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Master degree **DISSERTATION**

Strategies and materials to achieve circular economy system through additive manufacturing processes

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Abstract

The level of pollution in the world continues to increase every year, and the numerous recycling programs put in place by world governments, have found little results in this area.
Since the common means of production used every day have shown their limitations when it comes to reducing environmental impact, I decided to study and analyze the opportunities that a still emerging and revolutionary manufacturing process such as **additive manufacturing** could offer.
This paper is the result of studying existing literature and analyzing case studies, and aims to explore the true potential of this manufacturing system, evaluating the opportunities it offers, to be able to enable a true **circular economy system**, changing the means of production and transforming our society from a linear to a circular and more sustainable economic system.

Starting from the study of additive manufacturing technology and the concept of circular economy, I will explain in the next few pages what strategies are used by many companies and brands to achieve circular economic systems through additive manufacturing.
Then, through an in-depth **analysis of case studies** of more than thirty projects, all closely related to the use of the most effective 3D printing systems (**FFF, FDM**, and **FGF**) and with the goal of achieving a circular economic system, it will be easier to grasp the benefits of this union.

Finally, to give further solidity to this work, the last chapter will cover the aspect of **materials** with a focus on those most widely used in the 3D printing industry (**PLA** and **PET**) that have emerged from the literature review and case studies. These materials will then be compared with their more "environmentally friendly" versions, such as recycled PET and PLA reinforced with natural fibers, in order to find new and better options for future uses.

Il livello di inquinamento nel mondo continua ad aumentare ogni anno e i numerosi programmi di riciclaggio messi in atto dai governi mondiali, hanno riscontrato scarsi risultati in questo campo.
Poichè i mezzi di produzione abitualmente usati hanno mostrato i loro limiti quando si tratta di ridurre l'impatto ambientale, ho deciso di studiare e analizzare le opportunità che potrebbe offrire un processo produttivo ancora emergente e rivoluzionario, come la **manifattura additiva**.
Questo lavoro è il risultato dello studio della letteratura esistente e dell’analisi di casi studio, e si pone come obiettivo di esplorare il vero potenziale di questo sistema di produzione, valutando le opportunità che esso offre, per poter abilitare un vero e proprio **sistema di economia circolare**, cambiando i mezzi di produzione e trasformando la nostra società da un sistema economico di tipo lineare a uno circolare e più sostenibile.

Partendo dallo studio della tecnologia della manifattura additiva e dal concetto di economia circolare, spiegherò nelle prossime pagine quali sono le strategie usate da numerose compagnie e brand per raggiungere sistemi economici circolari attraverso la manifattura additiva.
Successivamente, attraverso un'approfondita **analisi di casi studio** di oltre trenta progetti, tutti strettamente legati all'utilizzo dei più efficaci sistemi di stampa 3D (**FFF, FDM** e **FGF**) e con l'obiettivo di raggiungere un sistema economico circolare, sarà più facile cogliere i benefici derivanti da questa unione.

Infine, per dare ulteriore solidità a questo lavoro, l'ultimo capitolo tratterà l'aspetto dei **materiali** con un focus sui quelli più utilizzati nell'industria della stampa 3D (**PLA** e **PET**) emersi dall’analisi della letteratura e dai casi di studio. Questi materiali saranno studiati dal punto di vista meccanico per capire quali siano le opportunità e capacità che possono offrire.

CHAPTER 1

Additive manufacturing historical background

What is exactly additive manufacturing, how did it
eveolve through time and what potential does it
have today

Additive manufacturing historical background

Today, additive manufacturing is a widespread way of production, used by manufacturers across nearly every industry. 3D printed components can be found almost everywhere — not just as a tool of production in factories settings, but even as end-use products and parts in every day life's objects.

While 3D printing technology still sounds like a new and fresh innovation, actually, it has come a long way since its introduction back in the 1980s. Today's additive manufacturing platforms carry some pretty impressive capabilities that are the result of almost 40 years of evolution.

The first additive manufacturing system appeared in the early 1980s, and from there it took off, branching out into several different types of technologies for turning CAD files into 3D physical objects.

Heading towards the end of the Cold War in the 1980s, the United States military increased funding for exploring science and new industrial technologies. This led to the experimentation of a diverse range of ideas and concepts with innovative potential, including additive manufacturing. In the early 1980s, Dr. Hideo Kodama became the first pioneer, taking the knowledge from 3D scanning and the layering pattern from 3D topographical maps, to create a first rudimental prototyping machine.

From this knowledge, in 1984, Charles Hull was able to develop the material Stereolithography Apparatus known as SLA, and with his new invention went on to establish the first 3D printing company two years later, in 1986, called "3D Systems". The first actual 3D printing machine was produced the next year, in 1987, which worked by printing layer by layer using Stereolithography Apparatus (SLA), a process that solidifies thin layers of ultraviolet light-sensitive liquid polymer using a laser.

The SLA-1, as a beta test system, was the first commercially available AM machine in the world and was the precursor of the once popular SLA 250 machine.

Following the release of this first 3D printer, inventors and creators began researching new methods and techniques for additive manufacturing and in the late 80s and early 90s, a bunch of whole new different additive manufacturing technologies were commercialized. The most important one is definetely the "**Fused deposition modeling**", or **FDM**, invented by Scott Crump in 1989, who founded his own company called Stratasys to commercialize his idea. FDM is an extrusion-based 3D printing technology that utilize thermoplastic polymers in a filament form, which is firstly melted and then selectively deposed layer by layer in a path defined by the CAD model. Due to its high accuracy, low cost and large material selection, FDM fastly became one of the most widely used 3D printing technologies across the world and today still reign supreme as the most used 3DP technology.

While also other companies flourished in this period, thanks to the creation of new additive manufacturing technologies like "solid ground curing" (SGC) and "laminated object manufacturing" (LOM), it was only in the early 2000s that more companies and enthusiasts took a keen interest in the capabilities and fundamental process benefits offered by 3D printing. Startng from April 2000 plenty of new technology introductions and evolutions started to emerge, giving birth to an actual race to build the best machine and become a leader in the industry (Wohlers et al., 2015).

A big news hit the market in 2005, when a new company called RepRap, founded by professor Adam Bowyer from the University of Bath, specialized in producing self-replicating machines. This open-source project led to the eventual proliferation of desktop FDM 3D printers, opening the market also to simple hobbyists or lovers of the technology.

In 2009, a company called MakerBot, influenced by these events, started producing DIY (do it yourself) kits, thought not for big industries or industrial production process, but for simples hobbyists interested in the idea of trying 3D printing to create models and build functional working parts for DIY projects.

Riding this wave and the hype generated in the hobbyist market, another 3D company was founded in 2011: Prusa Research, who developed the Prusa i3 design, based upon the company's early work on the RepRap machine.

With the Prusa i3 3D Printer now on the market, MakerBot sought to be a contender, making the Replicator 2, which was released in late 2012 and became the world's most popular 3D printer at the time.

With now an active competition and numerous investors in the market , all the companies specialized in 3D printing started to research to make their product the best choice for the customers, improving their models and trying to solve the main issues that all 3Dprintig machine were facing in those days: cheap printers were unreliable and lacked the mechanical properties for high-value applications, while industrial 3D printers were not affordable to the majority of relevant manufacturers.

In 2013 a new company called Markforged entered the industry with a revolutionary 3D printer design and the ability to use methods such as Fused Filament Fabrication (FFF) and Continuous Fiber Reinforcement (CFR), which allowed parts to be printed quickly and accurately with a variety of innovative material options. Markforged's proprietary CFR technology added strength to parts and introduced composite parts strong enough to replace metal parts in a much quicker and cheaper way (Wohlers et al., 2015).

Additive manufacturing timeline

1981 - 1987: The invention of Stereolithography

In **1981**, Dr. Hideo Kodama to created a first rudimental prototyping machine combining 3D scanning and the layering pattern from 3D topographical maps.

In **1984**, Charles Hull develops the first stereolithographic machine (SLA) that can print objects by solidifying thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser is tested.

In **1986** he found the first 3D printing company and in **1987**, the first model (SLA-1) is commercialized.

1981
1982
1983
1984
1985
1986
1987

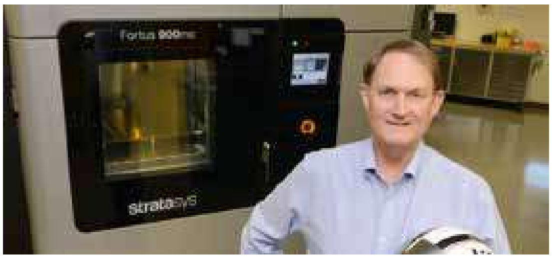
1988 - 1992: New technologies

In **1988**, Carl Deckard, patented the 'Selective Laser Sintering' (SLS) technology, a process that uses a laser to trace and solidify layers of powder polymers.

In **1989**, Scott Crump patented the 'Fused Deposition Modelling' (FDM) technology, probably the most popular 3D printing technology to date.

In **1992**, DTM Inc presented her first 3D SLS printer.

1988
1989
1990
1991
1992



1993 - 1999: 3D printing expansion

In **1993**, the MIT developed new 3D printing techniques based on inkjet printers, using more common materials and components.

In **1997**, Arcam commercialized the first metal 3D printer machines.

In **1999** 3D printing reached even the Medical Industry, as scientists were able to bio-print synthetic scaffolds of a human bladder.

1993
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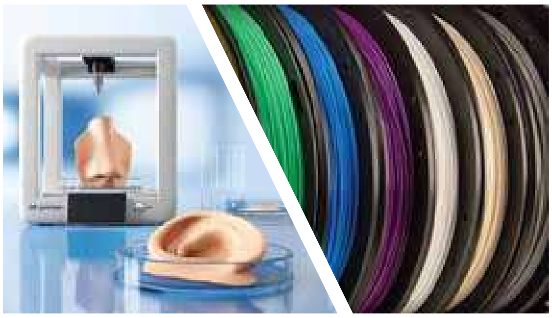
1995
1996
1997
1998
1999



2000 - 2008: RepRap and desk 3D printers

In **2002**, ZCorp revealed a multi-colored 3D printer, and ObJet Geometries released its first inkjet 3D printer.

In **2005** Adrian Bowyer proposed the idea of self-replicating printers, able to create infinite versions of themselves and launched an open-source project focused on the spreading of low-cost 3D printing.

The same year, ExOne patented 'Binder Jetting' 3D printing technology, a system capable of printing using metal and sandstone with complex geometries.

In **2008**, the release of the 'Darwin' RepRap 3D printer allowed people to 3D print at home, and the first 3D printed prostethics became reality.

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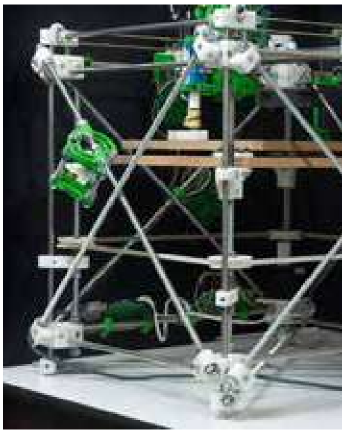
2008



2009 -2014: The budget FDM 3D printers

In January **2009**, BfB RapMan was released as the first budget FDM 3D printing kit.

In **2014**, the SLS and SLA patents expired, it was a great opportunity for cheaper alternatives to storm the market., since both technologies were now public property. A Vast number of companies emerged to offer budget machines that compete industrial 3D printers.

2009
2010
2011
2012
2013
2014

2015 - today: Late conquests

In **2015** Bound Metal Deposition is patented, which is similar to FDM, but uses metal.

In **2017**, companies such as 'ApisCor' and 'WinSan' begun developing massive concrete 3D printers, helping 3D printing enter the construction sector.

Today 3D printing keeps improving in terms of performance and quality of prints.

2015
2016
2017
2018
2019
2020
2021

Historical timeline

On the left, a moodboard with the faces and the innovations that made the history of 3D printing, starting from the top:
Charles Hull and the SLA-1 machine, Scott Crump (inventor of the FDM technology and founder of Stratasys), ... , Adrian Bowyer and his first RepRap machine, an example of the new wave of home 3D printers, details of next gen 3D printed objects (a metallic aerospace rotor component and a concrete house wall)

Today’s additive manufacturing

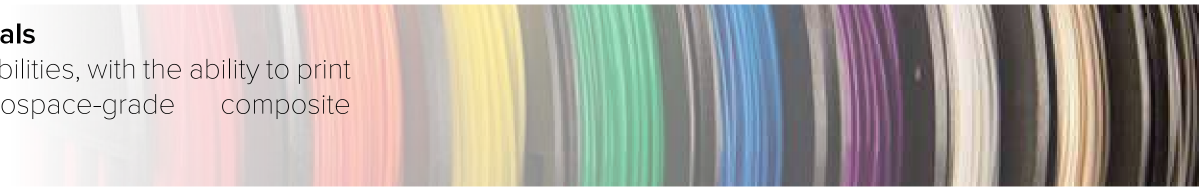
From 2015 up untill today, additive manufacturing has gone an intensive process of improvement and increase in both terms quality of prints and number of treateble materials, showing a prominent growth driver in some of the largest global industries (Bourell et al,. 2020). Compared to earlier additive manufacturing technologies, today’s 3D printing platforms are characterized by:

Improved power and reliability

Technological progress and evolution granted for higher print speeds, maximum part sizes, and surface finishes.

Ease of use

As earlier additive manufacturing platforms required specialized knowledge and carried higher learning curves. Modern 3D printing software is intuitive to use and does not require additive manufacturing expertise.



Wide range of materials

Broader material capabilities, with the ability to print in traceable, aerospace-grade composite materials.

Metal fused filament fabrication

Introduction of metal fused filament fabrication (FFF) technology, which has made 3D printing metal parts faster, safer, and more cost effective than ever.

Cloud connectivity

Cloud connectivity between each user and set of printers allows for distributed manufacturing operations. Users can initiate prints across 3D printers in different geographic locations, to ensure that the right part is available both where and when it is needed.

Industry 4.0

the new Industry 4.0 system spreaded in the whole world allows for connectivity with 3D printing software integrations, granting that part of the production can be initiated by requests in each factory’s core systems.

Scalability

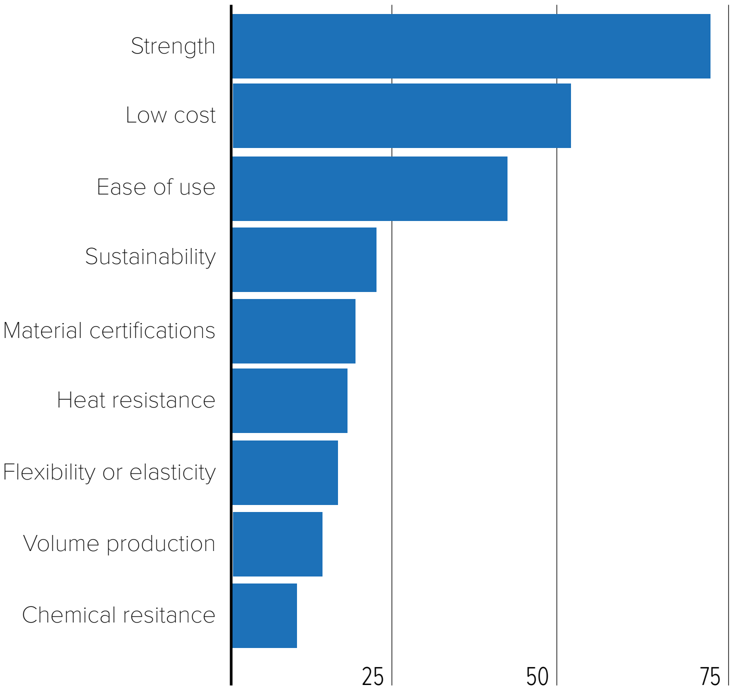
Derived by cloud-enabled interconnectivity combined with the expansion of different 3D printers that satisfy distinct manufacturing needs (such as metal, industrial 3D printers, and desktop 3D printers).

While today additive manufacturing allows to work with an extensive list of materials like metals, ceramics, composites and even smart materials (materials that have the potential to alter their geometry and shape when influence by external condition such as heat and water), polymers still remain the most used and the most prolific in the industry. The reason for such popularity is quite simple: other than their low cost compared to other materials, their natural low melting point present a significant technical and economical advantage, since it require less energy to reach the right viscosity to be printed. Other good traits of polymers are the characterstic low weight and processing flexibility which granted to these type of materials an always increasing role in multiple sectors, including the medical device production.

According to data on industry adoption of 3D printing, from 2021, 47% of manufacturers use additive technology, in particular 22.1% of the automotive manufacturer, 12.5% of the product development manufacturers, and 4.8% of the medical manufacturers. Other sectors in which the tecnology has shown its potential are Aerospace, education, and the defense industries, who are adopting additive manufacturing at ever increasing rates.

Focus on FDM technology

Today we can categorize 3D printing technologies in 7 main classes, distinguished by how they works, what material they can work with and what type of product they allow to produce: binder jetting, directed energy deposition, materials jetting, powder bed fusion, sheet lamination, vat photopolymerization and finally materials extrusion.



Most required properties from 3D printing

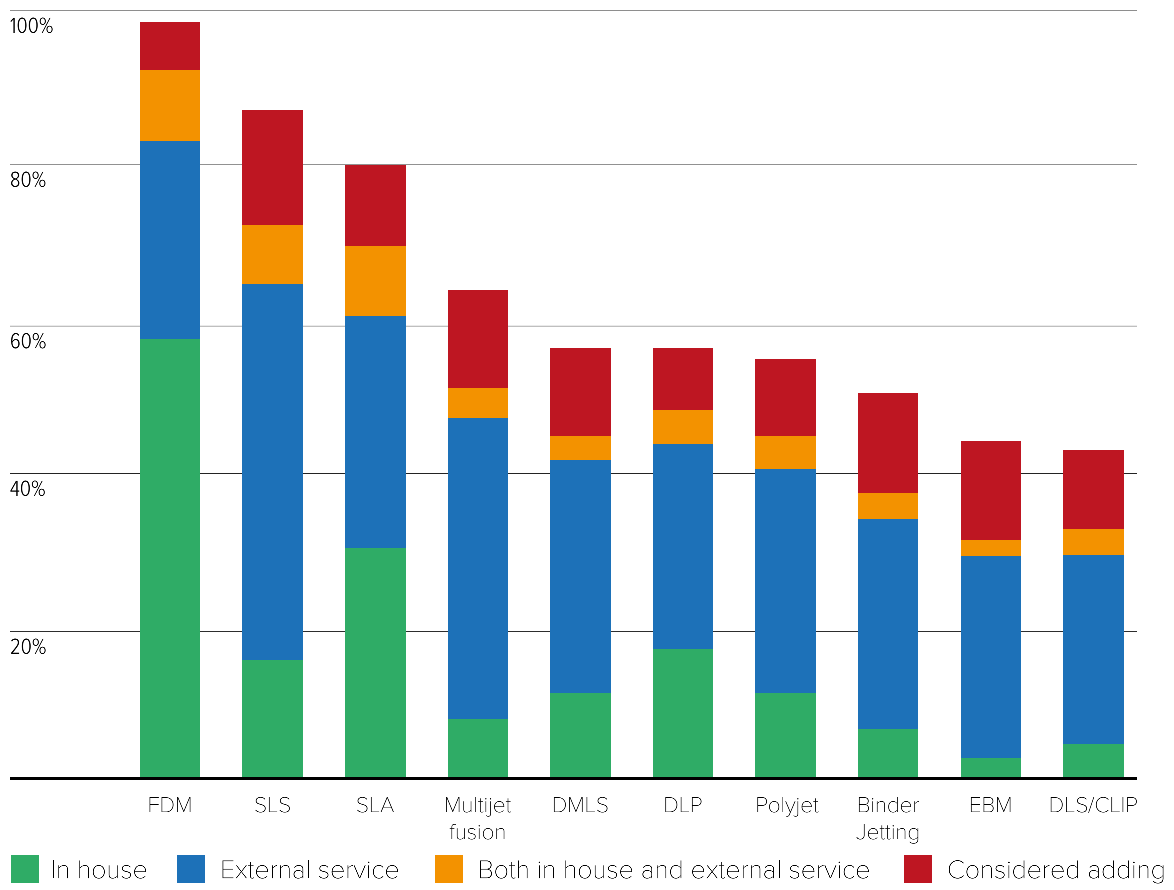
The graph rapresent the most required properties of the final products made using 3D printing processes. On the vertical axis are reported the properties expected to reach with the process, while on the horizontal axis is reported the percentage of companies interested in each property. For this study 237 manufacturing companies were interviewed.

Most used 3D printing processes

The graph on the right report the resul of the studies conducted by Beyerlein and Aboushama (2020), it reports the percentage of which additive manufacturing technology is most used and if it has been adopted "in house" by the companies or as an external service.

Even if each of these different technology has its own pros and cons, and each one has its sector in wich excell, there is one in particular that stands out from the crowd, a jack of all trade, that for obvious reason is, statistically, the most used in the whole world. We are talking of materialsextrusion, fused deposition modeling (FDM) in particular, the technology invented in 1989 by Scott Crump and still the most popular 3D printing system to date.
Material extrusion-based 3D printing technology can be used to print multi-materials and multi-colour printing of plastics, food or living cells. FDM is possibly the most flexible of all the AM technologies, and it's main advantages are:

- **High customisations and complexity**
  Being strictly related to a digital file design, a CAD model, FDM has vitually no limits in terms customization. Additionally, in FDM, there is no need to change the printing chamber to change the end products meaning that customization of products does not induce in any extra expenses.
- **Tool-less manufacturing process**
  Being an additive process FDM does not require any tool other than the printer and the digital model to compleat the product, even if at times some post print treatment are advisable.
- **Environment-Friendly products**
  FDM uses thermoplastic polymers to make products, granting reusability and recyclability. Additionally, FDM uses 90% of the raw material and produces minimal waste, almost none, posesing almost no threat to the natural balance. Another important factor is that FDM allows all companies to make any item locally thus, saving all of the expenses that would be lost in shipping, both in economical and ecological terms.
- **Reasonable Pricing**
  Buying and replacing parts of FDM printers don't require heavy investments since they are cheap and easy to install. This is enables low payback time, allowing companies to start earning from 3DP process almost immediatly.



- Time effectiveness

  Even if it obviously depends on the dimension and geometry of the object, FDM is capable of printing simple objects in half a day and more complex objects in just under a day, making it one of the fastest production processes in the entire industrial sector.

- Broad Range of materials

  FDM uses a huge range of materials for printing, allowing companies to change the material for printing very easily without harming the production expenses. Additionally, it is possible to use multiple materials at the same time to create complex structures very easily.

- Easy to Learn

  Requiring close to none manual skills to operate the process, to have good prints it is only needed a good CAD model, a technology that it is used by every manufacturing industry nowdays.

The printers used in this process have two main component, a heated nozzle, from wich the solid thermoplastic filament is heated to a semi-liquid state and deposited in ultra-fine beads along the extrusion path, and a heating bed, on which the filamenti is extruded on layer by layer by the nozzle.

FDM variants

Between the main features just listed for FDM process, the high customisations and complexity is definately the most interesting in terms of design potential. Being able to obtain complex geometries withouth needing a mold, granting well-detailed products in a hassle-free and budget-friendly manner and also being able to exploit an an enormous range of materials, are all features that can come in handy to any manufacturer in the world, granting this technology an extreme flexibility and adaptability in any sector.

Yet, even FDM has its limitations. Being a single process manufacturing system, a lot of issuses derive from the type of printer that is being used. The main challenges that any 3D printer has to face are relegated to its own capabilities, and can be collected in four main type of issues:

- Resolution issues

  FDM's products have relatively thick layer height and a rough surfaces, meaning that it's not ideal for parts with small details and that will require post-processing to achieve a smoother finish. Vapor smoothing, gap filling, and epoxy adhesion can improve a part's appearance, but will also lengthen production times.

- Technical issues

  FDM printers typically place filaments layer by layer in one direction, resulting in prints that are anisotropic and prone to breaking, especially where the layers meet one another. FDM parts can easily break when facing compressing forces parallel to their layers. Alternating between printing layers on the X- and Y-axes can strengthen a print, but for most applications, the lighter weight of an FDM part makes up for a slight reduction in strength.

- Structural issues

  Support structures are necessary when printing with FDM, which means that prints will require more material, time, and post-processing than if they were made with a process like HP Multi Jet Fusion, which does not require support structures. There are a variety of 3D printing processes that require support structures, though they can slightly increase costs and timelines.

- Dimensional issues

  Each 3D printer model is different from each other, but one thing that they all share is the fact that, obviously, no FDM printer can print anything bigger than itself. Smaller printers will require more prints to build the same object than a bigger one, meaning less strength and durability, worse resolution and finally higher cost and time of production.

Luckly for us, over the last years, FDM evolution brought to life alternative manufacturing process to help overcome these issues. We are now considering alternative extrusion-based 3D printing process like **Fused Filament Fabrication** (FFF) and **Fused Granulate Fabrication** (FGF, allso known as Pellet Printing).

Fused Filament Fabrication is the process of extruding a thin strand, or filament, of thermoplastic material through a liquefier and depositing it layer upon layer in a pre-determined tool path.
FFF employs the same process as FDM. It applies layers of filaments to a flat printing bed using a heated nozzle or extruder.
The difference between the two processi is that Stratasys's original FDM technology used a completely enclosed system. Its 3D printers had an enclosure that allowed for the temperare around the 3D print to be heated. This concept significantly improves print quality. It reduces warping and increases mechanical strength of the printed part.
In FFF machines the enclosure has been discarded with affordability in mind. The molten filament is still heated on the way to the 3D printer's nozzle. On the build plate, however, it is exposed to the ambient air temperature and cools more rapidly. The result is compromised print quality (warping) and strength. The reduction in strength is due to internal mechanical stresses caused by the rapid cooling of the print.

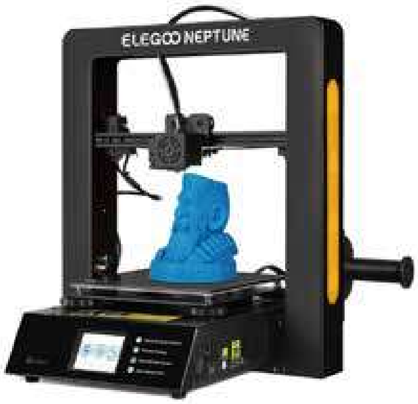
If FFF prints are qualitatively worse than FDM ones under almost every aspect, then why do we even conder such manufacturing process? It is easly explained:

- FFF machines are more affordable compared to FDM, with a price range ideal for home/hobby use.
- .FFF systems are smaller than FDM ones, so they fit better in homes or small offices.
- FFF has lower electricity requirements than FDM, reducing the cost of production.

FDM machines are well built, rugged, and capable and require little maintenance. FFF machines, on the other hand, range from the basic, open frame types to professional devices that seem like 'baby' FDM machines. Both technologies use similar X-Y-Z rails and stepper motors. Stiffness, however, is a big factor in model resolution/quality, since heavier machines print better models due to their greater mechanical and thermal stability.

Differencies between FFF and FDM

Above an FFF 3D printer, typical for home use and production of hobby types product.
Below a sturdier FDM printer, with an eclosed environment for better control of printing temperatures



Fused Granulate Fabrication (FGF aka Pellet Printing), is a similar process to FDM and FFF, but instead of using a strand of thermoplastic, it utilizes granules of the material, meaning pellets. While FFF and FDM filament materials are made by heating granules and forming them into a filament, FGF pellets skip this step, being fed directly in the printer whithout previous preparation. One less heating cycle potentially means that the pellet thermoplastics will process easier, perform better and cost less than comparable filaments.

FGF machine are also way bigger than both FDM and FFF ones and are used for heavier industrial production.

The FGF process is simple, it incorporates a robust barrel and screw extrusion system, similar to traditional plastic extrusion and injection molding, in which pellets are fed into. The screw conveys the pellets through a heated barrel with multiple heating sections, allowing the material to progressively heat up and melt.

Like in FDM and FFF, the material is then forced through brass or steel nozzles that deposit it layer by layer following the instruction of the digital model.

The main advantages of FGF are quite easy to predict:

- FGF machines are bigger and more sofisticated, allowing for precise and extremely accurate prints
- FGF systems are faster than FDM and FFF ones
- FGF printers have larger nozzles and throughput flow, meaning thicker and stronger layer, making the final product very resistant.

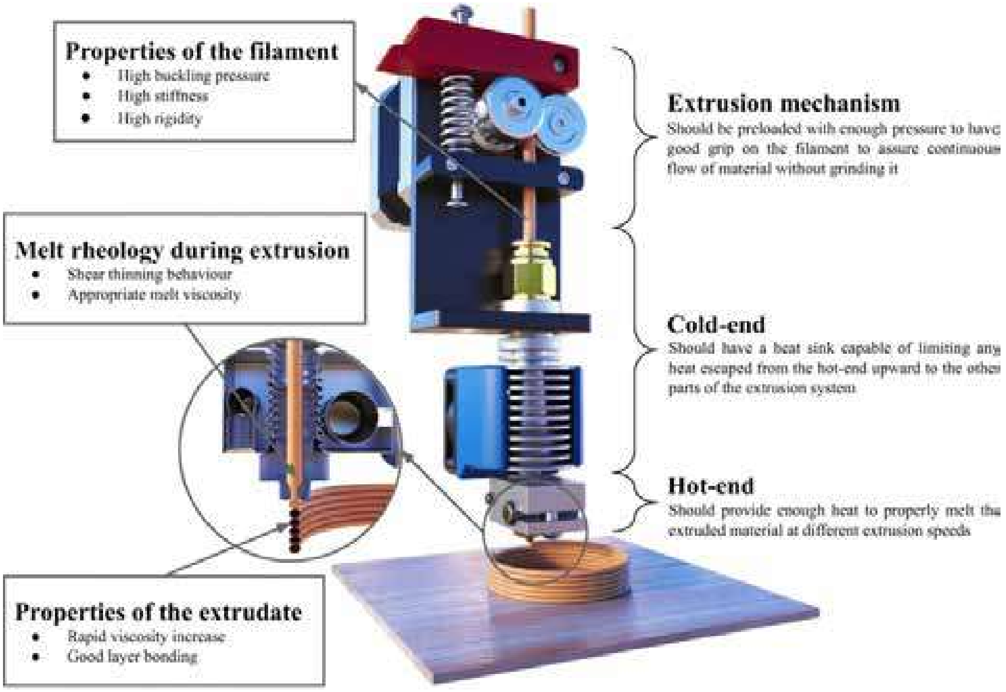
FFF vs FDM vs FGF

Table 1 report technical data on the three different typology of material extrusion process.
Data from https://www.dsm.com/content/dsm/additive-manufacturing/en_US/insights/blog/3d-printing-with-fused-filament-fabrication-and-fused-granulate-fabrication.html

	FFF	FDM	FGF
Feedstock	Filament	Filament	Pellets
Material base	Mainly PLA and some variants	Wide range of thermoplastics and composites material	Wide range of thermoplastics and composites material
Throughput	From 2.27g/hr to 113g/hr	From 21g/hr to 312g/hr	from 227g/hr to 9kg/hr
Layers height	From 0,05mm to 0,60mm	From 0,15mm to 0,7mm	From 1,0mm to 5,0mm
Bed width	From 0,40mm to 0,80mm	From 1,0mm to 3,0mm	From 4,0mm to 10,0mm

FFF/FDM extrusion system

The FFF and FDM extrusion system is basically the same, the only difference betwwen the two is the fact that the FDM oneis an enclosed ambient to better control the temperature and obtain a better print.


Properties of the filament

- High buckling pressure
- High stiffness
- High rigidity

Melt rheology during extrusion

- Shear thinning behaviour
- Appropriate melt viscosity

Properties of the extrudate

- Rapid viscosity increase
- Good layer bonding

Extrusion mechanism

Should be preloaded with enough pressure to have good grip on the filament to assure continuous flow of material without grinding it

Cold-end

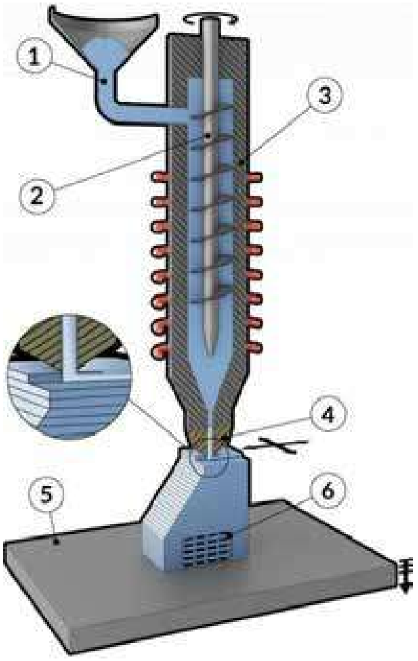
Should have a heat sink capable of limiting any heat escaped from the hot-end upward to the other parts of the extrusion system

Hot-end

Should provide enough heat to properly melt the extruded material at different extrusion speeds

FGF extruder

The FGF system is massive when compared to the FFF and FDM one. The extruder has built in a robust heated barrel with multiple heating sections, with a screw that conveys the pellets through the nozzle. The heated barrel allows the material to progressively heat up and melt the pellets.



As seen in the previous pages, FDM has a broad range of materials to choose from, yet the most prominent are definetively **thermoplastic polymers**.

Among the large variety of engineering thermoplastics applied in FDM, acrylonitrile-butadiene-styrene copolymers (**ABS**), polylactide (**PLA**), polycarbonate (**PC**), and polyamides (**PA**) represent the most prominent ones. Studies have addressed the role of path-planning and part-orientation on the anisotropic mechanical properties of ABS parts built by FDM. Several groups have developed ABS derivatives to ease FDM processing and improve materials properties of printed parts. For example, Masood et al. investigated the influence of metallic filler content on rheological properties and optimum process parameters and on thermal and thermo-mechanical properties. This work aimed at FDM fabrication of ABS/iron molds with improved thermal conductivity for injection molding and rapid tooling applications.

It was found that increasing the content of micrometer-sized iron powder allowed for a simultaneous increase of storage modulus, glass transition temperature, and thermal conductivity. Zhong et al. investigated FDM of ABS modified with short glass fibers and linear low density polyethylene (LLDPE). The incorporation of glass fibers was found to reinforce ABS and reduce internal stresses and distortions due to a reduction of the thermal expansion coefficient. LLDPE, on the other hand, enhanced toughness in the presence of compatibilizers. FDM of ABS-based nanocomposites containing vapor-grown carbon fibers (VGCF) was investigated by Shofner et al. Analogous to ABS/glass fiber composites, the dispersion of up to 10 wt % VGCF provided significant improvement of both strength and stiffness at the expense of toughness. Gray et al. developed a dual-extrusion process producing filaments from a polypropylene blend containing thermotropic liquid crystalline polymer (20 wt %), which surpassed the performance of FDM fabricated ABS.

While materials are certainly the most important aspect to study for understanding completely the physical behavior that the product will have, it is important to highlight that the mechanical properties of 3D printed parts depend also on a wide range of **structural and printing parameters**. These actually define a structure within the part, which is deeply connected with the material in making the properties of the printed component. These may change considerably even if only a single parameter is modified. This is already known in the case of FDM of unfilled materials, as the mechanical properties are strongly influenced by the infill geometry of the specimen. The situation is even more complicated in the case of a composite, an intrinsically inhomogeneous and anisotropic material. This strong connection between structure, material and the final mechanical properties is still at the core of current research interests and needs further understanding.

The most frequently reported printing parameters are listed in the table to the right. It can be seen that the most common nozzle diameter is 0.4 mm, albeit greater nozzles are also comprehensibly employed in the case of filled materials, up to 1.5 mm. The layer height is also centered around 0.2–0.3 mm, while the extrusion speed rate is more variable, ranging from 15 up to 100 mm/s. The extrusion temperature is always relatively high, greater than 180 °C, except for one paper, in which PCL was used, while the bed temperature is in the range 40–110 °C (Mazzanti et al., 2019).

Table from Mazzanti et al., 2019

Review of FDM&FFF printers technical data

Nozzle Diameter	Extrusion Temperature	Bed Temperature	Extrusion Speed Rate	Layer Height	3D-printer model
mm	°C	°C	mm/s	mm	
0.4	220	70	90	0.34	MakerBot-Replicator 2
0.5	230	110	50	/	LulzBot TAZ
0.75	190	40	25	0.3	MakerGear™ V2
0.4	210	/	15	/	Ultimaker Original
/	210	/	/	/	da Vinci 1.0
1.5	230	/	/	1	Diamond Age
0.4	210	/	/	/	Self-assembled
0.4	210	70	18	/	Prusa i3-Rework
/	180–200	/	/	/	Prusa i3
0.6	120	/	50	0.3	Prusa i3-Hephestos
/	230-245	70	21	0.2	Easy3DMaker
1	250	100	/	0.2	Printrbot Simple Metal
/	220–275	60–90	30–40	0.4	CreatBot DX-3D
/	220	/	/	/	MakerBot-Replicator 2
/	210	80	60–100	/	Blade 1
0.4	230–275	/	30	0.19	Zortrax M200
0.4	200–230	50	30	/	Creator Pro-Flashforge
/	205	/	20	0.1	Zmorph 2.0
/	/	/	/	/	MR300
1	230	/	50	/	/
0.8	230	60	30	0.4	MakerBot-Replicator 2
0.4	230–275	/	30	0.19	Zortrax M200
0.4	210	/	15	/	Ultimaker Original
0.4	200	80	/	0.05–0.3	Zaxe
0.5	/	/	/	/	Leapfrog Creatr
/	185	/	/	/	MR300
0.5	180	/	/	0.1	/
0.4	/	/	/	/	Accucraft
0.6	200	50	40	0.1	/
1	/	110	/	/	Diamond age
0.5	188	50	60	0.4	Profi3Dmaker

CHAPTER 2

Circular economy historical background

What is exactly circular economy, what is its main
goal and what potential does it have for
econonomy and ecology advance

Circular Economy definition

There are many definitions of the circular economy, ususally depending on the country we look in to. In China, for exemple, CE is promoted as a top-down national political objective, while in other areas such as the European Union, Japan and the USA it is a tool to design bottom-up environmental and waste management policies.

Nonetheless, the goal of promoting CE is always the same: the **decoupling of environmental pressure from economic growth**. A comprehensive definition could be: "*Circular Economy is an economic system that targets zero waste and pollution throughout materials lifecycles, starting from environment extraction to industrial transformation, and final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, safely back to the environment, in the case of a treated organic residual, like a natural regenerating cycle. It operates by creating value at the macro, meso and micro levels and exploits to the fullest the sustainability nested concept. Used energy sources are clean and renewable. Resources use and consumption is efficient. Government agencies and responsible consumers play an active role ensuring correct system long-term operation*." (Vermeulen et al,. 2019).

More generally, circular economy is a model of economic, social and environmental production and consumption that aims to build an autonomous and sustainable society in tune with the issue of environmental resources. The circular economy aims to transform our economy into one that is regenerative. An economy that innovates to reduce waste and the ecological and environmental impact of industries prior to happening rather than waiting to address the consequences of these issues. This is done by designing new processes and solutions for the optimization of resources, decoupling reliance on finite resources. The circular economy can infact be seen as a framework of three principles, driven by design:

- Eliminate waste and pollution
- Keeping products and materials in use
- Regenerate natural systems

It is based increasingly on renewable energy and materials, and it is accelerated by digital innovation. It is a resilient, distributed, diverse, and inclusive economic model.

Circular economy graph

Graph from https://www.legaltechitalia.eu

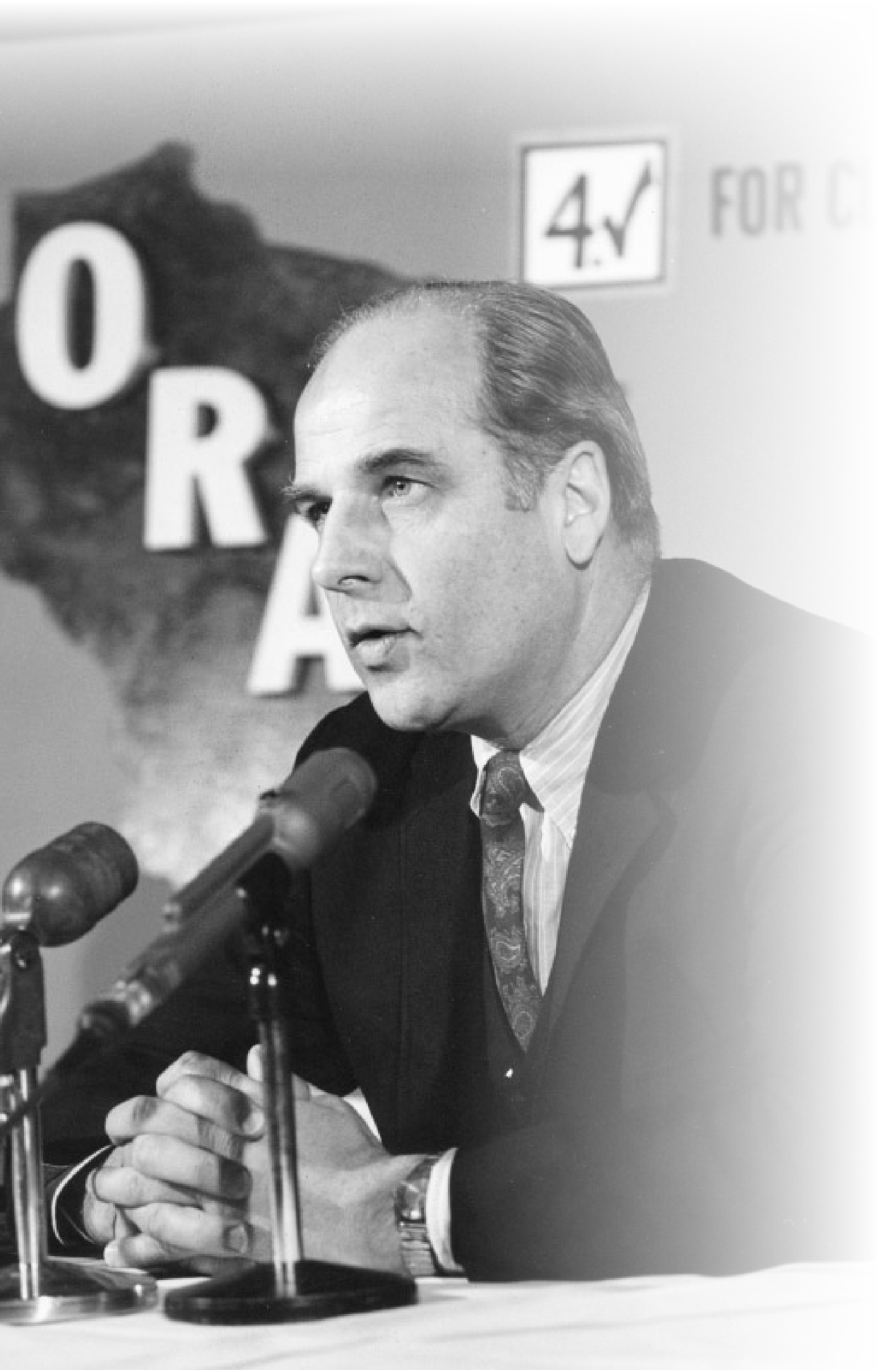
Circular Economy historical background

The idea of circular flow for materials and energy is not new but there is no clear evidence of a single origin of the CE concept, but contributors include great minds like professor John Lyle, his student William McDonough, the German chemist Michael Braungart and the architect and economist Walter Stahel. The CE concept may also have been inspired by works like: Rachel Carson's “Silent Spring”, the “Limits to Growth” thesis of the Club of Rome, and above the others, the "The Economics of the Coming Spaceship Earth", published by Kenneth Boulding in 1966, and inspired by his collegues Barbara Ward and Herman Daly. This last work is often cited as the first expression of the "circular economy", although Boulding does not use this terminology .

Gaylord Nelson

“Our goal is not just an environment of clean air and water and scenic beauty. The objective is an environment of decency, quality and mutual respect for all other human beings and all other living creatures.”

Gaylor Nelson Founder of the Earth Day and the 3Rs principle.



The 3R’s principle

Between the 1960s and the 1970s, during the time of the Vietnam War, Americans attention were raised to air pollution, waste and water quality, which were greatly ignored.

Gaylord Nelson, a U.S. Senator from Wisconsin, decided to bring the nation together for the first Earth Day on April 22, 1970. Twenty million Americans united under shared common values for protecting the planet. This historic day ultimately lead to the creation of **Environmental Protection Agency** (EPA) that same year and launched the slogan of the 3Rs: “**reduce, reuse, recycle**”, which soon became the principles of most strategies that aim to obtain real CE.

Many years later in 1989 The circular economy was then further modelled by British environmental economists David W. Pearce and R. Kerry Turner with their book “Economics of Natural Resources and the Environment”, in which they pointed out that a traditional open-ended economy was developed with no built-in tendency to recycle, which was reflected by treating the environment as a waste reservoir. Pearce and Turner developed conceptual frameworks for the CE concept such as resource-products-pollution modes, clearly taking inspiration by the principles the 3Rs (reduce, reuse, recycle) .

Circular economy scientific basis

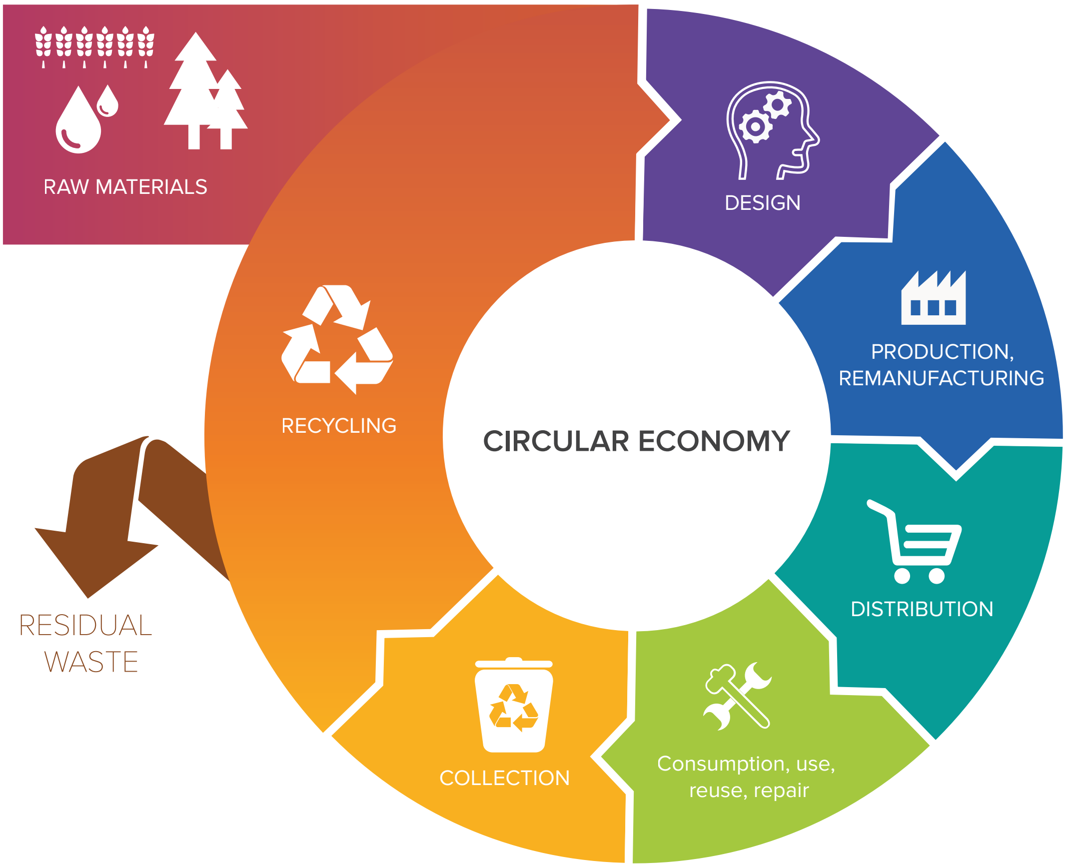
In the early 1990s, Tim Jackson began to create the scientific basis for this new approach to industrial production in his edited collection “Clean Production Strategies”, including chapters from pre-eminent writers in the field, such as Walter R Stahel, Bill Rees and Robert Constanza. At the time still called 'preventive environmental management', his follow-on book “Material Concerns: Pollution, Profit and Quality of Life” synthesized these findings into a manifesto for change, moving industrial production away from an extractive linear system towards a more circular economy.

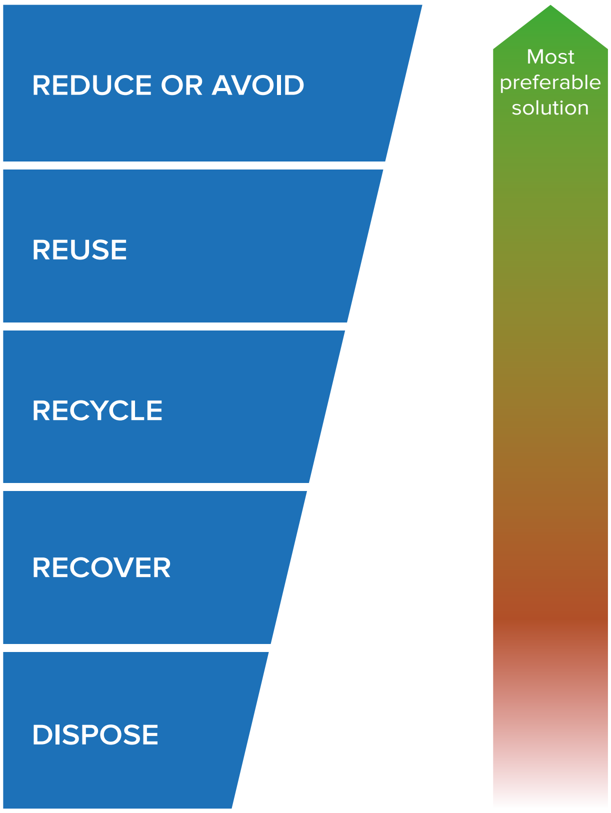
From here on, CE concept evolved differently in light of diverse cultural and social and political systems

In Germany, in the early 1990's, the CE concept was introduced into environmental policy with the intent to address issues associated with raw material and natural resource use for sustained economic growth. In China, in the late-1990's, an eco-industrial park model was promoted, and in the mid-2000's, the application of the CE concept was introduced in line with Hu Jintao's concept of a "harmonous society," which was later implemented with emphasis on waste recycling post consumerism and the development of waste-based closed loops within a company or among different processor and consumer groups. In China, the concept of CE is used as a mechanism for profitable product development, technology development, upgrading equipment, and improving industry management (Winans et al., 2017).

Circular economy

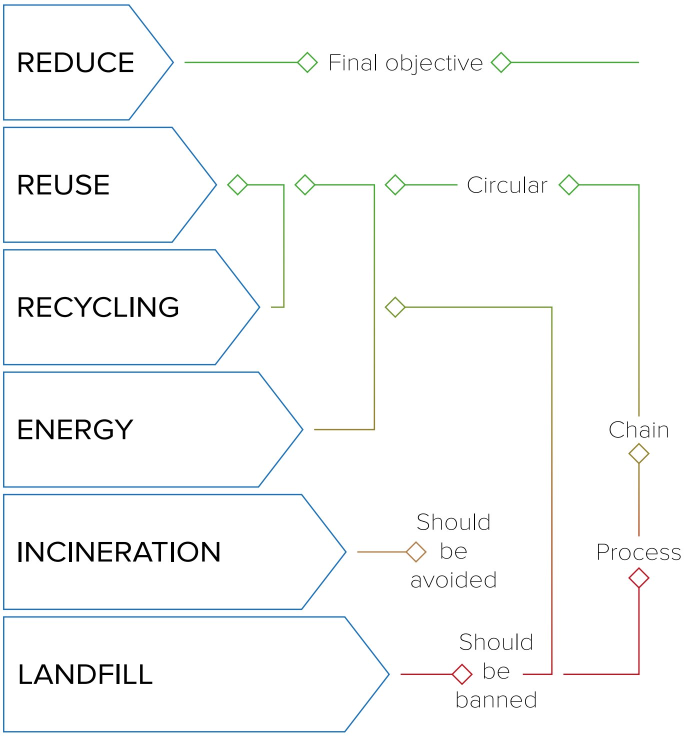
The concept of “preventive environmental management” proposed by Tim Jackson considered the whole production system of a product, from material extration to disposal and recycle. It was later deepen and rename “circular Economy” concept.
Graph from https:/europa.eu





Ladder of Lasink

Above: the upside down pyramid reboot of thinking on waste.
Below: Lasink's ladder on waste control hierarchy



The 6 points principle

In the 2010s, several models of a circular economy were developed that employed a set of steps, or levels of circularity, taking inspiration from the "Three R's principle" launched back in the 1970s, evolving it and amplifying it, adding always more "Rs", trying to enable circurlar economy to cover as much aspects as possible.

The first evolution of the 3Rs principle was the the one proposed in the report, commissioned by the Ellen MacArthur Foundation and developed by McKinsey & Company in 2013, named: "Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition". In this report the principle of the 3Rs of Nelson's slogan is ugraded with 3 new steps, adding up to 6 points, which include:

- Maintain/prolong
- Reuse/redistribute
- Refurbish/Remanufacture
- Recycle
- Energy recovery
- Landfill

In 2015 Dr. Ad Lasink published his "Ladder of Lasink" in which he proposed an upgrade of the work of the Ellen MacArthur Foundation with specific attention to the type of watses treated, proposing an actual waste management hierarchy, which indicates an order of preference for action to reduce and manage waste from most favorable to least favorable actions. The work of Lasink provides for 6 points, which include:

- Prevention
- Reuse
- Recycling
- Energy recovery
- Incineration
- Landfill

Finally, in 2017, Jacqueline Cramer, sustainable entrepreneurship professor and former Dutch Environment Minister, developed the model that today is considered the most comprehensive and extensive to achieve circular economy: the “10 Rs” principle, which, like the name says, is made up of 10 steps, each one reassumed by a single english verb that as an R as its first letter:

R1 - Refuse

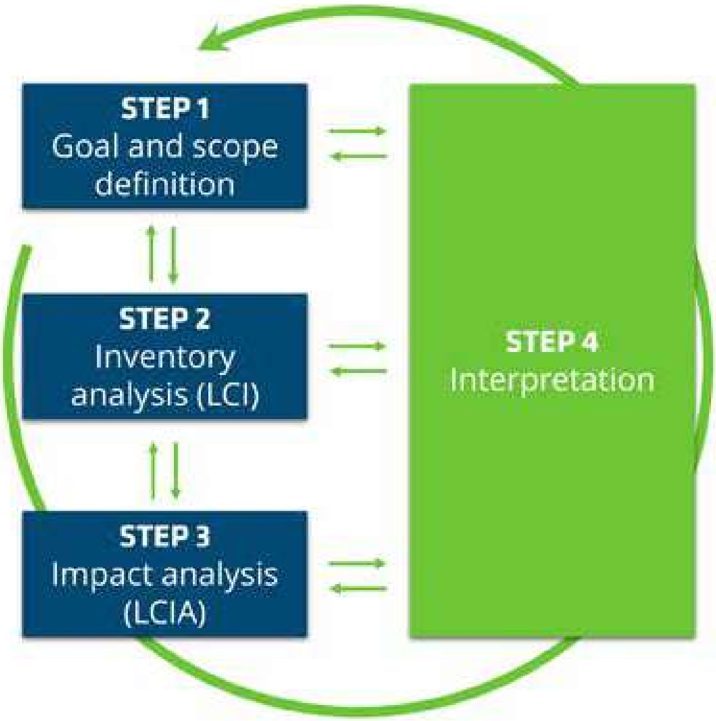
The refuse concept apply the philosophy “If you don’t need it, you don’t need to buy it” on an individual level. It is possible to see it as the upgraded version of Reduce, “buy less instead.”

Businesses can use this concept too, even if it might look like a nonsense. For example, can we refuse to make more products? It is well known that most developed countries tend to overmake and overconsume. Policy can push for a Refuse model, for example European Union’s Single-use Plastic ban, based on the 10 of the most common plastic waste found on the beaches, top being plastic drink bottles and cigarette filters.

In terms of consumes it is well known that the worldly population consume more than what is needed. Every year, we increase the goods we own by 25 billion tonnes – the equivalent of 93,000 Empire State Buildings. Much of this sits idle – cars lay dormant 92% of the time while offices are vacant for 58% of the year. We can change this by refusing to have such unnecessary and unsustainable products through solutions that maximise the usage of fewer goods (Bag et al,. 2021).

Inventory waste

Every year thousands of tons of industruial products are produced without being sell, contributing to worldly pollution withouth producing any value.



3

◇ R2 - Rethink

Rethink here refers to changing the fixed mindset we have with products. These can include redefining a different way to use the products and how long a product can be used. And it's more often used than we realize.

One such manifestation of Rethinking how we use things is the Sharing Economy. It challenges the status quo with questions like "why do we need to buy new?" "why do we need to own?" and "What happens when a Product becomes a Service?".

In terms of industrial design every product and every system needs to be rethought as well, with a focus on how to reduce its environmental impact. With the help of LCA analysis system it's possible to understand which "moment" of the life of a product is more impacting and focus on it to optimize the product's life.

The investment community is moving to help as well. SVB Financial Group, the holding company for Silicon Valley Bank, funds innovative startups and venture capitals working towards sustainable goals in industries such as mobility, finance, manufacturing and healthcare. By investing in innovative projects and supporting rethinkers, we can move faster to an eco-driven society.

R3 - Reduce

The central idea of a circular economy is dematerialisation or “doing more with less”. To achieve this it is mandatory to start using and manufacturing products in smarter ways.

This is a concept similar to the first point of this and being in the top three positions shows how powerful this can impact society and the environment. Even if it may sound like a nonsense, more brands keep putting the reduce concept into action everyday, this is due to an evergrowing awareness by the consumers and the market, which, in the last years, more frequently they gave thought to “do we really need this much?”.

What the designer can do by his part to adhere to this concept is to focus on the materials. Designing with materials that grant an easy recycle and/or reuse is definetly the best choice.

New materials typoligies can be a good option as well, since they can allows less impacting manufacturing systems and more long lasting products.

Amongst many others, we have seen opportunities in carbon fibres, bio-plastics, bio-based chemicals, low-impact steel and aluminium processes that could benefit a range of industries. US company Eastman Chemicals, for example, offers smart solutions for everyday products. Last year, it began commercial-scale recycling for a range of waste plastics that would otherwise be put in landfill.

R4. Reuse

To achieve zero-waste and reduce carbon emissions, we must look beyond the take-make-waste extractive industrial model.

The reuse concept was born to become one of the best ways to create a zero-waste lifestyle, since it moves the focus away from the disposable concept while not sacrificing convenience.

The Ellen MacArthur Foundation funded extensive researches on this concept, in order to find a way to make this concept more viable and applicable.

As a result of these reseaches the Foundation came up with four different models of the reuse concept, proposing a true Reuse “Revolution”:

Refill at Home – SodaStream is a home soda-making machine aiming to end the need to purchase soda and the plastic bottles that they come in. One cylinder cycle for creating carbonated water can potentially remove up to 60 1L soda plastic bottles from ending up in the landfill or ocean, as the same SodaStream bottle for many lifetimes.

Refill on the Go – Sell by weight businesses are examples of the Refill on the Go model. For example, Zero Waste Market, which has location all over the world, encourages customers to bring personal containers to stock up on things like condiments, wine, nuts and more. Food nets or cotton bags are encouraged for more items with a bigger body like vegetables and fruits.

This supermarket has even developed an intuitive system to facilitate the measuring system.

Refill at Home - SodaStream

Refill on the Go - Zero Waste Market

Return from Home - Loop

Return on the Go - DeliverZero

Return from Home – This model seek to find an alternative to all the packaging elements with which customers get in contact every day, like cardboard boxes from home delivery services like Amazon and Rakuten.
For example Aeon, one of Japan’s top retailers, collaborates with TerraCycle to use the Loop system, where Aeon’s products will be delivered in Loop Totes. This reusable bag will be collected, cleaned, and used for the next delivery.

Return on the Go – The COVID-19 pandemic brought about a high demand for takeouts, leading to increased waste of disposable food containers. Numerous new startups are tackling the problem, like DeliverZero and its reusable takeout containers. Customers can ask for DeliverZero containers from a smartphone app when ordering from DeliverZero’s partners. They can also return the containers to the nearest partner, where the containers will be brought to a local company for cleaning and reuse. At the moment is doing a pilot in Tokyo after its first pilot run in Okinawa.

More in general an area of major concern is fast fashion, which is getting faster – consumers buy 60% more clothes than in 2000, but keep each garment half as long. However, consumers are also becoming more sustainability-conscious and the sharing economy is rising. Online marketplace Vinted is an example of this shift. Vinted offers a peer-to-peer service where users buy, sell and swap secondhand clothing. Now in 12 countries, the platform has passed a valuation of $1 billion, making it Lithuania's first tech unicorn.

R5. Repair

The new term “Right of Repair” has found fertile ground both in Europe and in the east.

There is a quiet, gradual increase in the number of repair shops all oover the world. While there are chains of repair shops, independent startups have launched their own businesses. It will be interesting to see if this hints a shift from number of manufacturers to a number of repair craftspeople, while is reminiscent of the Circular Edonomy, when Repair was a norm.

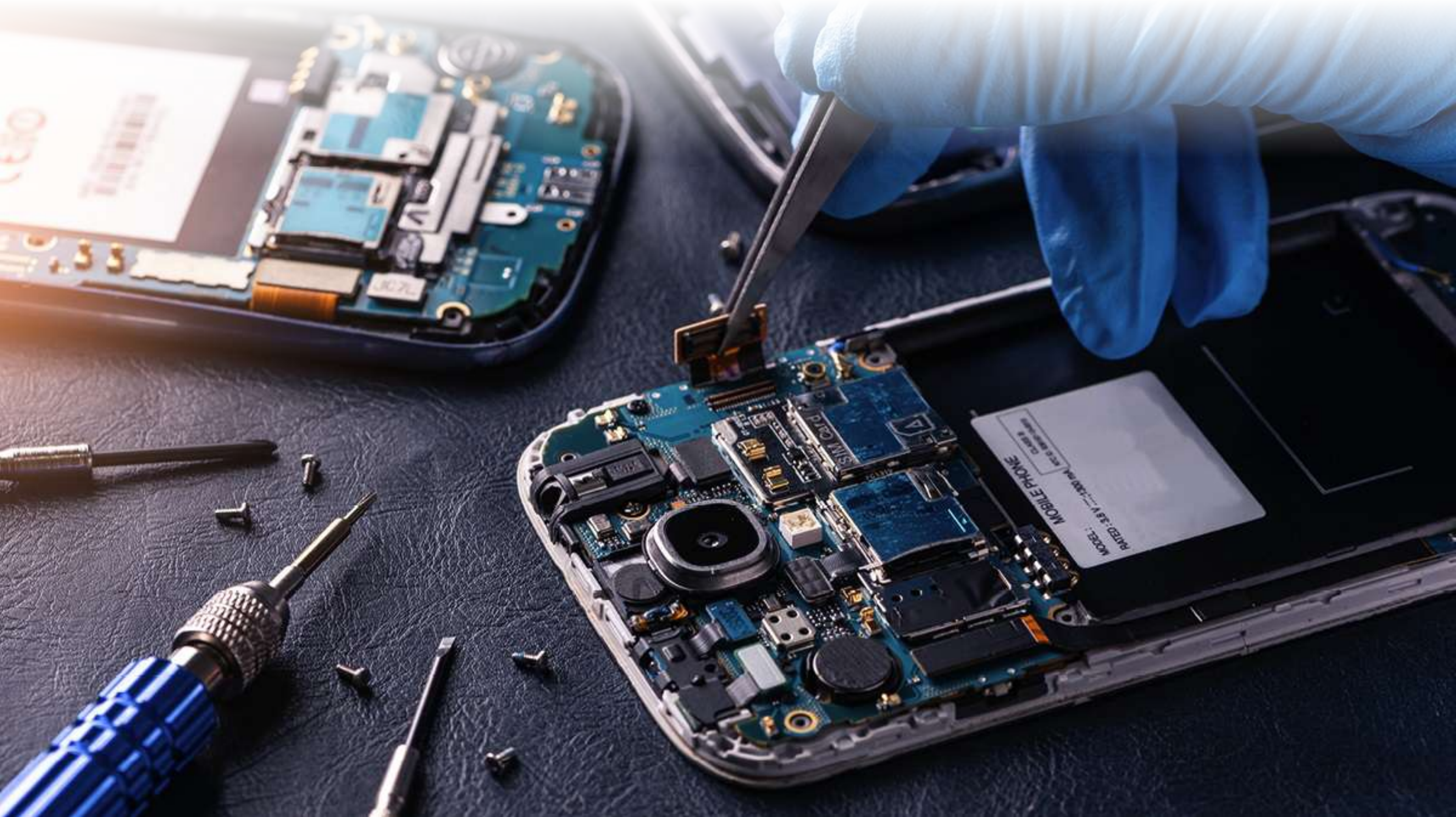
Planned obsolescence and a throwaway culture is a grim reality of today's society. Every year around 50 million tonnes of e-waste is discarded, a quantity heavier than all of the commercial airliners ever made. Against this, the “right to repair" movement is growing, demanding affordable repair solutions and better product manufacture.

In October 2019, the EU adopted an eco-design law which will force manufacturers of phones, tablets and laptops to make their products easier to repair.

One company is leading by example on the application of this concept. French Groupe SEB, a leading small appliances manufacturer, has made repairability one of the pillars of its sustainable development policy. It aims to extend product life cycles and to preserve rather than throw away.

Planned obsolescence

Planned obsolescence is a policy of planning or designing a product with an artificially limited useful life or a purposely frail design, so that it becomes obsolete after a certain pre-determined period of time upon which it decrementally functions or suddenly ceases to function, or might be perceived as unfashionable.



R6. Refurbish

Refurbishing is the process of restoring an old or discarded product and bringing it up to date to serve its initial function.

The refurbish concept explores how to revitalize old products. This concept seek answer for simple questions that we come across in our every day life: ”is there a way to restore the faded dye on clothes so they can be worn as something new?”, ”Can we replace the torn fabric of an old seat or sofa so it can continue to be enjoyed?”,...

It is important to point out that refurbishing is different from upcycling (repurposing), a preocess in which new, different value is created from an old object. Refurbishing, instead, aim to restore, to bring back the original value of the product in order to apply it and use it again for what was made for.

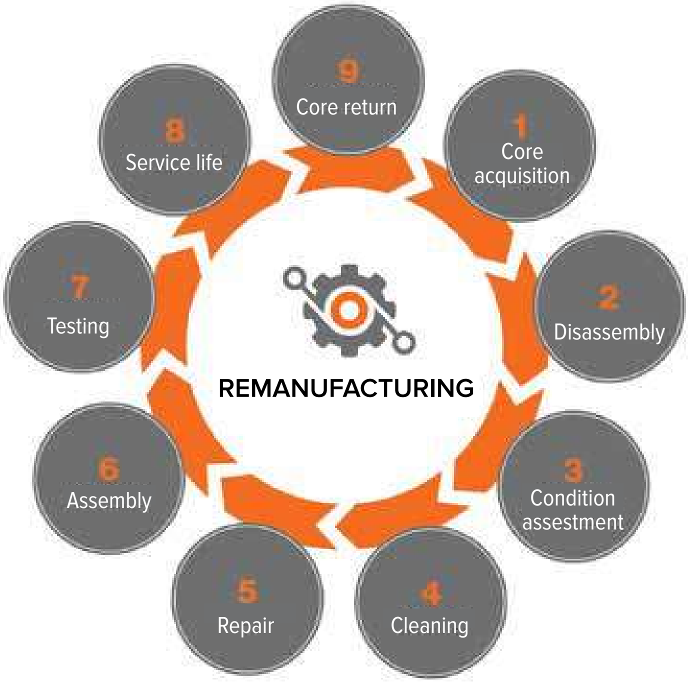
Ususally the damaged components are replaced resulting in an overall update while the product looks brand new. Enhancing the refurbishment of products can decrease the need for new materials, resulting in a reduction of waste and carbon emissions. As an example, two platforms specialized in e-waste, offer refurbishing solutions: the French Back Market and the Austrian Refurbed.

R7. Remanufacture

Remanufacture, or reconditioning, involves refurbishing and re-using parts of a discarded product in a new product with the same function.

Making new products from discarded ones is what Remanufacturing is about. It sounds intuitive, but there are obstacles like degradation of material when reused, so technological advances are needed.

Amongst the many areas in which items are remanufactured are aircraft components, engines, components, office furniture and medical equipment. Canon, for instance, has been remanufacturing devices with more than one function since 1992, echoing its ethos to maximise resource efficiency.



R8. Repurpose

When a product cannot be repaired or refurbished, it doesn't mean it should be treated as garbage yet.
Upcycling falls under the Repurpose, where we take the "broken" products and fix them to create different values than they had before.

What if an old ladder could be turned into a brand new bookshelf? Upcycling – repurposing a discarded product into a new one with a different function – is a growing trend. And the fashion industry is leading the way. Swiss brand Freitag transforms used truck tarps into highly functional, iconic bags. Airline Lufthansa has launched its Lufthansa Upcycling Collection, working with renowned designers to upcycle parts of its Airbus A340-600 D-AIHO into a home and accessories collection.

Cycle of remanufacturing

The process of remanufacturing can be divided in nine major steps:

1) Core acquisition: *the product is analyzed to find out what can be saved*

2) Disassembly: *the product is disassembled*

3) Condition assestment: *a further inspection is conducted to understand the kind of work every part need, and a plan of action is draw up*

4) Cleaning: *the parts are cleaned*

5) Repair: *the product is repaired following the plan drew in step 3)*

6) Assembly: *the product is reassemble with the new parts and the old one that have been saved*

7) Testing: *the remanufactured product is tested*

8) Service life: *if the product succesfully pass the tests it can go back on the market*

9) Core return: *at the end of it's life the product is brought back to the workshop to restart the remanufacturing cycle*

◇ R9. Recycle

Recycling is how we recover materials from waste, often through material or chemical recycling. Recycle takes the last second priority in the 10 Rs, which is scary to think how government policies have been so focused on the last two Rs. However, Recycle is still necessary for all the waste we have created and will be creating.

Today, only 9% of our used materials are recycled. But would it be possible to increase this number for less than it would cost to source the equivalent virgin materials? As public opinion moves increasingly against single use plastics, companies are looking to capitalise. For instance, in Australia, the cellulose used to bind roads together is made from paper, plastic and lids that were meant for landfill. And the UK has recently seen the launch of Loop, an online shopping service which delivers products in reusable packaging.

◇ R10. Recover

Recover is the final R, used as the final resort when the other 9 Rs are eliminated as possibilities. The most common form for this concept is the incineration of combustible garbage to recover as energy.

But what if waste wasn't actually waste ? It is known that through anaerobic digestion, microorganisms can break down biodegradable waste into materials, and there are now ways to use these processes to generate energy, as well as reduce pollution, water acidification and carbon emissions. Europe is a leader in the practice, with the biggest biomethane plant located in the Valdemingómez technological park in Madrid. While there are many benefits to this process, it is vital to ensure that bio-waste is sustainably sourced and is the last resort after all other "10R" options of the circular economy have been exhausted.

How to properly use the 10Rs

The concept of the 10Rs can easely cause some confusion, since the english verbs used to explain this points have a straight forward meaning, but sometime very similar to each other. To avoid to incur in such confusion, i report the study conducted by Vermeulen et al., 2019; a study focused on clear any misunderstanding about the R's meaning as weel to clarify what action every actor has to take to properly put in act the circular economy concept.

In doing so, we need to distinguish between two types of product life cycles: we need to distinguish between the product life cycles of "Produce and Use" and of "Concept and Design." Not doing so leads to part of the confusion as they refer to different actors and options. In the table below we show the synthesis as the comprehensive Product Produce and Use Life Cycle (the second product life cycle is shown in Reike et al. 2018).

Circular economy loops

Graph from Reike et al. 2018.

	Product life cycles	LIFE CYCLE 1: Product production and use		LIFE CYCLE 2: Product concept and design	Unspecified general word use (to be further avoided)
	R1 – R10	CONSUMER	PRODUCER / RETAILER	DESIGNERS	
Short loops	**R1** Refuse	Buy less, use less, reject packaging waste and shopping bag		refuse the use of specific hazardous materials or any virgin material;design production processes to avoid waste	
	R2 Rethink			Come up and use new, less impacting, manufacturing processes	
	R3 Reduce	using purchased products less frequently or with more care and longer		using less material per unit of production, or "dematerialization"	"eliminating waste, not dispose anymore"
	R4 Reuse	buying second hand, use online consumer to consumer services	send recollected products to their own repair centers, to manufacturer-controlled, or to third party repair centers	"re-use in fabrication"apply recycled materials	
Medium loops	**R5** Repair	by the consumer in their vicinity, or at their location, or through a repair company;or at a "repair café"	"send recollected products to their own repair centers, to manufacturer-controlled, or to third party repair centers	enable easy repairing	confused with refurbishment
	R6 Refurbish		"direct re-use" as economic activity via collectors and retailers, possibly with quality inspections, cleaning and small repairs		
	R7 Remanufacture		full structure of a multi-component product is disassembled, checked, cleaned and when necessary replaced or repaired in an industrial process.		"reconditioning", "reprocessing" or"restoration"
Long loops	**R8** Repurpose			reusing discarded goods or components adapted for another function	some use: "rethink" or "fashion upgrading"
	R9 Recycle	give back as separate waste streams	processing of mixed streams of post- consumer products or post-producer waste streams to capture (nearly) pure materials	apply recycled materials	"recover" often used asequivalent for generalrecycling: better
	R10 Recover		capturing energy embodied in waste, linking it to incineration in combination with producing energy, distilled water or useof biomass		often used as equivalent for general recycling

To sum up: what has fueled the diffusion of circular economy?

The CE concept started to become popular in different countries in the 1990s, buti t was only in the 2000s that it became an actual need, and for a prticular reason: the deteriorating relationship between economic growth and natural resource limitations.

The need to start capitalizing on material flow, to recycle, and to balance economic growth and development with environmental and resource limitations was sparked by three major events:

- the explosion of raw material prices between 2000 and 2010
- the chinese control of rare earth materials
- the 2008 economic crisis.

Today, the climate emergency and environmental challenges enhance all the problems already present and induce companies and individuals into rethinking their production and consumption patterns.

The concept of CE is framed to answer these challenges and offers companies and individuals a fruitable solution.

In short, the key and most portant idea behind the circular business models is to create loops throughout to recapture value that would otherwise be lost.

Circular development is directly linked to the circular economy and aims to build a sustainable society based on recyclable and renewable resources, to protect society from waste and to be able to form a model that is no longer considering resources as infinite.

Circular development, therefore, supports the circular economy to create new societies in line with new waste management and sustainability objectives that meet the needs of citizens. It is about enabling economies and societies, in general, to become more sustainable.

To sum up: main advantages of circular economy

It could enable an economic growth that does not add to the burden on natural resources extraction but decouples resource uses from the development of economic welfare for a growing population

Reduces foreign dependence on critical materials, lowers CO2 emissions

Reduces the production of waste, and introduces new modes of production and consumption able to create further value.

Secure the supply of raw materials

Reduces the price volatility of inputs and control costs

Reduce spills and waste, extends the life cycle of products

Serve new segments of customers

Generate long term shareholder value

CHAPTER 3

AM and CE meeting points

How can additive manufacturing enable circular
loops of recources and materials and help reach
true circular economy

In the previous chapters has been explained how AM's fast rate of innovation made possible for this new manufacturing technology to became one of the most effective solution for many manufacturing sectors, in particular thanks to its shorter lead times compared to conventional manufacturing processes.
Infact, among the variety of advanced manufacturing technologies that are currently emerging, AM stands out as one with most potential for changing the distribution of manufacturing and society.

From an ecologic point of view, current industrial applications of 3DP, are already enabling more circular production systems with the use of recycled and reclaimed materials as input for AM processes, since the process use less material due to its additive nature and the design of the system around the process that enable a closed-loop circulation of materials. The plastics used in 3DP are also commonly recycled plastics, such as ABS, PLA and PET, and while common plastic components are still recycled at low rates in centralised recycling facilities, distributed plastics recycling to produce filament for 3DP could help increased this rate at a lower economic and environmental cost.
These examples are showing that 3DP can facilitate the implementation of circularity concepts by directly using **reclaimed and recycled materials**, but also with more sustainable ones.

As its technical performance improves, the potential to use 3DP as a direct manufacturing process is gradually being realised in sectors such as aerospace, automotive, construction, pharmaceuticals and healthcare where personalisation is key.

In order to extend the values and advanteges of 3DP to other and broader sectors it is important to study and understand two major strong points:

- How can a distributed manufacturing system based on 3D printing can create a circular economy of closed-loop material flows
- What are the barriers that oppose to this circular 3D printing economy.

To better understand how 3D printing can enable the move towards a CE, I focused on the work by Despeisse et al., 2017, an extensive and accurate analysis on how the emergence of new advanced manufacturing technologies creates opportunities for changing how manufacturing activities are organised, in this case with a particular focus on additive manufacturing in relation to circular economy.
This work of Despeisse et al., 2017 is possibly the most extensive and accurate on the subject, yet, being a work from 2017, it lacks of some actuality. We already talked extensively, in the first chapter on additive manufacturing, about how the rate of innovation for 3D printing systems it's extremely rapid, and the more time pass, the more it grows faster.
It is logical to deduce then that even a short period of five years can really bring some major swings in the ways that additive manufacturing can bring improvements to circular economy. This is why i decided to implement the work of Despeisse et al., 2017 with new notions from more recent works, like the one from Hettiarachchi et al., 2022.

The six areas of research

We now aim to cover as much issues as possible regarding the entire product and material life cycles. Six areas of particular interst have been identified as critical to understand how 3DP can enable the move towards a CE, namely: 1 product, service and system design, 2 material supply chains, 3 information structure and flows, 4 entrepreneurial responses, 5 business model transformations, and 6 education and skills development. Accordingly, we will now dive in the exploration of these research areas with a multidisciplinary approach and a systems-level perspective.

1

Product, service and system design

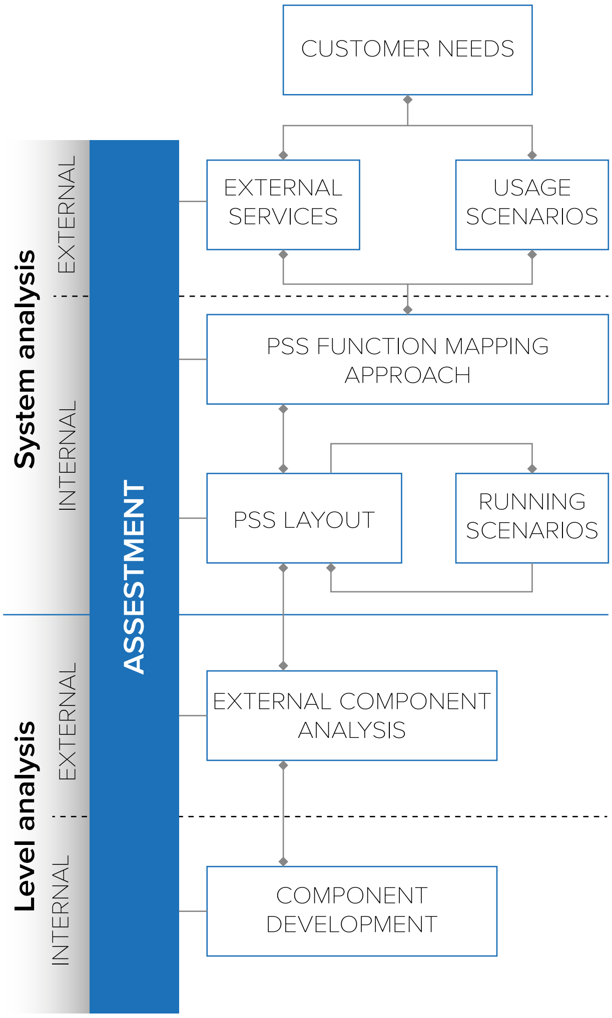
Designing for a CE requires a monumental shift in the way that organisations, designers and entrepreneurs develop, exploit and obtain value from products. However, the redesign task is not a simple one as there are strong interdependences between design, process and material selection. Design is particularly influential in how the entire value chain is configured in both forward and reverse processes. However, designers cannot wait for the development of a remanufacturing, reuse and/or recycling infrastructure and other alternative business models before they start to design for the CE; they must anticipate and prepare for the alternative economy. This is where 3DP comes in help of designers, since it is proposed as a tool to enable design for a CE when combined to a comprehensive understanding of the characteristics of the technology and resulting products.

Since most existing approaches to design for a CE involve recovery at product and/or component level, improving ease of disassembly, material and component separation and reassembly have been researched lately, in order to support maintenece, remanufacturing and refurbishment, to extend the life of valuable components and products.

Material selection as well has revealed to be very fruitful in generating an additional benefit during or at end of life of the product, reducing the environmental impact related to product creation, especially when supported with **life cycle assessments** tools and existing guidelines for design which grant an important aid for decision making. In design research this has been referred to as 'systems thinking' or 'life cycle thinking' (Despeisse et al., 2017).

Product-service system diagram

The graph from Vasantha et al., 2012



For the CE, the structure of material supply chains has significant implications, for example, local more flexible materials markets may be better suited to recycle highly distributed sources of consumer waste, avoiding information loss stemming from the aggregation of waste by large-scale recycling facilities. Furthermore, a more distributed materials market may incentivise the use of smaller concentrations of natural resources, leading to a reduction in transportation emissions and the environmental impact of intensive resource exploitation.

However, at present the market in raw materials for 3DP remains highly concentrated, since the feedstock is supplied by a handful of large polymer producers. This follows from the present reality that polymer production from petrochemical and bio-based feedstock is capital intensive, leading to high barriers to enter the market. In these types of markets, the minimum efficient scale for production remains large, raising the question of the technical feasibility of smaller-scale distributed materials production. This is especially the case for recycled materials as they require large centralised processes to convert mixed plastic waste into single polymers suitable for reuse (Despeisse et al., 2017).

To find a viable solution to this enigma it is necessary to quantify the impact of 3DP on the raw material supply chains, keeping in mind also the economic and technical aspects of materials supply and the needs of economies of scale production.

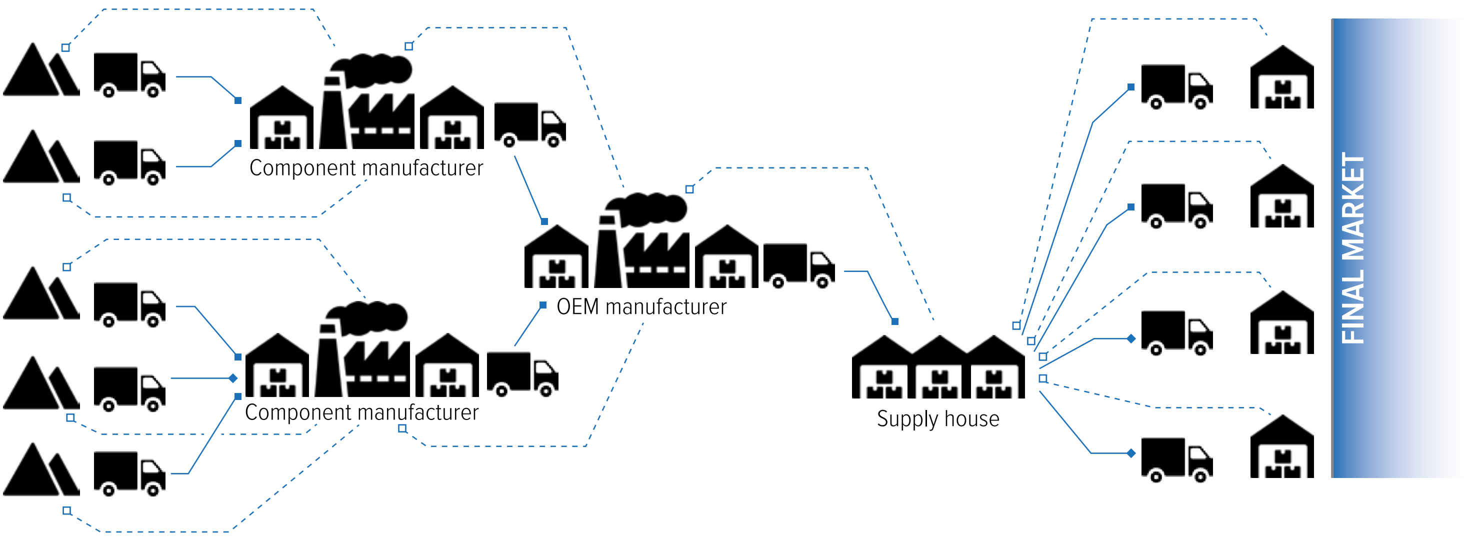
Tracking and tracing data on materials can play an important part in enabling circular material flows, as well as trade secrecy and patenting in materials production, and the disclosure of material sources within 3DP supply chains, since as a more distributed market for 3DP continues to develop, the demand for data on material characteristics and sources may change information structure and flows.

Supply chain flow

The graph show the flow of material and information in a product life, from the material extraction to the arival in the store where it will be sell. It is importanti to note how the information flow is always opposed to the material one, since it originates from the customer and the market.

Key

Component manufaturer or OEM manufacturer
Raw material supplier
Supply house
Inventory
Material flow ————
Information flow - - - - - - -
Distribution



Based on the design freedoms engendered by 3DP processes (Hague et al., 2003), the technology has shown significant potential in a range of high value manufacturing applications, such as medical products, automotive and aerospace components, industrial machinery and high-end consumer products, granting an extremely wide possibility of customization. In the context of CE, such products are known as “medium-lived complex products” and form a central focus point since, by harnessing 3DP's dual advantages of being able to deposit complex and functional structures and efficiently manufacturing individually differentiated units in small numbers, the value proposition of such products can be improved and their useful lives can be extended. However, the viability of extended-life assets hinges on their fitness for purpose and the degree of differentiation in terms of the target application. Only with such differentiation will the product’s use-phase extension be preferable over substitution with new products.

For a fully software mediated and toolless manufacturing process such as 3DP, unlocking manufacturing value requires two prerequisites regarding:

- design
- supply chain and production

Firstly, application-specific data must be fed into manufacturing design and design validation processes preceding 3DP operations. Only the incorporation of such data will yield the benefits obtainable from products differentiated to particular applications, for example resulting from optimisation-based design methodologies. Moreover, advanced predictive design methodologies can be employed to anticipate future use-cases, which will extend the usefulness horizon even further.

Secondly, the CE's focus on local manufacturing and the minimisation of environmental supply chain footprint will require efficient 3DP supply chains allowing for distributed manufacturing configurations minimising downstream logistics. This implies that networked production planning, scheduling and manufacturing execution functionality must be established to underpin 3DP (Despeisse et al., 2017).

Unlike conventional manufacturing technology, 3DP is a process capable of depositing complex product geometry in a single manufacturing process step. This means that, at least in principle, processing and assembly activities can be limited and very short supply chains are enabled, with an added side-effect of simplifying the measurement of resource consumption without having to consider long and complex supply chains

By linking the environmental footprint of 3DP with the volume of material deposited, research on the energy efficiency of 3DP processes suggests that cost minimisation by the technology operator can be expected to coincide with the minimisation of process energy and material consumption. The described relationship between operational variables results in correctly aligned incentives, where the private incentive of cost minimisation coincides with the deposition of the smallest amount of material and, in the context of energy inputs, the alignment of cost efficiency with the minimisation of the environmental impact of the process forms an important enabler for the minimisation of resource consumption.

4

Enterpreneurial response

The emergence of 3DP has been led by new entrepreneurs entering a new market, instead of establlished companies, who have been the originators of new models of 3D printers, materials and materials processing technologies, design software, and distribution platforms. Entrepreneurial ventures possess far fewer resources than established companies, however, the lack of these resources provides for greater flexibility as fewer sunk investments allow the venture to experiment more rapidly with their business model and novel product-market combinations.

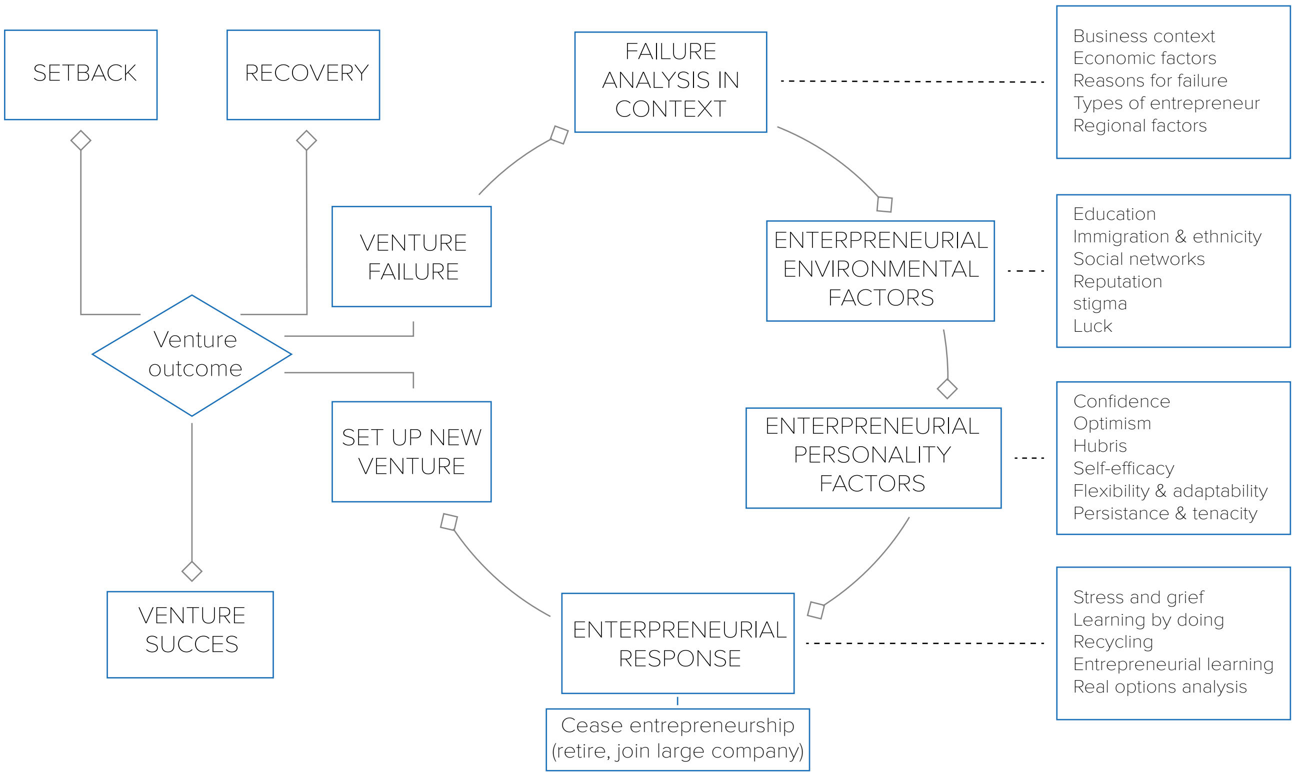
In addition to this entrepreneurial activity within the 3DP ecosystem, there are numerous entrepreneurs making use of the attributes of 3DP to make products and deliver services in novel ways, with a great number of these new ventures initially supported by crowdfunding on platforms such as Kickstarter.

While majority of opportunities are being realised in the traditional cradle-to-grave value chain, there is a small but growing number of entrepreneurs who are working within the 3DP ecosystem to create a circular economy, focusing around three categories of activities:

- Use of 3DP for repair and remanufacturing
- Production of 3DP filament, including the commercialisation of filament that contains recycled materials
- Local recycling systems for creating filament.

Entrepreneurial cycle

A framework to examine entrepreneurs attitudes to setbacks and failure in eraly stage of technology ventures (Vasantha et al., 2012).



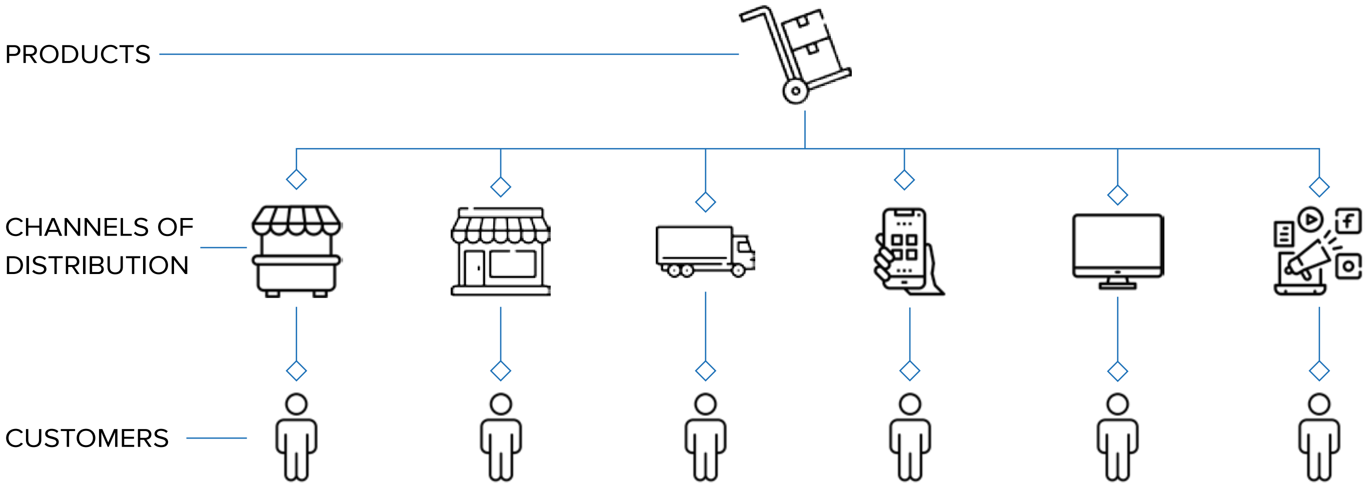
5

Business model trasformation

The implementation of a new technology like 3DP holds great potential for business model innovation, especially for distributed/home fabrication, a transformation which would involve a major shift from a manufacturer to a consumer centric business model, implying that firms can now conceive more open business models where consumers can be more directly involved in productive and value-adding activities. At the same time, these technologies could serve as foundations for the development of novel sustainable value propositions, for instance, by managing the production of on-demand spare parts, big firms can identify a number of new sustainable ways of capturing value by adopting a lean-manufacturing approach while reducing inventories.

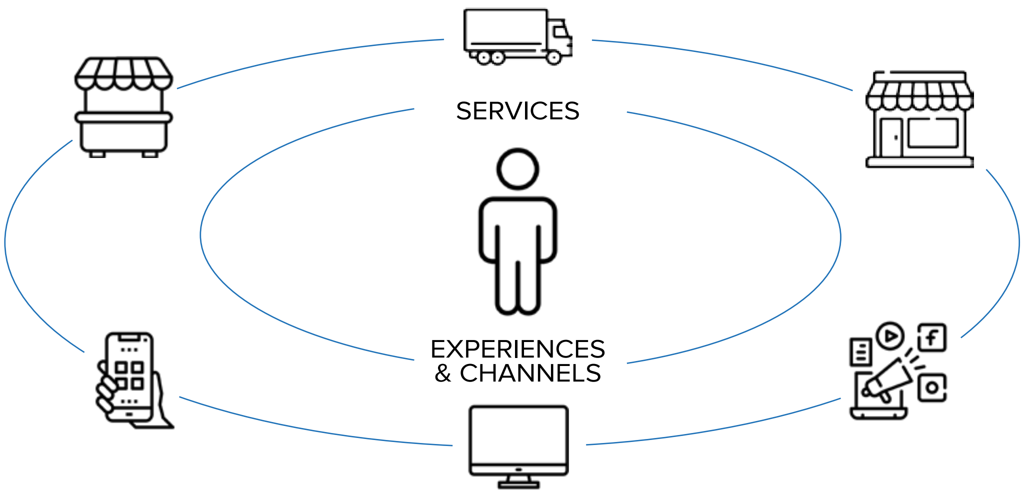
Opportunities also exist to increase efficiency and to create value through the use of 3DP for end-of-life parts generating reuse cycles for worn out components. Alternatively, new business models may allow companies to deliver value to their customers in innovative ways.

Finally, through the availability of flexible and versatile technologies such as 3DP, the identification of new uses of waste material may become more common. In this case, 3DP can support the establishment of new business models which create value from waste. Changing the relationship between manufacturers and customers presents opportunities to transform business model for CE with a service model including localised repair.



Business models

Above: old common business models. Below: new consumer centric business model. This new type of models usually are based on selling a service or product a monthly or yearly subscription revenue. They focus on customer retention over customer acquisition



For firms to adopt any new technology, they need to understand it first, allowing them to assess the relative merits in comparison to alternatives.

One of the problems with 3DP technologies (in terms of both processes and materials) is that openly accessible, neutral knowledge is extremely scarse since it remains property of the firms that developed it, making a real challenge to understand the real capabilities and limitations of 3DP and improve on them. In addition to this issue of knowledge access, there is a wide range of skills-related issues that need to be considered for the adoption of 3DP, since it encompass a broad set of technologies, used in numerous different configurations and application areas. For example, the impact of higher levels of design freedom on the skills required of industrial designers, and the need for specific materials-related skills. There is also the need to consider the skills issues that specifically link 3DP to CE, which adds an additional dimension to the analysis.

In order to solve these issues it can be helpful to develop a curriculum which lists and includes all of the opportunities and issues of design, material selection, material specification, properties, material re-use, process selection, application-specific, testing and measurement that the technology in exam has already been through. This type of curriculum needs to be redacted in such a way that can both form those who are entering as new workforce in the sector, as well to ensure that those already in the workforce are able to extend their existing capabilities. Nations are taking very different approaches to the development of 3DP skills, and integrating them into other aspects of policies through diverse structures.

For example, 3DP activities in Germany are being tightly bundled with Industrie 4.0 activities, emphasising the digital, connected, and system aspects of these technologies, while in Japan emphasis is being placed on the ways in which 3DP technologies have the potential to 're-skill' workers in regional manufacturing clusters.

These points gives already solid reasons to belive that joining the additive manufacturing technology with the concept of circular economy can bring massive adavantages both to enterprises that actuate such investment and the environment itself.

To further prove this position, in the work by Hettiarachchi et al., 2022 is clearly demonstrated, through an analysis of numerous case studies, how the ability of AM to extend the product lifecycle hints to its role as a digital enabler in the CE context.

Additionally, there are several key areas in need of further attention. For instance, A**M standards** and **quality control** need to be improved together with the maturity of the technology to embrace CE concepts in the production process.

Further, organisational changes need to be set in place. Realigning the organisational structure and absorbing the new organisational culture created by AM to overcome the inherent RP legacy of AM will be a key to thriving AM implementation in a sustainable environment. A skilled workforce and organisational awareness of digital technologies are also essential to achieving circularity concepts in an automated digital environment (Despeisse et al., 2017; Garmulewicz et al., 2018).

Similarly, building multitasking facilities for AM is a noteworthy development influencing the AM hub location decision from a supply chain viewpoint. In this scenario, both the manufacturer and remanufacturer utilise the same AM equipment in the same location in close vicinity to the customer. Hence, this multitasking facility approach enhances the value while reducing lead time, costs and the environmental footprint of the entire supply chain process, enabling CE.

It has also been observed CE implementation strategies are frequently associated with key AM decisions, supply chain actors and operational practices to smooth the transition towards CE.

Since the the new business model proposed have the customer and the technology maturity in its center, management should focus more on involving the customers' viewpoint and level of technology maturity when embracing AM in their production process. Moreover, managerial decisions should be made considering also how other supply chain actors and CE implementation strategies influence the operational practices where key AM decisions and drivers act as mediators. Especially, managers should understand the gravity of decisions relating to the location of manufacture, RP legacy and workforce skill to successfully implement AM in a CE-driven environment in the long run (Hettiarachchi et al., 2022).

CHAPTER 4

Case studies synoptic table and evaluation

What is exactly additive manufacturing, how did it eveolve through time and what potential does it have today

Case studies selection criteria

In the previous three chapter we have explored the concept of additive manufacturing, circular economy and the meeting points between the two. The literature present on the web is quite rich on these argument, and we could see extensively how 3D printing can facilitate the implementation of circularity concepts in both new and already solidified manufacturing processes. The analysis conducted up until now has been done merely on from a theoretical point of view. It’s now time to dive in the more practical and real world, by checking what the market can offer today, understanding how firms, designers and engineers are moving to join these two worlds.

In oreder to give solidity and reliability to my work i conducted a research on the web, on specialized sited like Dezeen.com, 3DPrint.com and Materialdistrict.com, collecting up to 31 cases that i deemed important and worth of a deeper analysis. In order to collect these projects i had to first envision a strict selection criteria, to filter the huge amount of information on the internet and find the the most suitable ones that could give credibility to my work.

The selection criteria to which i sticked for my reserch was based on the following principle:

- Ecological relevance

  The first and most important principle that a project have to follow, to be useful to my research, is that it must be related to the ecological issues treated in chapter two.

  Like we saw circular economy is a powerfull instrument that can help reduce the ecological impact of any company that decide to commits to its rules.

  In my case it become an instruments to locate the most innovative projects that tries to revolutionize the market and push the worldy industrial production to a more green and harmonious world, where the spectre of the ecological crisis is no more.

- Material extrusion additive manufacturing

  Seconldly its mean of production.

  In chapter three we saw how additive manufacturing can be a fantastic instrument to try to reach a looping economic system/society. The advantages of this manufacturing system are listed in chapter one and they make it clear on how it is the best way to actually reach the much coveted circular economy.

  Yet not all additive manufacturing processes meet our interest, in chapter one infact is also explained how systems that use material deposition processes are the most common nowdays, and that they offer way more opportunities than any other additive manufacturing processes, in terms of materials employed, shapes and possible geometries, volume of production and time to print.

  This is why i decided to narrow my research and focus it on projects realized with material extrusion manufacturing processes, in particular **FDM** technology and its “variants”: **FFF** and **FGF** manufacturing systems. This choice allowed me to find more realistic and futuribles projects, backed up by actual industrial production systems and not just simple prototypes.

- Circular economy strategy

  The third step of the research is the strategy to which the project stick to in order to reach the closest result to a true circular economy. The strategies followed by the collected projects are identified through the 10Rs strategies of the “**10Rs principle**” thoroughly explained in chapter 2. For every project has been individuated at least one strategy, and a maximum of three, which the project follow more or less knowingly. The strategies are reported with an “R” followed by a number from 1 to 10, like “R3” for example, meaning that the the project at issue follows the third strategy of the “10Rs principle”: reduce.

◆

Secondary raw material

Another discriminating factor that played an important role in the making of this research has been the secondary raw material, which is the material used at the beginning of the project, but that comes from a recycled source. Even if not all projects collected comes from recycled sources, since our aim is to look for projects with the possible lowest environmental impact, those who begin from already recycled material, will surely be object of interest.

Another element to keep in consideration in this selection area is the fact that since we have stated that the the manufacturing processes on which we will focus the research will be **FDM**, **FFF** and **FGF** 3D printing, we are limited to materials that can be treated in such processes. Luckily, the FDM system and its variants have a broad range of material that they can print, including thermoplastic polymers, ceramic materials, metals, composites and more.
An important element to bear in mind is that even if the FDM system theorically works the same way for all of these material "classes", the printers for each typology are sensibly different from one another in term of technical specifications and capabilities.

So, in order to keep this work the most linear and clear as possible i decided to narrow my research once again, focusing on those criteria that would allow me to find the most **realistic** and **futuribles** projects. For this reason i decided to remove from my research all those material with such properties that do not allow them to be printed by 3D printers used for **thermoplastic polymers**.
This mean that the materials i'll look for will be thermoplastic polymers or materials with physical properties similar to them.

◆

Final process material

The final process material, like the name says, is the material that compose the product at the end of the manufacturing process. Someone could wrongly think that the material ad the beginning and at the end of the process could be the same, but in process where recycled material is involved is rarely so.
Since second hand raw material usually have worse properties than virgin material, it is common practice to reinforce it or combine it with small percentage of the same virgin material, or with another compatible recycled material.
This mean that final material is completely different from the one at the beginning of the manufacturing process. While this is not directly a discriminating criterion for my research, it will be an interesting objects of evaluation later on.

◆

Year

The last factor that i took in consideration for my work is the year of realization of the project. This is quite an important factor, since, like explained in chapter one, additive manufacturing have an incredibly fast rate of innovation and evolution. Similarly to informatic and digital sectors, additive manufacturing is a type of industry that is subject to constant experimentation, development and evolution, receiving continuous update every day, from a simple adjustment in the printing process to completely new printable material typologies.
Such fast rate of innovation forced me to restrict the period of research, since what might have been the best and most innovative project ten years ago, today would be judged outdated and obsolete. for this reason i decided to focus only on projects from the period of the last five years, from 2017 to 2022.

Synoptic table for comparison of case studies

Year	Project name	Application field	10Rs satisfied	Starting Material	Final Material	AM technology	Final product	Project link
2017	Military blueprints	Military sector	R5, R6	PLA	PLA	FDM	Spare parts for hardware	https://www.dezeen.com/2013/05/07/3d-printed-guns-drones-military-print-shift/
2017	Dolphin board of awesome	Sport's hardware	R1, R9	Recycled plastic bottles and algae	Recycled thermoplastic polymer	FFF	Surfboard	https://www.santacruzwaves.com/2018/03/the-dolphin-board-of-awesome-2/
2018	Not only hollow	Furniture design	R9	Reclaimed polycarbonate	Recycled thermoplastic polymer	FGF	Cabinet	https://adorno.design/pieces/not-only-hollow-cabinet/
2018	Botella light	Furniture deisgn	R9	Recycled PET bottles	Brand new thermoplastic polymer	FFF	Lighting collection	https://betterfuturefactory.com/portfolio_page/unc-botella-light/
2018	Genesis eco green	Furniture design	R1, R9	Recycled plastic	Recycled thermoplastic polymer	FGF	Urban plant and insect habitat	https://3dprint.com/251283/genesis-eco-screen-3d-printed-urban-biodiversity-habitat-of-recycled-plastic/
2018	On-demand spare parts	Aerospace	R3, R7	Plastic waste from astronauts	Recycled thermoplastic polymer	FFF	Spare parts	https://3dprintingindustry.com/news/nasa-installs-tether-refabricator-aboard-iss-for-in-space-3d-printing-148728/
2018	Million waves	3D printing industry	R1, R9	Recycled ocean plastic	Recycled thermoplastic polymer	FDM	Filament for 3D printing	https://www.waste360.com/plastics/million-waves-project-looks-solve-two-global-issues-once
2019	Second Nature	Furnishing accessories	R4, R8	Plastic waste from ocean, nets	Recycled thermoplastic polymer	FFF	Tableware	https://thenewraw.org/Second-nature-Seashells
2019	The 3D bar	Furniture design	R4, R7	Recycled plastic from coffe cups	Recycled PLA	Robotic FFF	Bar furniture	https://www.caracol-am.com/portfolio/the-3dbar/
2019	Conifera	Exibition	R6, R7	Wood watse	PLA reinforced with wood fibers	FFF	Exibition pavillion	https://www.dezeen.com/2019/04/08/arthur-mamou-mani-cos-installation-bioplastic-bricks-circular-design-milan/
2019	Ice-Dream	Furniture design	R4, R7	Industrial scraps	Recycled PLA	FFF	Furniture	https://www.3dwasp.com/en/sammontana-3dprinting/
2019	AVR Tables and Stools	Furniture design	R7	Recycled PET bottles	Recycled thermoplastic polymer	FFF	Furniture	https://vanplestik.nl/en/2019/04/18/3d-printing-a-betterfuture-together/
2019	Deciduous	Exibition	R2, R7	Recycled PET bottles	Recycled PET based polymer	Robotic FFF	Exibition pavillion	https://www.m-e-a-n.design/projects/deciduous-3d-printed-pavilion
2019	Feel the peel	Food industry	R1	Orange dust	Natural thermoplastic polymer	FFF	Cups for orange juice	https://carloratti.com/project/feel-the-peel/
2019	Strat	Furniture design	R4, R9	Locally recicled plastic wastes	Recycled thermoplastic polymer	FGF	Seats collection	https://materialdistrict.com/article/3d-printed-furniture-belgian-plastic-waste/

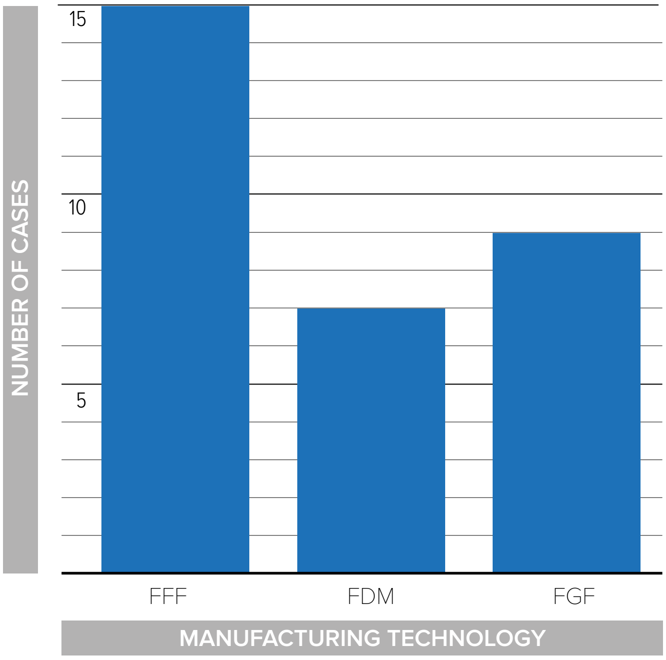
2019	DIY Prostethics	Medical design	R4,R5	PLA	PLA	FDM	Prostethics	https://www.dezeen.com/2019/09/06/diy-prosthetics-guide-desiree-riny/
2019	Plumen and Batch works lamps,	Furniture design	R1, R9	Locally recicled plastic wastes	Recycled thermoplastic polymer	FDM	Lamps	https://www.dezeen.com/2020/01/02/plumen-batch-works-lampshades-recycled-plastic/
2020	Let the waste be the hero	Furniture design	R4, R7	Recycled plastic from Toys	Recycled thermoplastic polymer	FFF	Furniture	https://betterfuturefactory.com/portfolio_page/circularbrainstorm-room-furniture/
2020	Gantri's lamp	Furniture design	R2, R3	PLA	PLA	FDM	Lightining collection	https://www.dezeen.com/2020/03/04/ammunition-and-gantri-3d-print-lamps-from-plant-based-materials/
2021	Icoesaedro	Tableware	R2, R3	PLA	PLA	FDM	Miscellaneus tableware	https://www.dezeen.com/2014/02/15/icosaedro-creates-ready-to-use-3d-printed-tableware/
2021	Ermis	Furniture design	R1, R8, R9	Recycled PLA	Recycled PLA	FGF	Lounge chair	https://www.dezeen.com/2021/11/08/the-new-raw-ermis-recycled-plastic-design/
2021	GLYPH	Urban furniture	R1, R8, R9	Recycled PP and PE	Recycled PP and PE	FGF	Urban seat/benches	https://3dprintingindustry.com/news/the-new-raw-launches-zero-waste-lab-for-recycled-3d-printed-furniture-147374/
2021	Pots Plus	Urban furniture	R1, R8, R9	Locally recicled plastic wastes	Recycled thermoplastic polymer	FGF	Urban seat/benches	https://thenewraw.org/Pots-Plus
2021	The elements	Urban furniture	R1, R8, R9	Recicled plastic wastes from the sea	Recycled thermoplastic polymer	FGF	Beach products	https://thenewraw.org/Elements
2021	Recycled 3D-Printed Chair	Furniture design	R7	Locally recicled plastic wastes (PET bottles)	Recycled PET based polymer	FFF	Seats	https://www.krilldesign.net/autogrill/
2021	Plastic surgery collection	Furniture design	R7	Locally recicled plastic wastes (PET bottles)	Recycled PET based polymer	FFF	Stool and vases	https://ninetyoneninetytwo.com/
2021	Aectual	Furniture deisgn	R7	Recycled PET bottles	Brand new thermoplastic polymer	FFF	Customized room dividers	https://www.aectual.com/sustainability/circular
2021	Primavera	Furniture design	R3, R9	PLA	PLA	FGF	Sculptural coffee tables	https://3dprintingindustry.com/news/nasa-installs-tether-refabricator-aboard-iss-for-in-space-3d-printing-148728/
2022	Kelp collection	Furniture design	R8, R9	Recycled fishing nets	thermoplastic polymer + wood fibers	FGF	Seats collection	https://www.dezeen.com/2022/04/22/kelp-collection-chair-interesting-times-gang-dezeen-showroom/
2022	BambooFill	3D printing industry	R9	PLA and natural fibers	Brand new thermoplastic polymer	FDM	Filament for 3D printing	https://3dprint.com/15855/colorfabb-bamboofill-filament/

Data analysis

AM is an emerging arena, and many scholars have focused on its technological evolution rather than exploring how it can be an enabler of the CE approach by considering broader perspectives. Yet in this analysis we could see clearly how these two concepts can interpolate each other, helping human being to reach a looping economy.

We explored how supply chain actors, key AM decisions, drivers, operational practices and CE implementation strategies are interrelated to operationalise AM in the CE context. The analysis highlighted the symbiosis required between product design and customers, as customers are shifting to the role of the designer during the AM implementation process. Moving beyond the disconnected discussions on customers and technology maturity in AM discourse, this study presents how centrality relies on both customers and technology maturity when implementing AM in a sustainability-driven CE environment. Moreover, the impact of both material suppliers and customers on the decision of the location of manufacture is key to achieving environmental sustainability by reducing the carbon footprint of the supply chain.

Graph 1: technology



The main data that we can extrapolate from this analysis are the following:

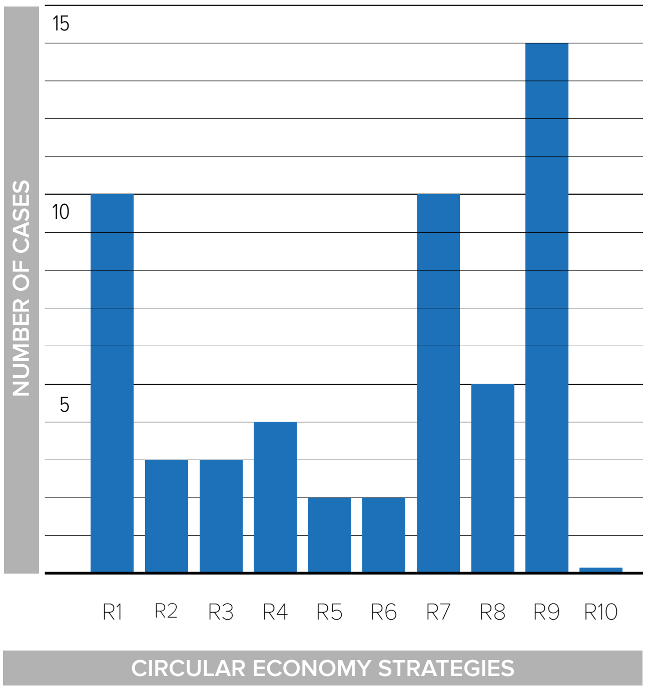
In graph 1 are reported the data about what manufacturing technology were the most used by all of the 31 case studies collected. It is important to note that even if half of the case analyzed were projects realized with FFF system, most of them were not actual product backed up with a true industrial production system, but rather concept or prototypes usefull for further developments of the concepts.

This is quite logical, since we had the chance to explore in chapter one that FFF printing systems are not suited for the production of high number of products or with high definition, but is ideal for mock ups and a first approach to the 3D printing world, bacause of the low printing speed, the low flow of material and the overall poor perforances of the printers.

What really stands out from this graph is how there is a major interest in FGF printing systems than FDM ones. If the popularity of FFF options can be retraced to the economic convenience of these machines, it's quite unusual to see an expensive manufacturing process like FGF take over its cheaper counterpart. FDM and FGF systems have definetly different aspects that charaterize each other, but the main differece between the two is the dimension of the prints.

It is quite interesting then to note that most manufactures are more incline to invest in projects that are phiscally bigger, even if that means to print and to consume more material, since they clearly prefer to print with pellets a raw material that offer major benefit in comparison with filament. Infact, the 9 cases reported that use FGF systems revealed to be the most interesting and most completed projects of the lot. FGF printing sytems are at the base of the production and design process of entire studios.

Graph 2: 10Rs step



Graph 2 shows the most reserched steps of the 10Rs principle by the 31 case studies collected. Almost half of the cases focused, or at least shown interest, in the **ninth R**, **recycle**, a result to be expected. Recycling have been the most common way that human beings adopted decades ago to safeguard the planet ecosystem. Judging from today's ecosystem status it was clearly not enough.

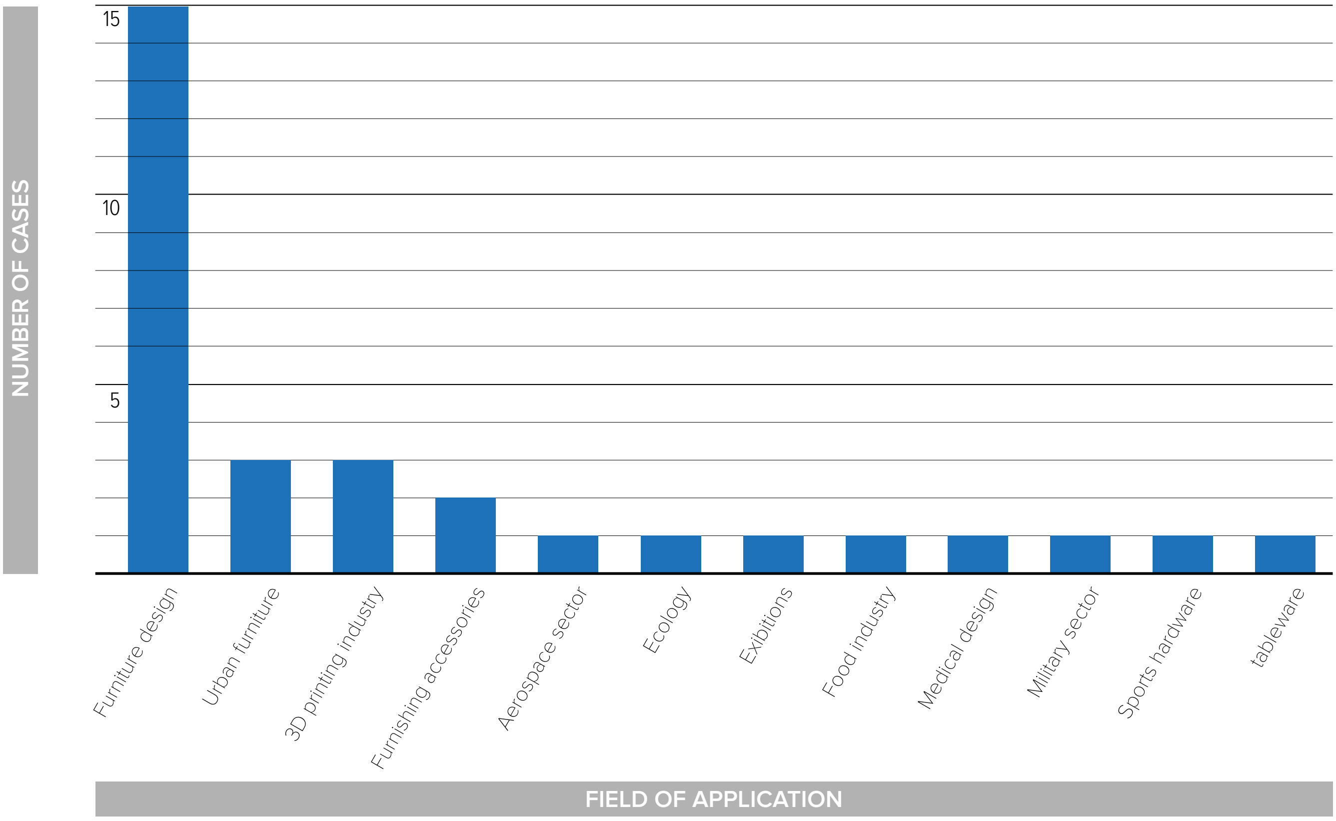
Something more interesting that we can etstrapolate from this graph is that a third of the cases (10 for each one) chose to pursue the stategies of R number seven, **remanufacture** and R number one, **reduce**. This choice is not trivial at all, it means that there is a growing interest in the market in the practice of reducing the unecessary production and to reuse or salvage defective or broken components. This business choices, the idea of reducing in particular, mean that most brands, firms and studios have to take actions that can be counterproductive to their actual business model, enabling a process of realaboration and internal revolution of the way of working of themself, but it doeasn't mean that they don't offer profitable opportunities, especially for sector's newcomer and when are paired with the new generation of mean of distribution.

Graph number 3, shows the sectors where the 31 case studies collected have been applied. Here the situation is clear, while there is a small interest in every field reported, the **funiture design** sector is absolutely dominant. The reasons for this phenomenon are quite deep. Infact, one part of the furniture business that has traditionally required significant time and financial investment is the **design process**. Prototypes have to be made, models tested and pieces reworked to reach a final product. 3D printing streamlines, simplifies and reduces the cost of designing furniture. Being able to create lightweight furniture prototypes quickly and inexpensively with 3D printing enables designers to test their creations more thoroughly and maximize the beneficial features in the finished product.

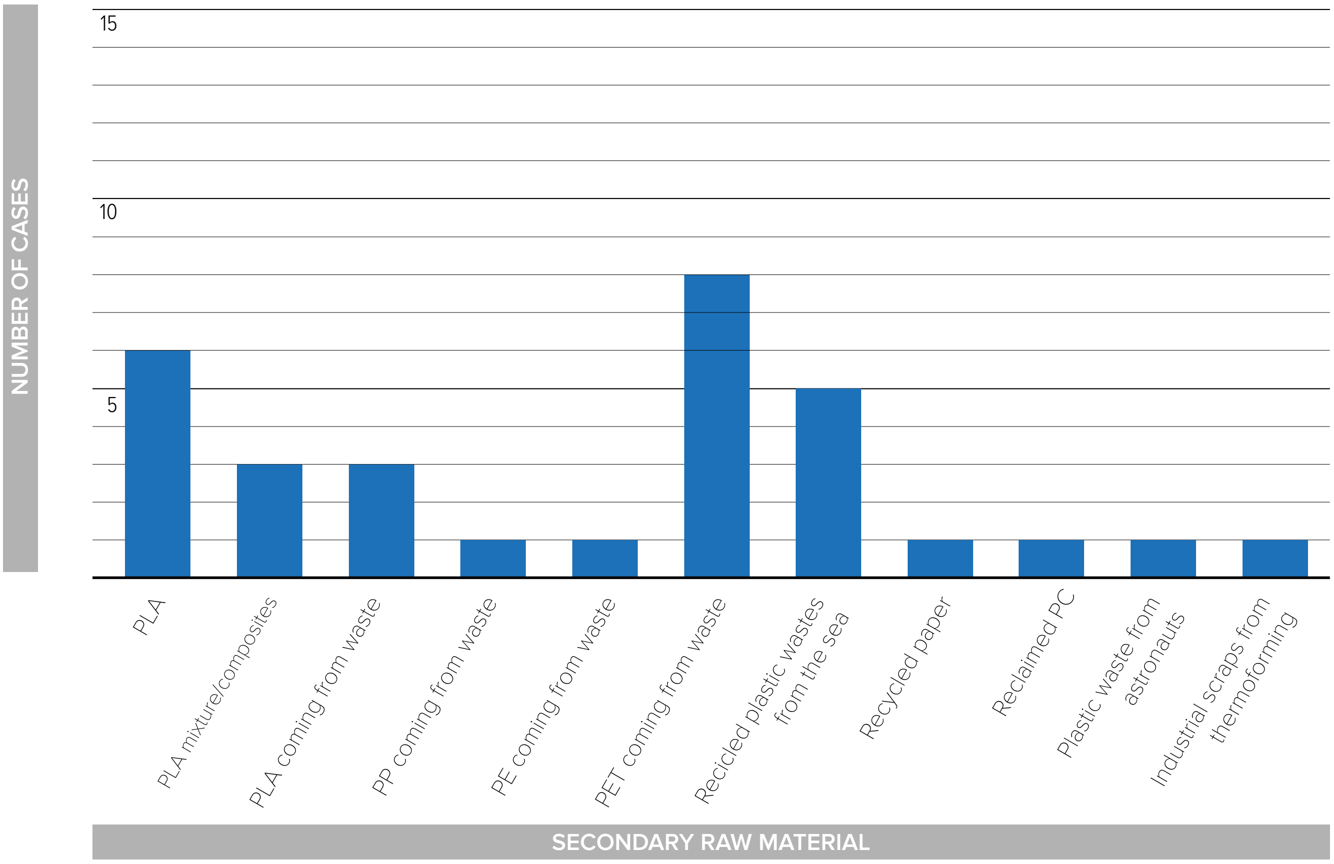
A rapidly growing number of furniture design firms are experimenting with 3D printing, supported by the lower production and design expenses, 3D printing lets companies develop furniture that is enhanced both from the aestethic point of view and from the functional one. In addition to giving designers the ability to create furniture that's simply not possible to make with traditional methods, 3D printing has made it cheaper for new businesses to enter the furniture game. Less design and production expenses equates to furniture that can quickly be made available to consumers at a lower price on both ends. It's truly a win-win for designers, manufacturers and customer who are looking for excellent furniture but with contained prices.

Lastly another great advantages for the furniture sector is the possibillity of **unlimited customisation**. The digital modelling allow for full customisation of furniture, whether in terms of size, shape or colour, or in terms of adapting the shape to the end user, which feel closer to the product and part of the design process, providing him with an added value.

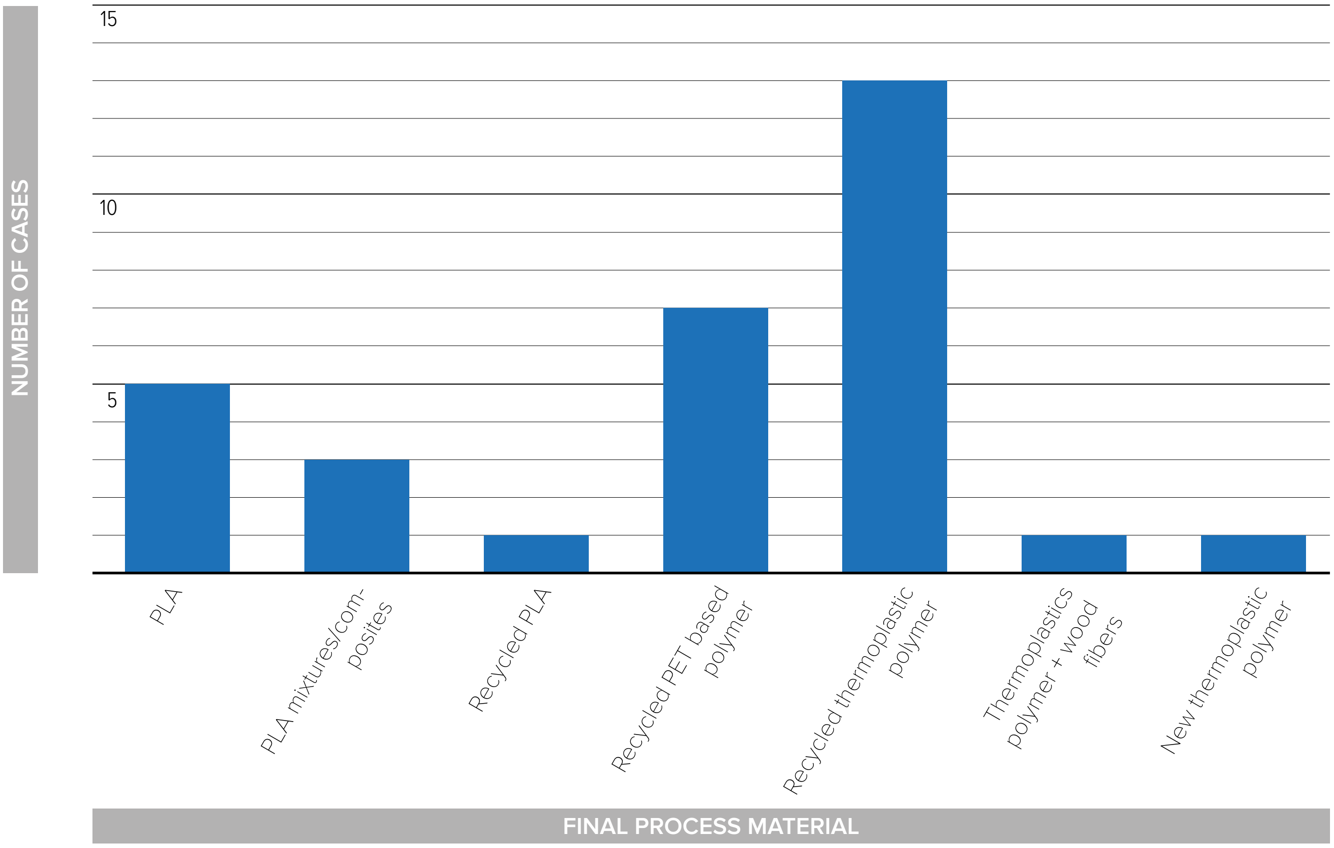
Graph 3: applications



Graph 4: secondary raw material



Graph 5: end of process materials



Finally, graph 4 and 5 in the previous page, tackle the issue of the **materials**, which materials are most used to launch the process, and what are those who come out of it, respectively.
Starting from the materials at the start of the process, the graph could actually be misleading, since the dominanting voice is the one of **PET** from waste sources (which is definetly an important voice) with 8 cases out of the 31 analyzed.
But i'd rather focus on the **PLA**, which, adding the voices of PLA mixture/composites and PLA coming from waste to the original voice of PLA this material is present in 11 out of the 31 cases.

From more theoretical analysis of the literature on the subject of AM applied to reach a circular economic loop, several points of interest have emerged that are worth reporting.
For example, the use of **degradable/biobased materials** for AM is a not very investigated area. Previous literature has mainly focused on virgin and recycled materials, although AM supports the use of a wide range of materials as inputs for the production process. This is possibly due to the fact that all the new material experimented by companies, studios and brands are usually immediately patented and the formula is kept secret, preventing competition to use the innovation produced by others, slowing down the development of the sector of innovative materials.

Another area that offers exceptional outputs but is poorly researched is the one that concern the first and most important step of 10R principle of circular economy: the promoting of the dematerialisation concept: **R1 – Reduce**. This step is the most important and the final objective of CE, the AM processes clearly has the capabilities to help reach it and expand it, yet today is an overlooked research gap requiring scholarly attention. Previous literature has mainly focused on how AM supports CE implementation strategies such as repairing, refurbishing and remanufacturing concepts to extend product lifecycles.

Finally, the developed conceptual framework and CLD analysis systems are powerful strategies to understand CE related problem, find a solution and prepare more accurate plans of action. These instruments of research need to be further validated as they are limited to the literature analysis, while they can certainly have more practical results. The proposed CLD can be further extended by developing simulation models using system dynamics or similar methods in future studies.
Therefore, future research should be conducted to empirically validate the conceptualisation and CLD by capturing practitioners' viewpoints.

CHAPTER 5

Case study exposition and in depth analysis

Exposition of all the case study reported in the synoptic table and analysis of their most important aspects from a circular economy point o view

Primavera by NYXO

What is this project

Primavera is a collection of sculptural coffee tables designed by 3D printing pioneer Nyxo Visionary Design, founded by Italian designers Mirko and Michele Daneluzzo. The collection was presented and launched at Downtown Design during Dubai Design Week 2021, and explores 3DP technology in the form of an iconic family of pieces that evokes the floral world and the circularity of the seasons.
Organic and fluid shapes combined with a geometric regularity that symbolize natural regeneration cycles. Bold colors, sinuous geometries, and delicate curves represent the new life of the material. The patterns of each piece evolve along with its height, gaining complexity from the base and top, reinforcing the pieces.

The collection is 3D-printed with PLA, and the tables can be recycled at the end of the products' lives, creating a closed-loop production cycle. The goal of Primavera is infact to pursue low energy and zero waste design, which can actually be obtainable with 3D printing.

Project's name:	Primavera
Author:	Nyxo Design Studio
Year:	2021
Technology:	FGF
10R's step:	R3, R9
Aim of the project:	Zero waste design
Main features:	Exploiting the process weak points for product aesthetic and functional aspect
Project link:	https://designwanted.com/nyxo-primavera-furniture-3d-printed/

What are its main design feature

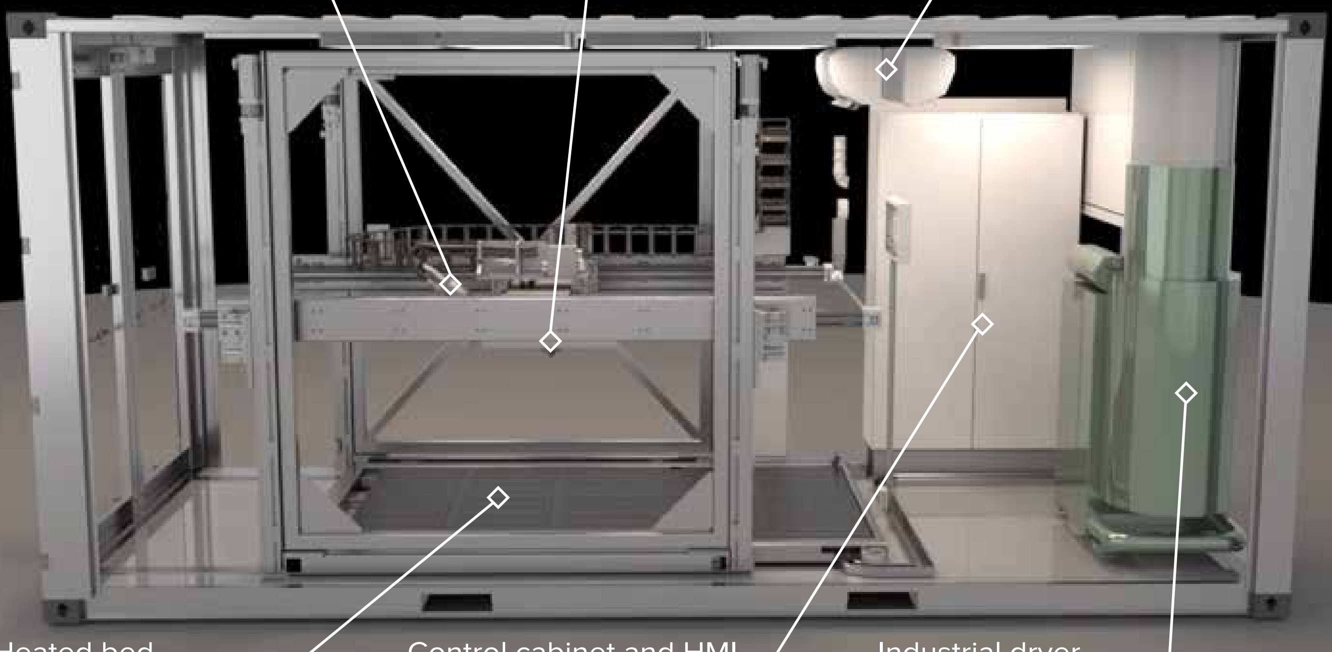
One of the most impressive feature of this product's design is the way it exploits one of the weak point of the FGF manufacturing process, the tactile horizontal ridging on the vertical surfaces, and transform it into an iconic element of the product itself. This is indeed a key design feature since, to print Primavera, the designers decided to use a Colossus XS Series printer made by Colossus Printers, an FGF printing system designed with a special accent on materials.

FGF system are already very efficient in terms of print-speed and volume of printinted material per hour, but this machine in particular has a build volume of 1600x1200x1300mm and reaches speeds of 200mm per second, an impressive result, granted by the ability of the system to work with direct pellet extrusion. Another main feature of this system is the ability to enable the designer to work with a larger selection of (recycled) materials and use various masterbatches directly in the print process, as well as making it more financially viable.

The nozzles of these printers usually range from 1mm-10mm, but in Priavera's case a custom size nozzle of 20mm was produced on request. This specific nozzle allowed to emphasize the ridges as each layer was formed, characteristics further enhanced by the foaming nature of the of PLA.
This material was chosen beacause it paired perfectly with the type of printing process and the shapes required by the final product, but as well for its intrinsic phisical properties which, combined with the final geometries of the tables, made them strong and durable, while keeping them light and manageble at the same time.
Every printer comes fully equipped with: a granulate fed extruder printhead, and a dehumidification unit for better print quality. All material profiles delivered with your printer contain the correct drying time and settings to ensure best quality. With the development of all Colossus Printers, special attention is places on being to work with a wide range of recycled materials, combining cutting-edge technology to give plastics a second life.

Colossus Mark II Static

Down is possible to see the main components of the Mark II Static model, identical to the XS Series model but with a bigger print dimensions



How does it help Circular economy

The goal of this project is to pursue low energy and zero waste design, a new materiality and circular-design aesthetic. The 3D printing technology used to create Primavera represents an important step towards a genuinely circular and sustainable production model.

The collection, infact, is 3D printed with PLA and the tables are engeneered in a way that enables an easy disposal, making possible to recycle the products at the end of their lives, broke down the material, and reuse it in in order to make new products, creating a closed-loop production cycle.

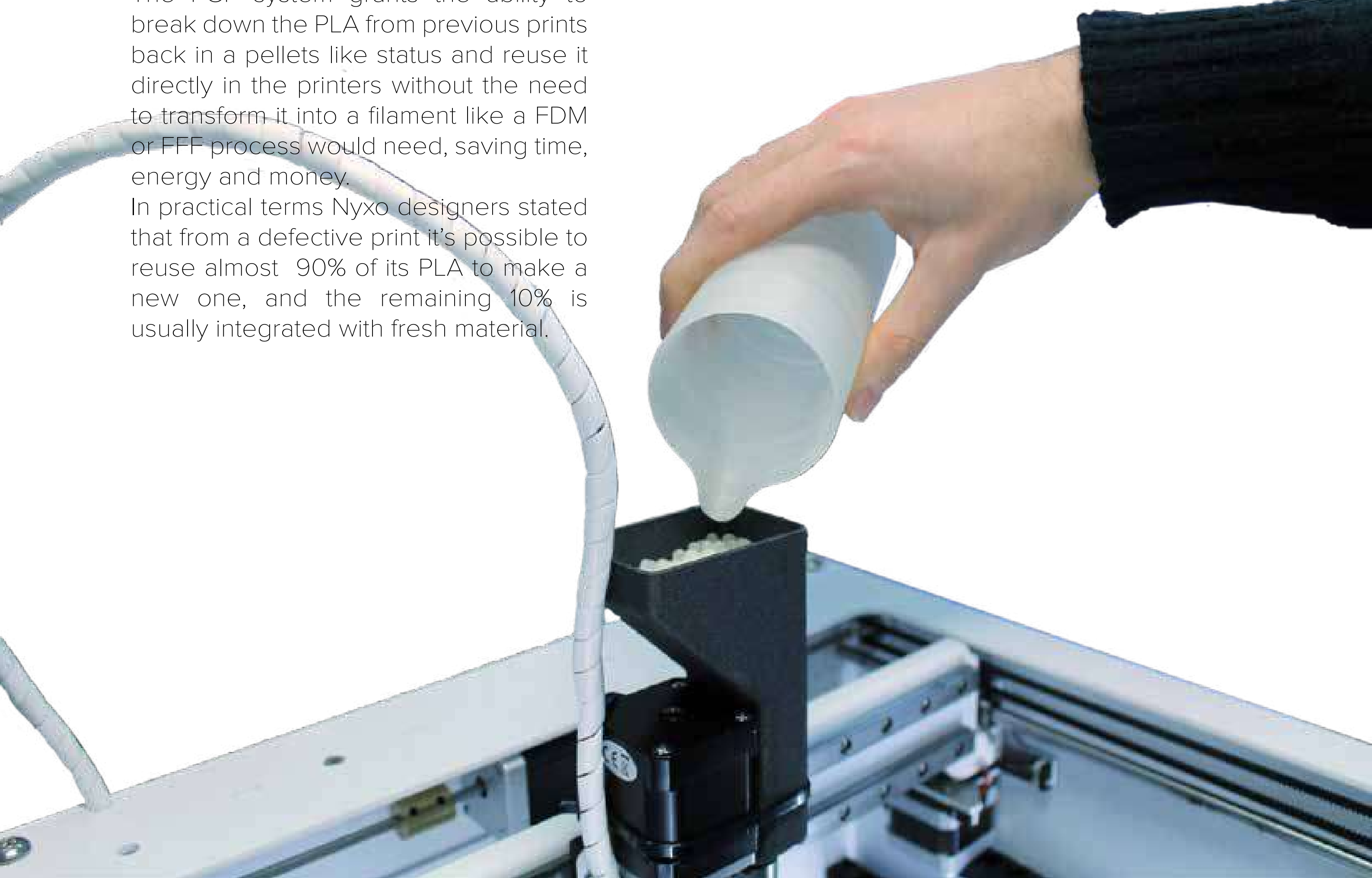
The ability to create e closed-loop production style are the result of the ability of Nyxo Studio to follow the 10R steps of circular economy, two of them in particular:

R4. Reuse

To achieve zero-waste and reduce carbon emissions, Nyxo chose a material and a manufacturinng process that allows them to reuse the broken and defective material, like misprints or chipped products, in order to make new ones without the need for virgin material.

The FGF system grants the ability to break down the PLA from previous prints back in a pellets like status and reuse it directly in the printers without the need to transform it into a filament like a FDM or FFF process would need, saving time, energy and money.

In practical terms Nyxo designers stated that from a defective print it’s possible to reuse almost 90% of its PLA to make a new one, and the remaining 10% is usually integrated with fresh material.

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RAW

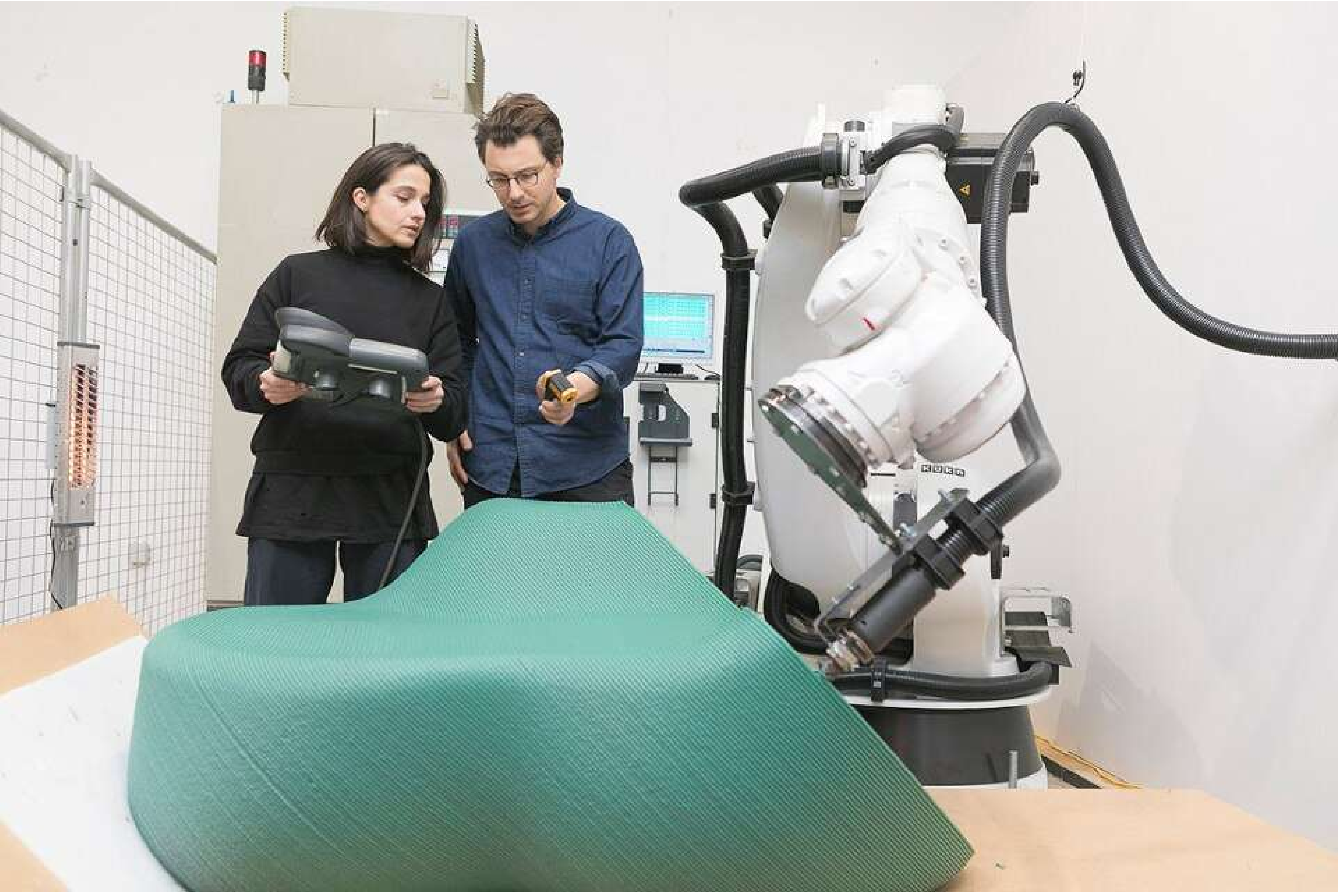
About the studio

The New Raw is a research and design studio based in Rotterdam (Netherlands) founded in 2015 by architects Panos Sakkas and Foteini Setaki with the ambition to give new life to discarded materials through design, robots and craftsmanship. The New Raw develops its own (digital) craftsmanship techniques through a formal and technical language that highlights the texture and the layer-by-layer character of its in-house robotic additive manufacturing process. The exploration of the possibilities that the robotic techniques provide transform plastic waste into beautiful and meaningful products that are 100% circular.

In this part of my work i decided to analize not only a a single project but the entire approach to design and circular economy of the studio through it's projects, in order to show all the different approach that The New Raw takes to reach circular economy.

Robotic 3D printers

Foteini Setaki and Panos Sakkas, senior designer at The New Raw Studio with their robotic arm FGF 3D printer



Before diving into each single project, it is better to understand what elements they have in common.

In all of these projects an aestethic feature that capture the viewer attention is the texture created by the layering of the **robotic FGF 3D printer** that realized the products. Being printed with an FGF extruder with a large nozzle is possible to see distinctly each layer of the print, an element that is usually seen as a defect in 3D printing systems here is exalted and soon become an iconic feature of the product itslef, in a similar way of the Primavera Coffe table made by Nyxo.

But the most unusual element of these prints is definetly the inclination of the layers. As we can see from the images the layers are not oriented on an horizontal plane like we are used to, but the plane where they are printed is either **inclined of 45°** or in a **continuous rotation of up to 90°**.

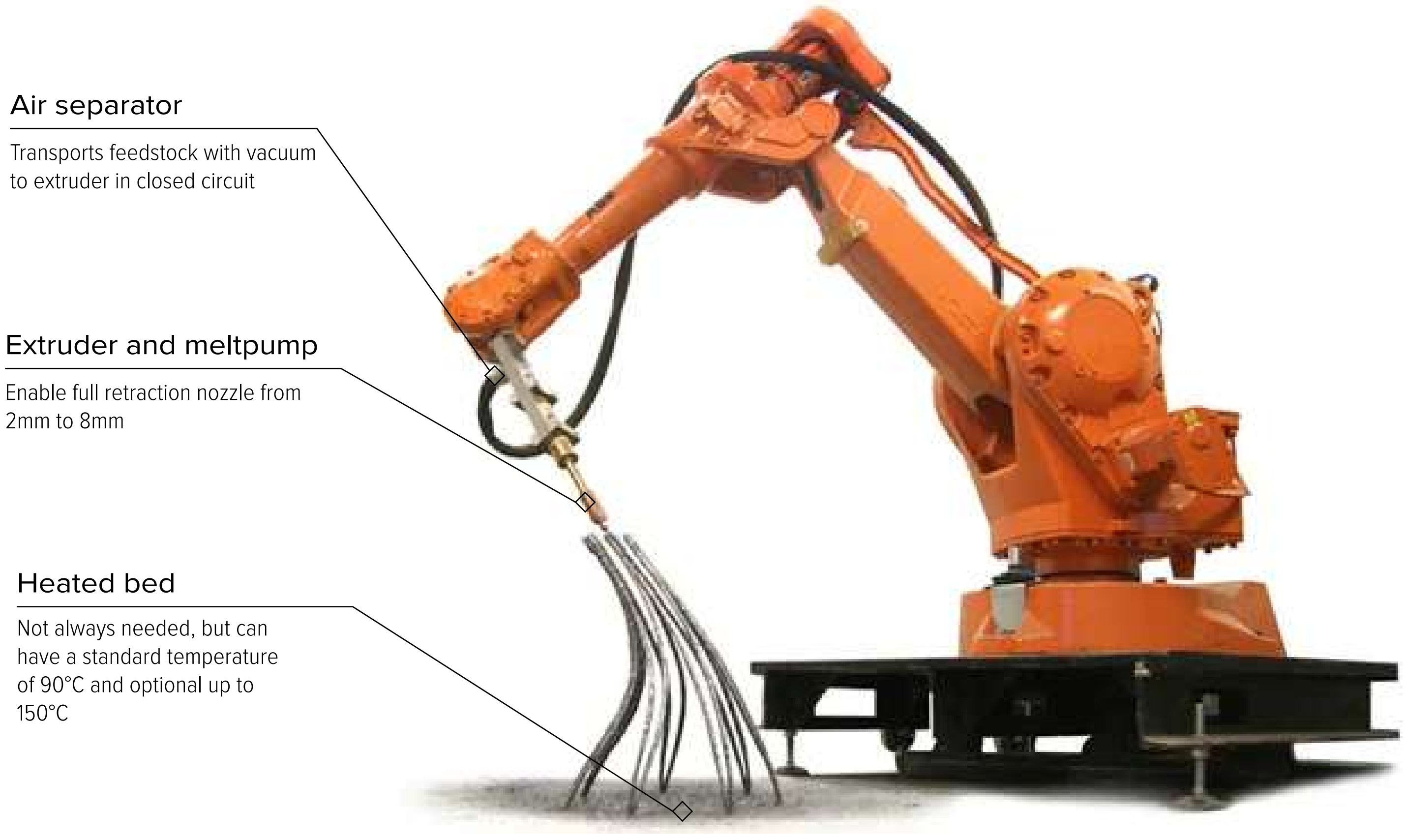
This quite unique feature is due to the fact that The New Raw Studio use an FGF 3D printing system mounted on a robotic arm.

Also called “Robot 3D printing” or “Robotic arm 3D printing” and “Robotic additive manufacturing” it combines a 3D printer head to extrude polymers, with a multi-axis robotic arm to create a much more flexible 3D printer than conventional models.

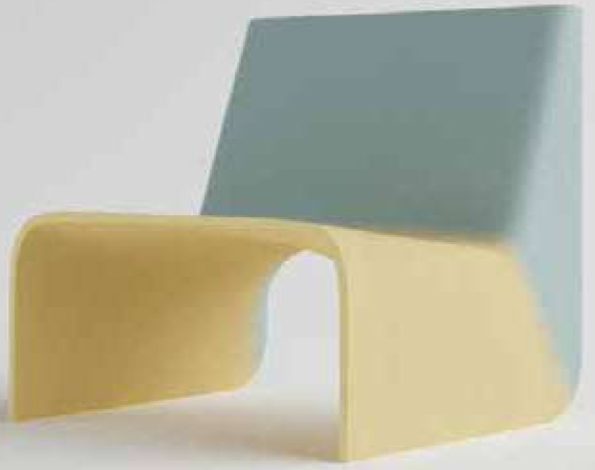
Increasingly used for large projects, such as mold-making, large-scale prototypes, artistic sculpture, architectural elements, furniture, and even rockets, the robotic arm, with its high movement range, opens up a whole new world of design freedom in 3D printing. The arm is able to print from practically any angle, enabling extremely complex, curved geometries. It also provides much larger print sizes than regular printers (up to 30 meters or more).

This system is obviously way more costly than standard FDM or FGF printers but has some major advantages. Infact printed parts from robotic arm 3D printers generally don't require supports, which further increases the degree of design freedom and saves money in material costs. This does require the structures to be self-supporting, which would normally rule out overhanging designs. However, many manufacturers have solved this problem by allowing the building platform to be reoriented, making it possible to create overhangs. Another unique feature is that these printers don't require slicing software to create the layers as with conventional printers, thanks to the multi-axis toolpaths that can be programmed with specialized 3D printing software. This can be an advantage or a drawback since operators must program instructions for both the 3D printer head and the robot arm. Programming the software the wrong way could cause the robotic arm colliding with the print, causing damage. Fortunately, more software options today have 3D printing modules that take a lot of the guess work out of the entire precess and advances in these programs are bringing them closer to a real CAD-to-print workflow.

Another distinguishing feature of robotic arm 3D printers is that they are mostly build-you-own. It's most common for companies to purchase a robotic arm, an extruding unit, software, and other parts separately. In fact, there are just a few complete systems available. This factor has kept robotic arm 3D printers from becoming mainstream solutions, but the technology is getting more common particularly in industrial manufacturing, where many companies already own robotic arms and can them outfit them with new equipment for new uses.



Ermis by THE NEW RAW



What is this project

Ermis is limited serie of mono-material, monobloc seats, born from the desire to find a new purpose for The New Raw's own scrap materials by turning them into durable "zero-waste" objects.

The graphic chair, is made using only one material: recycled polypropylene, since the studio decide to abbandon all the adhesives, resins and additional finishings used in traditional furniture manufacturing, allowing the design to be fully and easily recycled at the end of its life. Since the final product is made from plastic that has already been recycled, this creates what the studio describes as "an infinite loop of plastic waste", assuming that the material does not degrade in quality over time.

Project's name:	Ermis
Author:	The New Raw Studio
Year:	2021
Technology:	FGF
10R's strategies:	R3, R9
Aim of the project:	Zero waste design
Main features:	Exploiting an advanced manufacturing system to obtain better ecological results
Project link:	https://www.dezeen.com/2021/11/08/the-new-raw-ermis-recycled-plastic-design/

The recycle process of the misprints and the other prduction wastes begins with the designers shredding their 3D-printing waste into granules that are between three to five millimetres in size, which are then fed directly into the studio's advanced 3D printer and melted to create a recycled plastic filament that is then applied layer by layer to form the chair.

"The New Raw does a lot of research by design, which by nature is very wasteful since failures and their critical evaluation is an integral part of our method. Nevertheless at the end, we often leave a lot of material that needs to be managed properly, and finding a way to reuse this material and reduce the volume of waste coming from the research and development of the studio became the starting point to create this limited series."

"The orientation and proportions of the 3D-printed lines define the behaviour of the material and provide its distinctive ornaments. These lines are the bits and atoms of the Ermis chair." explained Foteini Setaki on the product.

Beyond minimising waste, this process also gives the design its distinctive texture and pastel-coloured gradient, which varies slightly from chair to chair. Sakkas and Setaki compare the tactile effect of the 3D-printed layers to the rings of a tree or the veins of marble.

Print your city initiative

Print Your City is an initiative launched by the sudio that explores the concept of applying 3D printing to plastic waste, as a way to re-design urban space. As the name suggests, Print your City is a call for action, rallying citizens to recycle household plastic waste in order to transform it into raw material for public furniture, via a 3D printing process.

The first outcome of the project, which creates a circular stream within the city, generating more engaged citizens and less CO2 emissions, is the **XXX bench**, a furniture piece designed for the Municipality of Amsterdam.

The studio recently expanded its ‘print your city’ initiative with the zero waste lab in Thessaloniki, Greece. Here as well,supported by the Coca Cola Foundation, the project invites citizens to bring their plastic household waste in the lab, design their own custom street furniture, and 3D-print it with the help of a robotic arm and on-site recycling facilities.

With zero waste lab, the new raw explores the possibility of citizens’ involvement in transforming public spaces through recycling the city’s plastic waste. part of coca-cola’s zero waste future program in greece, the lab closes the plastic waste loop with advanced technologies at local level. Besides transforming waste into furniture, citizens can learn more about the recycling process of plastic, read about the circular economy, and design new items of furniture for their neighborhoods.

With Zero Waste lab, the New Raw Explores the possibility of **citizens involvement** in transforming public spaces through recycling the city’s plastic waste. part of coca-cola’s zero waste future program in greece, the lab closes the plastic waste loop with advanced technologies at local level.

Besides transforming waste into furniture, citizens can learn more about the recycling process of plastic, read about the circular economy, and design new items of furniture for their neighborhoods.

Interested individuals can learn more on the initiative's website, Print Your City, where they can also generate custom designs for the street furniture, choose the preferred location they would like to see them placed, as well as select between several extra functions that promote a healthy and environment-friendly lifestyle. these functions can be integrated into the furniture, and include: a bike rack, a mini gym, a tree pot, a dog feeding bowl, or a bookcase, while the geometries of the objects are based on ergonomic curvatures that accommodate a relaxed body posture. each piece is finished with a metal tag that indicates the kilos of plastic used to create it.

The initial hybrid furniture prototypes were printed in summer 2018 and placed in Nea Paralia, Thessaloniki's main waterfront promenade, while more than 3,000 different designs have been submitted since the website was launched to the public in december 2018. Among the multiple location options available to citizens on the website, the first public space that, starting from january 2019, has been chosen to host Print Your City pieces is the hanth park in the city center. For the entire duration of the project, the new raw aims to recycle four tons of plastic waste, which roughly equates to the same amount produced by fourteen family households in greece.

XXX Bench

The first outcome of the project, the XXX bench, made with local citizen's wastes

GLYPH by THE NEW RAW

Project's name:	GLYPH
Author:	The New Raw Studio
Year:	2021
Technology:	FGF
10R's strategies:	R3, R9
Aim of the project:	Zero waste design
Main features:	Exploiting the process weak points for product aestethic and functional aspect
Project link:	https://3dprintingindustry.com/news/the-new-raw-launches-zero-waste-lab-for-recycled-3d-printed-furniture-147374/

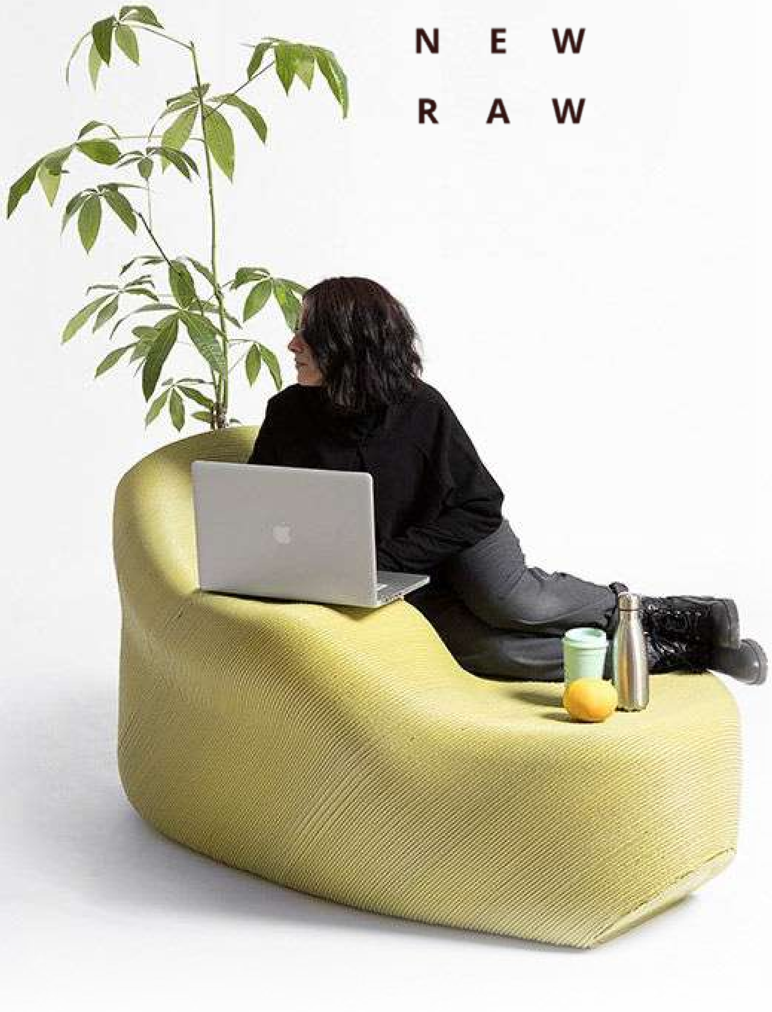
What is this project

Designed to inspire spontaneous behaviour, GLYPH is a collection of urban design that encourages playfulness and increases the bonds between users of all age groups through involvement, inclusion and interaction.
Conceived as an easy-to-apply system of play furniture to activate empty lots, these monolithic elements are light and portable, and can be arranged in multiple ways to build a colourful and unexpected open-air playground.
Even in this case the raw material for these prints comes from the population's waste, in particular recycled plastics like bottles and packaging. The idea that fueled this project was born from the notion that plastic packagings have a major design failure, they are designed to last forever but are used only for a few seconds and instantly thrown away. The designer then tried to solve this nonsense by giving residents a chance to us their plastic waste to build and shape their own cities, allowing them to live with a material that is meant to last forever and not just throw ita way. Being this project part of the Print Your City initiative, with the use of 3D-printing, the citizens are also involved and actually participate in the design of their city.
Each piece features different etchings from the laboratory, making them uniquely one-of-a-kind. The collection's name, derived from the Greek word γλυφή, means carving and nods to the ornamental engravings that adorn ancient temples. The benches' forms, too, pay homage to the archetypical shape of building blocks found in the city's ancient ruins, while their gentle curves also allow the furnishings to rock back and forth to animate public spaces.

The team used primarily **recycled PP and PE** plastics (which are most common in bottle caps), sorting, washing, shredding and melting the waste before extruding it with colour pigments to create the final product: Eight self-standing swinging benches that repurpose 240 kilograms of recycled material in total. The collection was produced in three sizes and pastel hues: wheat yellow, mint green and water blue.

Both lightweight and portable, the hollow plastic forms can be used independently or in groupings to create a "colourful and unexpected open playground." The versatile pieces were designed specifically to activate the empty lots of industrial Elefsina — they will be installed in various locations throughout the city as part of the European Capital of Culture — but they are equally well-suited to any environment that lacks a vibrant public space.

Pots Plus by THE NEW RAW



Project's name:	Pots Plus
Author:	The New Raw Studio
Year:	2021
Technology:	FGF
10R's strategies:	R3, R9
Aim of the project:	Zero waste design
Main features:	Exploiting the process weak points for product aestethic and functional aspect
Project link:	https://3dprintingindustry.com/news/the-new-raw-launches-zero-waste-lab-for-recycled-3d-printed-furniture-147374/

What is this project

Another great example of the Print your City initiative is the Pots Plus collection, which explores once again the possibility of using the city's plastic waste in order to build bespoke furniture with robotic 3D printing. The 3D printed street furniture has integrated planters that promote a healthy and environment-friendly lifestyle in the city. What's more, the geometries are based on ergonomic curvatures that accommodate a relaxed body posture. Halfway between tree pots, benches and street furniture. The seats are design to allow to rest to one oor two persons the same time, and they work as a plant holder as well, enhancing the ecological feeling of the product. Just like GLYPH this new seat is manufactured with recycled PP and PE, all coming from the waste of locals households, like bottle caps. The usual robotic FGF 3D printing system allows for a very strong a durable material, while keeping the total wheight of such massive products quite low, with only maximum of 68Kg for the lergest models. With the New Raw innovative process, for avery printed seat, up to 190 Kg of CO2 are saved, with respect to a normal injection molding system.

The elements by THE NEW RAW

What is this project

The Elements is a collection that consists of three different beach products: a changing room, a sunbed, and a modular walkway, which can be deployed quickly at various locations when new configurations are needed. Once again the studio chose only waste material to print their product, in this case, being a beach collection The New Raw collected over 720 Kg of marine plastic waste (for a single collection), and broke it down and transforming it into a 3D printing pellet. Employing a their robotic manufacturing process, each piece has been made with a total of 80% recycled marine plastic and is 100% recyclable to potentially become the raw material of future products.

As you can probably tell by the name, the design draws inspiration from the elements, mainly those that are expected to experience by the sea. Beyond being available in two fitting colour tones: aqua and sand, the organic shapes found in saltation patterns on the sand have been echoed in the rippled surfaces of each sculptural piece.

The studio encoded 3D textures, which are both ornamental and functional components used to achieve climatic comfort. For example, the sunbed and the changing room both feature an almost thatched-like pattern to support ventilation, light irradiation, water drainage, and cooling.

Project's name:	The elements
Author:	The New Raw Studio
Year:	2021
Technology:	FGF
10R's strategies:	R3, R9
Aim of the project:	Zero waste design
Main features:	Exploiting the process weak points for product aesthetic and functional aspect
Project link:	https://3dprintingindustry.com/news/the-new-raw-launches-zero-waste-lab-for-recycled-3d-printed-furniture-147374/

How does it help Circular economy

When it comes to environmental impact, we could saw how the entire philosophy of of the The New Raw Studio is focused on reducing it to the minimun. The whole studio is dedicated to produce only the exact amount of objects and material, reusing even the one wasted during experimentation, prototipation and test, as well as the one coming from defective products. Also, especially with the Print Your City initiative, by involving the citizens, the final customers, in the production process of the products, both in terms of material and product design, the studio was able to create a feeling of membership and involvement that boosted the way the product was percieved, satisfying the customer even more when using it.

In terms of circular economy The New Raw Studio is fully committed in using the 3D printing technology to reach the highest level of circularity. Thanks to the futuristic and expansive robotic 3D printing system their prints allows them to execute almost all of the 10R steps to achieve a perfect looping system, yet their main focus is on two of these step in particular:

- ### R9. Recycle

  Once again, even in terms of recycling, The New Raw do not focus only on its internal issues, but on the final consumer as well. While, internally, they are able to recycle almost all of the wasted material used during the manufacturing process, externally they collect wasted material from the environment as wella as the population to feed their robotic FGF machine. This system is extremely efficient since it work on multiple phases of the production, reducing the overall environmental impact of the studio as well as the one of the society.

- ### R3. Reduce

  The New Raw center a lot of it’s brand image on the concept of “dematerialisation”, in the way of reducing all types of wastes. The main representative of this mindset is the Zero Waste Lab, a name that speaks for itself, the association founded by the studio to manage all of its initiative and projects, including the Print Your City initiative. This last initiative is emblematic on the way of acting of the studio which aim to reduce not only its own wastes but those of the citizens as well, using the as raw material for its own projects.

  It is safe to say that The New Raw is one of the major representative of the philosophy “doing more with less”, since they aim to reduce not only their internal material consumption but to give life to the citizens wastes as well.


EL - AMRIA ALEXANDRIA
THE NEW RAW

Signal, Gio & Carve by GANTRI

Project's name:	Signal, Gio & Carve
Author:	GANTRI design studio
Year:	2020
Technology:	FDM
10R's strategies:	R2, R3
Aim of the project:	Sustaineble yet luxurious collection
Main features:	High quality 3D prints thanks to an innovative FDM system
Project link:	https://www.dezeen.com/2020/03/04/ammunition-and-gantri-3d-print-lamps-from-plant-based-materials/

What is this project

The collaboration between Ammunition and Gantri design studio gave birth to three new collections of lighting designed with a better approach to design, craft and sustainability in mind. Named Carve, Gio and Signal, the three collections are inspired by Gantri's brand new and patented 3D printing platform, called Dancer, and the intricate, organic and unexpected possibilities it provides compared to conventional manufacturing.
The three collection differ from one another in terms of lights typology and design that they offer, yet they all have clear aesthetic elements in common, like the round shapes and especially the smooth external finishing, quite unusual and rather impressive for a 3D printed object, that becomes the iconic and distintive element of this project.

The lights of the collection "Signal" are obviously influenced by the look of traffic signals, as well as the functional aspects of architectural louvers. Such simple geometry combined with the bold look of the louvers , the collection take a modern, sculptural look.

A circular head fronted with slats on all three designs, and a silver pole that extends from the head to the round base of the floor lamp, while the table light, attached to a cylindrical block, stands upright or can be positioned on its side.

Gio collection takes cues from 1970s Italian lighting designs, with its name providing a reference to Italian architect and industrial designer Gio Ponti. The designers leveraged new materials and processes to give them a fresh look, to enable the products to achieve a unique character also by manipulating the different elements making them interact with each other in a playful way. The elegant shapes connect and merge seamlessly, with a minerality and character found more commonly in craft, clay or ceramic objects. The familiar yet uncommon forms give them a sculptural quality, allowing the lights to live as standalone objects even when they are turned off and not in use.

The four versions, floor, task, desk and wall lamp share the similar rounded forms. Silver rods connect the curved head to the floor lamp base, while a rotatable sphere head on the task lamp directs light in any direction.

For the Carve series, the team created the shape by imagining a block that was carved into to leave a circular form that bulges from a rectangular chunk.

The weighty Carve line boasts a monolithic, sculptural shade, that deftly plays with perceptions of mass across its three seamless iterations. Unlike its siblings, however, the series provides more directional illumination, making this produtcs more dynamic, a feature particularly evident in the hovering shade of the floor model.

Signal collection

Gio collection

Carve collection

What are its main design feature

When looking at these collections, 3D printed with an FDM system, the first element that catches the eye has to be the smooth and refined external surface of the lamps. Such smoothness is quite unusual for a 3D printed product, since, as we already explained, the layering process of the FDM and FFF system inevitably cause an horizontal ridging that characterize the aestethic of all 3D printed products.

Unsitasfied with the result obtain with the Ultimaker 2+ Extended 3D printters, Gantri decided to switch the model of printer that they were using, realizing a completely printer more fitting to the company needs, both in terms of print quality and volume production: the Dancer

Using a patent-pending process based on an FDM multi-gantry system, the Dancer is designed for the production of the company's light fittings only. It leverages a total of four gantries alongside a rotating circular build plate. Manufactured at the company's San Leandro facility, the Dancer 3D printer is for internal manufacturing only, and will not be commercially available.

With this new printer Gantri aims to provide an efficient and sustainable alternative that overcomes the cost and time for designers launching a new product in today's industrial manufacturing model. Gantri CTO Christianna Taylor explained that the company "looked at existing 3D printing products from HP and others but none of those met our unique needs at Gantri", so instead of adopting an industrial system like one from the HP Multi Jet Fusion range, which would be expensive, the company decided to develop its own system. The result was the creation of an FFF-based machine with multiple print heads.

The key feature of Gantri's Dancer 3D printer centers on the coordinated multi-gantry system. Using a rotating circular build plate, the system's four gantries operate together to simultaneously 3D print a singular part. The intention is to eliminate the "deadzone" void in the middle of the build platform. Other features include a 450mm x 600 mm build volume with a custom-designed frame machined from aluminum. Gantri has developed a translation algorithm for converting 3D models for its multi-gantry system without additional input.

Dance multi-gantry system

The four printing heads work simultaneously and with a rotating heated bed to eliminate the "deadzone" void in the middle of the build platform, obtaining a better and more uniform resolution.

The printers are also integrated with Wi-Fi capabilities, and connects directly to the company's online order system. For gantri dancer it's not only an amazing 3D printer, "It is an amazing innovation, It combines advanced hardware, software and industrial engineering to make FDM 3D printing drastically more efficient." explained Taylor.

Another essential benefit of the Dancer 3D printer for Gantri is that it cuts the lead time for the company's "Made for you" production line, which includes the lights collections mantioned earlier, 3D printed from scratch. The lights production using the Dancer printer will take only two weeks, instead of the usual four. Dancer it's not only a hightech sofisticated 3D printer for Gantri, it is an active organism that fit into Gantri's ecosystem by utilizing the digital design process and seamlessly starts as the first step of hardware in the process followed by finishing, assembly, quality assurance and shipping.

Gantri's R&D department did't worked only on the technology and the 3D printing system, but as well as on the material used for these lights collections. Starting from a PLA base, two particulalr formulas were produced with the aim to get the perfect finish on the lamps without needing other finishing precess. The result were indeed two new types of "agumented" PLA, one to get an opaque finish and one to get a translucent finish. The formula and the testing of these new PLA are not public, but Ian Yang, founder of Gantri, stated that they chose the PLA for its natural origin and low environmental impact in comparison to other thermoplastic polymers, and that they kept this profile as low as possible during the realization of these new materials. For him "The whole point of 3D printing is obviously making the process much more efficient for designers, but a side effect of it is that we can produce products in a much more environmentally friendly way because there's less waste".

To enhance the production flow and to offer better products to its customers, Gantri went under a process of complete renovation, changing their production processes and the material they use. The full commitment to the 3D printing technology did also worked in favour of the ecological impact of the studio which as always been one of the most sensible point of the mission of Yang and it's co-workers.

As we could see, one of gantri's strong points is the variation of products offered to its customers, differently from its competitors, other luxury lighting brands, which usually lack of such an extended catalogue. This type of brand launch far fewer new model per year, simply because they're constrained by the amount of resources and oversight traditional manufacturing requires.

On the other hand, Gantri doesn't have such limits, since having the final product being 3D printed, the client (in this case Ammunition Design Group) is able to view a prototype as soon as they have a design.
This mean that once the design is confirmed by the client, every single light can be produced on demand. The lights are 3D printed, hand-assembled, and finished in California, a process that allows the local manufacturing and reduces the waste and international shipping typically associated with industrial production.
This ability to produce rapidly on demand prevent the need for a storage system, and reduce the production of products to the exact amount needed by the market, avoiding wastes.
To put it in the terms of the 10Rs step of circular economy, we can say that Gantri follows two of them, specifically:

- ### R2. Rethink

  Usually the concept of rethinking is applied to the manufacturing process of a single product, but in Gantri's case we can extend it to the whole company. By patenting a brand new FDM system, as well as two new PLA formula, Gantri step ahead of its competitors by a long shot. The main cause for the total renovation of the studio poduction system may have been business reasons, but it led to a production on demand, deprived of excesses and a wastes, reducing the cons of energy, materials and money.

- ### R3. Reduce

  The benefits of 3D printing for the circular economy, as well for the economy of the company itself are quite clear in case of Gantri.
  Being already a waste free manufacturing process, Gantri was able to reduce the production lines excess even more by adapting it to an on demand business. Selling all the products made by the company not only inflate the earnings, but reduce as well the scrap material that needs to be eliminated and the disposal of it. To avoid overproduction is one of the most important step to reach true circular economy, and Gantri found a way to achieve it in the closest way possible.


THE
NEW
RAW

Military blueprints

Project's name:	Military blueprints
Author:	Governments
Year:	2017
Technology:	FDM
10R's strategies*:*	R5, R6
Aim of the project:	on-demand replacement components
Main features:	Be able to resupply dangerous places even without stable supply chains
Project link:	https://www.dezeen.com/2013/05/07/3d-printed-guns-drones-military-print-shift/

What is this project

In this section we will explore not a single project, but the strategy used by the military sector to apply 3D printing into their world and how the additive manufacturing technology has impacted it.
The military is always looking for ways to stay ahead of the curve, with experimentation of any kind of technology, not only to improve the combat capabilities of the government. Back in the early 2000s the military was one of the first sector to adapt and incorporate 3D printing into their way of operate.
3D printing is today being used by military units from different countries all over the world especially to create replacement parts for critical vehicles, ships, and aircraft as well as new designs for safety equipment being worn by service members to prototypes for new defense weapons, medical supplies, and even runways and bunkers.

Processes of FDM additive manufacturing are being used to enhance the adaptability of the troops on the field, covering multiple instances.
The major benefits of 3D printing shines when it comes to creating tools and jigs to repair or reinforce current equipment or install new parts, like a3D printed multitool that can be clipped to their belts or jigs that can help guide them to attach helicopter blades more safely, or a strong 3D-printed enclosure designed to protect an antenna from being snapped off near the base during heavy use and driving through thick brush, or cases to protect the gear they already have while also ensuring a longer life for those pieces of equipment as they are being used on a daily basis, or even 3D-printed medical supplies can be produced quickly and easily in the field, which means soldiers can be treated faster and have a higher chance of survival in combat situations, like custom-made Epi-Pen carrying cases and stethoscopes to I.V. line control, tracheal tubes, splints, casts, covid swabs, face shields, earplugs and so much more.

Disrupted supply chains

3D printing allow to supply spare parts for vehicles, structures and hardware even without functioning supply chains

On-demand production

Quick and effective production of spare parts can turn the tides when applied in dangerous environ ment

High quality production

Having access to the most cutting edge technology, the military sector can print spare parts even for its most advanced hardware

What are its main design feature

The main advantage of additive manufacturing that is being exploited by the military sector is the possibility for on-demand manufacturing, which means that militaries can print the items they need when they need them and where they need. This feature obviously find a lot of fertile ground in the military sector, since it could be particularly useful in situations when time is of the essence and traditional supply chains are disrupted.

The use of 3D printing in the military also enables them to be more self-sufficient. With 3D printers, militaries can print replacement parts and components for their equipment, rather than having to rely on outside suppliers. Another great feature that could come in handy in moments when it could not be possible to rely on supply chains.

One area where the military is using 3D printing is to create replacement parts for land vehicles, ships, aircraft and even weapons. In the past, if something needed a new part, it would have to be ordered from a manufacturer and then shipped to the military base or flown in for a vessel deployed at sea.
This could take weeks or even months, especially today with the current supply chain issues plaguing the entire world and keeping important parts stuck in ports due to chip shortages and pandemic-created backlogs.
With 3D printing, the military can create the parts they need on-site whether that is on base, at the front lines, or at sea. In a matter of hours or days, they can be up and running again which can be critical in a warzone or situation where lives are in danger.

Another great feature of 3D printing technology that fits perfectly in the military sector is that vehicles, and other legacy machinery can be kept out of retirement much longer when a spare part is able to be 3D printed to put it back into service.
Instead of spending thousands of dollars to have a single custom part made, they are able to design and 3D print it in tough materials and even metal to save millions of dollars a year.
For the military, 3D printing is also opening up a whole new world of possibilities in areas where they are constantly looking to improve functionality, safety, and comfort for their service members.
For example, General Lattice and the U.S. Army have paired up to improve the impact absorption of the Army's combat helmet through 3D printing by incorporating advanced lattice geometries. The hope is to improve soldier protection in the field and a higher chance of survival after suffering a head impact. The 3D printed materials will be tested in real-world situations to help improve the design and ultimately begin implementing its use in the field.

Whether they are reworking designs for face shields, masks, and other pieces of safety gear, now more than ever, the ability to 3D print a prototype and make adjustments in a matter of minutes is crucial.

Example of simple hardware

Below some example of hardware 3D printed on the frontline:

Fig. 1 - A reinforcing exoskeleton for a vehicle antenna

Fig. 2 - A new case for a pair of binoculars, printed after the original casa was lost on the field

Fig. 3 - A holder printed to enhance the transportability and protection of Epipens for field medics.

War, and usually the whole military sector, are hardly areas of interest for circular economy, since the preservation of the life of every single person, being military personal or civilians (most of the time) are put above any other objective. Reducing pollution and wastes are certainly not the main target of the armies around the world, yet the adoption of 3D printing clearly represents an exception to this logic.

The reason for the adoption of additive manufacturing processes by the military it's not based on ecological needs, nor the will to reduce the environmental impact of their action, yet I found particularly fascinating how this technology operates in order to achieve a circular economy even without the user complete awareness. The additive manufacturing technology, by enablling the military to produce without the need of a stable supply chain, allowed them to enact three step in particular of the 10R principle:

◆

R5. Repair

Even without considering all the metallic 3D printed components realized for fixing vehicles and structure, the military produce numerous components with thermoplastics polymers to help the troop to enhance their performance on the field. 3D printed guns are quite common today, and even if they are not reliable as the original ones they, or even a broken component of the same, can surely works as a patch in, until proper new one can be restocked. .

◆

R6. Refurbish

Military equipment is subject to extreme condition and frequent damages. While it is expected to be durable, resistant and strong, being able to repair on the spot the damaged components of a vehicle or the troops equipment is definitely a useful feature. By fostering disassembling design it is quite easy for military personal to fix their gear when components break down or are damaged, even without reliable supply chains. Mixing state of art industrial pieces and makeshift ones is the key to keep key equipment running in high danger environments, and FDM 3D printing has shown massive opportunities in these fields.

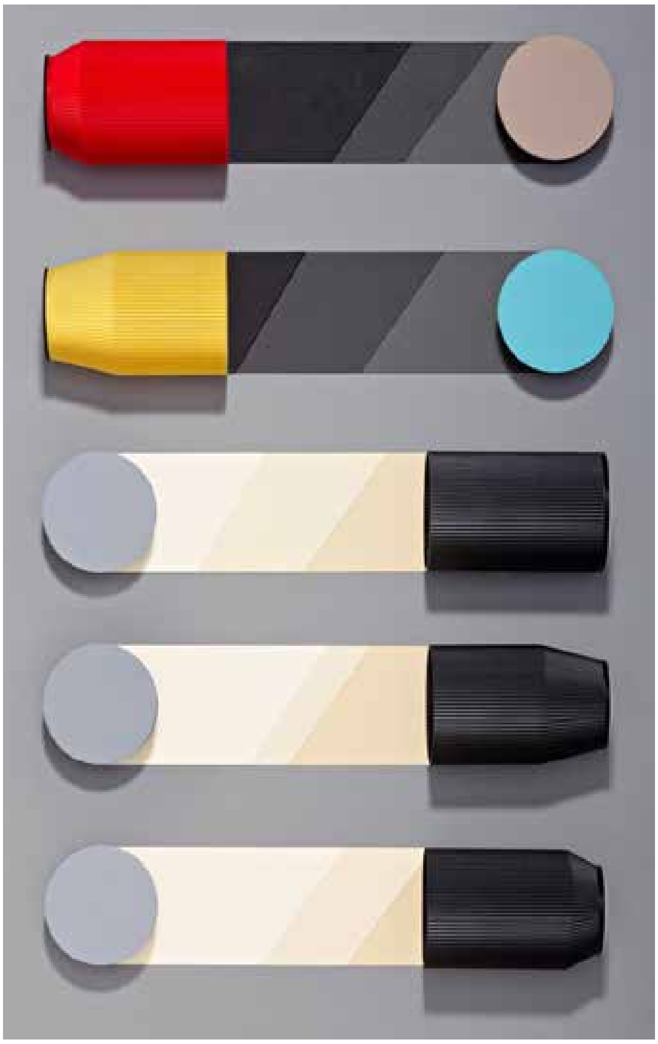
Icosaedro by Busatta and Buzzini

What is this project

Differently from Primavera and Gantri's lighting collections, products realized with top notch and innovative technologies, manufacturing systems and materials, Icosaedro is quite simple project.
It consists of a range of tableware, created by designers Barbara Busatta and Dario Buzzini, made to be printed out at home on a desktop 3D printer and ready to use straight away, right after the print is done. The range features 120x80mm containers in straight or tapered versions, available in black, red or yellow, with a variety of different colour combinations for the lid and base.
The main objective of Busatta and Buzzini's work was to challenge the common assumption that homemade 3D printing can only produce poor results and have little application in the domestic field. They tackled this problem by firstly realising the most versatile object that a person could need in its house, a tableware, and secondly, by designing a product to make them spare as much resources as possible, in terms of materials, times and money of course.

Project's name:	Icosaedro
Author:	Barbara Busatta & Dario Buzzini
Year:	2021
Technology:	FFF/FDM
10R's strategies:	R1, R2
Aim of the project:	Zero waste design
Main features:	Avoid the distribution process through homemade manufacturing
Project link:	https://www.dezeen.com/2014/02/15/icosaedro-creates-ready-to-use-3d-printed-tableware/

What are its main design feature



Even in its semplicity, this project need a level of precision and accuracy worth of the most delicate industrial process.
In this type of design, where only the product is sold via digital files and made at home by the customer himself, the need for all the typical element of the distribution process of industrial products, like packaging, transportation and more, is completely removed. The amount of resources saved by this choice is immesurable, but to be effective the print need to be almost perfect and satisfy various requirement, especially from the estethic and functional point of view. To empower the customer to manufacture he's own products, like in this case, mean that the manufacturing process must be accessible and understandable by anyone (who has the mean of production, in this case a 3D printer), eliminating all possible misunderstandings and error that he could make. The files will need to be immaculate, and obviously tested before being published on the internet, making sure that even the most inexpert of the 3D printer owner can obtain the best result from this product.

Citing the designes very own words, it is clear that "the focus of this exploration has been to elevate 3D printing, a technology that is very much talked about but is relegated to either cumbersome amateurish results or overly expensive artistic applications", as well to open a new type of business, in close contact with the clients and with a very low ecological impact, due to the complete elimination of the distribution process of the product.

The set is indeed specifically designed to be printed at home by anyone who owns an FDM or FFF machine, meaning that the product is ready to be used right after the print, without any other treatment or process necessary. This implies that there is no need for scaffolding, seams or flash to remove in order to finish the objects, and they become fully-finished products the very moment they are removed from the 3D printer.

"Normally, in order to hide imperfections and seams, objects created with this classic FDM technique require an extra treatment," explained the designers. "These products have been designed to minimise the finishing touches needed to make a 3D-printed product look immediately acceptable."

A lot of studies and experiment have been made on the geometry and cross-sections of the vessels, which are now designed to reduce the risk of flaws and deformations while making it stronger and sturdier at the same time, preventing damages caused by fall, collision or scratch. The original shape of the cross section also give the collection a distinctive aesthetic, a stratagem very effective in characterizing the products.

To push even further the 3DP market and involve customers even more in the production process, the designers made the designs for Icosaedro and Machine Series open source and available to download online. The models can be printed with all of the most common material used in the 3D printing industry, like PLA, ABS, TPU and more (given that the user has enough experience to set its printer in the right setting for each material). Busatta and Buzzini wanted anyone to be able to modify, improve and alter the designs using different materials or other types of additive printing.

How does it help Circular economy

For such simple projects like this Icosaedro, it's not easy to understand what improvement they are bringing from the ecological point of view, at first glance. A simple 3D printed tableware, realize with a common FDM or FFF machine, hardly can have a serious impact on the achievement of circular economy.

But let's zoom out from the single product and let's look instead at the whole business idea. It is possible then to see how this little tableware actually follows preatty strictly some of the most important step of the 10Rs of the curcular economy:

R2. Rethink

To reduce the environmental impact of a product means to consider the whole life of a product, not only it's manufacturing process. Usually the life of a product can be divided in five major step:

1 - Raw material extraction
2 - Manufacturing
3 - Distribution
4 - Use
5 - Disposal/recycling

Each of these steps has its own ecological impact when it comes to the manufacturing of a product, and depending from the product tipology one can be more influential than others.

Creating a new business that can completely eliminate one or more of these steps, just like Icosaedro does eliminating the distribution steps out of it's lifecycle, can grant serious benefits in the circular economy perspective.

R1. Refuse

Removing a step in the lifecycle of a product, the distribution step in the particular case of Icosaedro, means refusing to product all of the CO2 emissions coming from that very step, and reducing the emissions of CO2 in the atmosphere is one of the ultimate goals of circular economy itself.

Studies conducted through LCA analysis demonstrated mathematically the advantages of this approach. Even if the distribution process is usually one of the less impacting one, especially when compared to manufacturing and raw material extraction, is well known that the highest amount of pollutions in todays world is caused by vehcles emissions. Consequently, the stratey of reducing vehicles movements and their emissions is possibly one of the best actions that company can take from the circular economy point of view, even if does not concerns materials or manufacturing processes.

This goal can be reached, just like Icosaedro showed, by switching to a production based on digital models that can be sent anywhere in the world by a simple click. This is another amazing advantage of the additive manufacturing process, allowing to produce anything to anyone who has the right mean of production, in this case a simple desktop printer.

Feel the peel by CARLO RATTI ASSOCIATI

Project's name:	Feel the peel
Author:	C.R.A. Studio
Year:	2019
Technology:	FFF
10R's strategies:	R1, R2
Aim of the project:	Zero waste production
Main features:	Complete exploitation of the raw material (oranges), virtually doesn't produce waste
Project link:	https://carloratti.com/project/feel-the-peel/

What is this project

This project is an experimental Circular Juice Bar, made by CRA-Carlo Ratti Associati, in partnership with global energy company Eni, that aims to bring circular design into everyday life.

The project involves designing out waste and pollution from the production and consumption process, in order to obtain a regenerating natural system.

The "Feel the Peel" prototype is a 3,10-meter high orange squeezer machine, topped by a dome filled with 1,500 oranges. When a juice is ordered, the oranges slide down into the squeezer, that extract the juice and separetes it from the peels. The leftover orange peel falls into a see-through compartment at the bottom of the machine, where are collected, dried and milled to make "orange dust", which is then mixed with PLA to form a bioplastic polymer. At this point the polymer is heated, melted, and shaped into a filament, that is then used by the 3D printer incorporated into the machine to realize the cups.

The cup can then be recycled after use, with the material continually broken down and reused to make further cups in theory.

What are its main design feature

In order to bring the concept of circular economy in our everyday life the designers decided to work on an everyday object, this machine is infact a a very “simple” orange juicer, topped with a huge dome that can hold up to 1500 oranges. The impressive feat of this machine is that it doeas not limit itself to extract the juice from the orange (otherwise we would not be talking about it), but instead is able to firstly separate the orange peel from the rest of the fruit, dry this peel, mill it, turn it into dust and then, after being combined with PLA dust and transformed into a filament, use it to disposable cups to drink the freshly-squeezed juice from the very oranges at the beginning.

Now let’s focus more on the additive manufacturing side of the project. In order to create the orange peel cups, the bioplastic is heated and melted to form 3D printing filament using an FDM system. The 3D printer, whose model is unfortunately unkown, but it is presumably provided by Wasp, whose logo is emblazoned on the side of the unit, resides in the middle of the juice bar machine. Visitors have also the possibility to watch as their cup is created and then filled with juice.
After the drink is finished, the cup can be recycled, it could even potentially be broken down and re-made into another cup to keep the circular economy going. Ratti explained also that in future iterations of the machine, the studio will aim to extend these functions to other sectors, including the printing of fabric for clothing from an orange peel, modifying the machine accordingly and making it a versatile core unit that can be adpted to more sectors.

The hopes are surely very high for this concept machine, afterall it is presented like a machine that can really solve most waste related problems in numerous fields, but is that actually true? As designers and engineers our job is to be objective and evaluate a product looking both at its present capability, as well as its futurability.
Let's dive then in a more critical approach to this project, focusing obviously only on the 3D printing side of the machine. The main issues with this project is definetly the chosen manufacturing technology: FFF 3D printing.

The first and most important problem related to the chosen FFF system is the time, considering that it will take at least half an hour to 3D print a cup, it will be impossible to adapt this solution in an actual bar, since it doesn't allow to serve a thirsty crowd. From this point of view it will be necessary to either pre-print a huge number of cups or upgrade the 3D printing technology with a more powerfull machine with way lower printing times, possibly a FDM system, which is way faster and more reliable.
Secondly, the FFF technology today isn‘t considered food-safe, but that is related merely to the material used for the print. This case could be be an exception since the filament is composed 80% of orange peel dust, which is edible of course, and only the remaining 20% is made of PLA. Yet some doubts remain on the filament making process, which could influence the orange dust.
Thirdly and finally, the concept isn't exactly self sustaining, since the orange powder must be added with PLA and differently from the FGF system the FFF one print material in filament form, requiring an additional indirect step in the manufacturing process of the cups.

How does it help Circular economy

The fact that this is a flawed project from the circular economy point of view doesn't mean that it isn't interesting. Afterall, this is nothing but a prototype and the first take on the subject by a great studio like CRA, and for being a first take it surely show a huge potential.

The theorical approach is definetly the most advanced we saw up untill today, a project that truly tries to bring the circular economy concept to the everyday life of any person in the world.

Carlo Ratti, founding partner at CRA and director of the Senseable City Lab at the Massachusetts Institute of Technology, explained that infact this was not only a fascinating prototype, but: "The principle of circularity can be an inspiration for tomorrow's everyday life objects, we played around a machine that helps us to understand how oranges can be used well beyond their juice. In the next iterations of these projects, we might add new functions, such as printing fabric for clothing expanding the impact of circular economy even more".

Stricktly in terms of the circular economy steps, Feel the Peel is possibly the project that tackles most of them (except for remanufacture, refurbish and repair), but most importantly it tries to put into work the two most important:

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R1. Refuse

In the process to extract the juice from the oranges only the pulp of the fruit is needed, this make the peel an immediate waste, since it doesen't contain any pulp and has to be remove to reach it.

With this project CRA Studio refused to just eliminate an element of the fruit withouth exploiting it first, making the most out of the raw material and using the 100% of it instead of the usual 70%.

Another important feature of this project is that the cups produced by the FFF machine installed in the juice bar are designed to be recovered after their use, by braking them down and remelted into a filament, in order to reuse the same material to print other cups, actively refusing to produce new waste and making the material enter a circular loop.

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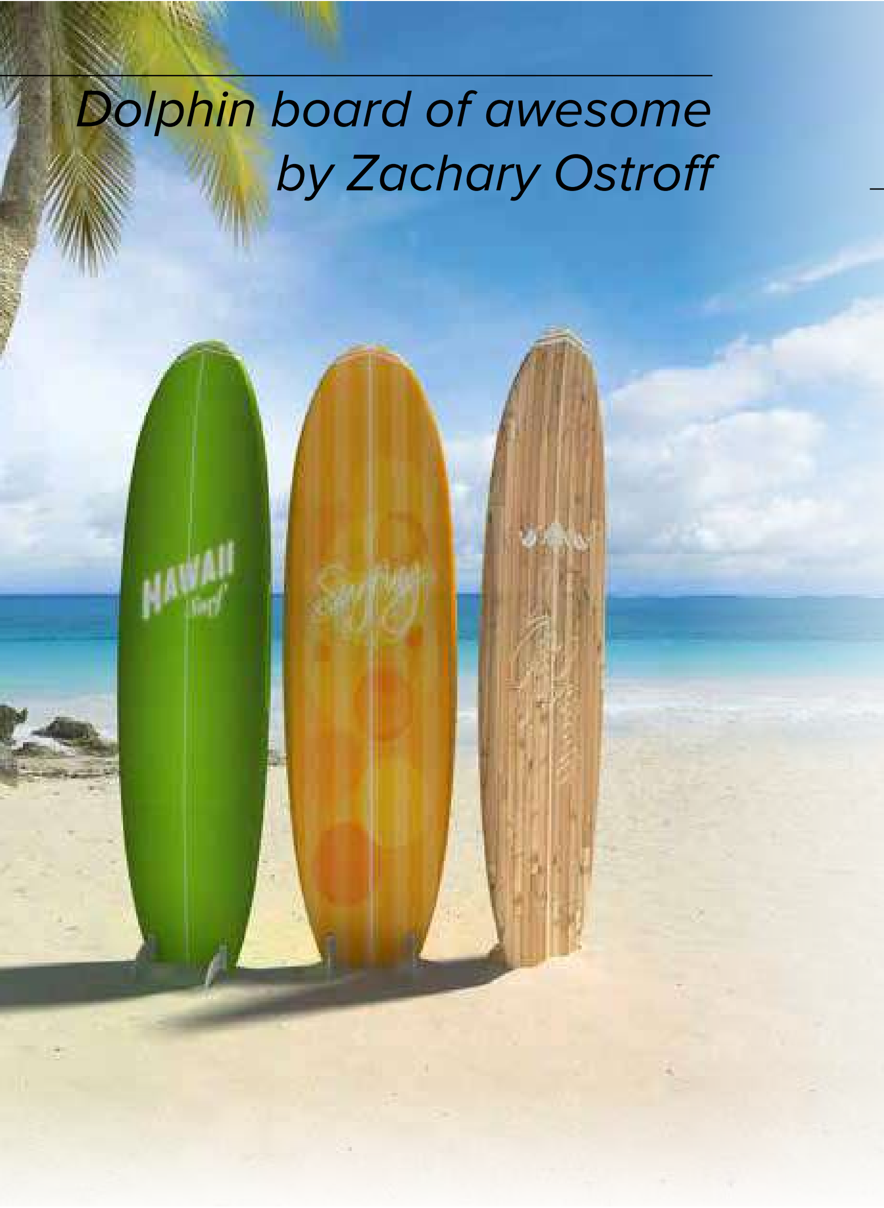
R2. Rethink

The rethink concept is at the base of this very project. The rethinking process usually focus around the manufacturing technology or the mean of distribution between all the steps of the life of the product, but in this case even the approach to the raw material was tackled.

By reimagining to avoid a natural waste such the orange peel, which usually can't physically have any other role than to be a waste, the CRA Studio was actually able to enable a true circular economic system in its purest form, by using the 100% of the resources given by the raw materials.

Dolphin board of awesome
by Zachary Ostroff

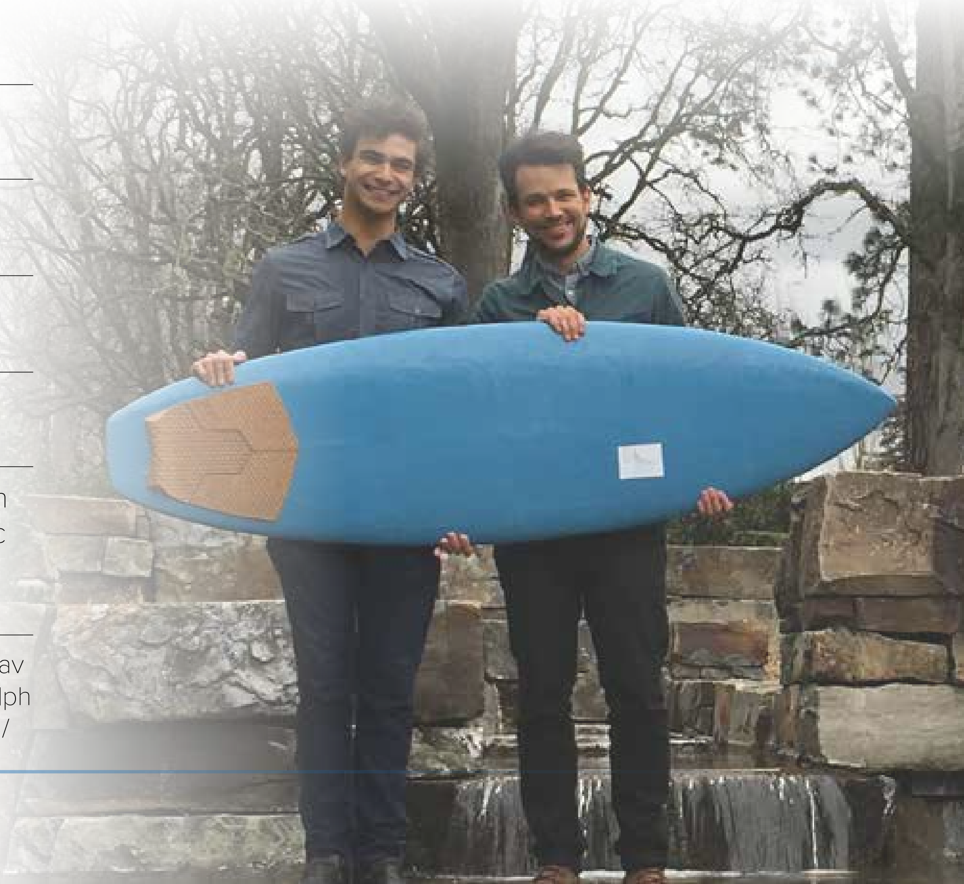


What is this project

The Dolphin Board of Awesome is a 3D-printed, recyclable, and compostable surfboard, made by the young designer Zachary Ostroff. The board is printed with a mix of sustainably sourced algae, discarded plastic water bottles, and custom printable designs.
The algae used in The Dolphin Board are sourced mostly from lakes in Mississippi where the invasive plant life edges out other life forms. This process exploit extracting the algae for manufacturing purposes, solving two problems at once: it stops the spreading of the algae and uses it as a raw material. The algae is fermented and transformed by a partner company called ALGIX into a PLA natural variant, which is then transformed into filament and printed.

The result is a surfboard that he says is less expensive and more durable than the majority of surfboards currently on the market.
Because the boards can be shaped digitally and sent as a file to a 3D printer anywhere in the world, Ostroff's concept cuts down drastically on shipping costs and associated fuel consumption.

Project's name:	Dolphin Board of Awesome
Author:	Zachary Ostroff
Year:	2017
Technology:	FFF
10R's strategies:	R1, R9
Aim of the project:	Ecological surfboard
Main features:	Exploit the overgrown exemplars of parasitic algae as raw material for 3D printing
Project link:	https://www.santacruzwaves.com/2018/03/the-dolphin-board-of-awesome-2/



GENESIS Eco Green by BigRep

What is this project

GENESIS Eco Screen is the first 3D printed urban plant and insect habitat. An amazin feature of the project is that this eco-friendly installation was 3D printing itself live at the historic Thaersaal at Humboldt University in Berlin, and spectators were welcome to come and watch the process.

This 3D printed installation address some major environmental challenges, like urbanization deteriorating biodiversity, plastic waste, and overconsumption of energy and other resources. The innovative prototype is a great example of a scalable circular economy and how to make urban architecture more green, and it could not have been accomplished without BigRep's large, serial production 3D printers, agent modeling, and custom-made generative design algorithms.
The GENESIS Eco Screen is made up of 16 segments, and its full size measures at 4000 x 4000 x 300 mm. The intelligent algorithms and agents are similar to AI in that they are able to design complex geometries autonomously, using just a few pre-set parameters; one example of this was a data analysis of sun exposure across the installation.

Project's name:	GENESIS Eco Green
Author:	BigRep
Year:	2018
Technology:	FGF
10R's strategies:	R1, R9
Aim of the project:	Move public opinion
Main features:	The exibition build itself and a home for plant and insect at the same time
Project link:	https://3dprint.com/251283/genesis-eco-screen-3d-printed-urban-biodiversity-habitat-of-recycled-plastic/

Not Only Hollow by Dirk Van Der Kooji

Project's name:	Not only Hollow
Author:	Dirk Vander Kooij
Year:	2018
Technology:	FGF
10R's strategies:	R9
Aim of the project:	Ecological surfboard
Main features:	Exploit the overgrown exemplars of parasitic algae as raw material for 3D printing
Project link:	https://www.santacruzwaves.com/2018/03/the-dolphin-board-of-awesome-2/

What is this project

This cabinet is the product of The glass-like outer ring is the product of Dirk Van Der Kooji house-developed 3D printing FGF robotic system. It is a system very similar to the one used by The New Raw Studio, with high grades of customizability and freedom of shapes.

The chosen material for the project is Reclaimed polycarbonate, whose origin range from recycled CDs, chocolate molds, and more. Being an FGF system the material is reduced to pellets, which are then poured directly into the printer that extrude the molten material into a single molten thread. As the robot draws upwards, the unlikely source material settles into crystalline hills and valleys, following the instructions of the digital design.

The solid wood shelving serves as main structural support, and grounds the form with a countering simplicity. As the oak appears to sink into its foamy casing, the plastic reveals impressive strength.

The "iced bubbles and oak", like Van Der Kooji likes to call his product, is a displays of synthetics and original, of recycled ad natural material, a choice that he decided to follow in order to honor the opposing materials equally. The embrace sees knots in wood echo pulsating printed strata: both, ultimately, are textures of growth.

This project is the testimony that it is possble to combine natural and recycled material in order to reduce the ecological impact of the industrial products to gradually reach a true form of looping circular economy.

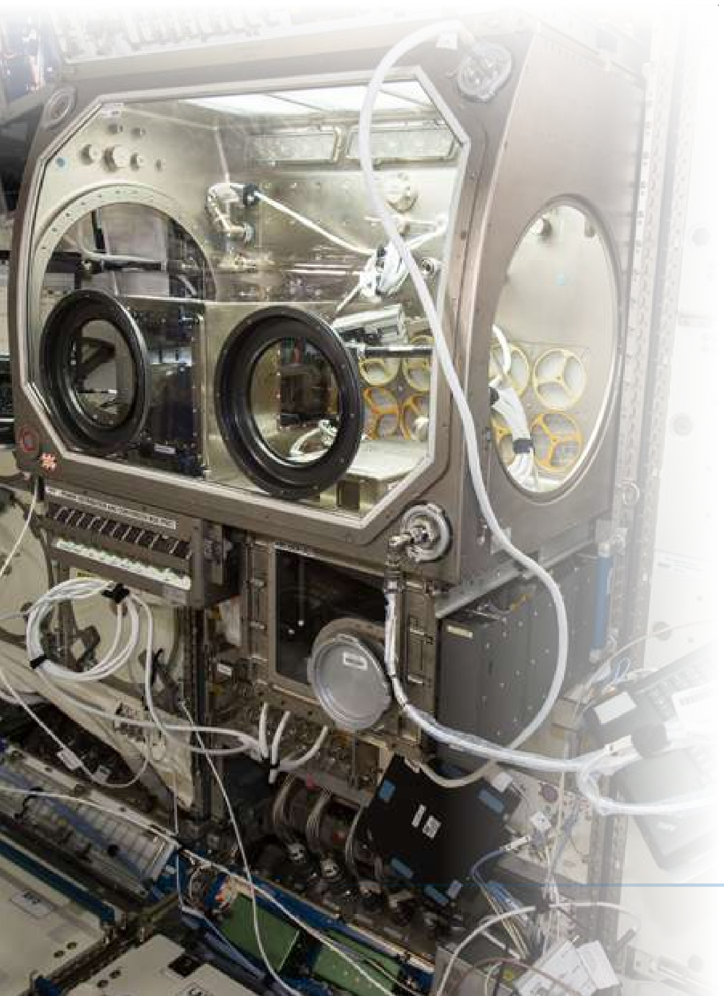
Refabricator by NASA

What is this project

The need for NASA to explore the potential of 3D printing in space came up since it is impossible to know which parts of station or space vehicles would fail at any given time, a problematic that has always forced to store a massive inventory of spare parts on Earth. This is where the Refabricator is needed, in order to minimize the cost of spare parts and enable in-situ resource production in the future.

The ISM project initiated by NASA's Advanced Exploration Systems "serves as Agency resource for identifying, designing, and implementing on-demand, sustainable manufacturing solutions for fabrication, maintenance, and repair during Exploration missions."

According to Niki Werkheiser, ISM project manager at Marshall Space Flight Center, "The Refabricator is key in demonstrating a sustainable model to fabricate, recycle and reuse parts and waste materials on extended space exploration missions."



Project's name:	Refabricator
Author:	NASA
Year:	2018
Technology:	FFF
10R's strategies:	R3,R7
Aim of the project:	Production of spare parts
Main features:	Allows for repairs and refurbushment of equipment in space, in absence of supply line
Project link:	https://3dprintingindustry.com/news/nasa-installs-tether-refabricator-aboard-iss-for-in-space-3d-printing-148728/

Botella Light by BETTER FUTURE FACTORY

What is this project

The Botella light is a lighning project developed by Better Future Factory and made out of a unique filament produced by in house by the company. A peculiar feature of this product is that the 3D printing process creates a lampshade with textured surfaces that plays with the light, dispersing it in unexpected ways.

From the material and ecologial point of view this project is quite innovative as well. The filament is indeed made out of recycle PET plastic bottles, recovered from local citizens waste production.
When printed, through accurate FDM systems, the amount of recycled filament consumed for each lampshade is more or less the same of two recycled PET bottles.
Even if FDM is usually considered a manufacturing process more fitting for prototiping and mock ups, due to its low cost and low time of realization, it was possible for Better Future Factory to realize more than 300 exemplar of the lights, which quickly went sold out and called for a second edition production.

Project’s name:	Botella Light
Author:	Better Future Factory
Year:	2018
Technology:	FDM
10R’s strategies:	R9
Aim of the project:	Reuse local waste
Main features:	Reuse local plastic bottles waste as raw material, enabling a recycling system
Project link:	https://betterfuturefactory.com/portfolio_page/unc-botella-light/

AVR tables and stools by BETTER FUTURE FACTORY

What is this project

This project is composed by a collection of 3D printed tables and stools made for the opening of the new location of AVR. The collection includes a bar table and a reception desk from recycled PET bottles, which are placed in the entrance hall of the new AVR building at their Rotterdam location.

The shapes of PET-bottles are integrated in the structure of the tables, which can be discovered through a glass plate. This stilistical choice was made to recal the material used to print these products, a filament made from locally recycled PET, in a similar fashion of the Botella Light project reported before.

The recycling process does not stops here, since on this project collaborated also the company Van Plestik, which took care of the big scale 3d printing, and Planq company who produced the seating for the stools from recycled jeans, making all the product part of a 100% recycled origin collection (except for the glass table tops).

Project's name:	AVR tables and stools
Author:	Better Future Factory
Year:	2019
Technology:	FFF
10R's strategies:	R7
Aim of the project:	Reuse local waste
Main features:	Reuse local plastic bottles waste as raw material, enabling a recycling system
Project link:	https://vanplestik.nl/en/2019/04/18/3d-printing-a-betterfuture-together/

Second nature by THE NEW RAW

What is this project

Similarly to the other project of The New Raw Studio, the Second Nature project begins with the collection and sorting of second hand rwa material, the ghost gear depending on material type: nets, ropes, floaters or weights. The plastic waste coming from the sea is then processed in a grinder to create a textured filament for the 3D printing process. Second Nature is a collection of safe food tableware completely made of a recycled thermoplastic polymer (base PET).

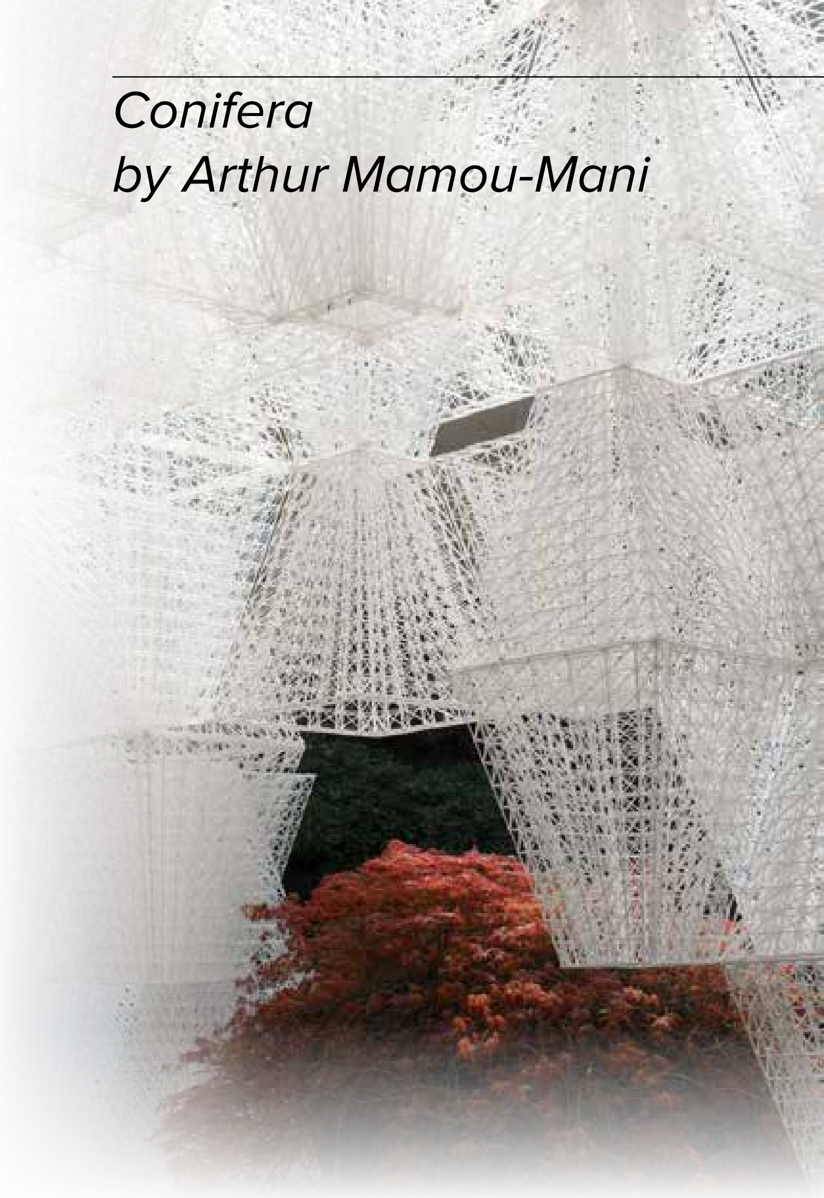
The project also draws inspiration from five edible species of Mediterranean seashells: Mitra Zonata, Pecten Jacobeaus, Pinna Nobilis, Strombus Persicus and Tonna Galea which are currently protected due to their intensive fishing. In giving the ghost nets a second life, Second Nature has created shell-shaped ornaments as well as a series of colorful tableware as part of its ongoing research project promoting a circular economy through recycling and reuse of local waste plastic.

Project's name:	Second nature
Author:	The New Raw Studio
Year:	2019
Technology:	FFF
10R's strategies:	R4, R8
Aim of the project:	Reuse of local waste
Main features:	Exploits the local waste production as raw material cleaning the environment as well.
Project link:	https://thenewraw.org/-Second-nature-Sea-shells

Conifera by Arthur Mamou-Mani

What is this project

Conifera is a large-scale parametric structure made up of 700 modular bio-bricks, each 3D printed in a mixture of PLA and wood fibers, each secured together using PLA cable ties.
Each brick has a lattice structure to take full advantage of the strength of the material, but to also allow light to permeate through the installation.
Three colours feature across the installation, ranging from clear and white to orange and brown. The translucent elements are PLA in its purest form, while the white sections contain a pigment, and the brown hues are achieved from adding wood pulp to the mixture.
The project takes its name from the Conifer tree, the very same wood which was used to additivate the PLA and print the structure.
The main feature of this exibition is its reusability and the possibility to be moved and enlarged, avoiding to have to reprint the whole structure for a new exibition, but simply rearrange the bricks to have completely new experience.



Project's name:	Conifera
Author:	Arthur Mamou-Mani
Year:	2019
Technology:	FFF
10R's strategies:	R6,R7
Aim of the project:	Reusable exibition
Main features:	Exploit the mechnical properties of the material to make an evolving structure
Project link:	https://www.dezeen.com/2019/04/08/arthur-mamou-mani-cos-installation-bioplastic-bricks-circular-design-milan/

The 3D Bar by CARACOL

What is this project

This project is the first attempt to create an entire set of bar's furniture using 3D printing technology in a collection that include stools and tables. In fact, the organic shapes of "The 3D Bar" were created through a generative design process based on robotic FFF 3D printing technology, similar to the one used by The New Raw Studio.

Another important element of this project is the raw material used to produce the filament that is then used for printing. The designer at Caracol decided to opt for a waste material from the production of coffee capsules called "Gea", a type of single-serving coffee capsules by Flo SpA.

More specifically the final filament is made from Pla Ingeo residues, a technical biopolymer, 100% biobased and bio-degradable, which can be discarded after use among the waste organics to become quality compost. As well as releasing the coffee it contains, an important fertilizer for plants, to the soil.

The encounter with 3D technology makes it possible to not waste this material but to enhance it in accordance with the logic of a perfect circular economy.

Project's name:	The 3D Bar
Author:	Caracol Studio
Year:	2019
Technology:	robotic FFF
10R's strategies:	R4, R7
Aim of the project:	Zero waste design
Main features:	Exploits the waste from used coffee capsule as raw materia, the final product is compostable
Project link:	https://www.caracol-am.com/portfolio/the-3dbar/

Million Waves
by Million Waves

What is this project

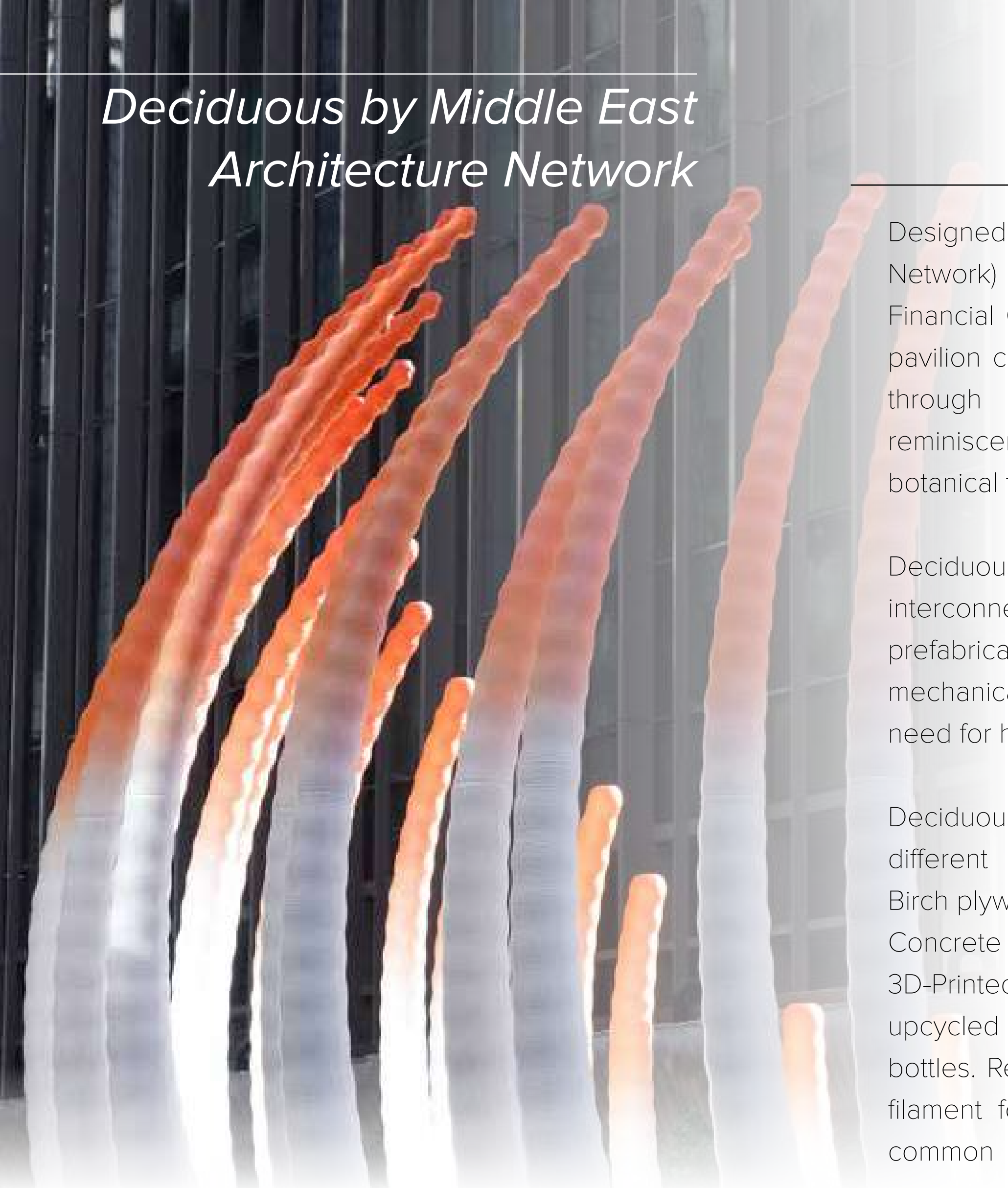
The Million Waves Project, in partnership with GreenBatch, an Australian company that recycles plastic into 3D printing filament, takes these two global issues and provides a sustainable solution. The group makes 3D-printed upper limbs for third world children, who doesn't have accest to this type of services, from reclaimed ocean plastic.

Other than the awesome humanitarian service that million waves provide, its action on the research for the circular economy are also remarkable. By recovering the plastic in the ocean and turning into e PET base filament they already doing a great service to the planet, but its not all.

By exploiting the trait of 3D printing being a digital based technology, they can develop 3D models and send them to their customer, which can then print them at home or at a dedicated place. This means to save resoutces both in terms of money and pollutions, since the whole distribution phace of the lifecycle of the product is completely skipped.

Project's name:	Million Waves
Author:	Million Waves
Year:	2018
Technology:	FDM
10R's strategies:	R1, R9
Aim of the project:	Accessible prostethics
Main features:	The project recycle wasted material and reduce pollutions at the same time
Project link:	https://www.waste360.com/plastics/million-waves-project-looks-solve-two-global-issues-once

Deciduous by Middle East Architecture Network



What is this project

Designed by MEAN* (Middle East Architecture Network) for DIFC (Dubai International Financial Center), Deciduous is a 3D printed pavilion constructed to allow visitors to walk through it, conveying an experience reminiscent of walking through an abstracted botanical form.

Deciduous is designed to come together in interconnected parts, and is completely prefabricated off-site. The parts can be mechanically joined on a clean site with no need for heavy machinery.

Deciduous is composed of a hybrid of 3 different sustainable materials: CNC-milled Birch plywood flooring, Robotically 3D-Printed Concrete Base, and a series of branching 3D-Printed PETG stems, a plastic polymer upcycled from 30,000 discarded water bottles. Recycling plastic PET bottle to make filament for 3D printing may seem a quite common practice by now, but in reality is nevere enough, due to the huge amount of plastic packaging that are wasted every day.

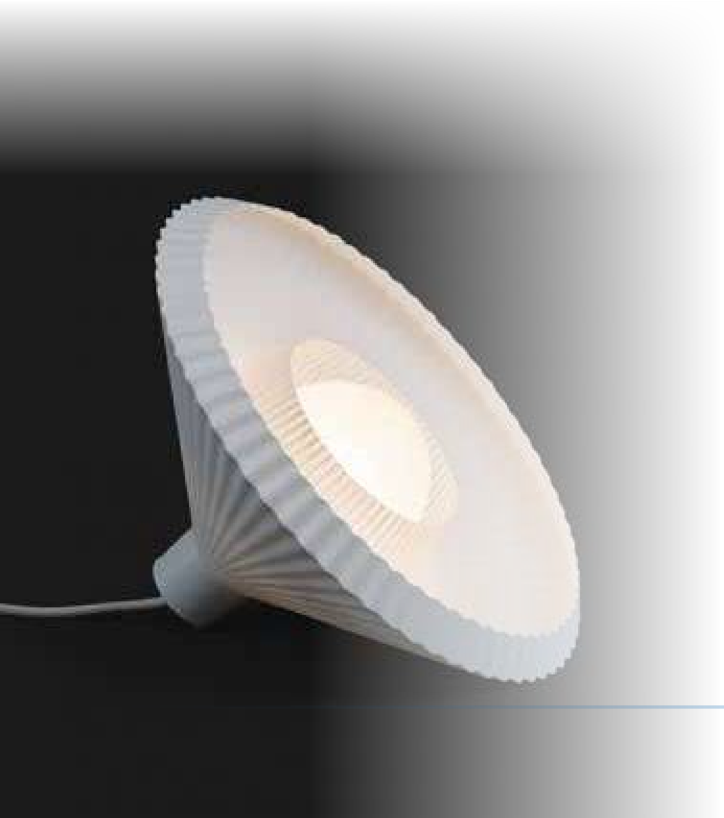
Project's name:	Deciduous
Author:	M.E.A.N.
Year:	2019
Technology:	Robotic FFF
10R's strategies:	R2, R7
Aim of the project:	Reuse waste design
Main features:	Exploit the neverending amount of plastic waste as second end raw material
Project link:	https://www.m-e-a-n.design/projects/deciduous-3d-printed-pavilion

Lampshades collection by Batch.Works and Plumen

What is this project

This project by Batch.Works and Plumen consist of a collection of five lampshades developed in an effort to confront ecological issues associated with waste plastic.
The shades are indeed produced at Batch.Works' east London workshop using plastic recycled from water bottles, fridges and other sources of plastic pollution.
The manufacturing system used is FDM, the recycled waste is infact broke down and transformed into a filament before bein printed. The filament material is then a very similar PET like thermoplastic polymer, sourced from Amsterdam social enterprise Reflow, which recycles and repurposes waste plastics.
This material, combined with FDM manufacturing enable two major path to reach circular economy, firstly it reduces the amount of waste produced, and secondly the lampshades can be returned to the manufacturer for disassembly and recycling at the end of their lifespan, favoring looping system.

Project’s name:	Lampshades
Author:	Batch.Works
Year:	2019
Technology:	FDM
10R’s strategies:	R1, R9
Aim of the project:	Zero waste design
Main features:	Create a circular loop of material by enabling recycling and reuse of the same material
Project link:	https://www.dezeen.com/2020/01/02/plumen-batch-works-lampshades-recycled-plastic/



Straat by Joachim Froment

What is this project

Straat is a furniture collection which includes stools, lounge chairs, tables and more, it is entirely made by 3D printing locally collected plastic waste with a 3D printer made by Colosus, which is integrated in a container and can therefore be easily transported to locally produce furniture anywhere.

The closed loop shape of the furniture pieces is adding mechanical strength to the structure, and it is printed continuously without interruption to save time and money. The collection's soft curves are both for aesthetic reasons, to evoke lightness, as well as improving the mechanical properties.

The aim of this project is to create products made of local recycled materials destined to be sold on a local market and offering a service as well to recycle the products in order to close the loop and participate entirely to a circular economic system. This way of design together with the technology could compete with current industrial processes offering a potential new form of industrialization with adaptable custom made products and offering a potential new way to create sustainable objects at an affordable price.

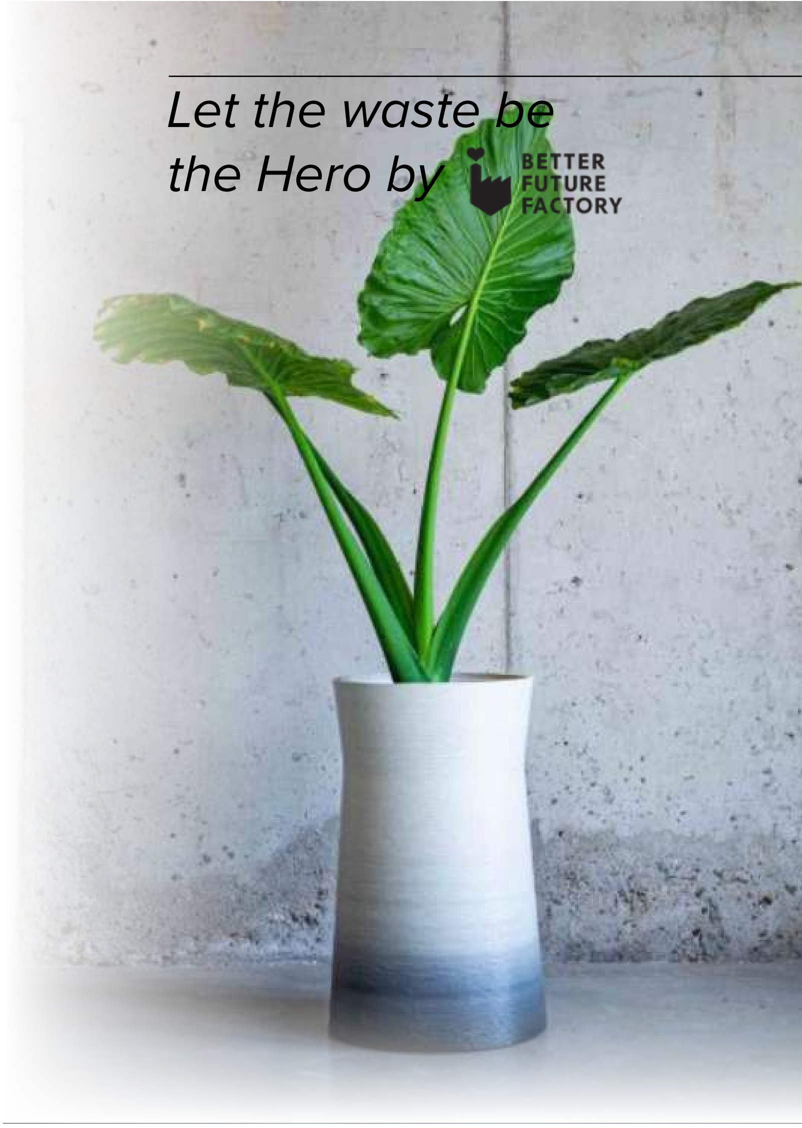
Project's name:	Straat
Author:	Joachim Froment
Year:	2019
Technology:	FGF
10R's strategies:	R4, R9
Aim of the project:	Zero waste design
Main features:	Exploit local waste production as raw material and enable a circular economy
Project link:	https://materialdistrict.com/article/3d-printed-furniture-belgian-plastic-waste/

Let the waste be the Hero by BETTER FUTURE FACTORY

What is this project

Let the Waste be the Hero is project made by Better Future Factory for a major Danish toy manufacturer, where the company designed and produced through 3D printing process a unique set of furniture pieces, using the client waste material as raw source for the production of the 3D printing filament.
The set of furniture consists of a meeting table, stools, flower pots and lighting.

For producing the different furniture pieces BFF company used different production techniques other than 3d printing, like sheet pressing and vacuum forming. This choice of combining different manufacturing processes allowed them to create a limited series without investing in expensive moulds or setting up dedicated production processes. Part of the succes of this project is the collaboration with the best production partners to get to the best end result.



Project's name:	Let the waste be the Hero
Author:	Better future Factory
Year:	2020
Technology:	FFF
10R's strategies:	R4, R7
Aim of the project:	Waste remanufacture
Main features:	Reuse plastic wastes as raw material, and return them to the client as a new product
Project link:	https://betterfuturefactory.com/portfolio_page/circular-brainstorm-room-furniture/

Plastic Surgery
by 91 - 92

What is this project

Plastic Surgery is a collection of 3D printed stools and vases by Ninetyoneninetytwo studio, a Copenhagen based sustainable 3D printing studio. The role of the studio is to design, develop, and produce everyday objects and furniture made from recycled plastic.

The aim of the project, as well the one of the studio, is that to make 3d more involved in daily life. By using 3D printing technology, the studio can localize their production, minimize material waste, and reduce energy consumption.

The material used for this coollection, as well as others made by the studio is a EU-sourced filaments from recycled plastic, a thermoplastic polymer with a base of PET and PETG, the most common material used for drinking bottles and packaging.

rPET and rPETG, the recycled material used for the filament of the studio, are both durable and high incompetence.

Project’s name:	Plastic Surgery
Author:	91 - 92
Year:	2021
Technology:	FFF
10R’s strategies:	R7
Aim of the project:	Reusable Design
Main features:	Recycle and reuse of local waste plastic for furniture that can be reused
Project link:	https://ninetyoneninetytwo.com/

Column by Aectual

What is this project

Column is just one of the many amzing project made by Aectual Stdio which has circular economy as its main focus.

Infact, Aectual Circular, is the brand new circular design and digital production service that allows products made by Aectual to be easily shape-shifted from one material into new interior design solutions over time. The service is built upon innovative XL 3D printing technology in combination with plant-based plastics and recycle material. This project offers unprecedented design freedom whilst being 100% circular: after use infact, Aectual takes back the building products and directly recycles and reprints them into new products. Architectural additive manufacturing seamlessly fits the transition to circular manufacturing. A product is digitally designed, and then 3D printed, and after use it's possible to recycle the material and can directly reprint a smarter designed version than it was before. On top of that, commercial interiors such as stores, hotels, event spaces and offices, have a life cycle of 3 to 5 years, or even less, this usually results in tremendous amounts of waste but for aectual is an amazing business opportunity.

Project's name:	Column
Author:	Aectual
Year:	2021
Technology:	FFF
10R's strategies:	R7
Aim of the project:	Zero waste design
Main features:	Build a circular economic and loop by printing and recycling the same material
Project link:	https://www.a-ectual.com/sustainability/circular

Kelp collection by Interesting Times Gang

What is this project

This project, made by the swedish studio Interesting Times Gang, consists of a 3D-printed chair made from recycled fishing nets.
Named Kelp Collection, the chair has a curved and organic shape that is made possible by 3D printing, the aim of the prject was to bring attention to the fact that vast amounts of known underwater kelp forests have been eradicated due to unsustainable fishing practices and rising ocean temperatures

Kelp Collection is infact made from a material that uses recycled maritime gear such as ropes and fishing nets, which is where it gets its green colour from.
The maritime gear is combined with wood fibres, a recycled FSC-certified bi-product from the saw mill industry, to create the furniture's bio-composite material.

Project's name:	Kelp collection
Author:	Interesting Times Gang
Year:	2022
Technology:	FGF
10R's strategies:	R8, R9
Aim of the project:	Reusable Design
Main features:	Recycle and reuse of local waste material for furniture that can be reused
Project link:	https://www.dezeen.com/2022/04/22/kelp-collection-chair-interesting-times-gang-dezeen-showroom/


THE
NEW
RAW

CHAPTER 6

Most relevant material in depth analysis

Analysis of the most relevant materials that came out from the case study analysis and comparison between them and their “standard” version

Most relevant materials

As seen previously in chapter one, and from the analysis of the case studies reported, FDM 3D printing systems have a broad range of materials to choose from, even when focusing only on thermoplastic polymers.

The literature on materials for 3D printing is clear, thermoplastic polymers are the most suitable materials that can be printed through FDM. Besides offering a clear environmental advantage in terms of recyclability, thermoplastics are the most common polymers and thus guarantee a greater choice of materials. These range from the so called “commodities”, like the polyolefins (i.e., polyethylene PE and polypropylene PP), passing through intermediately priced materials, such as acrylonitrile-butadiene-styrene (ABS), up to engineering plastics, which include polycarbonate (PC), polysulfone (PSU) or polyetherimide (PEI) and biodegradable materials like poly-(lactic acid) (PLA). Amorphous polymers are preferred over semicrystalline ones: Besides the lower solidification shrinkage, due to their liquid-like structure in the solid state, also their properties in the molten state are better. This can be explained in terms of melt viscosity that decreases with the distance between the processing temperature and the polymer glass transition temperature. In the case of semicrystalline thermoplastics, this distance is relatively high, as the processing temperature must exceed the crystal melting temperature, which is usually about 1.5 times the glass transition temperature expressed in °C. In amorphous materials, as there are no crystals, it suffices that the processing temperature be simply greater than the glass transition temperature by about a 100 °C.

Switching from the theoretical analysis to a more practical approach, like already discussed in chapter four, the case studies reported a keen interest in two materials when it comes to 3D printing for circular economy, two materials that offer better qualities in terms of physical properties and possibility of enabling a circular economic loop.

The two candidates are PLA and PET, which, in form of pure virgin material, recycled and/or recovered variants, as well as composites and additivated version, they added up to 19 out of the 30 cases collected, almost two thirds of them.

This is why i decided to dedicate this chapter to a more deep study of these materials, and focus on the properties that makes them such great candidate to be employed in additive manufacturing in order to reach a new circular economic model, as well as new material that can enhance even more these candidates.

Polylactic Acid - PLA

Polylactic Acid (PLA), ranks as the most popular material for 3D printing overall, particularly FDM. Its ease of use and minimal warping issues make PLA filaments the perfect starting point for 3D printing. PLA is also one of the most environmentally-friendly 3D printing materials and, unlike ABS, is biodegradable. Among other PLA advantages are also its low cost and a wide assortment of colours and blends. However, the brittleness of the material makes PLA more suitable for non-functional prototyping, decorative and low-stress applications.

PLA is a common thermoplastic polymer derived from natural sources such as corn starch or sugar cane, in contrast to many other thermoplastics which are produced from non-renewable sources such as petroleum. The main advantages of PLA include:

◆ Low printing temperature

PLA has a relatively low printing temperature compared to other thermoplastics (e.g. for PLA an ideal printing temperature starts from around 180°C, while ABS this is around 250°C). PLA is less likely to warp and clog the nozzle during the printing process and, compared to ABS and other thermoplastics, PLA typically produces better surface details and sharper features.

◆ Biodegradable

PLA is an eco-friendly material, as it's biodegradable, non-toxic and also requires less energy to 3D print and emits fewer greenhouse gases than petroleum-based materials. Compared to petroleum-based thermoplastics, which take thousands of years to break down, PLA parts can typically (naturally) break down within a few years, or even months. The other great feature of PLA is it biocompatibility with a human body

◆ Variety of colour and blending options

PLA is easily pigmented and comes in a diverse range of colours and blends. The material can also be mixed with wood, carbon and even metal, whilst pigments can also be added t to get luminescent or glittery filaments. This makes the choice of PLA blends virtually endless.

◆ Easy post-processing

PLA prints can be easily sanded, polished and painted, allowing for an improved surface finish with relatively little effort. You can also drill, mill and glue PLA parts — but be careful not to melt the part. To prevent melting your PLA part, simply keep the process slow and the tools cold (you can achieve this with water, WD-40 or proper cutting fluid).

◆ Ease of use

PLA is one of the easiest material filaments to 3D print with. The material easily adheres to a variety of surfaces and doesn't require a heated print bed which, again, adds to its ease of use. Unlike ABS, PLA also does not emit smelly fumes when printed.

Even if it's one of the most used materials, PLA presents also some limitations when it comes to 3D printing:

- Low heat resistance
  Therefore cannot be used for high temperature applications. In high temperatures, PLA can rapidly deform, especially if under stress.
- Low tensile strength
  PLA is typically weaker and has a lower tensile strength than its counterparts, ABS and PETG. Since PLA parts, when 3D printed, are quite brittle, the material is more suited to aesthetic rather than mechanical purposes.
- Not safe for food
  While PLA containers are food safe when not 3D printed, PLA is not food safe when 3D printed. This is because the 3D printing process creates tiny gaps and pores between the layers of your print. These gaps tend to keep moisture and bits of food, leading to a build-up of bacteria and mould.

PLA technical data

The table on the right report the most important data to know about PLA in order to print it correctly.

Table 1: PLA datasheet

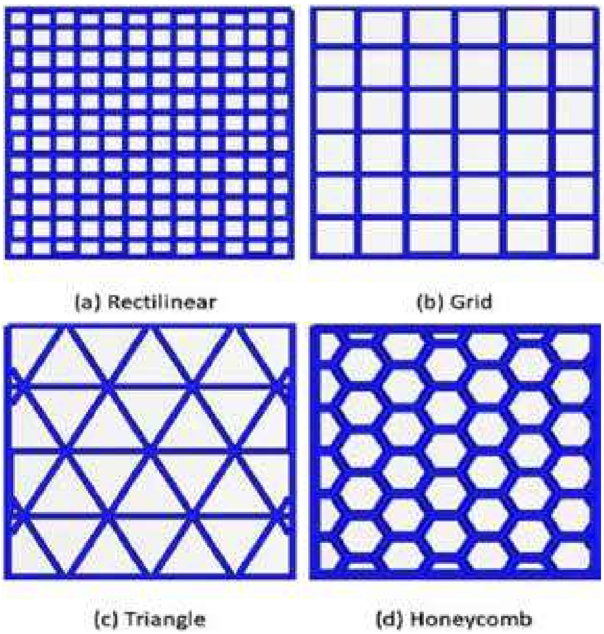
Data taken from MatWeb.com

Properties	U.M.	Value
Density	g/cm^3	1.2 - 1.4
Elastic modulus	GPa	2.0 - 2.6
Elongation at break	%	6.0 - 7.2
Flexural modulus	GPa	3.8 - 4.1
Flexural strength	MPa	80 - 86
Glass transition temperature	°C	57 - 63
Heat deflection temperature (at 455 kPa (66 psi))	°C	62 - 66
Melting onset	°C	160 - 165
Shear modulus	GPa	2.3 - 2.4
Specific heat capacity	J/kg	1800 - 1850
Strength to weight ratio	kN	36 - 39
Tensile strength	MPa	49 - 51
Thermal conductivity	W/m	0.13 - 0.14
Thermal diffusivity	-	0.053 - 0,056
3D printing extrusion temperature	°C	180 - 210
3D printing flow tweak	-	0.95 - 1.20
3D printing bed temperature	°C	45 - 65

To further prove the capabilities of PLA and understand the opportunities that it can offer, as well as its limitations, it is necessary to run tests to examinate its mechanical properties.
Before diving into the material aspect it is important to remember that we are taking in consideration samples of 3D printed material. The additive manufacturing process is a production process known for affecting the mechanical properties of the material in some serious ways. The main parameter that can influence the print quality and, consequently the mechanical properties of the samples are:

Layer thickness
In 3D printing, a part is printed layer by layer. Each layer has a thickness. Layer thickness in 3D printing measures the height of each layer and is measured on the z-axis. Layer thickness is directly associated with the time consumption of the manufacturing process. Abeykoon et al. observed that as the layer thickness is decreased, the number of layers required for the completion of the process increases, which results in the increment of time consumption for the fabrication of the specimen. In FDM, the layer thickness typically ranges from 0.17 mm to 0.33 mm.

Infill density and pattern
The amount of filament printed within an item is known as infill density, and it has a direct impact on the print's strength, weight, and printing time. Different 3D print infill styles, or infill patterns, can affect the object's absolute power without adjusting the print's weight or filament used. Akhoundi and Behravesh observed that the triangular infill pattern shows the highest tensile strength, while the lowest is shown by honeycomb. Triangular and honeycomb infill patterns possess the most tensile strength amongst the three infill patterns.
The flexural intensity of the triangular, honeycomb, and hexagonal infill patterns is most incredible. With a bed temperature of 40 °C and the primary layer thickness of 0.2 mm, the overall difference was 11.42 percent, but the triangular design had the most mass at a similar infill percentage. The strength is influenced by the filing pattern, which arranges rasters to impact heat transfer. As a result, the linking between rasters and layers would be compromised. The filling pattern determines the raster orientation, and to reduce material consumption and overall cost, the amount of infill percentage is critical.



Typical printing pattern

Triangular infill pattern shows the highest tensile strength, while the lowest is shown by honeycomb ones. (Doshi et al., 2022)

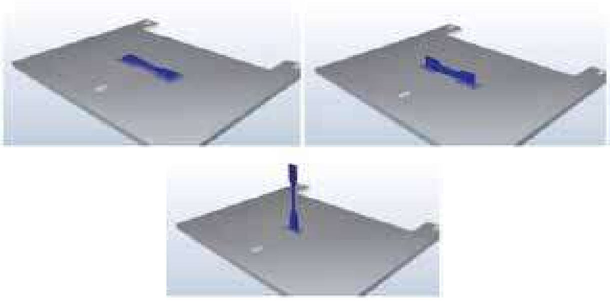
Printing speed
Printing speed is a calculation of how easily a 3D printer can create a model from raw materials. It generally refers to the amount of material that has been deposited into an object over a while. High-speed 3D printers will deposit more material in less time than their slower counterparts. FDM printers have a 3D printing speed of about 100 mm/hr on

average. FDM printers can be tweaked to improve their 3D printing speed. Some FDM printers can print at speeds of up to 500 mm/hr, five times faster than the industry average. Žarko et al. experimented with a MakerBot Replicator Fifth Generation FDM 3D printer with different parameters such as infill percentage, layer height, extrusion temperature, and printing speeds for printing embossing equipment. The lowest (10 mm/s) and highest (200 mm/s) speeds that Makerbot Replicator supports, with 90 mm/s being the manufacturer's recommended optimum speed. The quality of the line, circle, and various square elements was measured using various printing speeds. It was found that more minor elements are more difficult to replicate precisely.

Increases in element distance, radius, or length reduce the likelihood of thickness, perimeter, or area variation by visual and quantitative analysis. According to the visual and quantitative analysis, variations in printing speed affect the consistency of straight line, circular, and squared element replication and their accuracy in measurement.

Build orientation

Build orientation of an object with FDM is usually linked by the object's structure after seeing build feasibility, build efficiency, and build accuracy. FDM objects produced at various angles display anisotropic tensile strength variations, calculated based on build orientation. The raster angle and build orientation are vital in affecting mechanical properties, manufacturing expenses, and surface roughness. Build orientation has a remarkable impact on the raster angle on the developed FDM part's surface irregularities and mechanical behaviour. Durgun and Ertan analyzed the compressive experiment and found out that the ultimate compressive strength reduces when the specimen's orientation is altered. It is highest at 0° orientations and the least at 90° orientation. The compressive stress at 0° is found to be greater than transverse orientation.



Typical printing pattern

Compressive strength is highest at 0° orientations and the least at 90° orientation. The compressive stress at 0° is greater than transverse orientation.
(Doshi et al., 2022)

Raster angle

The angle between the X-axis of the printing surface and the nozzle path during an FDM process is defined as the raster angle. A raster angle of 90°separates the adjacent layers. The raster angle determines the form accuracy as well as the mechanical performance of printed material. Characteristic raster angles are 0° to 90° in 15° increments. For instance, upon testing 45° specimens, it builds a raster tool path ascended at 45° to the x-axis in the base layer, and then the tool path direction will alternate in each next layer up. The tensile mechanical properties of FDM-fabricated samples are significantly affected by raster angles in general. Uddin et al. founded that when the orientation angle was 0°, the tensile strength increased as the nozzle temperature increased until it reached a certain point, depending on the material used, at which point it began to decline. The changing trend of elastic modulus with temperature was the same.

Table on the parameters influence

In the following table are reported all the documented variable parameters that can affect the mechanical properties of 3D printed objects, as well as the respective affected property.The referencies are reported at the end of this work (table from Suteja et al., 2020).

Reference	3D Printing Parameters	Mechanical Properties
1	◇ Build Orientation ◇ Layer Thickness ◇ Infill Deposition Speed	◇ Tensile Strength ◇ Flexural Strength ◇ Ductility
2	◇ Infill Density	◇ Compression Strength ◇ Time
3	◇ Layer Thickness ◇ Infill Angle ◇ Infill Density	◇ Flexural Force
4	◇ Build Orientation ◇ Infill Density ◇ Infill Deposition Speed ◇ Extrusion Temperature ◇ Layer Thickness ◇ Infill Pattern	◇ Accuracy and Repeatability ◇ Young Modulus ◇ Tensile Strength ◇ Yield Strength
5	◇ Infill Density ◇ Infill Pattern	◇ Tensile Strength
6	◇ Extrusion Temperature ◇ Layer Thickness ◇ Infill Pattern ◇ Infill Density	◇ Dimensional Accuracy ◇ Tensile Strength ◇ Young Modulus ◇ Ductility
7	◇ Infill Density	◇ Tensile Strength ◇ Young Modulus ◇ Failure Mod
8	◇ Layer Thickness ◇ Infill Density ◇ Number of Outer Shell Layer	◇ Strength ◇ Stiffness ◇ Ductility
9	◇ Shell Thickness ◇ Infill Deposition Speed ◇ Layer Thickness	◇ Tensile Strength
10	◇ Material Type ◇ Infill Density ◇ Infill Pattern ◇ Printer Type	◇ Tensile Strength ◇ Young Modulus ◇ Yield Strength ◇ Specific Strength
11	◇ Infill Angle ◇ Extruder Temperature ◇ Feed Rate	◇ Tensile Strength ◇ Young Modulus
12	◇ Material Type ◇ Infill Density ◇ Infill Pattern ◇ Load Orientation ◇ Strain Rate	◇ Tensile Strength ◇ Stiffness
13	◇ Infill Density ◇ Infill Pattern	◇ Young Modulus ◇ Maximum Bending Stress ◇ Deflection
14	◇ Infill Density ◇ Infill Pattern	◇ Stiffness ◇ Strength
15	◇ Layer Thickness ◇ nfill Density ◇ Extruder Temperature	◇ Maximum Failure Load ◇ Elongation ◇ Part Weight ◇ Build Time
16	◇ Coloring Agent	◇ Strength
17	◇ Infill Pattern ◇ Infill Width	◇ Compression Load

Having cleared the influence that the manufacturing process can have on the material, it is now possible to finally proceed to the analysis of the materials themself.
Starting with the PLA, the literature study has highlighted a keen interest in the material mechanical properties variation that happens based on the parameter set during the printing process. Since the mechanical properties of PLA are usually in the same ranges reported in Table 1, what is of most interest is to understand how such properties can change based on the setting and adjustment made during the print. The most influential parameters that can alter the properties of the material have already been mentioned, yet the literature shows that the layer thickness, the raster angle and the build orientation are those of most interest to researchers.

In the research conducted by Lokesh et al., 2022, a further study was conducted by testing 3D printed specimens with varying parameters, focusing on the variation of tensile strength, values for ultimate stress, elastic modulus, and average elongation at break. The results are recorded and tabulated in Table 4. It is possible to observe that the sample with raster angle of 30°, build orientation of 45° and 0.1 mm layer thickness report the maximum strength when compared to the other specimens printed with different process parameter. Another important factor to note is that as the build orientation angle increases, the UTS eventually increases as well, while strength was observed to slightly decrease with the increasing of raster angle. The layer thickness, on the other hand, is clearly the most dominant factor when it comes to UTS, since the latter shows an increasing trend with the decrease of the layer thickness. Layer thickness and UTS have a clear inversely proportional relationship, and maximum UTS is observed for 0.1 mm layer thickness. This phenomenon is due to the fact that as the layer thickness value decreases more pressure will be applied between layer and nozzle, resulting in better bonding between the printed layers, allowing to reduce the void spaces between them as well.

Table 3: tensile results

Study on variation of tensile strength, values for ultimate stress, elastic modulus and average elongation at break at the varying of printing parameters (Lokesh et al., 2022).

Sample	Layer thickness	Raster degree	Build orientation	Ultimate stress	Elastic modulus	Elongation at break
-	mm	°	°	MPa	MPa	%
SMP1	0.1	30	0	**46.51**	**1870**	**2.164**
SMP2	0.1	30	45	**46.65**	**1876**	**3.268**
SMP3	0.1	30	90	**42.90**	**1680**	**3.207**
SMP4	0.2	45	0	**43.74**	**1691**	**4.077**
SMP5	0.2	45	45	**39.30**	**1623**	**2.718**
SMP6	0.2	45	90	**39.90**	**1632**	**4.470**
SMP7	0.3	60	0	**30.07**	**1610**	**3.740**
SMP8	0.3	60	45	**30.34**	**1618**	**2.853**
SMP9	0.3	60	90	**27.93**	**1584**	**3.239**

A further analysis of the literature brought to my attention another useful tool frequently used by researcher to understand what variants have a higher impact on the mechanical properties of the 3D printed object.

The tool in question is a collection of statistical models, the ANOVA (Analysis of variance). The analysis of variance can help to further interpret the effect of each process parameter in their interaction on the UTS.

In the case of the work of Lokesh et al., 2022 the ANOVA analysis shows that layer thickness is the parameter with maximum contribution towards the variance of UTS, with a value of 88.41%.

The other two process parameters, raster angle and build orientation, presented values of only 0.78% and 3.57% respectively. The importance of layer thickness is confirmed by the fact that the mean value of UTS increases with the decrease of layer thickness, and reach a maximum value when the build orientation is at 45° with respect to the z axis.

This is phenomenon is due to the equal load distribution along x and y axis that is reached only at 45° of inclination, which ensure maximum load bearing strength for printed specimen.

Parameters contribution on UTS testing, percentage

In the table the values of contribution of influence on the mechanical propertiest plottet through the ANOVA analysis (Lokesh et al., 2022).

Parameters	Contribu-tion
-	%
Layer thickness	88,41
Build orientation	3,57
Raster angle	0,78
Layer thickness*Build orientation	0,06
layer thickness*Raster angle	0,15
Build orientation*Raster angle	4,75
Error	2,29
Total	100,00

Samples design

Design of the samples, realized following standard references ASTM D638 and ASTM D695 for tensile and compressive tests

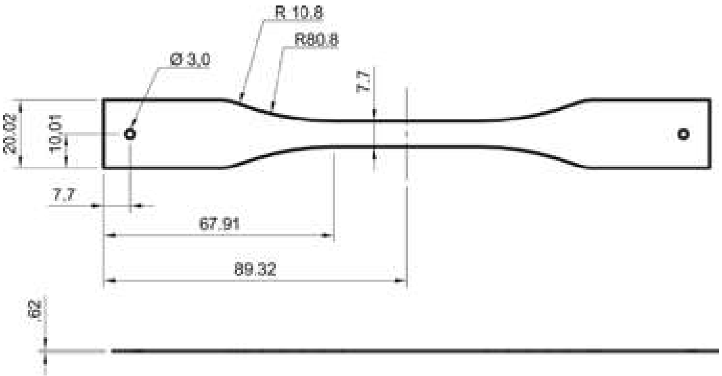


Table 4: Parameters contribution on UTS testing

DF: Degree of freedom; Seq SS: sum of square; Adj SS: adjusted sum of square; F: Fisher value; P: Probability. (Lokesh et al., 2022).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
layer thickness	1	379.533	1.716	1.716	0.35	0.615
Build orientation	1	15.328	3.678	3.678	0.75	0.478
Raster angle	1	3.345	15.121	15.121	3.07	0.222
Error	2	9.843	9.843	4.921		
Total	8	429.29				

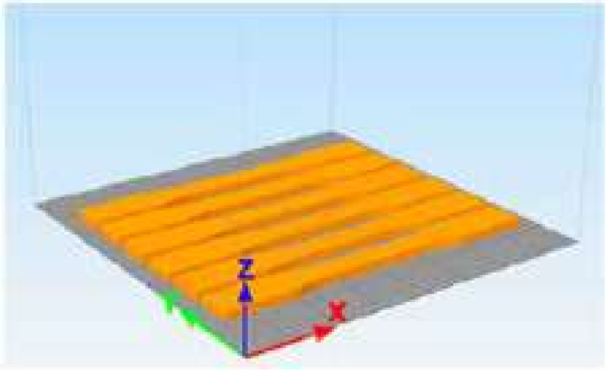
Table 5: Parameter contribution ranking for flexural Property

In the table the values of contribution of influence on the mechanical propertiest plottet through the ANOVA analysis (Kumar et al., 2020).

Level	Infill density	Infill angle	Infill speed
1	20.30	24.36	21.10
2	21.56	21.80	21.98
3	22.90	18.61	21.68
Delta	2.60	5.75	0.88
Rank	2	1	3

Samples design

Design of the samples, realized following standard references ASTM D638 and ASTM D695 for tensile and compressive tests



The same procedure, the analysis through mechanical test and analysis of variance, can be executed for other types of properties of the PLA, like the flexural properties.

In the work by Kumar et al., 2020, for all the printed specimens flexural test and pull out test has been performed and properties were recorded using UTM interface on machine as given by tables 7 and 8, and for those values the properties were analysed using ANOVA. From rank table 5 it is very clear that effect of infill angle is most prominent as it was ranked 1st, infill density was ranked at 2nd and infill speed was least significant for the process of printing. Stress versus strain relationship as seen from figure 1 (flexural tested samples) clearly demarcates the difference among printed samples (with different conditions). Sample at SMP7 (as per table 3) has shown maximum strain as well as stress. Similar result were observed for pull out tested samples.

From Kumar et al., 2020 data it appeared that infill density of 100%, infill angle of 45° and infill speed of 70 mm s–1 are the optimized condition for peak load of flexural property.

Table 6: Parameters contribution on flexural testing

DF: Degree of freedom; Seq SS: sum of square; Adj SS: adjusted sum of square; F: Fisher value; P: Probability. (Kumar et al., 2020).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Infill Density	2	10.131	10.131	5.0654	7.62	0.116
Infill Angle	2	49.830	49.830	24.9150	37.47	0.026
Infill Speed	2	1.215	1.215	0.6074	0.91	0.523
Residual Error	2	1.330	1.330	0.6649		
Total	8	62.505				

Table 7: Flexural properties of FDM based 3D printed samples with standard deviation

PL: Peal Load; PE: Peak Elongation; BL: Break Load; BE: Break Elongation; PS: Peak Strength; BS: Break Strength. It should be noted that each sample was printed with 3 repetitions on FDM setup so that deviation in properties may also be reported. (Kumar et al., 2020).

FLEXURAL PROPERTIES						
Sample	PL	PE	BL	BE	PS	BS
-	-	mm	N	mm	MPa	MPa
1	12.7 ± 1.21	7.61 ± 0.31	13.11 ± 1.20	14.56 ± 1.01	9.16 ± 1.01	9.46 ± 1.01
2	11.2 ± 1.04	5.98 ± 0.15	10.08 ± 1.01	10.24 ± 1.56	8.08 ± 0.65	7.27 ± 1.05
3	7.8 ± 0.65	1.99 ± 0.08	5.06 ± 0.56	4.55 ± 1.20	5.63 ± 0.21	3.65 ± 0.51
4	18.1 ± 2.21	7.89 ± 0.51	16.29 ± 1.42	15.77 ± 3.32	13.06 ± 2.21	11.75 ± 1.04
5	11.7 ± 1.21	6.84 ± 0.21	10.53 ± 1.35	13.49 ± 1.67	8.44 ± 1.01	7.60 ± 0.51
6	8.1 ± 1.03	2.66 ± 0.11	5.67 ± 1.05	6.65 ± 1.45	5.84 ± 1.03	4.09 ± 0.56
7	19.6 ± 3.10	8.23 ± 1.35	17.64 ± 2.21	20.47 ± 3.35	14.14 ± 2.52	12.72 ± 2.35
8	14.2 ± 2.21	6.35 ± 0.74	12.78 ± 1.67	17.52 ± 3.20	10.24 ± 1.67	9.22 ± 1.53
9	9.78 ± 0.65	3.2 ± 0.24	7.8 ± 1.05	7.84 ± 1.14	7.05 ± 0.65	5.63 ± 0.58

Table 8: Pull out properties FDM based 3D printed samples with standard deviation

PL: Peal Load; PE: Peak Elongation; BL: Break Load; BE: Break Elongation; PS: Peak Strength; BS: Break Strength. It should be noted that each sample was printed with 3 repetitions on FDM setup so that deviation in properties may also be reported.(Kumar et al., 2020).

FLEXURAL PROPERTIES						
Sample	PL	PE	BL	BE	PS	BS
-	-	mm	N	mm	MPa	MPa
1	50.21 ± 4.52	32.45 ± 3.54	48.21 ± 4.20	30.4 ± 3.54	36.22 ± 4.52	34.78 ± 2.65
2	45.21 ± 3.54	29.13 ± 4.52	40.12 ± 3.14	28.56 ± 4.52	32.61 ± 3.54	28.94 ± 3.54
3	42.23 ± 3.12	26.12 ± 4.01	38.54 ± 3.54	25.87 ± 3.61	30.46 ± 2.65	27.80 ± 4.52
4	55.05 ± 5.54	32.15 ± 4.52	52.14 ± 4.52	34.18 ± 3.54	39.71 ± 3.54	37.61 ± 2.65
5	50.23 ± 4.52	28.12 ± 3.54	46.24 ± 3.61	30.61 ± 4.52	36.23 ± 4.52	33.35 ± 3.54
6	40.63 ± 3.12	24.13 ± 2.36	38.62 ± 3.54	28.51 ± 3.54	29.31 ± 3.54	27.86 ± 4.52
7	63.41 ± 4.85	40.12 ± 4.52	59.91 ± 4.52	40.12 ± 3.61	45.74 ± 3.42	43.21 ± 3.67
8	59.54 ± 3.12	35.26 ± 2.81	55.63 ± 3.54	36.54 ± 4.52	42.95 ± 2.65	40.13 ± 3.54
9	56.23 ± 4.52	33.85 ± 3.54	50.84 ± 4.52	32.12 ± 3.61	40.56 ± 4.52	36.67 ± 4.52

Conclusions on PLA

The literature study revealed that, when working with 3D printed thermoplastics, especially PLA, depending on the mechanical property that has to be enhance, the combination of optimal parameters to use is different.

Numerous printing combinations add up to flexibility in terms of time consumption to manufacture, post process or required effective strength and stiffness.

In particular, it emerged that raster angle, build orientation and layer thickness have demonstrated to be influential on the UTS of the 3D-printed PLA specimens. The experimentation through ANOVA methods explained that layer thickness and raster angle have a negative correlation when combined with build orientation.

To be clearer, ANOVA analysis showed that contribution of layer thickness is way more influential with respect to the other two process parameter, and raster angle has the least significance with contribution with less than 1%. The data collected from the case studies suggested that in order to obtain the maximum UTS of 46.61 MPa registered in these tests, the optimal condition for the above-mentioned parameters are: 0.1 mm for layer thickness, 30° for raster angle and 45° for build orientation.

Similar test conducted to analyse the flexural properties of similar PLA samples revealed that the most important parameters to maximize such properties are infill density, infill angle and infill speed. The optimal values reported for these parameters appear to be: infill density: 100; infill angle: 45° and Infill speed: 90 mm x s–1., while the worst results have been reported by samples printed with values of infill density: 60, Infill angle: 90°; and infill speed: 90 mm x s–1.

For the record, the maximum strain absorbing capacity has been reported by samples that presented values of break elongation of 20.47 mm and strain capacity of 0.4094 during the flexural tests; and values of of break elongation of 40.12 mm and strain capacity of 0.8024 during the pull out tests. Both of these records have been reached by the same samples, printed in the optimal condition reported above.

From the literature study further, more general, conclusion can be done on the influence of the layer orientation, layer height, filament width, printing velocity, fill density, and infill pattern on the flexural performance of PLA specimens.

Firstly, the orientation of the stacking of the layers is the most influential parameter in the rigidity, in the flexural resistance, and in the maximum deformation.

The layer height and the filament width had a great significance in stiffness and flexural strength and no influence on maximum deformation.

Printing velocity had a small, but significant effect on rigidity and flexural strength and no influence on maximum deformation.

The fill density and infill pattern had no effect on the studied mechanical properties.

The orientation of stacking layers in Y, the layer height of 0.1 mm, the filament width of 0.6 mm and the printing velocity of 20 mm/min was the optimal combination obtained that will allow maximizing rigidity and flexural resistance.

The printing direction in Y-axis showed the best mechanical behaviour owing to its resistance depending on the strong intralayer bond.

The large filament width, the small layer height, and the low printing velocity formed test specimens with better compaction and better welding between wires, and generated a better rigidity and resistance to bending.

It could not be ensured that higher layer height improves fatigue life.

Polyethylene terephthalate - PET

PET (polyethylene terephthalate) is the other material that stood out of crowd during the analysis if case studies in chapter four. It is a transparent and lightweight thermoplastic polymer resin part of the polyester family that is derived from petroleum. First synthesized by the DuPont Company in the 1940's, PET has become the world's most used plastic. Most commonly found in the form of plastic bottles, PET can be easily modified for use in a wide range of applications with the modifier being identified as a suffix letter in the name.

A sector that sees extensive use of PET and its derivates is the textiles industry, which utilizes PET in both new and recycled form to create polyester fabrics.

In dentistry and orthodontics as well, is used for dental aligners with some of the more recent brands, like Invisalign and Smile-Direct Club, creating plastic, form moulded alternatives to traditional metal braces.

But the main application of PET is in packaging for food, beverage, cosmetics, soaps, detergents and various other reactive chemicals. This huge employment in contact with food and chemical reactive substances is possible thanks to PET limited reactivity to moisture and chemicals.

- Waterproof
  PET is commonly used to produce water bottles and containers. With the right settings it is possible to achieve waterproof results also on desktop 3D printers.
- Food safe
  Like already mentioned, PET is widely employed for food and beverage packaging thanks to its limited reactivity to moisture and chemicals.
  On the other hand 3D printing, as a manufacturing process, is not food safe, since eventual gaps between the layers may be place of proliferation for bacteria. PET could be the solution to this problem if printed with the right printer and with high precision.
- Transparent
  PET is naturally colorless and transparent, a trait that can be exploited for aestethic purposes. Unfortunately, glass-like transparency is impossible to achieve on desktop 3D printers just yet.
- Strength
  Stronger than PLA, making it a great solution for more structural application
- Odorless
  Differently from other thermoplastics polymers like ABS, when melted and printed it doesn't produce bad smells, it is almost completely odorless.
- Recycling
  PET is easy to recycle and it is widely recycled on the industrial scale, especially given its sheer volume of production, which makes it one of the most produced plastic typology on the planet.

The most useful benefits, especially for 3D printing, for which the material stands out are:
Unfortunately, just like PLA, even PET presents some limitations when it comes to 3D printing, the most noteworthy are:

- Retraction
  PET is not suitable to sustain retraction stress. Especially when 3D printed, regardless of the printer's model, It is hard to tune it to make it retract without causing stringing and oozing.
- Fragility
  PET is quite brittle a quality that prevents its emplyment in numerous application fiels. Luckly, like mentioned above, PET can be easily modified to obtain variants of the material with better properties.

PET and technical data

The table on the right report the most important data to know about PET n order to print it correctly.

Table 9: virgin PET datasheet

Data taken from MatWeb.com

Properties	U.M.	Value
Density	g/cm^3	1.5 - 1.8
Elastic modulus	GPa	6.0 - 14.6
Elongation at break	%	0.50 - 6.0
Flexural modulus	GPa	5.5 - 16.0
Flexural strength	MPa	120 - 278
Glass transition temperature	°C	57 - 63
Heat deflection temperature (at 455 kPa (66 psi))	°C	230 - 250
Melting onset	°C	245 - 255
Shear modulus	GPa	4.6 - 8.9
Specific heat capacity	J/Kg	1720
Strength to weight ratio	kN	-
Tensile strength	MPa	108 - 157
Thermal conductivity	W/m	0.23 - 0.27
Thermal diffusivity	-	-
3D printing extrusion temperature	°C	271 - 295
3D printing flow tweak	-	0.95 - 1.20
3D printing bed temperature	°C	60 - 100

When it comes to 3D printing PET the approach of the literature is different from the one shown for the PLA. Instead of looking for the perfect parameter of print to maximize the mechanical properties of the material, it has been observed an interest in the internal geometry of the samples, which can affect the mechanical properties of the 3D printed product and can be extremely determinating in structural application. Through tensile test, hardness measurement and surface roughness measurement. Numerous studies have been conducted aimed to investigate how the 3D printing occupancy rates effect the mechanical properties of PET material products.

The tensile strength of samples with different occupancy rates is reported in Table 10, while the data about the elongation have been reported in table 11.

It is possible to notice that, as expected the average value of tensile strength of samples increase with the occupancy rates. the samples with 20% occupancy rates have average tensile strength value of 30,71 MPa and samples with 80% occupancy rates have average tensile strength value of 49,41 MPa.

On the other hand, the elongation has an opposite behaviour, since it increases as the occupancy in lower. That the highest elongation average value is in fact 0,47%, a value reported by samples with 20% occupancy rate while the lowest elongation average value is 0,21% of samples with 80% occupancy rate.

To sum up, the Breaking elongation is higher in the sample with lower occupancy rate, while sample with higher occupancy rate have higher toughness.

An important note is that tensile strength does not change significantly for occupancy rate higher of 50% and so using higher occupancy rate is not efficient in respect of process time.

Table 10: tensile strength values recorded

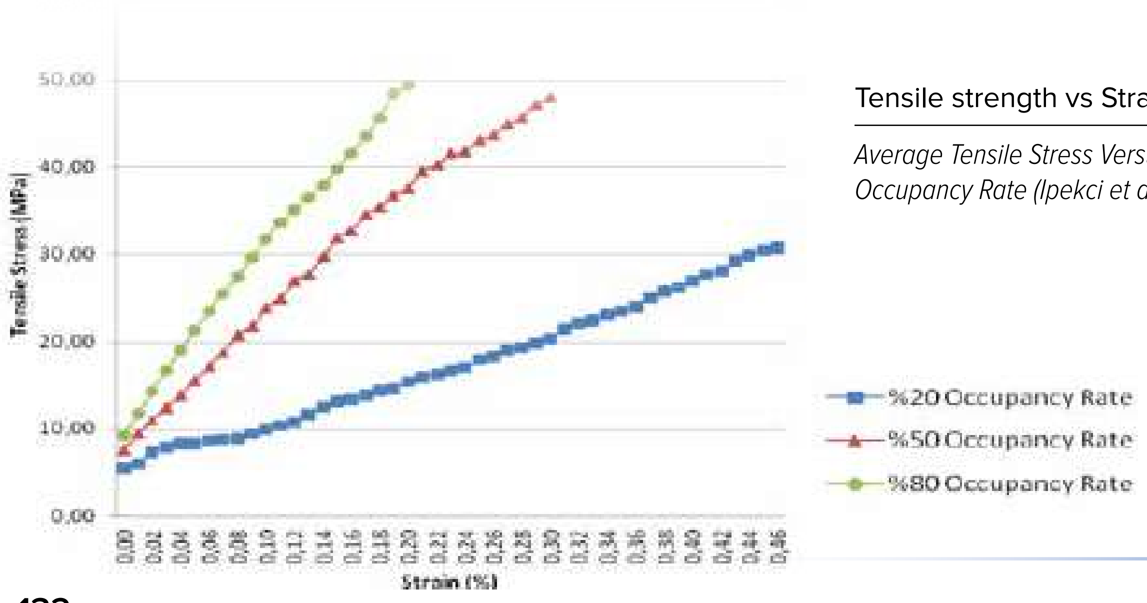
The value for the tests resul are expressed in MPa (Ipekci et al,. 2018)

Occupancy rate	Test 1	Test 2	Test 3	Average
20%	30,58	28,53	32,97	30,71
50%	42,85	54,17	46,88	47,98
80%	47,93	51,41	48,40	49,41

Table 11: elongation values recorded

The value for the tests results are expressed in % (Ipekci et al,. 2018)

Occupancy rate	Test 1	Test 2	Test 3	Average
20%	0,46	0,51	0,44	0,47
50%	0,30	0,32	0,32	0,31
80%	0,22	0,23	0,20	0,21



Tensile strength vs Strain values

Average Tensile Stress Versus Strain Values for Occupancy Rate (Ipekci et al,. 2018)

Other than the occupancy rate of PET 3D printed samples, there is also another area that is cause of interest in the scientific literature: the internal geometry. One of the most crucial points about the internal geometry of 3D printed PET components is the presence of discontinuities, a common defect in 3d printed thermoplastic polymers that can mine their integrity and mechanical properties.

Numerous studies focused on understanding how to regulate the properties of low-density structural materials by investigating the influence of the shape and construction of the part, taking into account the presence of perforations.

In the work by Szczepanik et al., 2018 for example, specimens with polygonal, circular, and square perforations were designed. Various shapes of the perforation forced different directions of the flow of material during printing, so the mechanical properties were affected. Bending and compression tests appear to be highly effected by the structure of the samples.

In comparison with fully dense models, the bending strength of PET always decrease. To be more specific, in the case of a sample with holes with a polygonal shape, with 6 sides and a circle diameter of 2 mm, the bending strength decrease by 54%. In the case of of a sample with holes with square shape, with diameter 3 mm, and angle of rotation 0°, the bending strength decrease by 1,64%. Finally, In the case of of a sample with holes with a circular shape, with diameter 4.25 mm, and angle of rotation 0°, the bending strength decrease by 83%.

Studies on the compression tests appeared to be particularly relevant as well. Compression results in fact, have demonstrated that the perforation type of a specimen's structure (holes) decreases the strength differently, hence, the values of specific strength range from 26.5 MPa to 32.9 MPa for the PET samples.

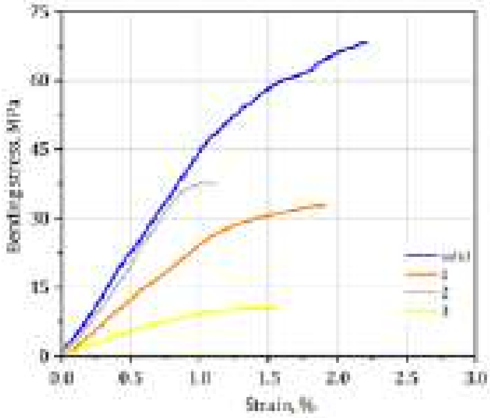
Table 12: bending tests results

The structure types of the samples analyzed can be four:
0: fully dense
1: polygonal shape, 6 sides, circle diameter 2 mm, angle of rotation 30°, loop spacing 5.6 mm, pattern direction 0°, number of instance 41,
2: square shape, diameter 3 mm, angle of rotation 0°, loop spacing 5.4 mm, pattern direction 0°, number of instance 39,
3: circular shape, diameter 4.25 mm, angle of rotation 0°, loop spacing 5 mm, pattern direction 0°, number of instance 45.
(Szczepanik et al., 2018)

Structure	$\sigma_{0.2}$	σ_b	ε_c	ρ	$\sigma_{b0,2}/\rho$	σ_b/ρ
-	MPa	MPa	%	g/cm^3	-	-
0	48.9	69	2.22	1.13	43.3	61.1
1	29.2	33	1.91	0.8	32.7	41.3
2	36.9	37.5	1.1	0.82	45	45.7
3	7.5	10.5	1.58	0.55	13.7	19.2

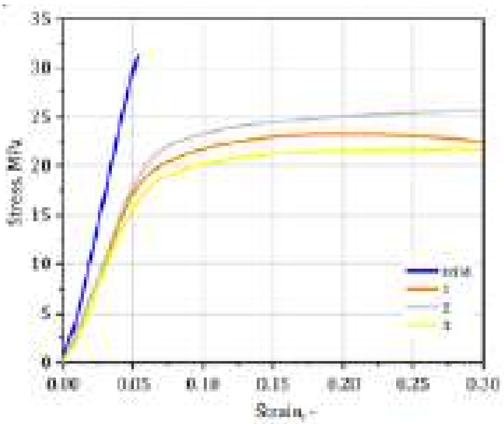
Graph 1: Bending stress vs strain

The value for the tests resul are expressed in MPa
(Szczepanik et al., 2018)



Graph 2: true stress - true strain compression curve

The value for the tests results are expressed in %
(Szczepanik et al., 2018)



Recycled - PET

From the study of the literature and the analysis of the case study, reported also in chapter five, the role o PET in the 3D printing industry seems closely related to the concept of recycling.

Most company and brands, as well as researchers and scientists, seem interested in the recyclability of this material and the opportunities that it can offer. In chapter four and five, out of the 8 case studies reported that employed PET as a starting material, all 8 of them used recycled version of it, sourcing from wastes of different kinds (mostly coming from food and beverage packaging).

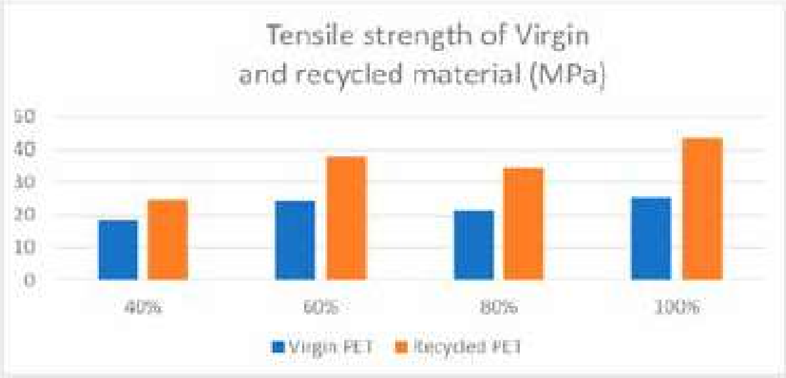
The study of scientific literature has showed a keen interest from researchers in the capabilities of the recycled PET (rePET), especially when comparing it with the virgin version of the material itself, in order to grasp the differences in the mechanical properties between the two, and if the recycled version can actually be a viable option to enable a circular economy system.

Material test: PET vs rePET

In order to have the most reliable result from the analysis of a recycled material, the literature revealed an interesting trend among the tests of rePET. Instead of using waste material recovered from the “real world” is common practice to grind down virgin PET (most commonly from plastic bottles, since it’s the easiest way to obtain PET), to obtain the pellets to produce the filament that will be then used to print the samples. This procedures result particularly useful since it allows to avoid to incur in results altered by contaminating agent, and allows for more precise measurement.

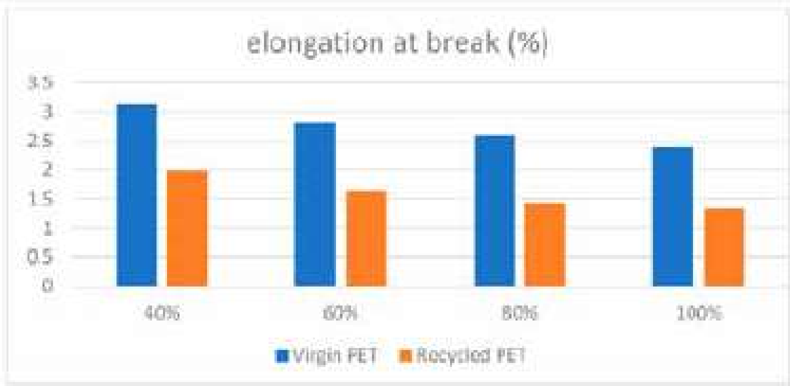
Graph 3: Tensile strength comparison

Tensile strength of a recycled and virgin 3D printed PET



Graph 4: Elongation at break comparison

Elongation of a recycled and virgin 3D printed PET



In the literature, the type of tests that appear more frequently for this material are simple comparison of tensile strength values, difference in stress-strain curves, and elongation at break.

In the work carried out by Oussai et al., 2021, a first batch is printed with virgin PET filament (achieved by grinding some PET virgin material). The same batch is then “recycled”, is in fact grinded once again and from the same material a new recycled batch of sample is printed, and their mechanical properties are compared to the virgin batch.

In the analysis of the test of tensile properties of polyethylene materials the extension/strain ratio appear to be sufficient to estimate strain. The PET tensile specimens’ strain/extension ratio has been recorded to be around 0.243 after plotting the strain from extensometers against the crosshead extension (Oussai et al., 2021). The strain from the crosshead extension, which forms part of the modulus calculations, were estimated via the aforementioned method.

The average tensile strength and elongation at break of the virgin and recycled materials are illustrated in Graph 3 and Graph 4 and in Table 12 for the virgin material and Table 13 for the recycled one.

Table 12: virgin PET

Tensile strength and elongation at break of virgin PET filament (Oussai et al,. 2021)

Virgin PET	n° of tests	Tensile Strength	Elongation at Break
(%)	-	MPa	(%)
100	5	25.26	2.39
80	5	21.34	2.61
60	5	23.92	2.81
40	5	18.10	3.12

Table 13: recycled PET

Tensile strength and elongation at break of recycled PET filament (Oussai et al,. 2021)

Recycled PET	n° of tests	Tensile Strength	Elongation at Break
(%)	-	MPa	(%)
100	5	43.15	1.33
80	5	34.21	2.45
60	5	37.80	1.64
40	5	24.33	1,98

The properties of shear, tensile, and hardness served as the parameters for both the recycled and virgin test samples, and the results were obtained with this focus. The tensile modulus of the elasticity and the yield strength of the 40 virgin specimens and 40 recycled specimens were examined. Table 7 and Table 8 illustrates the results. Establishing an offset value of 0.11 mm enabled the analysis of the yield point. The tensile specimens were used to form a pre-set relationship between the strain and the crosshead extension which, in turn, allowed the tensile modulus to be measured. An estimate of the strain can be deduced without the extensometer use by analysing the extension/strain ratio and utilizing the reference.

Table 14

Average shear strenght (above) and average hardness (below) recorded by samples of virgin and recycled PET (Oussai et al,. 2021)

	Virgin	Recycled
Average shear yield strength (MPa)	28,448	29,253
Standard deviation	0.69	2.00
Average hardness (shore D)	73.10	68.71
Standard deviation	0.725	2

Further theorical study

While the variance between the recycled and original is evident, the results are very encouraging. However, it is important to note the 3–9% decrease in the average mechanical properties of the recycled samples in comparison with the virgin samples. Additionally, the increase in standard deviation signifies an increased variability of the recycled material's results.

The capacity to mix plastic wastes and require less energy are two areas that must be improved upon within chemical recycling in order to become more sustainable. The use, technological development, and demand of polymers that cannot be recycled should also lessen. Plastic solid waste can only be recycled via mechanical recycling, as per a review of the literature. Through melting, shredding, and re-moulding after washing, organic residue is removed from the polymer and the resultant material becomes ready for manufacturing again once it is compatible with virgin plastic. Chemical recycling refers to the method distinct from standard mechanical recycling which selectively produces fuels, gases or waxes using catalyst, otherwise known as pyrolysis. The present technologies involved in this process exact at high energy cost, which impedes prevalent use. The burning of materials and the resultant collection of energy is another option known as incineration. The inability to reuse or recapitalize are drawbacks of this method, yet its strengths lie in its convenience as mixed wastes require no sorting. While sophisticated laboratories test recycled plastic waste, incineration is not energy efficient.

The stoppage of the material flow presented by the PET was found to be the principal issue linked to the rPET extrusion. Various elements caused the reduction in hardness, tensile strength, and other properties. One such element could be the recycled filament's properties degrading and other factors include the limit in the inter-layer adhesion and the extrusion interruptions when 3D printing. Flaws in the samples and recycled filament could also be caused by nozzles clogging. The potential presence of microscopic impurities in the filament is the principal problem regarding filament re-extrusion as the process is often carried out without a filter.

Conclusions on PET

The literature and case study analysis revealed that, when it comes to PET the main focus for this material is the on its structural capabilities.
A deep analysis has been on its mechanical properties and how these can be influenced by the internal geometries and shape of the object itself. Numerous studies have been conducted aimed to investigate how the 3D printing occupancy rates effect the mechanical properties of PET material products. The tests on the mechanical properties of different samples with different occupancy rate reported that, logically, the higher the occupancy rate, the higher will be the toughness of the product, while lower occupancy rate will have higher breaking elongations. An important data that emerged by the literature analysis is that tensile strength does not change significantly for occupancy rate higher of 50%, so using higher occupancy rate is not efficient in respect of process time and final weight of the product.

After the occupancy rate, the issue of internal geometry has been analysed. By confronting different samples, printed with different internal patterns, it was possible to ascertain that a fully dense 3D printed PET object will present the highest mechanical properties, but in order to reduce the weight and the density of it, a valuable option is to practice geometrical holes along the cross section axis. The most effective shapes for the holes appeared to those most geometrical and with the least number of sides, like triangle and squares. The data reported from the analysis of samples with such qualities confirmed a decrease of the bending strength decrease, but only by the 1,64%, a negligible value for most applications.

Finally, due to the data reported in case study analysis in chapter four and five, as well from the study of the available literature, a huge interest was found in the recycling of PET waste material, and the reuse of such waste in the 3D printing industry. Consequently, a comparison between the mechanical properties of virgin and recycled 3D printed samples of PET seemed logical, in order to better evaluate the possible applications of the recycled material.
From the data collected, the elongation at break and the average hardness of the recycled samples reported a slight decrease, while, surprisingly the tensile strength and the average shear yield strength actually presented increased values.

With this work for my master degree, my aim was to explore new strategies and materials to achieve a circular economy system through additive manufacturing processes.

After clearing some basic notion about the whole **additive manufacturing** industry, between the numerous variants of 3D printing systems, i decided to focus my research on the material extrusion processes, especially on the **FFF/FDM** ones, and their variants like **FGF** and **robotic FFF/FGF**. This choice was taken after a deep market analysis, where i could observe that this additive manufacturing system is not only the most employed, but as well the richest in terms of research and innovation rate.

The concept of **circular economy** was then tackled in a similar way. The basic notion and its history have been analysed first, then a more in depth study was conducted to understand what strategies does it suggest to achieve a real looping system in terms of material and resources. Attention has been brought to the **10Rs principle** and the Ladder of Lansink, the two most modern and most efficient concept that act like a textbook in order to achieve circular economy.

Once the theorical studies have been exhausted, i turned my attention to the practical world, drafting a **synoptic table** containing more than thirty case studies worthy of attention. The case studies collected concerned design projects made with additive manufacturing means of production (FFF, FDM or FGF systems) and with a keen interest in the ecological side of design.

Focusing on the circular economic strategies adopted by these projects it was possible to see how the most followed ones have been: **R9-Recycle**, **R7-Remanufacture** and **R-1-Reduce**. From the material point of view on the other hand two materials stood out from the crowd: PLA and PET, which have been further studied in order to fully grasp their capabilities and limitation.

Studying the lireture availeble on the PLA, numerous studies reported an interest in the variable parameters intrinsic in the 3D printing process that can alter the material mechanical properties during the printing process. This why the analysis focused on what parameters can alter what properties and in which way.

In particular, it emerged that **raster angle, build orientation and layer thickness** have demonstrated to be influential on the UTS of the 3D-printed PLA specimens. The experimentation through **ANOVA** methods explained that, layer thickness and raster angle have a negative correlation when combined with build orientation.

The PET, during the case studies analysis, showed large employment as a **second hand raw material**, being recycled and reused from food and beverage packaging in multiple projects. The analysis of this material properties has been enforced through the knowledge from the availeble literature, as well as case studies.

Diffrently from the PLA, the literature revealed more intrest in the **structural capabilities** of this material rather than systems to henhance the mechanical properties. The analysis of the case studies has revealed that indeed the internal geometries of the sample have a massive influence on the properties of the material and alter drastically it's behaviour.

Overall the recycled PET presented encuraging results for future application since its mechanical properties appeared closed to those of virgin PET.

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POLITECNICO
MILANO 1863