompass design for recycling, design for disassembly, design for remanufacture, or design for energy efficiency, and obviously make large use of life cycle assessment methods to evaluate the effectiveness of more sustainable substitute materials.

7.2 Material substitution for sustainability

Europe has launched several initiatives to promote research and innovation in raw materials and to find candidates for natural resources substitution. However, while there is a tremendous interest in raw material substitution, the lack of a simplified approach to comparing the materials' sustainability and effective legal frameworks make final market applications extremely challenging. The market for new raw materials can only be established if industrial sectors are appropriately sensitized and stimulated (Bontempi 2017). The aspect that differentiates the sustainable design based simply on the fossil-based material substitution to biobased from the one that includes the Poly-Paper, is to take into account the whole life cycle of materials. Bioplastics are sustainable and derived from biological sources but at the end of their lives, given the complexity of the recycling world, they are inexorably undergoing a downgrade after a single life cycle. For the design with the Poly-Paper, as it is difficult to compete with an equal ratio to replace fossil based plastics with 100% material from biological resources, we want instead to replace the plastics with cellulose-based materials, or rather paper in combination with the Poly-Paper, resulting in a much higher percentage of recycled and recyclable substances and with a consequent decrease of material that downgrade.

7.2.1 Life Cycle Engineering of Composite Material

For decades, the development of polymer composites has been driven almost exclusively by performance criteria such as high specific stiffness. It is only in recent years that life cycle considerations have become prominent features in the design of composite-based products, with a particular focus on an <u>increased durability, increased use of renewable resources, and increased reuse of products and recycling of materials</u>. Which route, or combination, would provide the optimal solution in terms of sustainability, that is, for economic, technological, and environmental criteria, is not always evident. In fact, each of these aspects could also show negative implications. Increasing the durability of a product could have adverse effects on developing novel products with lowered environmental burden: a typical example is that of cars. Increasing the use of renewable resources might imply increasing the use of hazardous substances for cultivation and processing and would considerably impede the number of times the material can be recycled. Finally, increasing the recycling level of materials goes along with well-recognized drawbacks, including the drop-in quality of used materials, which imply, when recycling, an overdesign to compensate for such a drop, with a clear economic implication.

As far as the durability concern, there is, however, no general definition, since it obviously depends on the application to be used in an unknown future. Limiting factors to composite durability could be identified from aging and degradation of the material constituents depends on the field of application, to structural or functional failure of the composite part or an improper design and processing cycle. The limitations to part re-use as well as material recycling, result from the inherent complexity of the constituent assembly, and therefore difficulties in disassembly. It is also linked to product obsolescence, a limiting factor to composite durability that finds its causes in the rapid technological progress (Leterrier 2000).

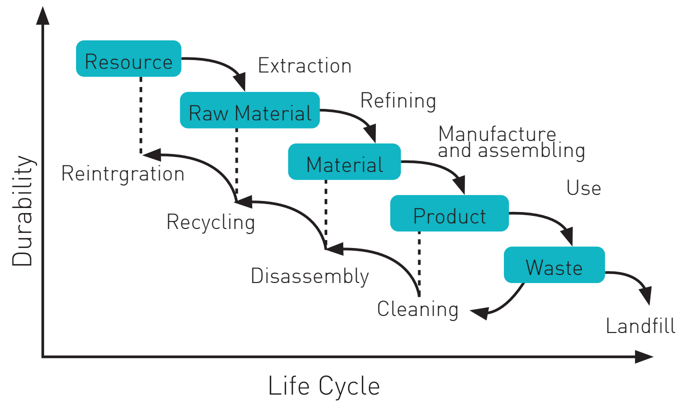


Fig.7.1 Material durability Life Cycle

Schematics of the drop in durability of materials at each life cylce step (Leterrier 2000)

As described by the Leterrier scheme it is possible to observe the influence of the life cycle steps on the durability of a material and how it drops at each individual step. To optimize the use of these materials, there is therefore a need to facilitate the upgrading operations to keep the added value always high. For example, recycling, including mechanical recycling and chemical recycling, brings the durability of the constituents back to a higher value once regained the material from the existent products. It is nevertheless a lower priority option than reuse or refurbishment, particularly when it requires larger material and energy inputs compared to the preceding life extension alternatives, but it turns out to be the most virtuous when only the material needs to be taken into consideration. In the case of Poly-Paper, its compatibility with the paper waste opens scenarios where, even in a multi-material product hypothesis, that can be treated as a single material by reducing the disassembly operations and facilitating the recycling phases.

7.3 End of Life design (EoL)

The design phases of a product, such as the problem definition, the information gathering and the idea generation phase, are commonly considered as important steps in product development as they go to define its costs and its effectiveness on the market.
But besides optimizing these project objectives, there is a strategy that designers are nowadays forced to use to reduce the environmental impact and to optimize possible economic gains over the total product lifecycle. It focusses on different End-of-Life (EoL) treatment strategies in the early stages of the design process. As described in the article “Design for end of life: a design methodology for the early stages of an innovation process” of Peeters and Dewulf, the three key motives of why designers commonly consider the End-of-Life (EoL) are ecological impact, brand image and economics, thanks to a growing customer’s environmental awareness, that is creating opportunities for ‘green marketing’. It is also important underline that decisions made in the front-end influence all subsequent phases of the innovation process, by spending more energy in the early stages on analysis and strategic design different design improvements can significantly reduce disassembly costs and increase revenues through retrieved materials. Some indications can be provided by the waste hierarchy, which guides consumers and business to generate the minimum amount of waste per product. It stimulates a circular economy and it promotes sustainability because it shows opportunities for waste minimization. The waste hierarchy, or Lansink’s Ladder, distinguishes six steps of waste management to reduce and manage waste in order to maximize the efficient use of natural resources. It ranks waste management options according to what is best for our environment. Prevention and reusing waste are the top priority (avoidance). Recycling and high-quality energy recovery is the second priority (recovery). The least preferred is burning waste and dumping waste on landfills (disposal). The intention of the hierarchy of waste management is to step up the ladder and reduce the amount of waste and the need of virgin resources (https://www.recycling.com/downloads/waste-hierarchy-lansinks-ladder/). The overview of EoL options is in line with ‘Lansinks’ ladder’, which is a hierarchically ordered list of EoL methods. Besides the different EoL options, the design

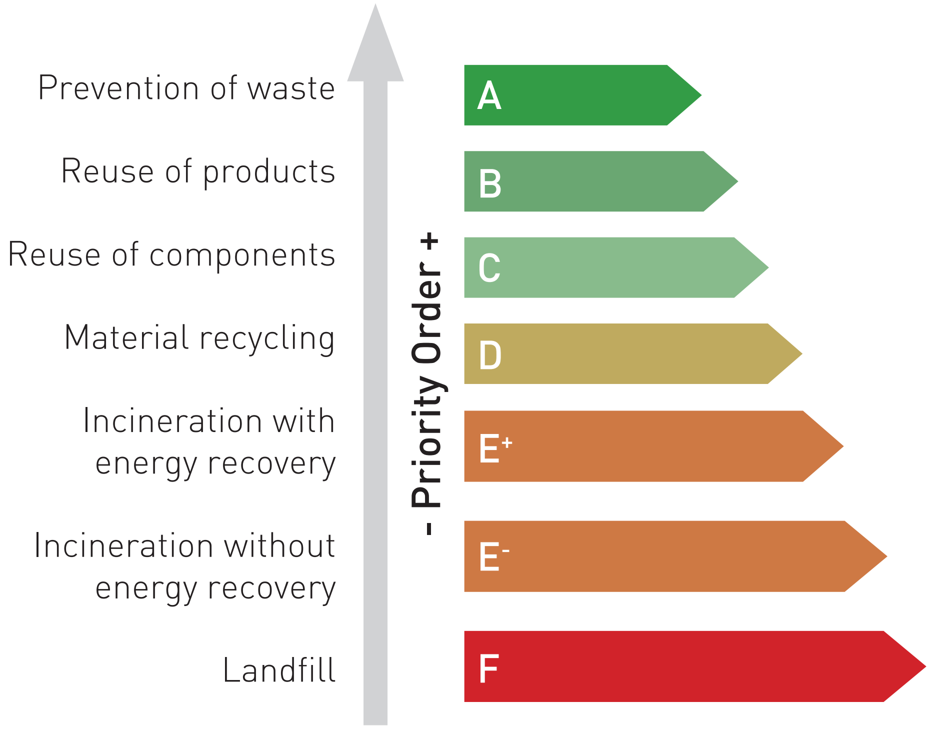
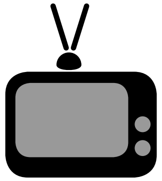


Fig.7.2 Lansinks Ladder

method applied overview also includes the most crucial processes of the EoL options, such as collection, testing and (dis)assembly. In EoL design, the designers are focused on generate ideas of how to avoid or improve different EoL options applying different design approaches, such as design for the prevention of waste, for (active) disassembly and for modularity to facilitate these processes. As for the positioning of the Poly-Paper in the “Lansinks’ ladder” it is obvious that the strategies in the first places would be preferable to increase the sustainability of a product. However, because of the market dynamics identified in some product categories such as that of the consumer electronics, are hardly feasible due to the rapid technological advancement of the products contained in it, so that the reuse of components not subject to obsolescence and the recycling of materials could be effective.

Electronics EoL

Among the goods categories that are focusing more on the end of life design of products, there are above all those that include electronic components. The these products waste are in fact characterized by an intrinsic multi-materiality, easily identifiable between the bodyshells, often made of polymeric material, and the internal electronic components. Another common feature that these objects have is the low awareness about their disposition that often bring to wrong user's behaviour in the disposal, that simply include them in their regular garbage. These wastes are then placed in markets that directs them in developing countries where the disposal is practiced by incineration, often without even considering the thermal enhancement and thus ending in the worst way regarding sustainability. Despite increasing public awareness and international treaties banning, the export of e-waste to developing nations, the quantity of discarded computers, TVs, cell phones and other electronic garbage finding its way to other countries continues to increase annually. According to the United Nations, approximately 46 million tons of electronics were discarded globally in 2014, an amount estimated to grow to 50 million by 2018. Fortunately, there are more and more users that take right behaviors disposing electronics via donation, returning it to the supplier or taking it to drop-off centres or depots. More importantly, the organization points to initiatives within member companies to implement design principles that make it easier to dismantle end-of-life electronics. For example, Cisco stipulates that all mechanical parts greater than 100 grams consist of one material and that all plastic parts more than 25 grams be material coded and therefore easily identified by recyclers (https://www.design-engineering.com/features/end-life-design/).

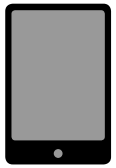


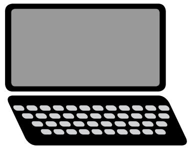
51%

The weight that a 65' television has been reduced by since 2012

72%

Tablet reduction weight - the greatest of all electronics device



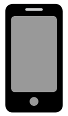


38%

The percent of weight reduction seen in computers

19%

Smartphone reduction weight



11sec

to take apart an iPhone6 by the Apple Liam robotic system

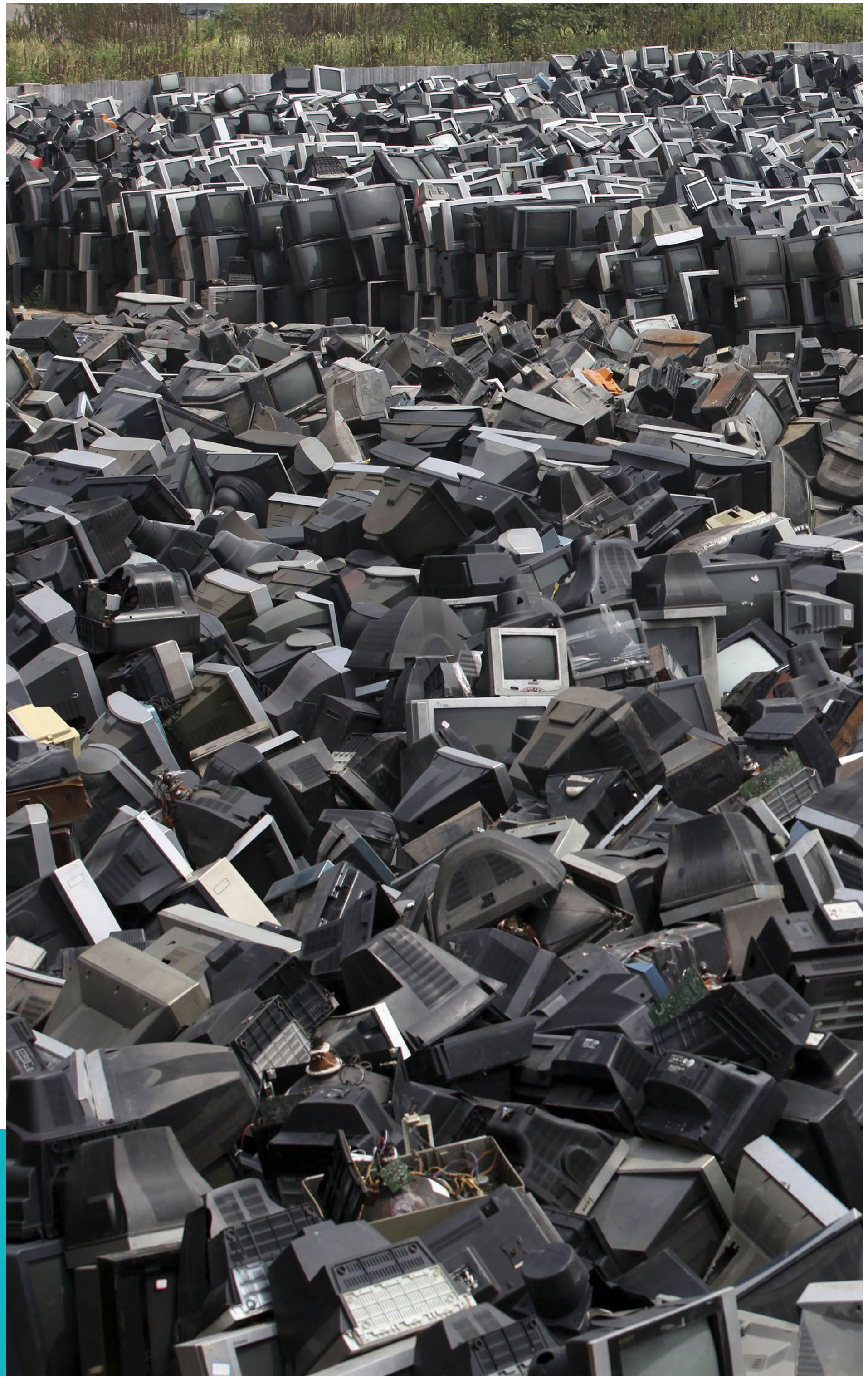


Fig.7.3 Electronic products - landfill

7.4 End of Life in Design Phases

In the design of a product's the end-of-life part also plays a fundamental role. This aspect can be considered at different stages with objectives that optimize the product and all the surrounding environment. As described also by Alex Diener in the article "Afterlife: An Essential Guide to Design for Disassembly" there are pre-design goals, target that have to be reached thanks to a design mindset oriented on sustainability, and goals that could be reached in a post-design phase to improve the EoL characteristic of a product. (https://www.core77.com/posts/15799/afterlife-an-essential-guide-to-design-for-disassembly-by-alex-diener-15799). Design is a critical stage in any product lifecycle as 80% of the environmental impacts of the product will be decided during this stage (https://www.thersa.org/discover/publications-and-articles/rsa-blogs/2015/05/Redesigning-the-Razor).

7.4.1 Pre-Design goals

Even before approaching the design path that leads to a product it is important to consider the boundary conditions. It is therefore appropriate to consider how end-of-life planning can impact on the reduction of labor and material cost. Design for disassembly solutions emphasize simplicity. In fact, products that disassemble easily often assemble easily, saving time and money on labor. As far as saving materials concern, examining the anatomy of a product, it is often possible to find components that can be combined or deleted altogether, saving material and production costs. In addition, when products can be refurbished, the material and production costs are greatly reduced.

7.4.2 Design Project Goals

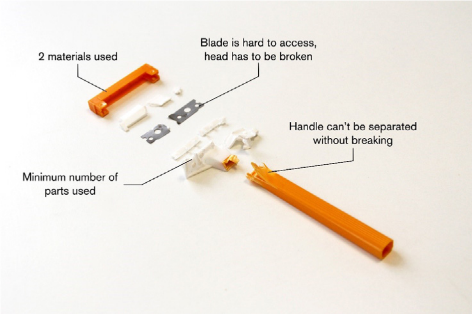
Taking into consideration the goals of the real project phases, the evaluation of products should be based on three core factors: material chemistry, design for disassembly, and recyclability. It concerns materials, the type of connections and tools used to separate the parts and if the components have been marked with their material type or how and if the type of materials is communicated. Since there is a vast array of different materials, processes, assembly methods, and manufacturers, it can lead to information overload for the design phases. A first point to consider is to minimize material types. If a design can be made of fewer parts and material types, it will be easier to sort and recycle. Another aspect to minimize are the fastener types. In general, decreasing variation decreases cost. If the design can be accommodated with the lowest number of screw types, material costs, management and labour time will be saved; designers can also substitute screws with in-mold snap hooks if possible. Other sides to avoid are permanent fixing (adhesives, co-molding) of different materials and paintings. For example, a co-molded toothbrush or kitchen tool will not be recycled. It is very important to remember that dissimilar materials cannot be recycled together. After having considered these factors that characterize the physicality of the product, the design concept for disassembly should also consider the user experience around the object. If it has to be repaired, disassembled or disposed, it is important to visualize or simulate the steps not only for the production and the assembly, but also to repair or disassemble the product, defining all the actors: manufacturing and assembly people, the consumer(s), the service tech, remanufacturing people, and recyclers. This helps to define what actions can be performed by each of these figures, optimizing the results for each type of action or use. The design must be developed for easy repair and provide access to parts. If it can be worn out, it will need to be replaced, and the design should support that. Batteries, moving components, contact areas or parts subject to obsolescence, are all examples of parts that will need replacement at some point. The challenge is two-fold: make it easy to replace and make the parts accessible for renewal. If these two factors aren't considered, the life of the product is severely limited. Snaps are beneficial because they eliminate screws but can be invisible and frustrating if there are no indicators revealing their location. Common tools and fasteners are recommended to ease and streamline disassembly. It is also important to provide instructions that will never be lost – for example emboss or deboss indicators to guide users through disassembly - because by the time a product needs to be taken apart, the user manual is likely gone and thus also the possibility of a correct end of life.

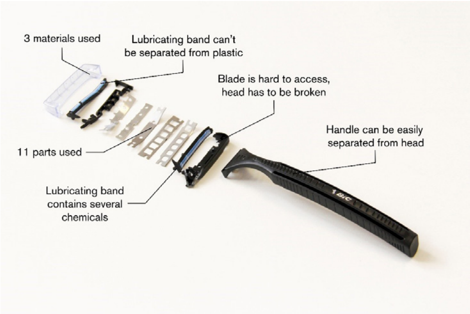
7.4.3 Post-Design goals

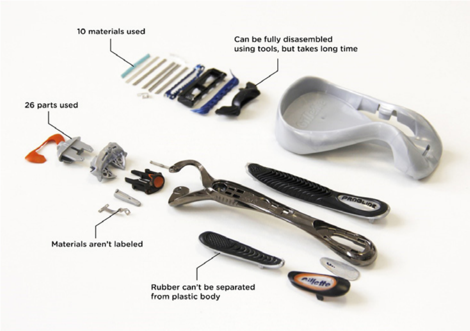
After the design-core phase, it is important to observe the object's end, compare how it is used with the hypothesis made during the design phases. Here designers can learn how their decisions impact the end-of-life result. Observe and identify the behaviours and reactions to the improvements, assess the sustainability and impact of design choices made. Turn that feedback into goals is fundamental to improve and evolve incrementally the products to create higher standards that lead step by step to a world changing.

Razors

Tearing down a product is an illuminating process for the designer to analyse a current product and identify key information about its production. A project carried out by the Great Recovery Program and Fab Lab London has taken as an example of a case study a disposable product such as razors to analyze critical issues. They used the problems encountered during the disassembly stage, and convert them into design challenges in order to improve the design of the razor (https://www.thersa.org/discover/publications-and-articles/rsa-blogs/2015/06/redesigning-the-razor-part-3).







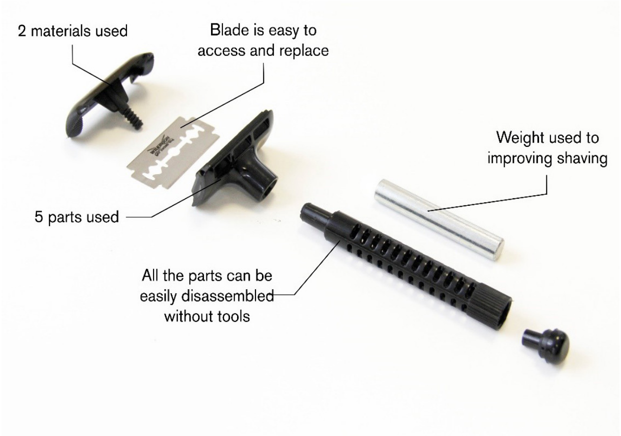


Fig.7.4 Design issue for disassembly and disposal in razors

on the right page

Fig.7.5 Car Brakes designed for disassembly

7.5 End of Life strategies

7.5.1 Design for Disassembly (DfD)

Design for Disassembly is a design strategy that considers the future need to disassemble a product for repair, refurbish or recycle. Its application enables more efficient and sustainable disposal solutions as well as a reduction in costs due to the simplification of the components. DfD defines parts to replace or repair with a simple and intuitive experience. It aims to facilitate product disassembly into easily recyclable components or by not having 100% new construction, product components with no defects can be put back into production. Disassembly of multimaterial products into monomaterial constituents is a prerequisite for product life extension, to ease maintenance and repair operations, and also for material recovery into useful applications, and turns out to be a key challenge in the life cycle design of complex products (Leterrier 2000). To achieve a correct disassembly, or better, an Active Disassembly by the final user, the design it is very important. It is possible to achieve through product simplification that also improve the reliability. The product must provide an easy access to assembly points and easy identification of the type of material. The disassembly of components should use an all-encompassing stimulus, rather than a fastener, specific tool or machine (https://www.slideshare.net/awaisahmed54379/design-fordisassembly). Realize products that follow principles linked to modularity and made with the least possible number of materials, preferably single-material, offers the cleanest, non-destructive, quick & efficient component separation (https://sustainabledesigncards.dk/design-for-disassembly/). In the case of plastic products, design guidelines often target metal inserts, clamps, and screws, which should be built to be easily separable, or even avoided and replaced by snap-fit systems (https://slideplayer.com/slide/6518893/).

Design that makes it easy to remove and replace product elements that wear out first. This is often seen with i.e. linings in coats but can also be mechanical parts or sealings.

Design that makes it easy for the user to disassemble the product and replace the exact broken part such as the Fairphone (www.fairphone.com)
Design where materials can be separated and re-used or re-cycled after the product is fully discarded by the user, by avoiding e.g. glues and mixed fibre materials. An example is Herman Miller's Aeron chair (https://www.hermanmiller.com/en_lac/our-values/environmental-advocacy/design-for-the-environment/).

Fig.7.6 Packaging designed for disassembly

Fig.7.7 Fair phone

Fig.7.8 Mirra - Herman Miller disassmbled chair

Recyclable Laptop Designed for Disassembly

A team of students from Stanford and Aalto University in Finland designed a prototype for a laptop that can be disassembled easily so the electronic components can go into an envelope for mailing to an e-cycling program and the rest can go into the household recycling bin. All the disassembly operations can be done by hand in less than two minutes without any tools. Devices are often designed with the look and feel of its shell first in mind. But the Stanford-Aalto team started from the inside, looking first at the electronics needed for a laptop and designing around those components to make the device easy to take apart for recycling (https://www.greenbiz.com/blog/2011/02/01/recyclable-laptop-designed-disassembly).

Fig.7.9 Recyclable laptop designed for disassembly

7.5.2 Design for Recycling

The Design for Recycling is strictly connected to Design for Disassembly and target almost the same features. It addresses more specifically the selection of materials and sets their recycling rate,with particular attention to the treatment of products' components, for the ultimate aim to recycle the substances of which they are composed (Leterrier 2000). Design for Recycling (DfR) it is increasingly taken into consideration at the design stage. In applying DfR, both the product and its end-of-life (EoL) scenario should be considered since the recyclability of products depends on their EoL treatment processes as well as the composition of the materials (Umeda et al. 2013). The use of recycling techniques reduces the costs associated with the extraction and processing of raw materials, drawing resources from materials that have already undergone processing. Recycling, including mechanical recycling and chemical recycling, during production, use, and after use of materials brings the durability of the constituents back to a higher value.

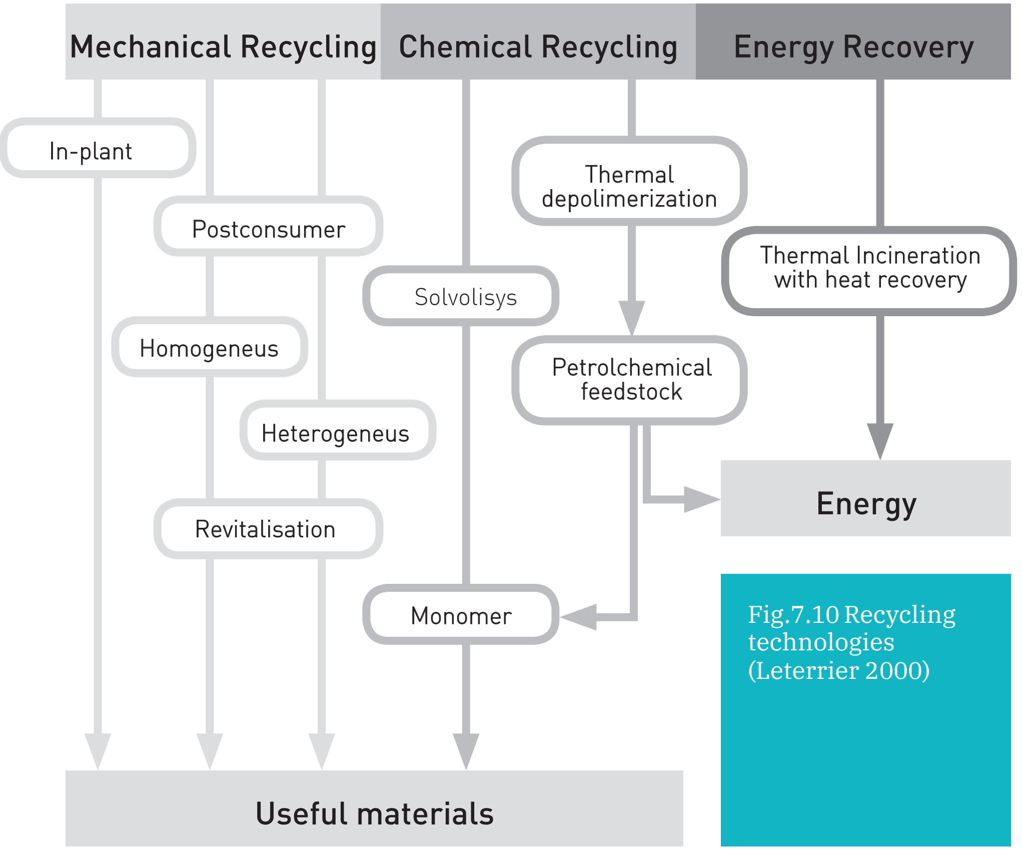


Fig.7.10 Recycling technologies (Leterrier 2000)

To increase the recycling potential is needed a process and material integration that require a reduction of numbers of materials used or single-material products. This class of materials include neat and short-fiber reinforced grades developed for injection molding processes, as well as continuous fiber reinforced composites processed by compression molding or autoclave bagging operations. The former possesses high design freedom, but limited stiffness, which is opposite to the latter.

In the article "Generating design alternatives for increasing recyclability of products" Umeda et al. propose a design support method for improving the recyclability of electronic and electrical products. In fact, reducing the environmental impact of the EoL treatment is an increasing concern for the 6.5 million metric tons of Waste Electric and Electronic Equipment (WEEE)(Peeters and Dewulf 2012). The method estimates the recycling rate of a product based on its end-of-life scenario. The recyclability rate is defined as the mass fraction of recyclable materials to the total mass of the product. One of the issues in estimating the recyclability rate at design stage in the current practices, is that such difference is often omitted, which results in over-estimation of the recyclability rate. To calculate the recyclability rate, are defined three "process types" based on the criteria for electronic and electrical products, which in turn are defined by the "guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment" (IEC/TR 62635 2012). The first type considers products that are disassembled and sorted manually into an object that requires selective treatment after sorting, such as smelting and depollution. For example, printed circuit boards and fluorescent tubes are categorized in this type. The second type considers products that are disassembled and sorted manually into a single material object. For example, the vegetable compartment of a refrigerator, made only of polypropylene. It is important in this typology to avoid irreversible couplings between heterogeneous materials or overly complex product architectures that would increase the costs of disposal making recycling less advantageous. The third type sees products that are shredded and sorted by machines and separated into material fragments. In each process-type, if the recyclability rate of a component or material type is zero, this means that the object is not recycled. When the component's process-type change, the designer should modify its EoL scenario. If needed, the layout and geometry of the related components are modified to adapt to the new process (Umeda et al. 2013).

7.5.3 Design for Remanufacturing

Remanufacturing is the process of returning a used product to at least OEM original performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent (Peeters and Dewulf 2012). From a customer viewpoint, the remanufactured product can be considered the same as a new product. It involves dismantling the product, restoring and replacing components and testing the individual parts and whole product to ensure that it is within its origin design specifications. Performance after remanufacturing is expected to be at least to the original performance specifications. Reconditioning, on the other hand, is the process of returning a used product to a satisfactory working condition that may be inferior to the original specification.

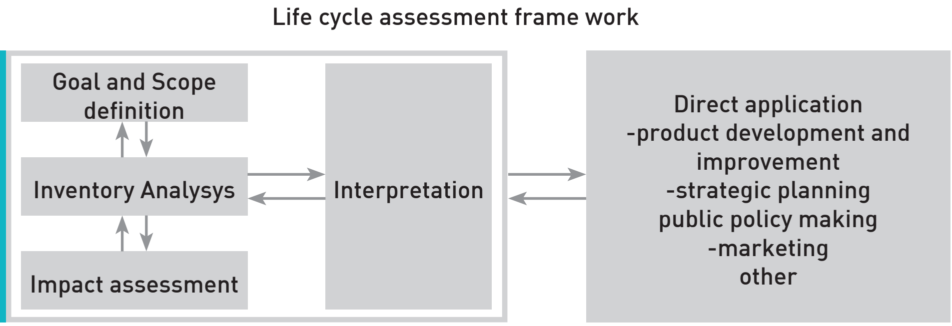
In most cases remanufacturing businesses have been grown in response to a business opportunity, not driven by an altruistic 'green' mission. Mostly they are producers of durable (usually metal) manufactured assemblies. The inherent value of the materials and the cost of production enable this equipment to be remanufactured to an as-new condition. This process saves tens of millions of tonnes of materials worldwide, can make more profit than new equipment and is lower cost to the end user (http://www.remanufacturing.org.uk/what-is-remanufacturing.php).

Nonetheless, specifically designing products for remanufacture is a relatively new concept as far as most manufacturers are concerned. A remanufacturing system collects EoL products, returns them to their original condition then retails them at an as-new price. Importantly, remanufacture results in the extension of a product's life and promotes the re-use of components and materials. It is a means of generating (even potentially doubling) profits, preventing waste and conserving natural resources (http://www.eurekamagazine.co.uk/design-engineering-features/technology/a-design-for-end-of-life/22911/).

7.6 Life Cycle Assessment

These guidelines lead to influence on the environmental impact of products. The instrument that aims to measure this impact is the LCA. It measures the environmental impacts of every step in the life cycle of a product, starting with the extraction of the raw materials, the energy needed to manufacture the product, transportation or distribution of the product to the consumer, the use of the product by the consumer, and ending with the ultimate disposal of the product at the end of its lifespan (McIntosh and Pontius 2017). The reference standard is the ISO 14040:2006 that describes the principles and framework for life cycle assessment but do not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA which may vary depending on the use to be made of the results of the analysis (ISO 14040 1997). LCA practice has evolved, however, separately from the standards, and over the years methodological developments and practical applications have given rise to multiple approaches and modes of LCA (Cucurachi, Giesen, and Guinée 2018). From the book "environmental management - science and engineering for industries" a description is given of the four main stages of an LCA (https://www.sciencedirect.com/topics/earth-and-planetary-sciences/life-cycle-assessment). First step is about to define how big a part of product life cycle will be taken in assessment and to what end will assessment be serving. The second step consist into an inventory analysis that gives a description of material and energy flows within the product system and especially its interaction with environment, consumed raw materials, and emissions to the environment. In the third stage, details from inventory analysis serve for impact assessment. The indicator results of all impact categories are detailed in this step; the importance of every impact category is assessed by normalization and eventually also by weighting. Finally, the interpretation of a life cycle involves critical review, determination of data sensitivity, and result presentation (Muralikrishna and Manickam 2017).

Fig.7.11 Stages of an LCA according EN ISO 14040



Every technology system assessed with LCA exists in a network of connected technologies. and makes use of an intricate network of interlinked processes. It determines that LCA studies have traditionally been ex-post analyses of well-defined systems. Environmental life cycle assessment (LCA) is used to achieve improvements, as well as to compare alternative products. It finds its usefulness when the interpretation phase enables the selection of more environmentally friendly materials and technologies (Leterrier 2000). For all approaches that deal with experimental proof of concept, a validation in the lab, or pilot plant, and that deal with speculations on the future of technologies, it is possible to use the admittedly broad definition of ex-ante LCA. The typical practice in such assessments involves evaluating the technology system at scale, i.e. using multiple scenarios that detail a future in which the technology system operates at full operational scale. Scenarios are used in the ex-ante application to estimate and simulate alternative futures of e.g. full-market penetration, and maximum efficiency (Cucurachi, Giesen, and Guinée 2018). Since the Poly-Paper is just an experimental material it is possible to make an early-on assessmentsthat aims to replace the Poly-Paper on other materials and combine it with paper to reduce the polymers quantity and perhaps the weight of the object focusing especially, as we have already seen, on the end of life of products enhancing recycling.

Knowing the possible strategies to be used to address a Circular Economy design, we now have sufficient elements to generate targeted concepts. Creating product proposals aims to provide cause for reflection to guide the development in parallel of both the new material and the objects in which it is applied. The ideas that will be generated want to be a starting point, from which it is hoped that the material will be able to spread on the market in the future.

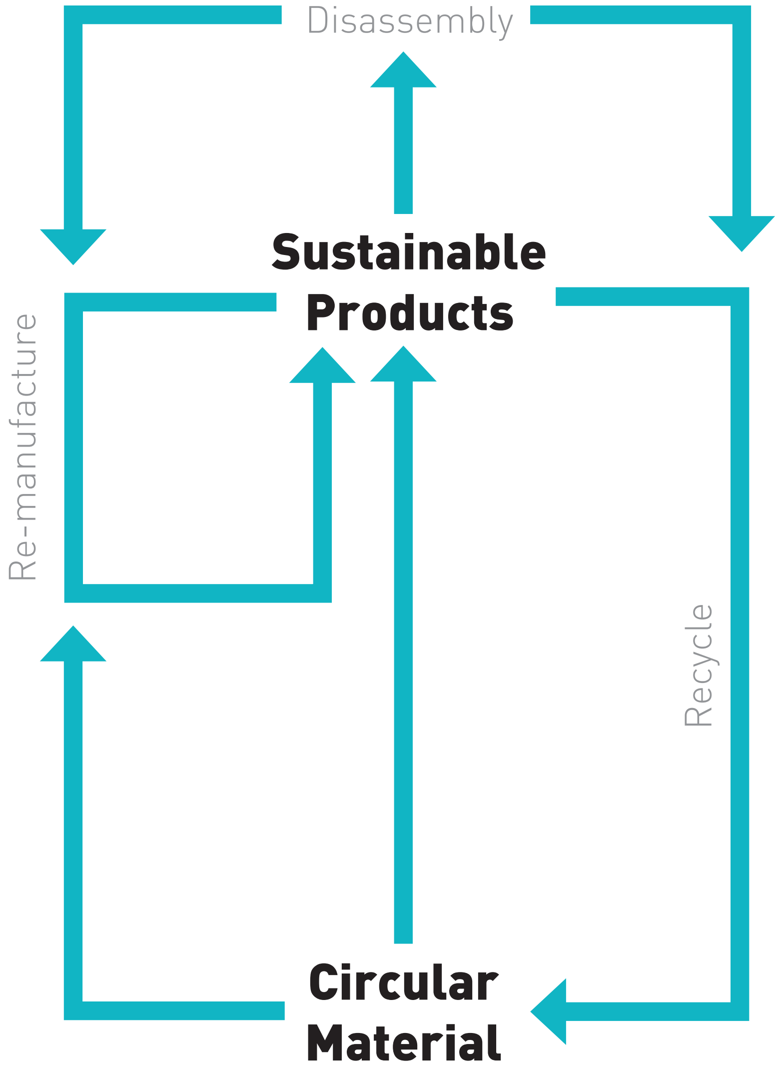


Fig.7.12 Circular Materials and Design Strategiers for a Sustainable product path

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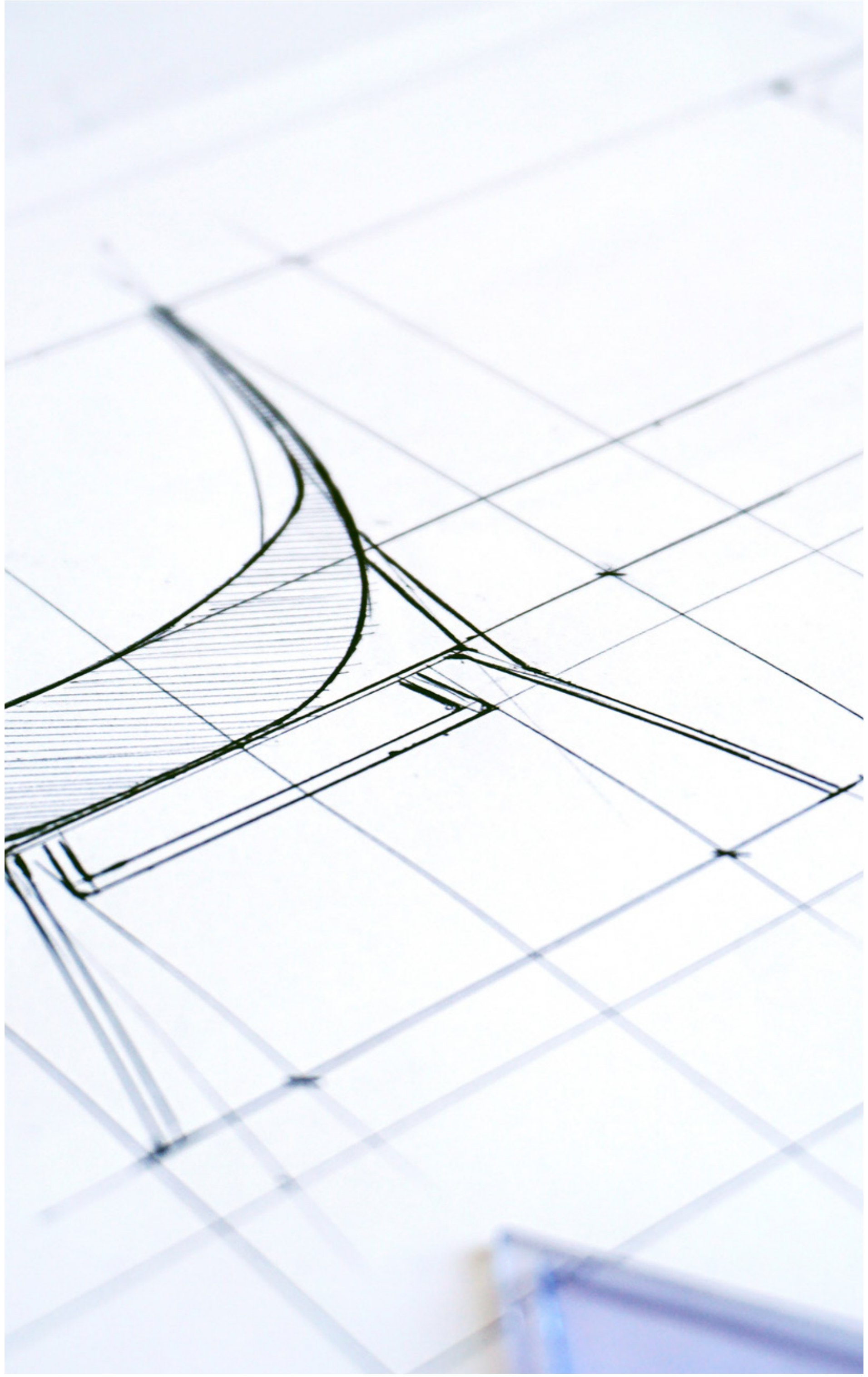
List of Figures

8

Designing with Poly-Paper



8.1 Aims

To define the design aspects that see an interesting use of the Poly-Paper with a view facing the Circular Economy, the research has considered both aspects related to materials and to product sectors. As for the materials, the new frontiers of biobased polymeric materials and their properties, paper and the new and interesting properties of the Poly-paper have been investigated. The market research, guided by the interest in the end of life of products and therefore materials, led to the identification of product categories for which to develop new products with a design oriented to the end of life with specific characteristics for each category.
We want to provide application ideas for the use of Poly-Paper in combination with paper materials. In fact, the use of this new material wants to introduce the paper into products that to date do not see it as a protagonist, highlighting its properties of simplicity of workmanship, customization and sustainability. The Poly-Paper can be used to produce objects with complex three-dimensional surfaces that can be detailed with the technologies related to the processing of thermoplastic materials such as texturing and photoengraving on the mold, moreover the precision of polymeric objects wants to give to the object a better-quality perception and longer life than a homologous paper item. The use of Poly-Paper opens the doors to technical applications of different paper materials (corrugated / alveolar cardboard or paper pulp) to date limited because the detailing and the components is not comparable with the processing of polymeric materials. In turn, paper and cardboard, thanks to ease of processing low cost and sustainability, enhance the use of Poly-Paper as a material that is also sustainable and can be introduced into a virtuous and consolidated cycle of recycling such as the paper ones.

Design Values

The values that we want to link to this material are naturally bound to the environment respect and recyclability. To achieve this goal, it is necessary to develop proposals in fields of application that increase the sustainability of a product thanks to the Poly-Paper. We must also take into account that "recyclable" does not necessarily imply "recycled," and "recycled" does not necessarily imply "environment friendly"(Umeda et al. 2013). The innovativeness linked to the use of this new material lies in the objective of fill the gap between consumer and recycler, introducing it into products that today have an unclear end of life and that therefore often leads to a downgrade of components and materials of which the products are composed.

8.2 Poly-Paper for products

To define a design scheme material driven, referring to the one defined in the texts of Michael Ashby "Materials: Engineering, Science, Processing and Design" (Ashby, Shercliff, and Cebon 2013), it is advisable to define functions, constraints, objectives and free variables for each product category. These parameters will have differences depending on which object is to be made and how the materials will be used. Generally, the functions of an object, a part of it or a component, define what face or role the aforementioned part covers in the context of the object. The constraints describe the indispensable conditions that must be met. In addition to the constraints linked to the functionality of the object, in this case, also the use of Poly-Paper as a characterizing material can be seen as an indispensable condition for the product.

The objectives indicate which aspects of the product must be maximized or minimized such as sustainability, workability, costs, etc. For the effective use of the Poly-Paper it will therefore be appropriate not only to maximize the percentage of cellulose, seen under the light of sustainable material, but also and above all to maximize the functional aesthetic yield in itself, which makes the product attractive to replace materials that are disposed of in the plastic recycling cycle with materials that are disposed of in the paper recycling cycle. The free project variables consist of parameters that can be modified according to the needs described by the three previous points. Can be considered as variable the composition of the Poly-Paper and the combination of technologies and semi-finished products used to make the products. Following what emerged from the research, the general project objectives were defined considering the aspect examined in the materials analysis of the case studies of Chapter 5.

Biobased

The biobased percentage of material could run from 40-50%, if all the components are made of Poly-Paper (considering the composition of material of at least 40% of cellulose) to almost 90% optimizing the presence of the Poly-Paper and maximizing the presence of paper and cardboard parts. Among the most desirable solutions is the use of parts that use recycled paper.

Biodegradability

Regarding biodegradability, combining the characteristics of paper and Poly-Paper, the period of time in which the product degrades should not exceed twelve months, also because both matrix and reinforcing material are compostable substances (CES Database 2018) also products who see the use of Poly-Paper are considered compostable in turn.

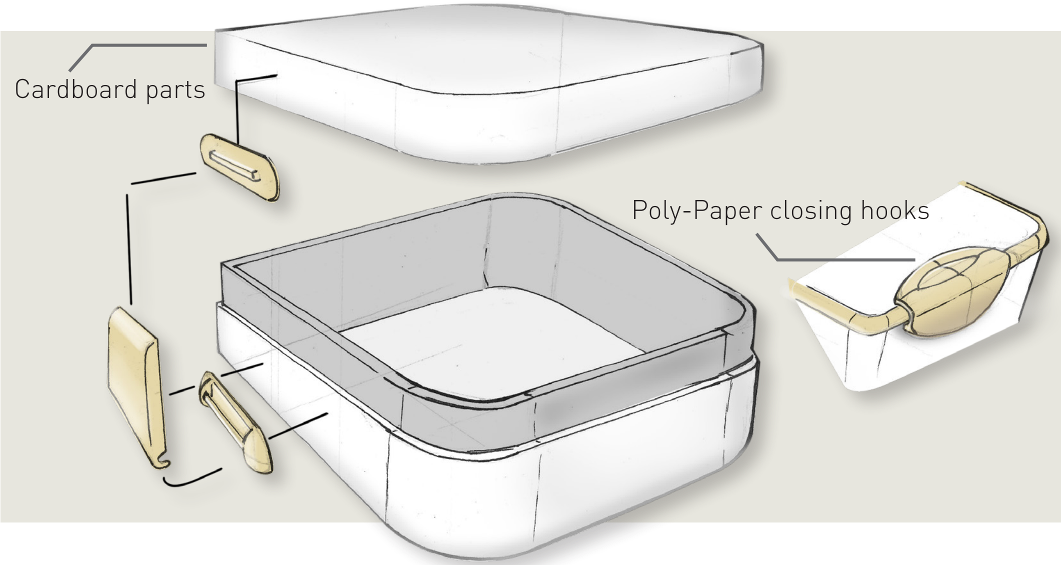
Lifetime expectation

The objects considered, as already discussed in chapter 6 should guarantee a life expectancy from 6 months to 2 years if correctly used, replacing plastic products or paper and board products with a strong box-like aesthetic connotation.

8.3 Disposable

8.3.1 Poly-Paper for material substitution and recycling

Disposable objects, as we have seen, are all those objects designed for limited use in time, which are thrown away once their function is over. Often these products are made of plastic because their functions require high detail to make hooks, closures, hinges, etc. The use of the Poly-Paper could change the product architecture, identifying parts of the product with mechanical functions or requiring a precise coupling and containing parts that can be made in paper materials. As already widely discussed in the previous chapters, although the products are presented as coupled materials, the goal they can achieve is to be disposed of as a single-material object in the paper. The types of applications that may seem advantageous in terms of production speed can be found in products that need an assembly phase, as it may be difficult to compete with products that need only one processing cycle (i.e. eggs container). To optimize the material substitution to paper and Poly-Paper, in case of containment functions, it is preferable to use it for dry products (loose food, cosmetic, generic casket). Special attention must be paid to water-based liquids that are not compatible unless resorted to waterproofing methods used for paper that do not make lose the recyclability feature. It is also important that there are no contacts with oils or substances that pollute the material making the little beneficial recycling.



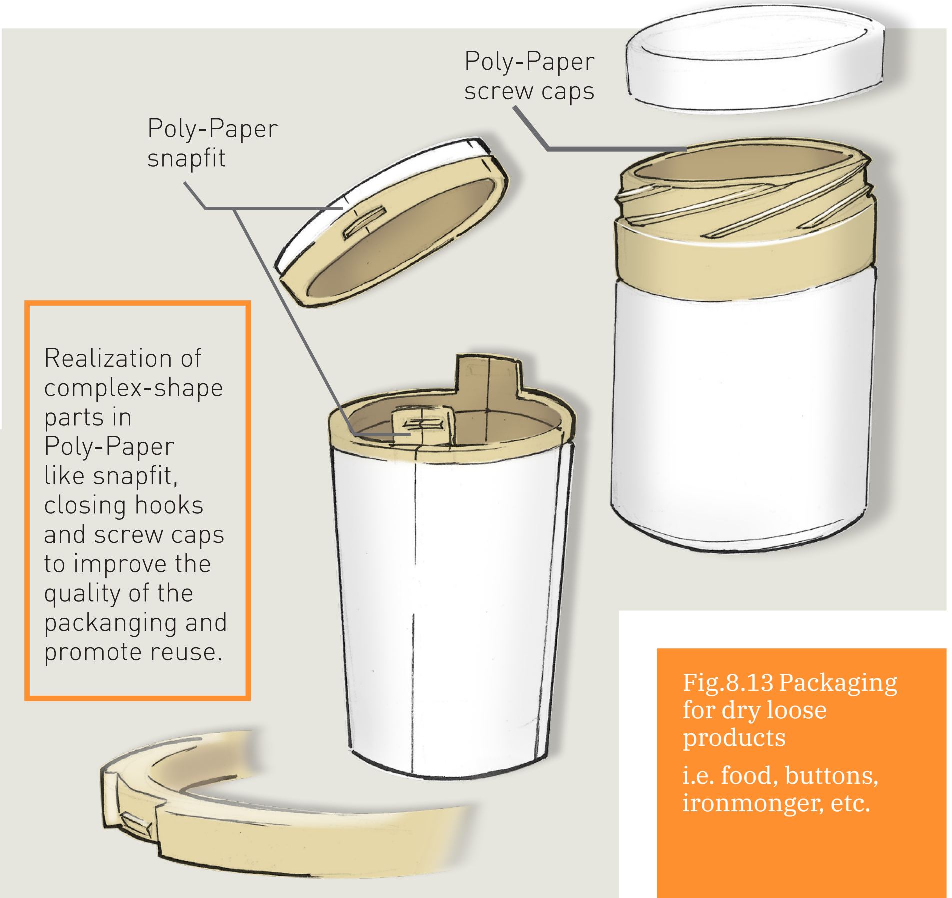


Fig.8.13 Packaging for dry loose products
i.e. food, buttons, ironmonger, etc.

Fig.8.14 Disposable Spools

For sewing thread, electric cables or 3D printing filaments

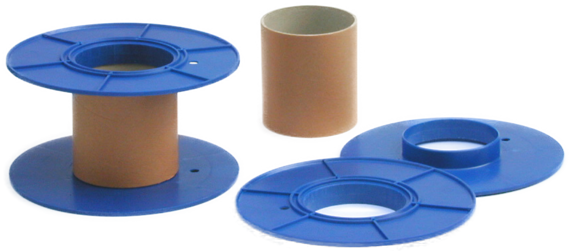


Fig.8.15 Paper spools

Fig.8.16 Poly-Paper spools - Skech from sewing thread to electric cables

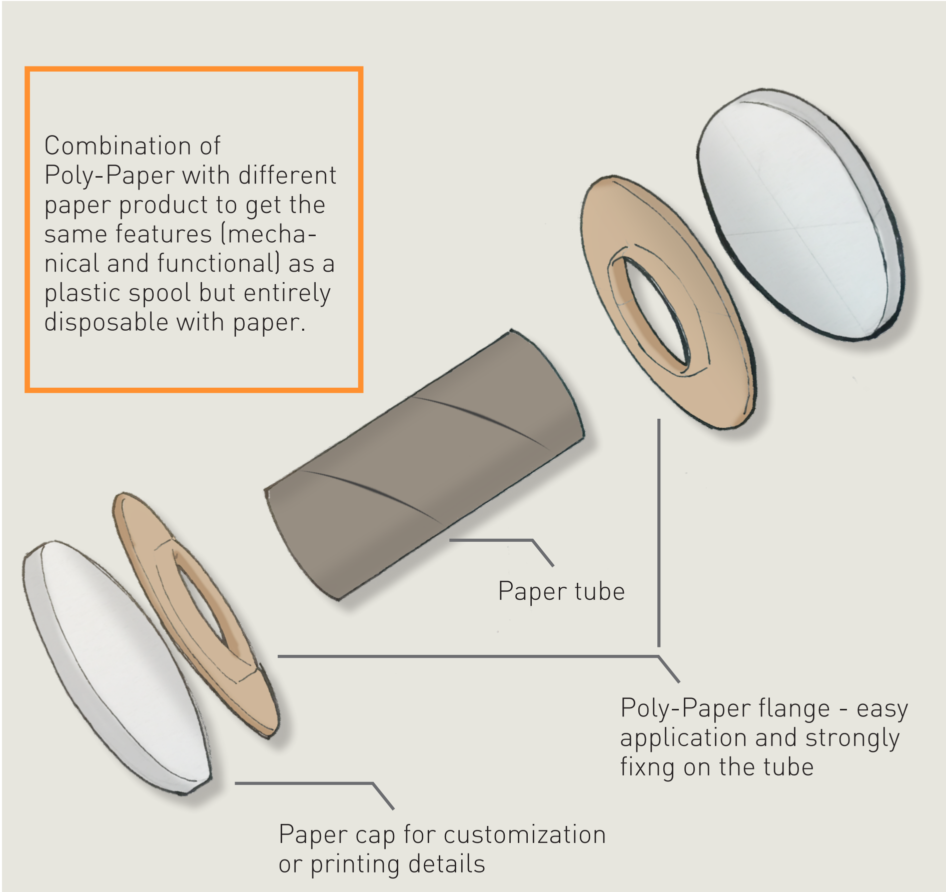
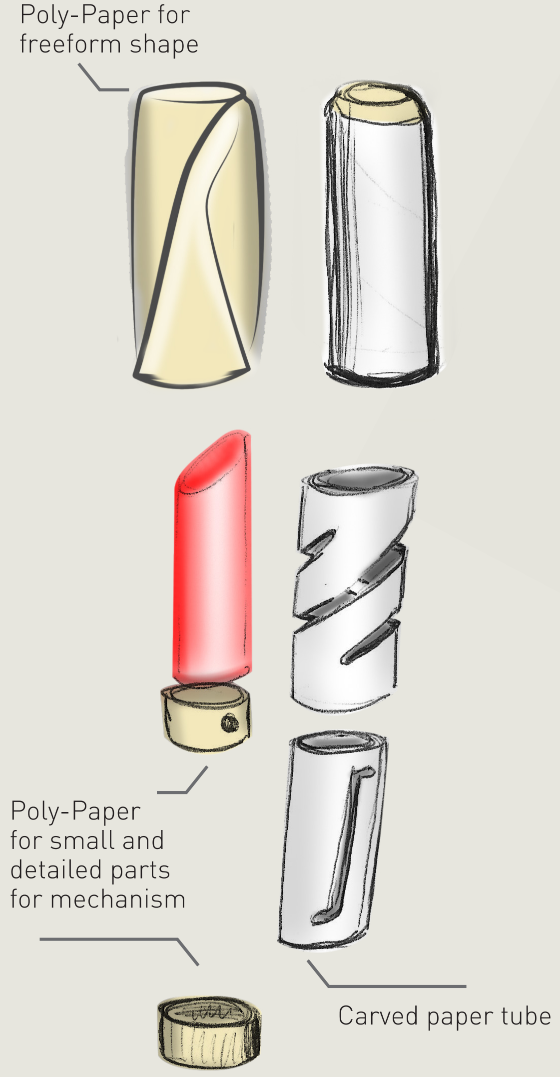


Fig.8.17 Lipstick packaging products

For a lipstick packaging Poly-Paper could be used for the complex parts and small paper tube for the main body parts. Poly-Paper is also suitable if a more complex shape for the cap is required to differentiate the product.



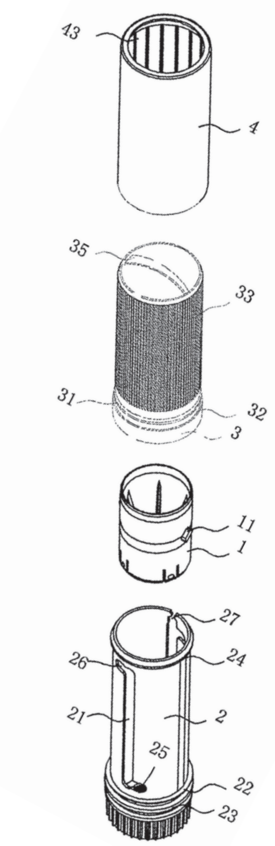


Fig.8.18 Lipstick - Skeches

Fig.8.19 Lipstick - Patent drawing

Containers for cosmetics – Eyeshadows

Beauty and personal care packaging volumes continue to grow globally, driven by changing lifestyles and consumers adopting new hygiene routines. Functionality and sustainability in packaging have also become essential purchasing criteria. An example that effectively responds to the requirements described above, eyeshadow containers have been considered. The typologies of these containers are varied and range from pocket-sized to caskets with multiple containers and accessory compartments. The shape of these products can be simple, round or square, or very elaborate as can be seen from the products offered by various cosmetic brands.

Fig.8.20 Eyeshadow packaging - Typologies

Traditional Materials

The most common type of plastic used in cosmetic packaging is PP. Other plastics include PET and acrylic ingredients. Acrylic plastic has the appearance of glass but doesn't break like glass. From an aesthetic perspective, plastics can be made in various colours or tints, depending on the material (https://www.desjardin.fr/en/blog/cosmetic-packaging-suitable-materials-for-cosmetic-containers).

Production Technologies

The production technology of the components of an eyeshadow primary packaging is the injection moulding and thermoforming.

Critical issues

A wide variety of cosmetic packaging is made from plastic, due to its convenience and hygienic qualities. Unfortunately, plastic tends to contribute to a large amount of waste and once it is used, products usually won't be reused or refilled and often is not disposed correctly.

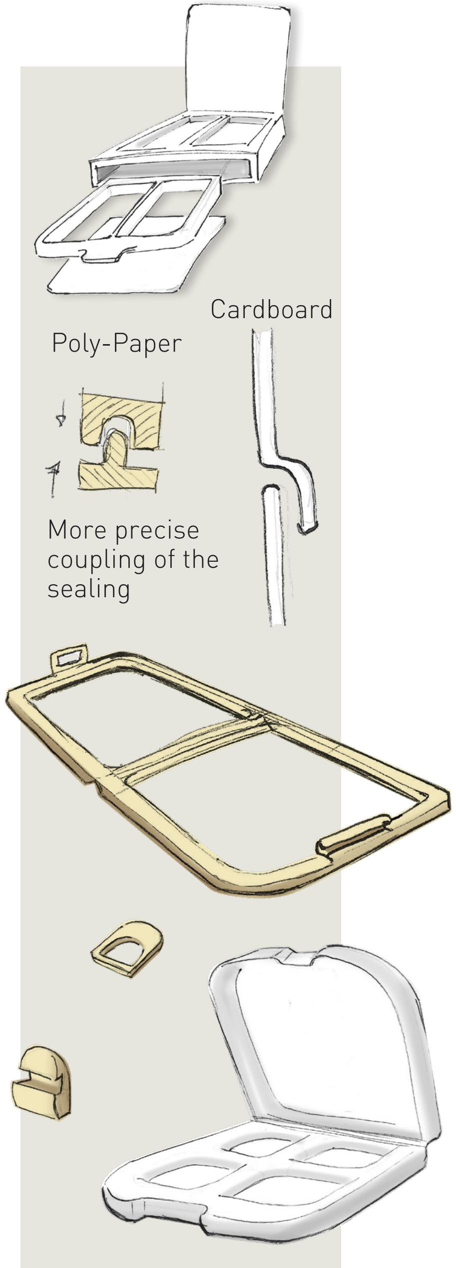


Fig.8.21 Eyeshadow packaging - sketches

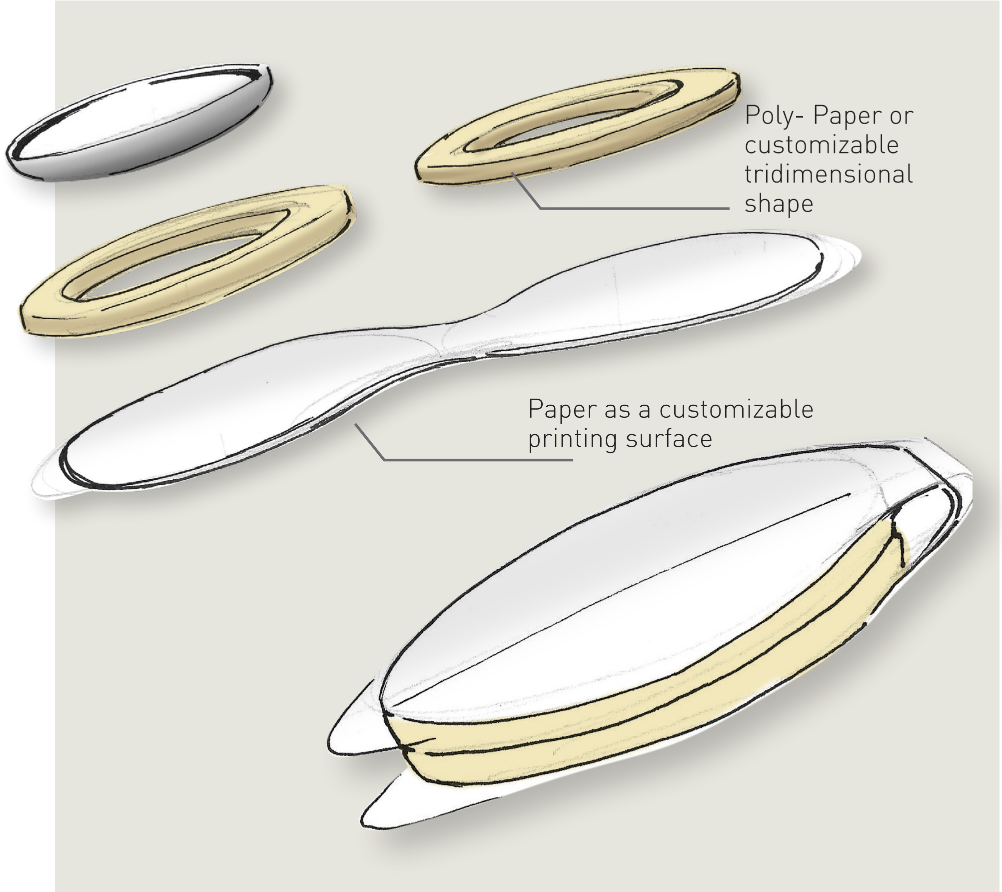


Fig.8.22 Eyeshadow packaging - Concept Sketches

Description

The packaging presents parts that require a precision coupling, or a high level of detail made in Poly-Paper while the shells are made of thermoformed paper pulp to fulfill the functions of container and components suitable for brand communication or customization.

Added Values

Thanks to the combined use of Poly-Paper and paper it is possible to create containers with the same functionality and with a high potential for customization. At the end of its life, the product can be safely disposed whole in the collection of paper without the need for separation of parts or components.

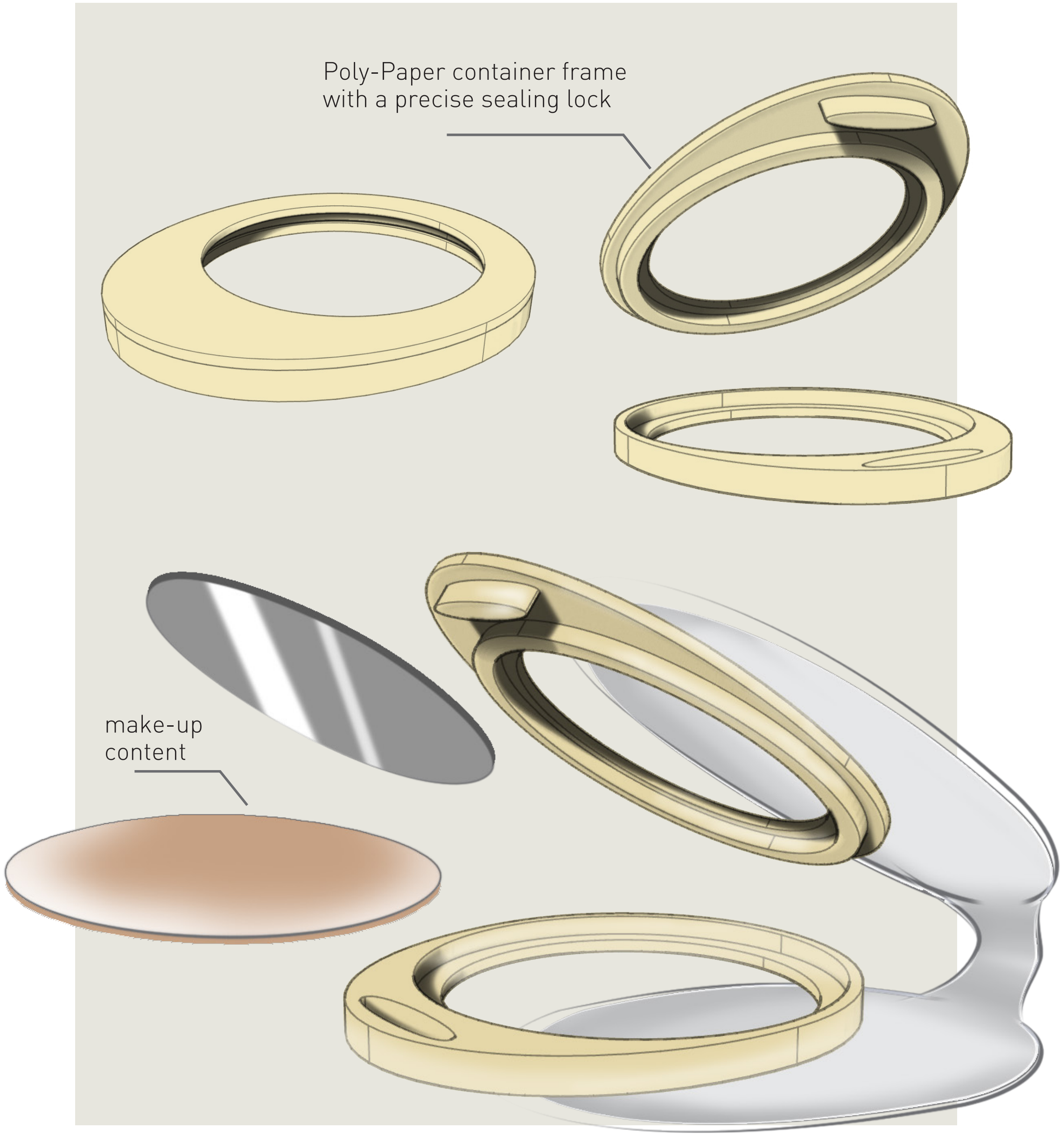


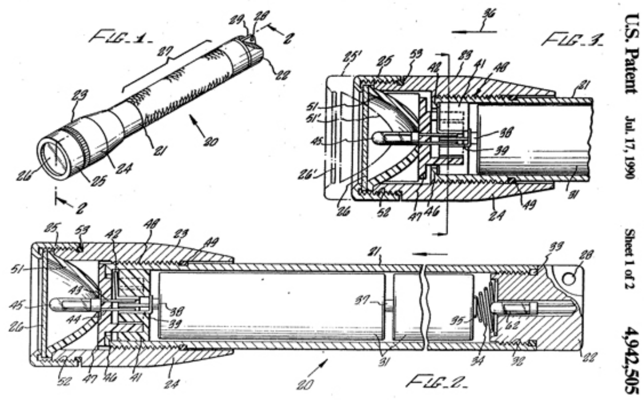
Fig.8.23 Eyeshadow packaging - Concept Sketches and parts

Fig.8.24 Eyeshadow packaging - demonstration model

8.4 Consumer Electronics

8.4.1 Poly-paper for disassembly

In the proposals for the category of consumer electronics, the design approach regard the disassembly for disposal. Electronic products are characterized by a heterogeneity of materials of which they are composed the bodyshells, made of polymeric material rigid or elastic, and the internal electronic components. They were taken into account as strongly subject to programmed obsolescence and due to the variety of products, such as computer accessories and mobile devices, audio products and videos and much more, result in a large number of wastes very often difficult to dispose as discussed in chapter 7. It is for this reason that for these products must be developed an end of life guided the design for disassembly approach, where it is important the splitting of part subject to technological obsolescence and the one subject to stylistic or aesthetics obsolescence (in case of changing of trends or worn out). The Poly-Paper and paper introduction in this product sector, aims to facilitate the recognition of these parts to bring the end user to an active disposal to minimize the amount of non-insertable material in consolidated recycling cycles. The new polymeric material is used both for technical and aesthetic reasons. Taking advantage of its thermoplastic properties, it is possible to create complex details such as cups, snapfit and thin ribs for the coupling or positioning of the electronic parts. With the Poly-Paper, frame compositions or complex parts are possible by welding, to make production equipment cheaper and to avoid the joining of bodies that sometimes have a mere aesthetic function. An effective design would lead to insert and communicate which parts of the product can be actively disposed by the end user as they are replaced with cardboard and Poly-Paper. The replacement of material aims to increase awareness of the correct disposal of products through their materiality, impacting on the problem of the disposal of electronic waste. The objects must contain morphologies and systems related to the disposal of the paper as pre-cuts, joints or printed indications.



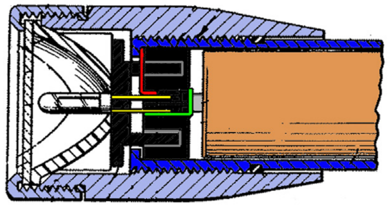
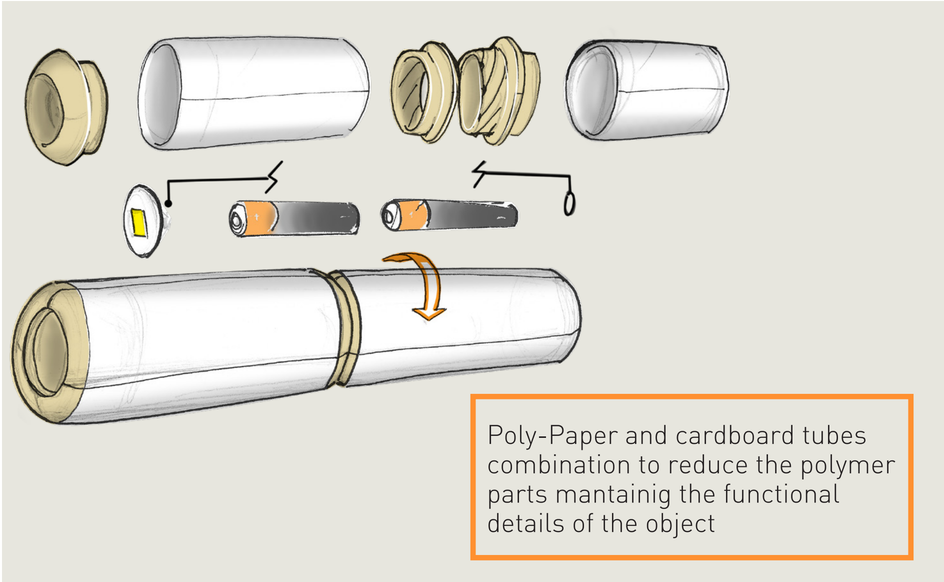


Fig.8.25 Torch - Patent drawing

Fig.8.27 Torch- Products

Fig.8.26 Torch- sketches

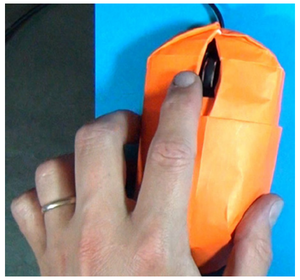


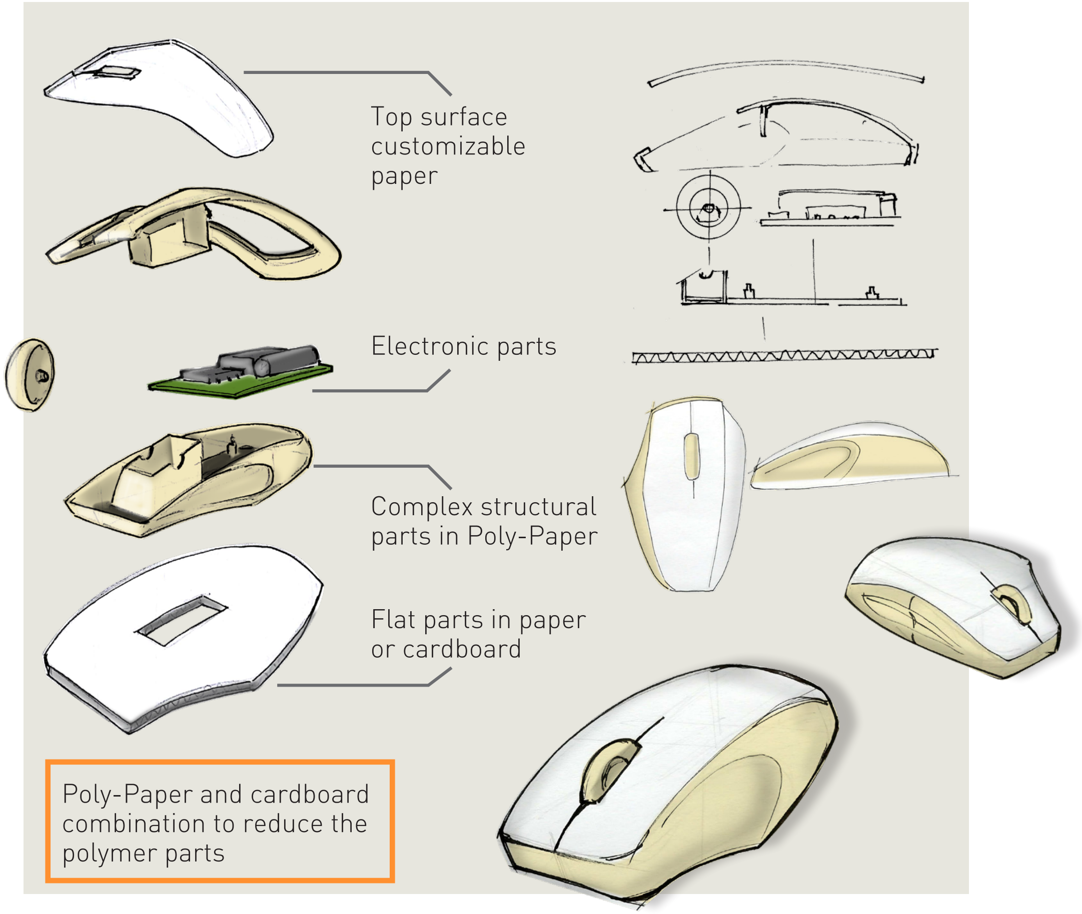
Poly-Paper and cardboard tubes combination to reduce the polymer parts mantainig the functional details of the object

Fig.8.28 Mouse - Product

Fig.8.29 Origami Mouse

Fig.8.30 Mouse - Sketches





Keyboard

A computer keyboard is a typewriter-style device widely used as an input tool for numerous electronic devices such as personal computers, tablets, smartphones etc. There are various types of keyboards that differ in size and number of keys. The most commonly used keyboards are standard keyboards such as the 101-key US traditional keyboards or the 104-key Windows keyboards, include alphabetic characters, punctuation symbols, numbers and a variety of function keys; and the laptop size with smaller dimensions and fewer keys (https://en.wikipedia.org/wiki/Computer_keyboard). Regarding the duration specifications the manufacturers provide lifespan estimations measured in key presses and clicks because

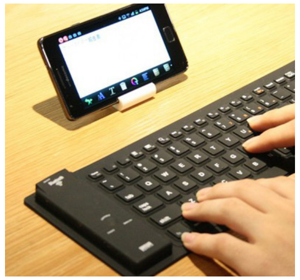


Fig.8.31 Keyboards - Products

a time-based measure would not apply to all users. Different users have different usage patterns. A worker, for example, press on the keyboard an average of 11698 keys per day or 4.2 million keypresses per year. An average product promises a lifespan between 20-30 million clicks, that means 7.2-10.5 years. Unfortunately, the top of the range keyboards tries to impress users and diversify the different accessories between them with 100 million keystroke lifespan. This would mean 195 years, and the keyboard will stop working much earlier than that (https://www.digitalcitizen.life/how-long-are-millions-keystrokes-and-clicks-years).

Fig.8.32 Key presses statistics

Traditional Materials

The most commonly used materials are ABS or HIPS for the shells. Inside there are, in addition to the usual electronic components, a silicone membrane to ensure the return of the keys and return the tactile feedback of the pressure during use, then three cellulose acetate sheets, two of which have printed electrical circuits that when they are closed generate the input of the selected letter.

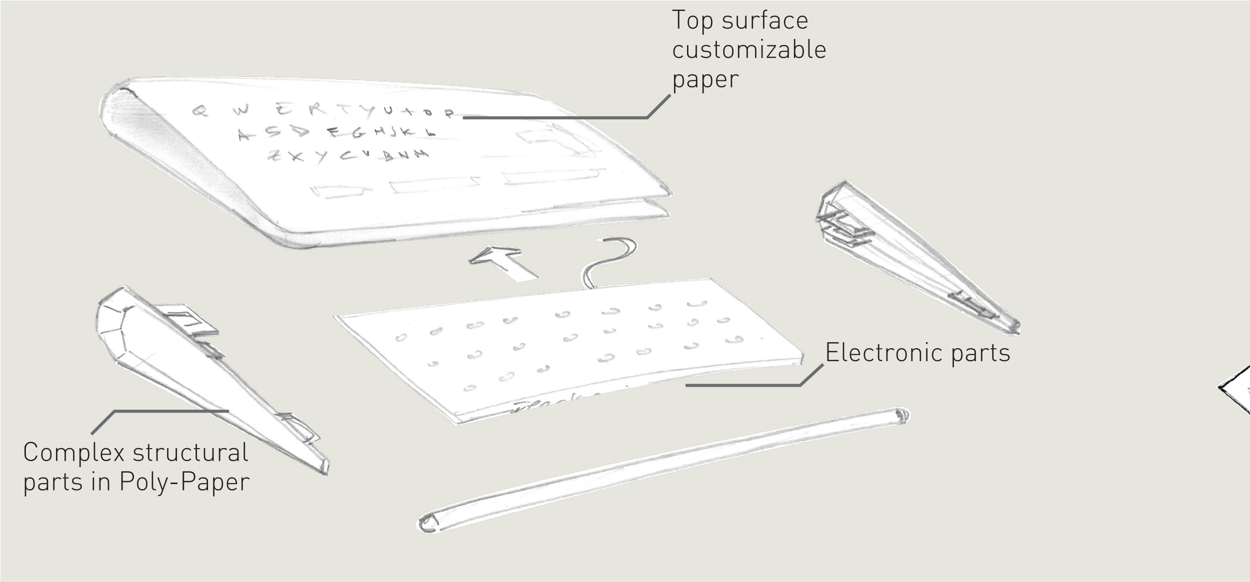
Production Technologies

Being polymeric materials, the production technology of the main components is injection molding, which is optimal for the realization of complex parts such as bodies for consumer electronics products. For the finishing part where the symbols are applied to each key, pad printing is commonly used (https://en.wikipedia.org/wiki/Pad_printing).

Critical issues

The main problem of objects like keyboards is the difficult disposal. It is due to the multi-material nature of the components and, in addition to a lack of awareness of the user to the disposal of these products, there is no invitation or indication on the object on how and where dispose it that often direct it to the undifferentiated waste. The materials used also have a durability not in line with the average life of the product and therefore, if not correctly disposed of or recycled, they lead to an inexorable downgrade of the materials used.

Fig.8.33 Keyboard - parts analysis



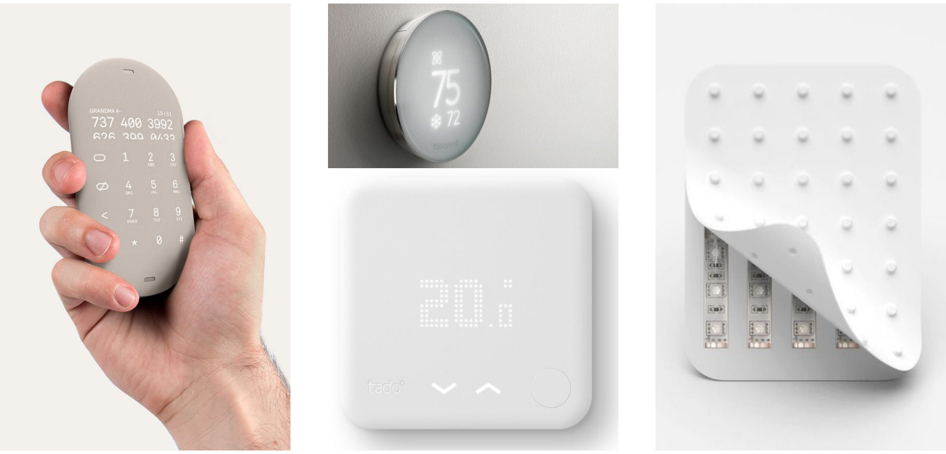


Fig.8.34 Keyboard - moodboard and trends

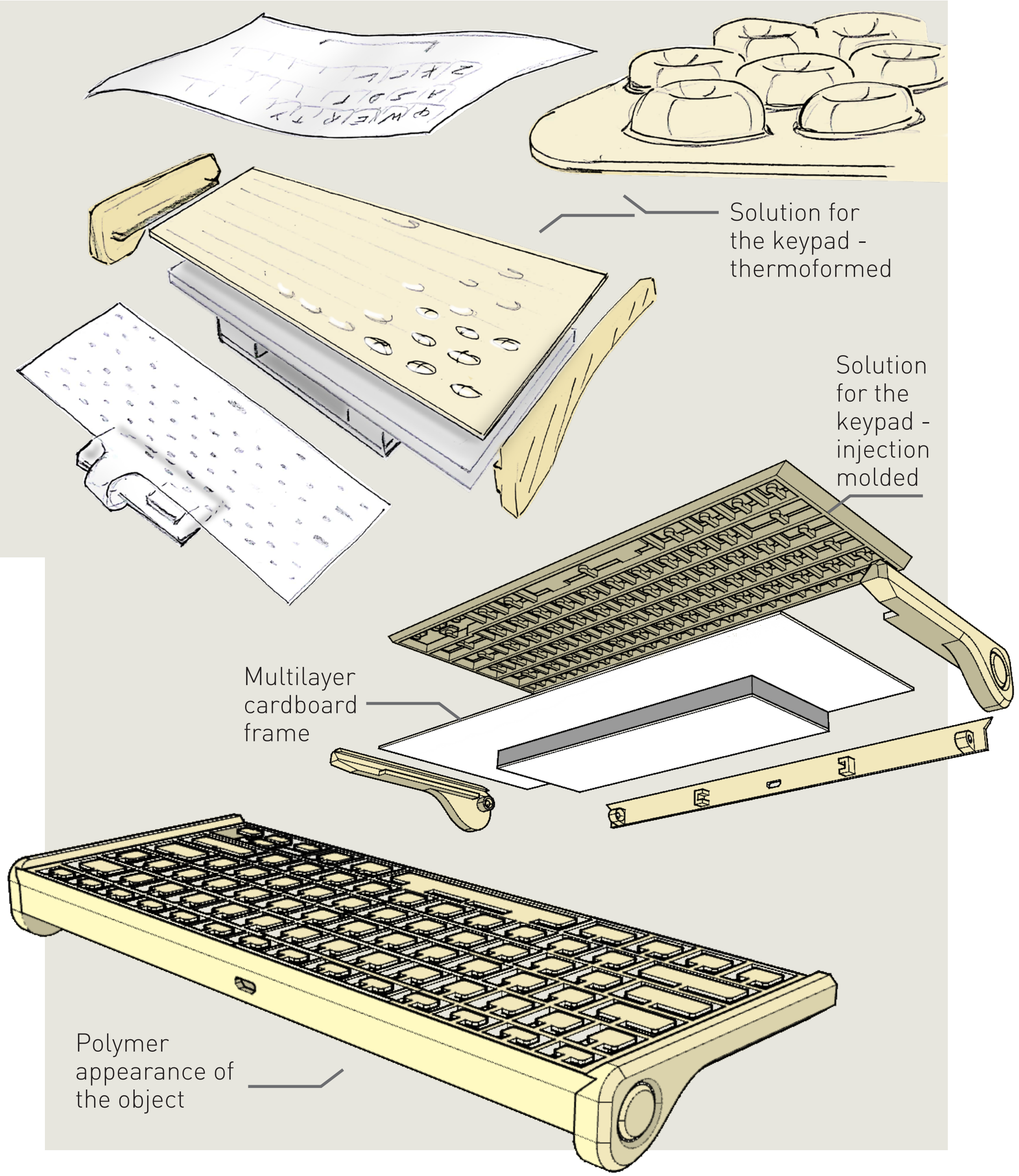


Fig.8.35 Keyboard - Sketches

Description

The keyboard is made up of Poly-Paper and corrugated cardboard parts. The polymer parts produced by injection molding have both functional and aesthetic details. In fact, they interact with electronics by providing the structure of the keys and giving the object a qualitative aspect linked to plastic products and not to those made of paper and cardboard. The central structure is composed of corrugated cardboard that acts as a support for the keys and container of electronic components. The entire central body is covered by a sheet of paper printed and cutted with the symbols of the key, which could give an infinite possibility to the customizations of the keyboard itself. On the paper cover there are indications for maintenance and disposal of the product to provide the final user.

Added Values

Thanks to the combination of Poly-Paper parts and cardboard parts, in addition to the necessary electronic components, we first want to introduce cellulose-based materials in a world that sees a predominant presence of plastic materials. This shift of material brings the end of life of materials closer to that of the product and having a consolidated recycling cycle increases its sustainability. We want to simplify the product by reducing the number of components and complexity, making the user an active actor from assembly and customization to maintenance and disposal.

Fig.8.36 Keyboard - 3D printed demonstrator parts

Fig.8.37 Poly-Paper Keyboard - Parts

Fig.8.38 Poly-Paper Keyboard - Assembled

Smartphone Cover

The smartphone cover is used for the protection of the device from bumps, falls and dirt, to help the grip as well as to give a personalized character or appearance to the object. Around the cover there are also examples that, in addition to surrounding the smartphone as a normal cover, also add more features, such as low-tech like support three feet, or high tech such as the Polaroid printer or viewers for augmented reality.

Fig.8.39 Smartphone cover

Fig.8.40 Smartphone cover - typologies and cusomization

Fig.8.41 Smartphone cover - Functional

Traditional Materials

The materials of which cell phone covers are composed are mainly plastics such as polycarbonate, polypropylene, soft polyurethane. Besides these there are also numerous examples of the use of silicone rubber or elastomeric polymers. Then there are other examples that use materials such as leather or metals (https://technofaq.org/posts/2016/02/the-best-mobile-cases-material/).





Fig.8.42 Smartphone cover - Common materials

Fig.8.43 Smartphone cover - Cardboard

Production Technologies

Production technologies are those related to plastic materials such as injection molding or co-molding in case the product is not composed of a single piece or material. With elastomeric materials, for simple shape is used compression molding and for complex shape of silicone cover is used a molding with a previous cold casting of three-dimensional decorations. Tridimensional textures, pad printing or UV printing are used for decoration and customization.

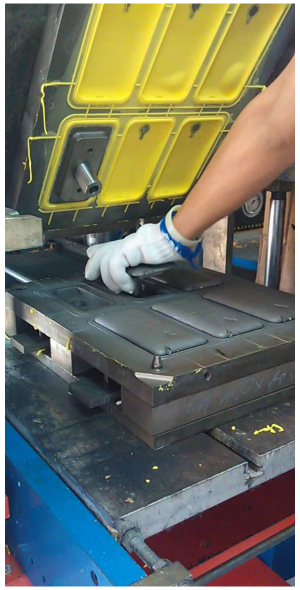
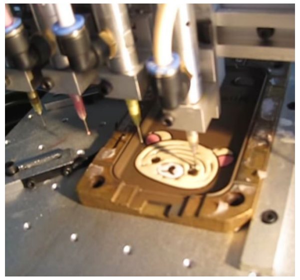
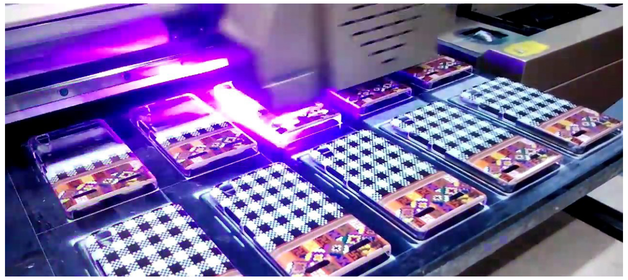


Fig.8.44 Production technologies for smartphone cover







Critical issues

The criticality of these products lies in the fact that the life span of the product is much lower than the duration of the materials that compose it. Moreover, there are no indications for the correct disposal of the product that often risks ending up in the collection of undifferentiated waste.

Description

The proposal includes a cover with an injection-molded Poly-Paper edge to give shape and finish comparable to a plastic product. The back surface is made of cardboard decorated and personalized by printing and laser or die-cutting to adapt to different models of cell phone with carvings that provide the necessary flexibility to be fitted.

Added values

The first added value of this type of product is to bring the life span of the product to that of the material. Moreover, the use of the mixture between Poly-Paper and paper aims to make the user more aware of the nature of the material and guide the end of life towards a cycle that can re-upcycle the cellulose of which it is composed.

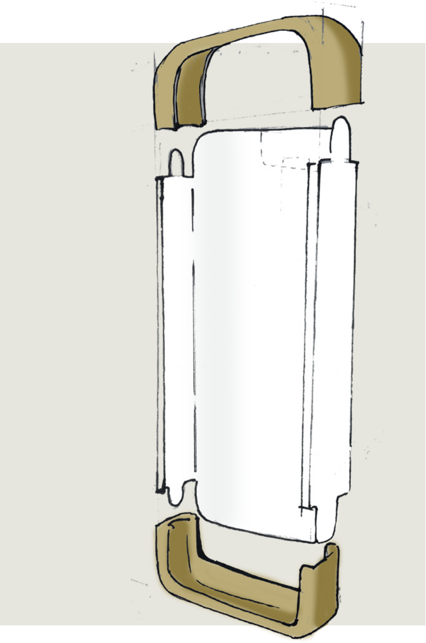
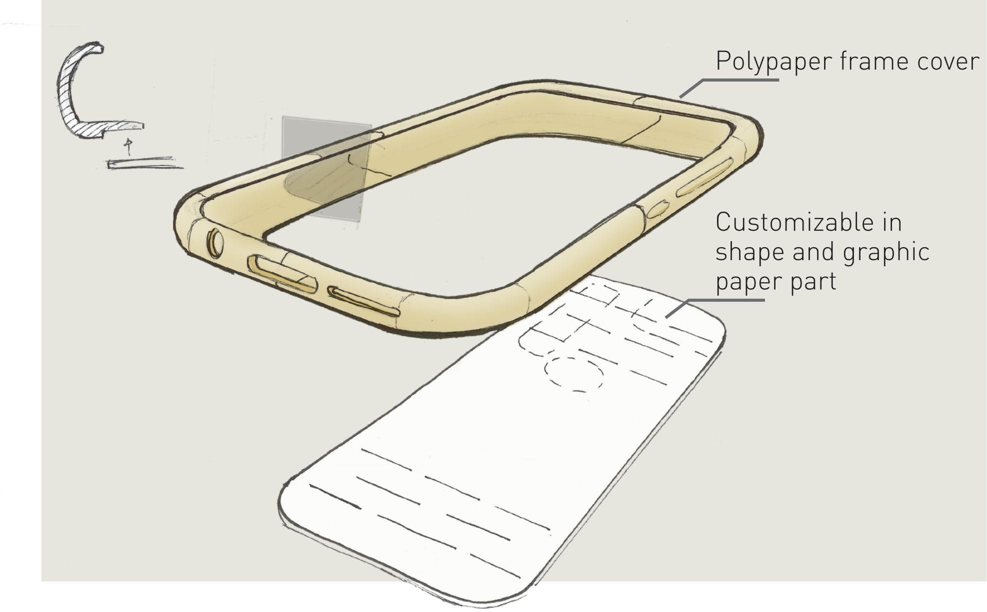


Fig.8.45 Smartphone cover - Sketches



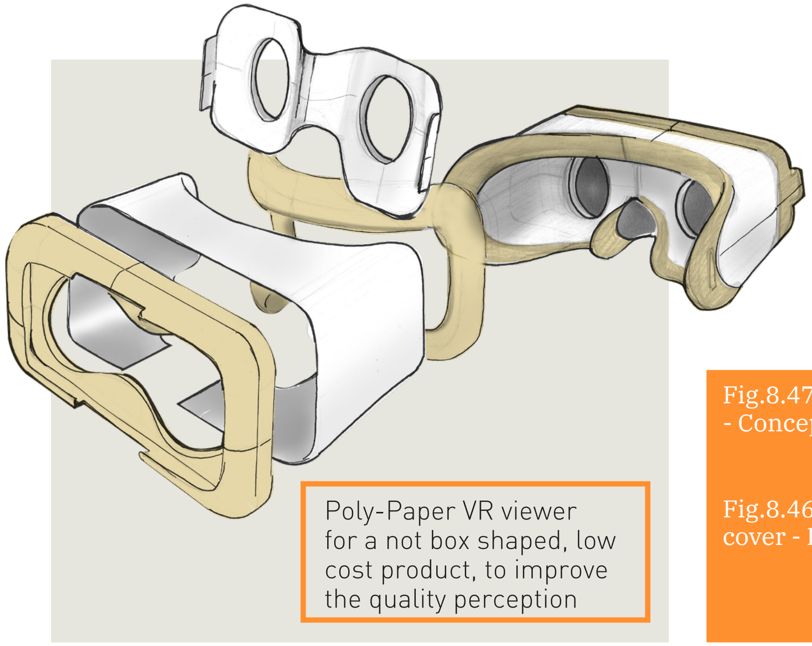


Fig.8.47 VR viewer - Concept

Fig.8.46 Smartphone cover - Demonstrator

8.5 Toys

8.5.1 Poly-Paper for customization and refurbishment

As regards the proposals relating to the toy market, the aspect of interest linked to the Poly-Paper is that of customization and lengthening of the life of the product thanks to the repair. The toy market presents a huge variety of products, many of which are made of plastic. They too, as with disposable or electronic products, once again show the life of the product much lower than that of the materials. The toy market is very fast, due to the short duration of the toy fads and to the fact that they are bound by their nature to a limited use over time as often related to the age of the user. The hypothesis of use has been directed towards toys for children with an age ranging from 6 to 13 years. The choice was made because the peculiarities brought by the Poly-Paper could be enhanced at best. Firstly, there is the development of personalization: this can be done by the children through coloring, assembly and addition of paper parts in turn personalized. You can also assume new types of toys or gaming experiences through the shape memory forming characteristic. Secondly, but not less important, there is the development of a refurbishment carried out directly by the user. In fact, thanks to the weldability with water the parts that could be accidentally broken by children could easily be repaired to extend the life of the toy.

Fig.8.48 Wasted Toys

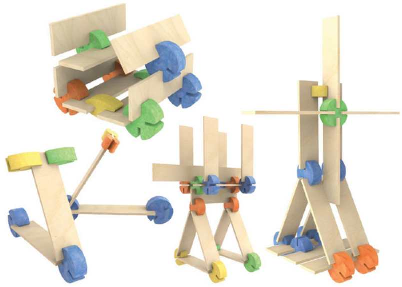
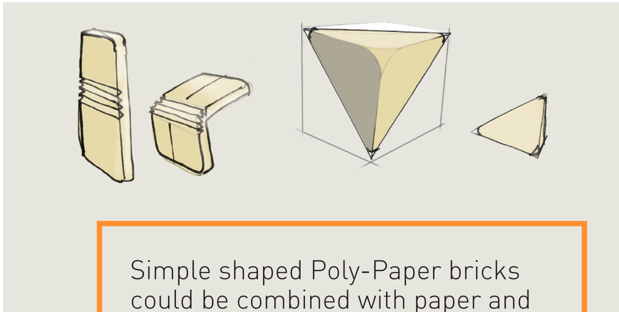
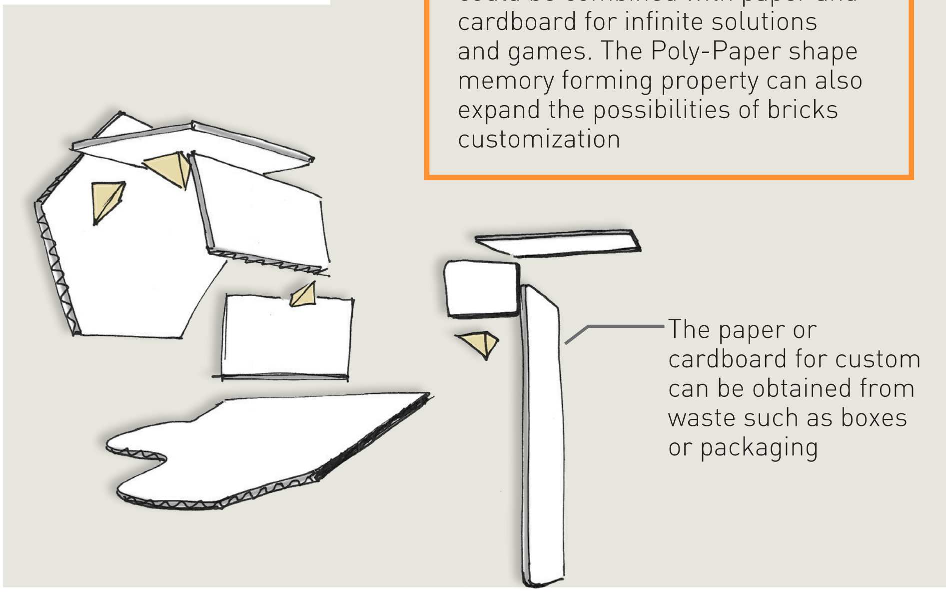


Fig.8.49 Poly-Paper - Simple Building Bricks





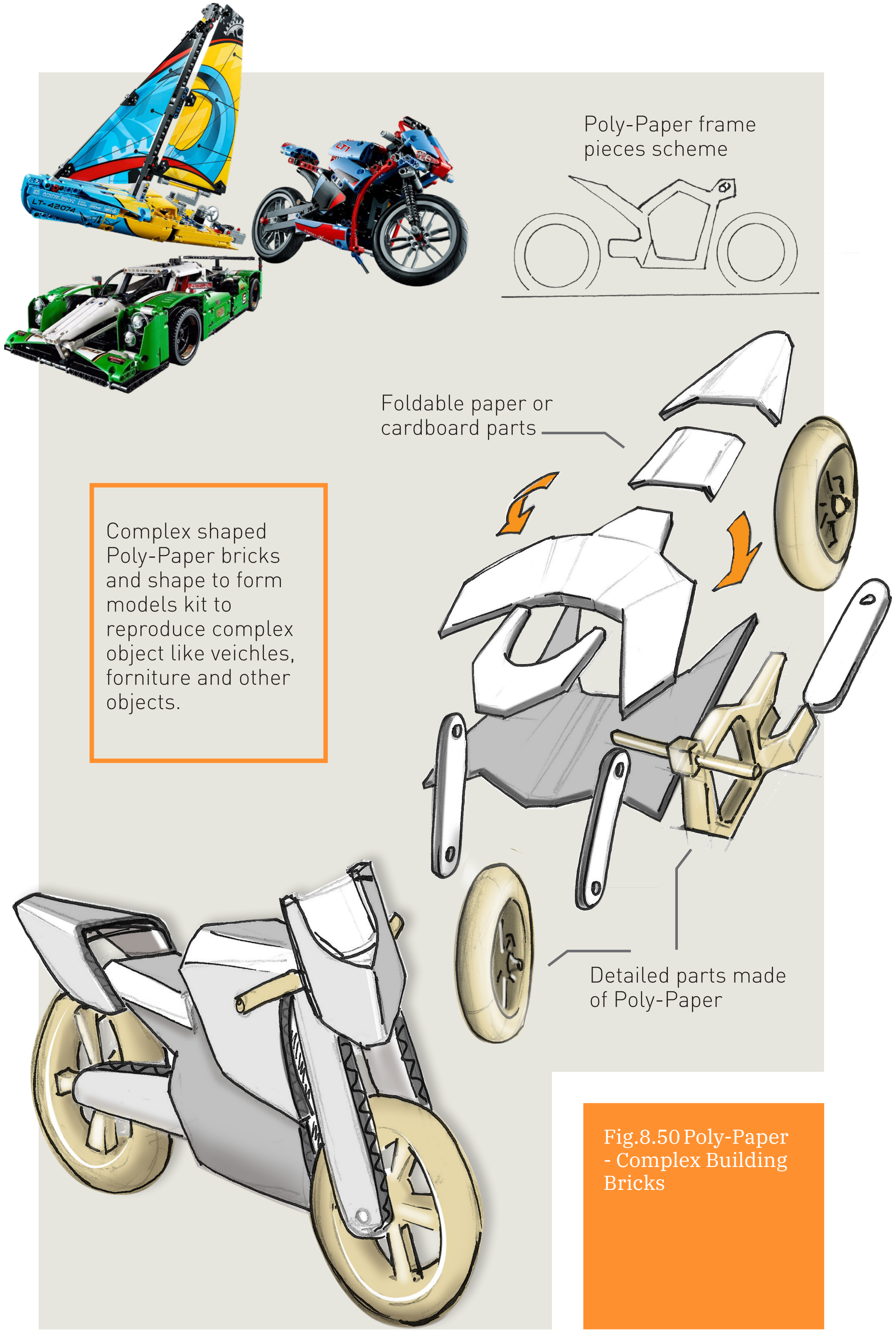


Fig.8.50 Poly-Paper - Complex Building Bricks

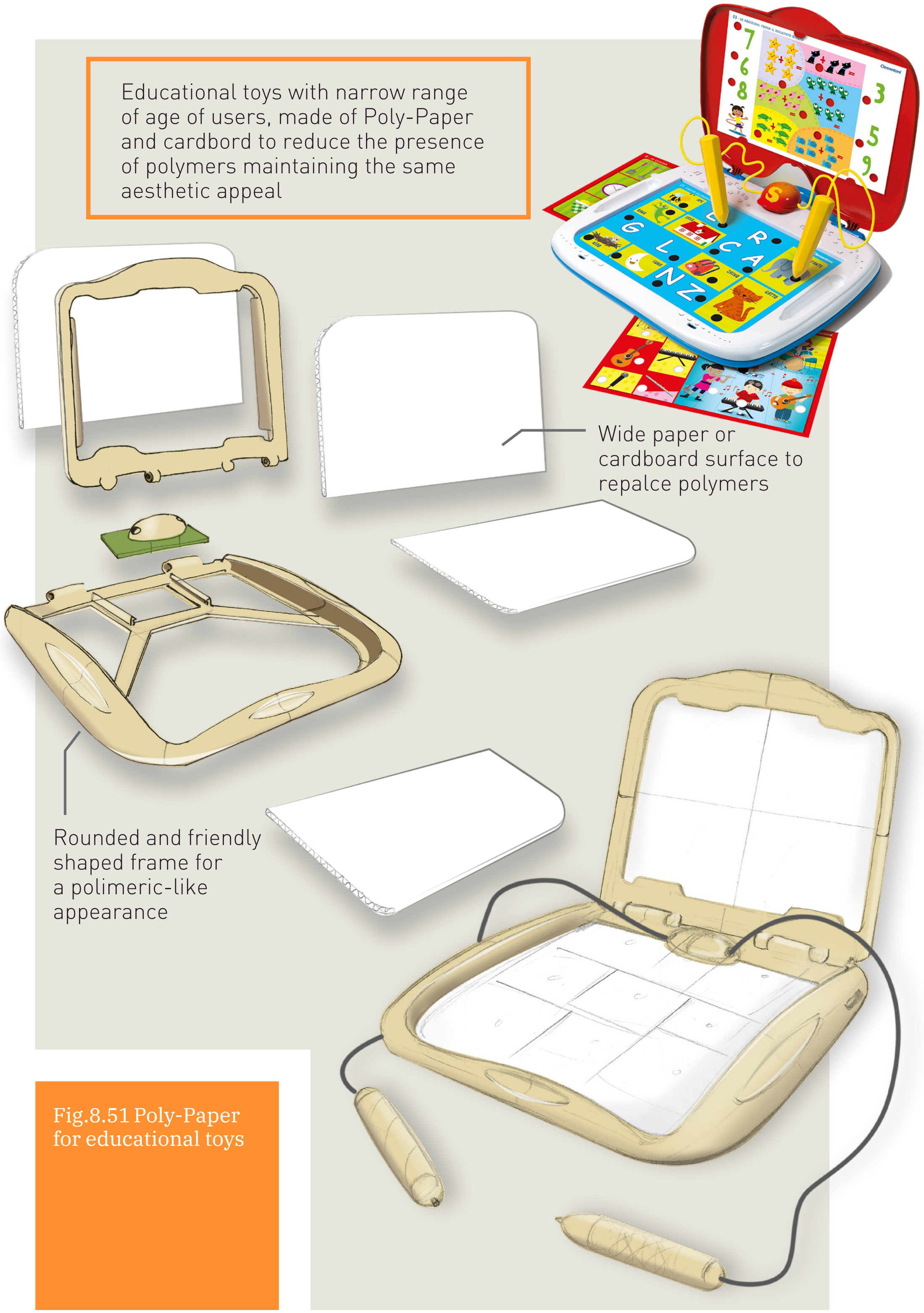
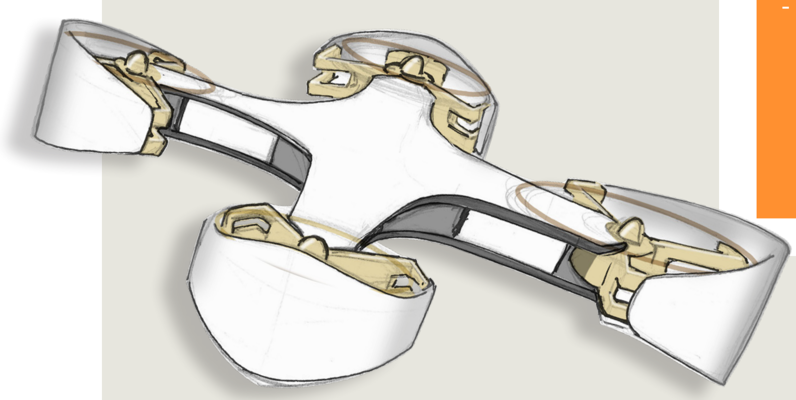


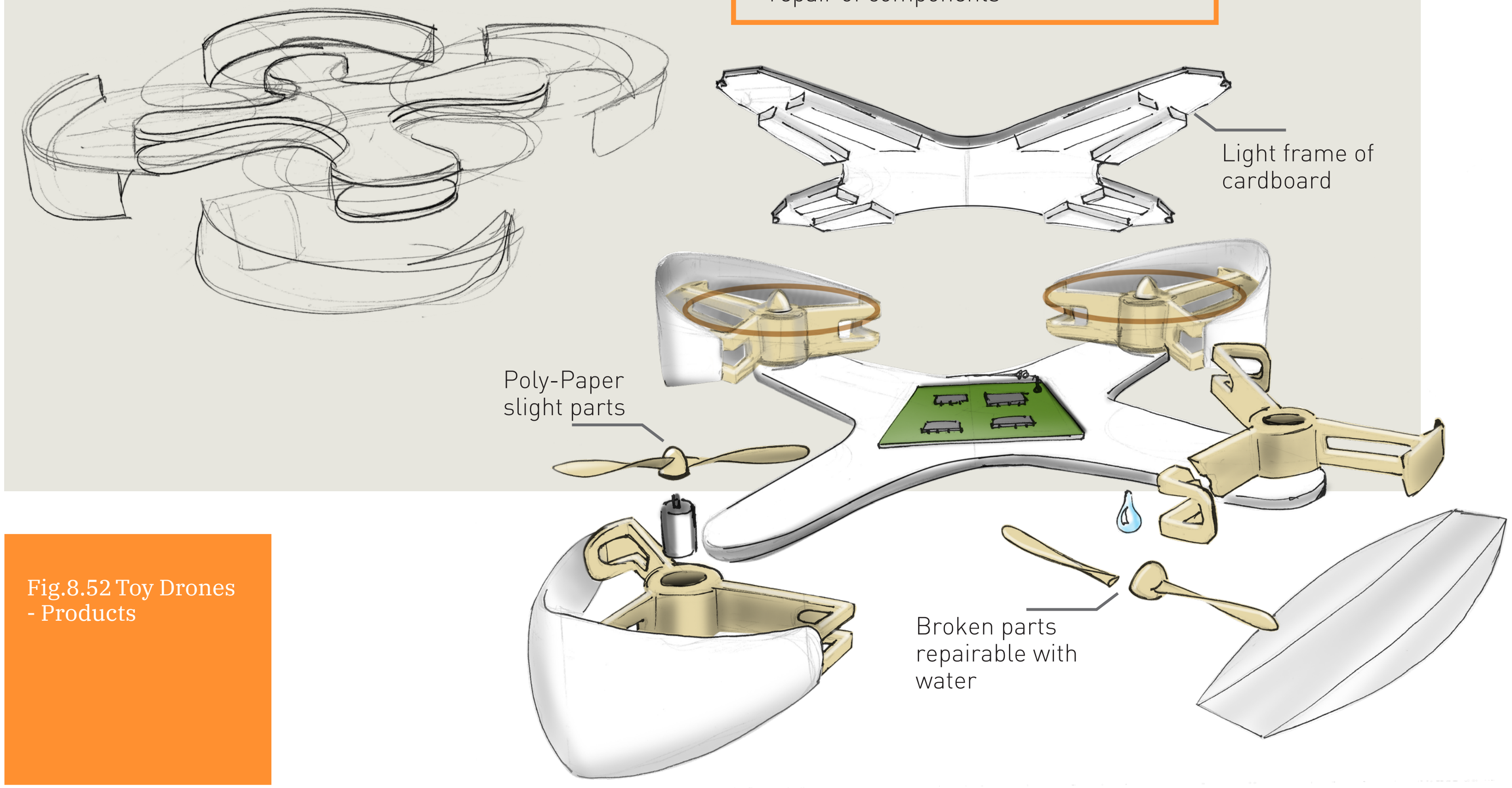
Fig.8.51 Poly-Paper for educational toys

Fig.8.52 Toy Drones - Products

Fig.8.53 Toy Drone - Sketches



Complex parts frequently subject to breakage or damage, as propellers or protection bumpers for drones, could be made in Poly-Paper to facilitate the repair of components



Action Figures and Models

The world of toys, and more particularly that of models and action figures, includes from fashion dolls, up to soldiers and models in general of animals or objects such as houses or means of transport. Depending on the age group to which they are directed, they present a variation in materials, details and finishes.

Fig.8.54 Action figures and models

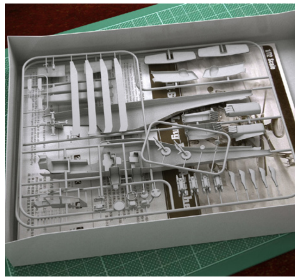


Fig.8.55 Paper model toys

Traditional Materials

The models are made of ABS or HIPS, which, as materials, guarantee excellent finishes and good mechanical performance. As far as concern fashion dolls and action figures, they are made of several types of plastic. The arms are made of EVA (ethylene-vinyl acetate) the torso is made in ABS (acrylonitrile-butadiene-styrene) or polystyrene-co-acrylonitrile (SAN). The head is made from a hard vinyl compound and the eyes are created using a developmental water-based spray paint system from a proprietary supplier. Polypropylene forms the bend-leg armatures while the outer legs are made of PVC, although of a different kind than earlier models (http://www.craftechind.com/plastic-materials-usedin-barbie-dolls/)

Production Technologies

The predominant production technology is that of injection molding, but some parts involve the use of rotational molding or extrusion and blow molding. For the details, manual or automated painting techniques are used.

Critical issues

One of the main problems of these products is the considerable variety of materials used even for a single product. Secondly, regarding the consumer perspectives on product lifetime (Gnanapragasam et al. 2017), they have the lowest level of satisfaction with duration. In fact, the average life span of a toy fad is about eight months from its launch until it's marked down (https://www.ngpf.org/blog/question-of-the-day/question-of-the-day-whats-the-average-lifespan-of-a-toy-fad/). The combination of these two problems creates critical issues regarding the environmental sustainability aspect of plastic toys.

Fig.8.57 Common production technologies for toys

Fig.8.56 Broken Toys

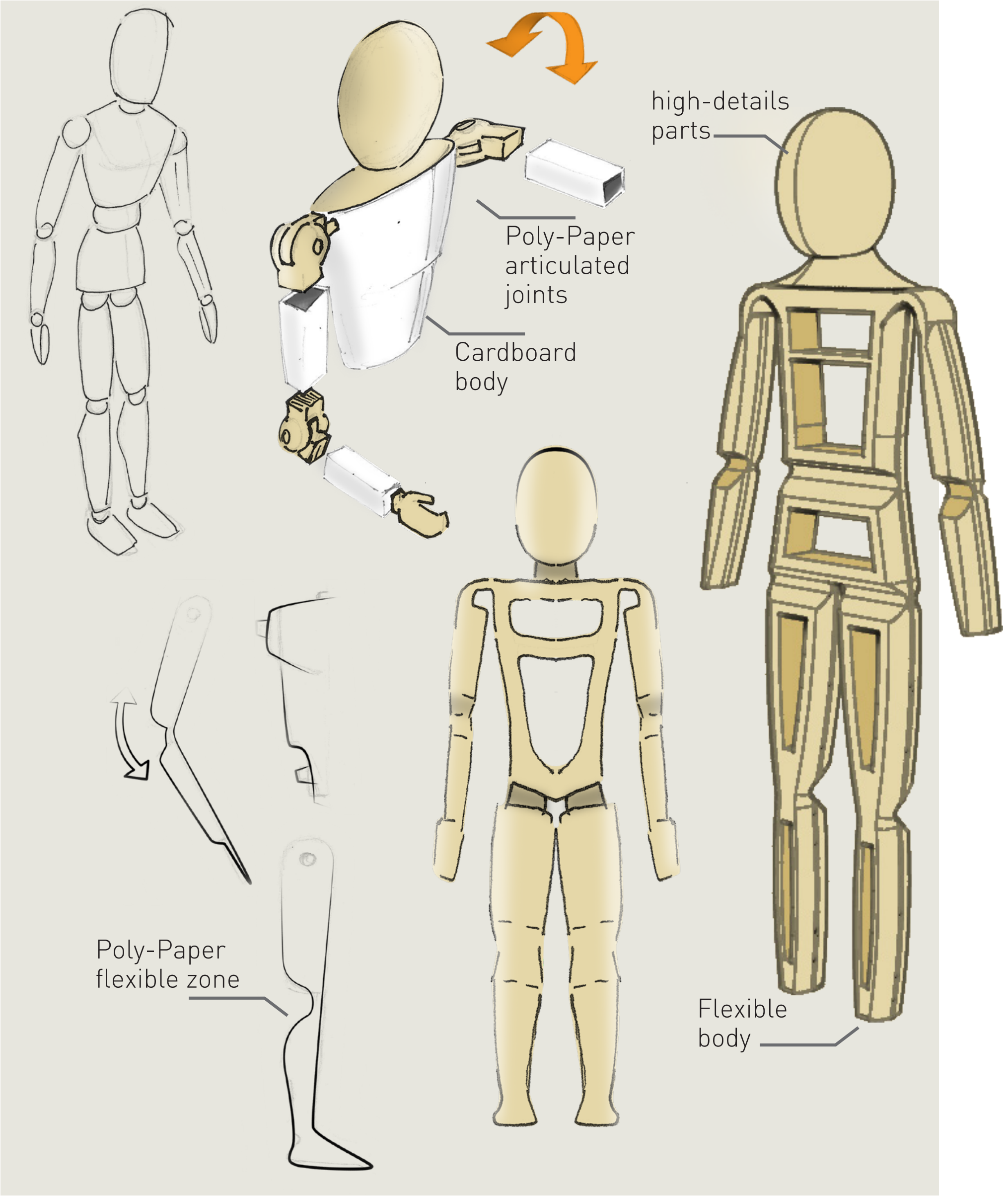


Fig.8.58 Action figures - Sketches

Description

Creation of a skeleton or body structure in Poly-Paper which aims to replace traditional polymeric materials. Specifically, the Action figures, centrally discharged limbs and junctions that take advantage of the good elasticity of the material for the simulation of movements and to extend the possibilities of customization. On the body can be applied reversibly (through joints or snapfit) or irreversible (welding or gluing by water) customizable parts in Poly-Paper or paper and cardboard. In addition, the Poly-Paper skeleton aims at introducing a new refurbishment point of view into the toys that, in case of damage, can be repaired by simply using water, giving the possibility of extending the life of the product until it is desired user.
Another interesting aspect of Poly-Paper is the Shape Memory Forming to give new ways of using the components that supplied in standard forms can be customized not only in terms of finishes but also in the morphology of the product. This aspect can be used both for action figures and for generic models. A leading example can be brought by the well-known Lego brand, which started from the famous “brick” module is evolving its series of products creating numerous special pieces.

Added values

The use of Poly-Paper in the toy world would like to improve products as more sustainable, disposable in the paper recycling cycle as if it were a single-material product. In addition, to increase the play possibilities and expand the users’ imagination limits, introducing the Poly-Paper and paper as easily and highly customizable materials at low cost would allow a better gaming experience valorizing the product use.

Fig.8.59 Action figures - 3D printed demonstrator parts

Game Pieces

Considering all the parts that make up a board game, box and game board for most of the time made of high-weight pressed cardboard. Cards are also made of cardboard. The components included in the package that are often not made of paper are the thermoforming inside the package to stock the game parts and the pieces. The thermoforming in plastic, as observed in chapter 3, can be replaced with a component with the same functionality made with thermoformed paper, in this case the use of Poly-Paper could be not very effective as the component is mono-material and made in one productive cycle. The pieces, or pawns, are much more interesting when it comes to making Poly-Paper. In fact these components are very often made of plastic with common shapes such as skittles or particular and characteristics for the game (i.e. Risiko tanks or ad hoc pawns of the versions of monopolies)

Fig.8.60 Game pieces for board games

(www.thegamecrafter.com).

Traditional Materials

The game pieces could be made of very different materials, they have been made in wood or metal in the past, but nowadays the polymeric materials are more commonly used. They are mainly made of ABS or acrylic resins.

Production Technologies

The technologies used for the production of the game pieces, according to the level of detail to be obtained, are injection molding or compression, or the casting of resins.

Critical Issues

The criticality of these small objects is not high, but they have been taken into consideration because they are potentially the only components of board games not to be made of paper and therefore potentially be disposed of incorrectly or pollute

paper waste.

Description

The product has a modular volumetric shape that can be characterized thanks to the use of Poly-Paper. We therefore want to create pawns in the form of components that the end user will assemble in a personal way with the invitation to personalize them through the use of paper and cardboard, which depending on the user can be printed or drawn by hand. The greater gaming experience aims to make users aware of the fact that the product, at the end of its life, can be disposed of entirely in the paper recycling cycle.

Added Values

The use of Poly-Paper for the pieces could enable the possibility of user's customization thanks to the weldability with other Poly-Paper or paper and cardboard, as well as make a kit completely disposable in the paper thus avoiding any contamination.

Fig.8.61 Game pieces - Products

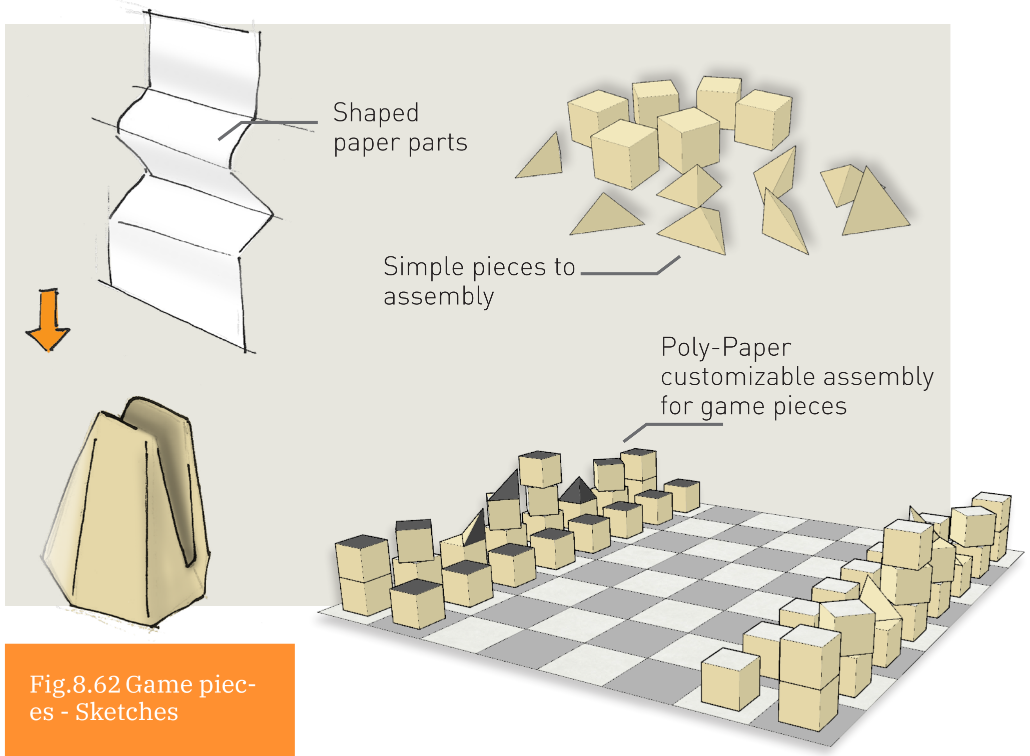


Fig.8.62 Game pieces - Sketches

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Conclusion

The research was carried out to the identify strategies for designing with new materials for the Circular Economy. The theme stems from the need to find applications of new materials to encourage their inclusion in the market and suggest future development paths. To achieve this goal, many points were touched that led to understanding the complexity of the factors involved. They have been structured into three macro-phases: analysis and research, the laboratory experimentation and concept and prototyping.

The study of the context has brought out the importance that the values of the Circular Economy have in our daily life. It emerged that sustainability, the main point of this new economic system, can be faced according to different points of view. The topic was very broad: reduction of the exploitation of primary resources, improvement of good's efficiency of use, extension of product life, and the change of consumption patterns, are the main criteria towards which the circular economy for sustainable development is orienting (chapter 1).

For the more in-depth definition of the context, aimed above all at the new polymers and sustainable composites, the main categories of biopolymers have been identified, examining their properties, production technologies, applications and peculiarities. Thermoplastic polymers derived from starch (TPS), cellulose acetate (CA), PLA, PHA and composites with natural fibres (NFC) have been considered. Later, materials such as paper and cardboard were also analyzed. The critical issues identified concern not only in mechanical performance or the production and costs of the raw material, but above all the disposal. In fact, it has been noted that there are problems of contamination between materials derived from biomass and fossil origin, due to a lack of correct communication of biobased materials and a general lack of awareness of end users towards the correct conferment of these materials in recycling (chapter 2).

The definition of the context and the examination of the materials led to the creation of case study cards organized in three sections, which include biobased polymers, paper and cardboard and other circular materials. Each profile includes information on comparison features on aspects concerning the environmental impact of the material, typical applications, production processes and sustainability issues. This allowed us to produce comparison matrixes to graphically understand the different qualities, characteristics and applications of the materials. The matrixes have allowed to define scenarios in which to be able to insert future case studies of the next circular materials, to guide them towards product developments consistent with their peculiarities. The comparison values considered were the percentage of biobased resources, the biodegradability and the average life expectancy due to the link between the material and its applications. These characteristics have been selected as the most important for the product development related to the values of the Circular Economy (chapter 5).

Among the examples of neo-materials, taken as possible case studies, there is the Poly-Paper. Obtained through the combination of recycled cellulose fiber and a polymeric matrix, it has as a great peculiarity a workability like common plastics but is allocable in the recycling cycle of paper and cardboard.
For this reason, the world of cellulosic semi-finished products and paper and cardboard products has been treated in order to complete the definition of the general context in which the case study must fit, considering with particular interest products characterized by having a lasting nature, such as for example furniture, architecture, leisure products (chapter 3).

In the experimental setting, for the in-depth study related to the case study, the production and tests on the material have made it possible evaluate the appearance, performance and behavior of the Poly-Paper as the percentage of cellulose contained in it varies. The responses to external agents such as humidity, heat or mechanical stress have also been observed, thanks to the use of demonstrators created using additive technologies. The material has shown a good resistance and workability through 3D printing despite its high sensitivity to humidity, however much lower than paper materials. On the contrary, it has proved to be very interesting as regards its weldability and surface finish characteristics by moistening its surface. The production of extruded semi-finished products and the creation of slabs made it possible to successfully experiment with the thermoforming of the material through compression and vacuum, adding new information on the development of the material (chapter 4).

The comparison between the characteristics of Poly-Paper and its direct competitors (biopolymers and cellulosic materials) shows how its' mechanical properties are comparable to those of TPS.
The comparison also suggested how the combination of cellulose and Poly-Paper can result in products with good mechanical and processability qualities, equal to those of polymers and with competitive costs related to materials.
A cross-cutting research between product categories of consumer

products has been useful for matching data on the life expectancy of products in relation to materials. This combination is fundamental to be able to direct a neo-material towards market sectors driven by its own characteristics. The fields of application that have proved most interesting for the Poly-Paper development, responding in a more congruous way to the percentage of biomass derivation, biodegradability and life expectancy of the materials are, therefore, those of personal objects, hobbies, toys and electronics of consumption. The products of these families, in fact, with a life expectancy variable between six months and two years, are those that need a material that can be formulated as polymers but which, by their nature, is destined to last for a limited period. After that, the categories of Mono-use, but above all, the Disposable objects (those which pushed the development of this new material) resulted interesting for the recycling of material, also having to deal with a too short life expectancy related to products (chapter 6).

For each product category identified, dedicated assumptions were made with different end-of-life strategies to demonstrate how the factors to implement sustainability change according to the products (chapter 7). For the application of the Poly-Paper, it has been tried to take into account the greatest number of aspects in order to increase its market appeal in favour of greater sustainability. Firstly, the design for disassembly has been considered for consumer electronics products, because they are to be decomposed into different parts due to their multi-material nature before they can be reprocessed or disposed of correctly. With the case study of the Poly-Paper, ideas were provided to differentiate parts subject to technological obsolescence from those subject to aesthetic obsolescence in order to invite the end user to a correct arrangement or replacement of the components. The strategy of design for recycling has been applied to long-lasting packaging products and to products with specific characteristics (mainly related to the sensitivity of the material to moisture). For example, supports and containers for non-wet bulk products or packaging for cosmetics have been taken into consideration. For these cases the compatibility between Poly-Paper and paper proved to be fundamental for the replacement of common polymers while maintaining a high level of formal freedom and customization. As a last interesting approach for lengthening the life of a product, as well as for its end of life, design for re-manufacturing was taken into consideration, a criterion applied to leisure products and toys (chapter 8), where the characteristics of weldability and self-repair have demonstrated the applicative potentialities of the new material taken in analysis as a case study.

The application proposals, rather than the optimization of production costs, pay attention on defining a conscious strategy of development concept that considers the fundamental aspects for those who decide to design with circular materials: technical / functional characteristics, aesthetics, application fields, end of life product and material. This brings in addition to the economic advantage, also an advantage in terms of environmental sustainability. Thanks to the use of the matrices it was possible to frame the scenarios and the product categories best suited to the characteristics of the Poly-paper. The alignment of the values of the material with those of the circular economy makes it the link between biopolymers and paper materials, enhancing the characteristics of both, reducing the quantity of bioplastics destined to deterioration due to composting and expanding the application scenarios of cellulose based materials.

This study emphasizes the importance of developing circular materials that provide new fields of investigation and application in consumer products, looking for sustainable application solutions that see them as protagonists of the next future.

Conclusioni

La ricerca ha condotto all'identificazione di strategie per progettare con nuovi materiali per l'economia circolare. La tematica nasce dalla necessità di trovare applicazioni a nuovi materiali per favorire il loro inserimento nel mercato e suggerire futuri percorsi di sviluppo. Per il conseguimento di questo obbiettivo, sono stati toccati numerosi punti che hanno portato a capire la complessità dei fattori coinvolti. Sono stati strutturati in tre macro-fasi: la fase di analisi e ricerca, la sperimentazione in laboratorio, e la fase di concept e prototipazione.

Lo studio del contesto ha portato in evidenza l'importanza che i valori dell'Economia Circolare hanno nella nostra vita quotidiana. Ne è emerso come la sostenibilità, punto cardine di questo nuovo sistema economico, può essere trattata secondo diversi punti di vista. L'argomento è risultato molto ampio: riduzione dello sfruttamento di risorse primarie, miglioramento dell'efficienza di utilizzo dei beni, estensione della vita dei prodotti, e il cambiamento dei modelli di consumo, sono i principali criteri verso cui l'Economia Circolare si sta orientando per uno sviluppo sostenibile (capitolo 1).

Per la definizione più approfondita del contesto, rivolto soprattutto ai nuovi polimeri e compositi sostenibili, sono state identificate le maggiori categorie di biopolimeri, esaminandone proprietà, tecnologie di produzione, applicazioni e peculiarità. Sono stati presi in considerazione polimeri termoplastici derivati da amido (TPS), acetato di cellulosa (CA), PLA, PHA e compositi con fibre naturali (NFC). In seguito, sono stati analizzati anche materiali come carta e cartone. Le criticità individuate riguardano non solo prestazioni meccaniche o la produzione e i costi della materia prima, ma soprattutto lo smaltimento. È stato infatti notato come vi siano delle problematiche di contaminazione tra materiali derivati da biomassa e di origine fossile, dovuti sia ad una mancanza di comunicazione corretta dei materiali *biobased* e una carenza generica di consapevolezza degli utenti finali verso il corretto conferimento di tali materiali nel riciclo (capitolo 2).

La definizione del contesto e l'approfondimento sui materiali hanno portato alla creazione di schede di casi studio organizzati in tre sezioni, che comprendono polimeri *biobased*, carta e cartone e altri materiali circolari. Ogni profilo include informazioni su caratteristiche di confronto su aspetti riguardanti l'impatto ambientale del materiale, applicazioni tipiche, processi di produzione e problemi di sostenibilità. Ciò ha consentito di produrre matrici di confronto per comprendere anche graficamente le diverse qualità, caratteristiche e applicazioni dei materiali. Le matrici hanno permesso di definire gli scenari in cui poter inserire futuri casi studio di nuovi materiali circolari per orientarli verso sviluppi di prodotto coerenti con le loro peculiarità. I valori di confronto presi in considerazione sono stati la percentuale di risorse derivate da biomassa, la biodegradabilità e l'aspettativa di vita media dovuta al legame tra il materiale e le sue applicazioni. Queste caratteristiche sono state selezionate in quanto di maggior importanza per lo sviluppo di un prodotto affine ai valori dell'economia circolare (capitolo 5).

Tra gli esempi di neo-materiali, da prendere come possibili casi studio, è presente il Poly-Paper. Ottenuto tramite la combinazione di fibra di cellulosa riciclata e una matrice polimerica, ha come grande peculiarità una lavorabilità al pari delle comuni plastiche ma è conferibile nel ciclo di riciclo di carta e cartone. Per questo motivo, il mondo dei semilavorati e prodotti in carta e cartone è stato trattato al fine di completare la definizione del contesto generale in cui il caso studio deve inserirsi, considerando con particolare interesse prodotti caratterizzati dall'avere una natura durevole, come ad esempio arredo, architettura, prodotti per il tempo libero (capitolo 3).

In sede sperimentale, per l'approfondimento relativo al caso studio, la produzione e le prove sul materiale hanno permesso di poter valutare aspetto, prestazioni e comportamento del Poly-Paper al variare delle percentuali di cellulosa in esso contenute. Sono state inoltre osservate le risposte ad agenti esterni come umidità, calore o sollecitazioni meccaniche grazie all'utilizzo di dimostratori creati tramite tecnologie additive. Il materiale ha dimostrato una buona resistenza e lavorabilità tramite stampa 3D nonostante la sua alta sensibilità all'umidità, comunque di molto inferiore ai materiali cartacei. Ha anzi dimostrato di essere molto interessante per quanto riguarda le sue caratteristiche di saldabilità e finitura superficiale tramite l'inumidimento della sua superficie. La produzione di semilavorati estrusi e la creazione di lastre ha permesso di sperimentare con successo la termoformatura del materiale tramite compressione e sottovuoto, aggiungendo nuove informazioni sulla processabilità del materiale (capitolo 4).

La comparazione tra le caratteristiche del Poly-Paper e i suoi diretti competitors (biopolimeri e materiali cellulosici) mostra come le sue proprietà meccaniche siano paragonabili a quelle dei TPS. Il confronto ha inoltre suggerito come la combinazione di materiali cellulosici e Poly-Paper possa risultare in prodotti dalle buone qualità meccaniche e delle qualità di processabilità pari a quelle dei polimeri e con costi, relativi ai materiali, competitivi.
Una ricerca trasversale tra categorie merceologiche di prodotti di consumo è stata utile per incrociare dati relativi alle aspettative di vita dei prodotti in relazione ai materiali. Questa combinazione è fondamentale per poter orientare un neo-materiale verso settori di mercato guidati dalle sue stesse caratteristiche. I campi di applicazione che si sono rivelati più interessanti per lo sviluppo del Poly-Paper, rispondendo in modo più congruo alla percentuale di derivazione di biomassa, biodegradabilità e aspettativa di vita dei materiali sono quindi quelli di oggetti personali, hobby e giocattoli e di elettronica di consumo. I prodotti di queste famiglie, infatti, con un'aspettativa di vita variabile tra i sei mesi e i due anni, sono quelli che hanno bisogno di un materiale che per formabilità sia polimerico ma che per loro natura sia destinato a durare per un periodo limitato nel tempo. Dopo questi, le categorie monouso, ma soprattutto gli oggetti usa e getta (quelli che hanno spinto lo sviluppo di questo nuovo materiale) sono risultati interessanti per il riciclo del materiale, dovendo anche fare i conti con un'aspettativa di vita, relativa ai prodotti, molto breve (Capitolo 6).

Per ogni categoria di prodotto identificata, sono state fatte delle ipotesi diverse e dedicate con strategie relative al fine vita, per dimostrare come i fattori per implementare la sostenibilità cambino a seconda dei prodotti (capitolo 7). Per l'applicazione del Poly-Paper si è cercato di tenere in considerazione il maggior numero di aspetti al fine di aumentare la sua appetibilità sul mercato a favore di una maggiore sostenibilità. Il *design for disassembly*, ad esempio, è stato considerato per i prodotti dell'elettronica di consumo, poiché proprio per la loro natura multi-materica devono essere scomposti in diverse parti prima di poter essere rielaborati o smaltiti in maniera corretta. Con il caso studio del Poly-Paper sono stati forniti degli spunti per differenziare parti soggette ad obsolescenza tecnologica da quelle soggette a obsolescenza estetica in maniera da invitare l'utente finale ad una corretta disposizione o sostituzione dei componenti. La strategia del design per il riciclo (*design for recycling*) è stata applicate a prodotti di packaging di lunga durata e per prodotti dalle specifiche caratteristiche (relative soprattutto alla sensibilità del materiale all'umidità). Sono stati presi in considerazione ad esempio supporti e contenitori per prodotti sfusi non umidi o packaging per la cosmetica. Per questi casi la compatibilità tra Poly-Paper e carta è risultata fondamentale per la sostituzione dei comuni polimeri mantenendo comunque una elevata libertà formale e di personalizzazione. Come ultimo approccio interessante per l'allungamento della vita di un prodotto, oltre che per il suo fine vita, è stato preso in considerazione il design per il recupero (*design for re-manufacturing*), criterio applicato ai prodotti per lo svago e giocattoli (capitolo 8), dove le caratteristiche di saldabilità e autoriparazione hanno dimostrato le potenzialità applicative del nuovo materiale preso in analisi come caso studio.

Le proposte di applicazione volgono l'attenzione non tanto all'ottimizzazione dei costi di produzione, quanto a definire una strategia consapevole di sviluppo di concept che tenga in considerazione degli aspetti fondamentali per chi decide di progettare con materiali "circolari": caratteristiche tecnico/funzionali, estetiche, campi di applicazione, fine vita di prodotto e materiale. Questo porta, oltre che al vantaggio economico, anche un vantaggio in termini di sostenibilità ambientale. Grazie all'utilizzo delle matrici è stato possibile inquadrare gli scenari e le categorie di prodotto più adatte alle caratteristiche del Poly-Paper. L'allineamento dei valori del materiale con quelli dell'economia circolare fa di esso l'anello di congiunzione tra biopolimeri e materiali cartacei, potenziando le caratteristiche di entrambi, riducendo il la quantità delle bioplastiche destinate al deterioramento dovuto al compostaggio e ampliando gli scenari applicativi dei materiali a base di cellulosa.

Questo studio vuole sottolineare l'importanza dello sviluppo di materiali circolari che forniscono nuovi campi di indagine e applicazione nei prodotti di consumo, alla ricerca di soluzioni applicative sostenibili che li vedono protagonisti del prossimo futuro.

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