ADDITIVE MANUFACTURING TECHNOLOGIES

The additive manufacturing technology can be used to help the strand of society with limited resources in a sustainable way.

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“Make it matter.”

Hewlett Packard enterprise (HP)

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B. LIST OF ABBREVIATIONS

Additive Manufacturing	AM
Subtractive Manufacturing	SM
Direct Digital Manufacturing	DDM
Local Digital Manufacturing	LDM
Multinational Company	MC
STereo Lithography/Standard Triangle Language	STL
Computer Aided Design	CAD
Computer Aided Manufacture	CAM
Numerical Control	NC
Developing Country	dP
Developed Country	DP
International Centre for Numerical Methods in Engineering	CIMNE
Rapid Prototyping	RP
Proportional-Integral-Derivate controller	PID
Volts	V
Amps	A
International Organization for Standardization	ISO
Selective Layer Sintering	SLS
Direct Energy Deposition	DED

Hewlett and Packard	HP
National Aeronautics and Space Administration	NASA
Non-Governmental Organization	NGO

1. INTRODUCTION

Additive manufacturing technology (AM), most commonly known as 3D printing, consist of building parts, layer upon layer, directly from 3D model data. In order to print in 3D, a Computer Aided Design (CAD) program must be used to design a part, which is sliced into thin cross-sections called layers that are built up from the bottom to create the part.

This technology is far to be considered novel. It was born thirty years ago under the name of rapid prototyping. This term emphasized the idea of quickly basis model creation from which the final product can be derived. However, nowadays, due to the improvement in computer technology (processing power, graphics capability, machine control), the increase of material properties knowledge, and the development of manufacturing process quality, restricting AM possibilities to its original conception is unthinkable, that is, AM has evolved to a legitimate manufacturing process. Attending to the wide range of possibilities provided by the AM techniques, the positioning of AM as the cornerstone of a so-called third industrial revolution (The Economist) is not surprising.

During its history, a great number of printing processes have been invented, such as vat photo-polymerization (resin), selective laser sintering (powder bed), poly-jet or laser engineered net shaping (LENS) and, the most commonly known and used, material extrusion. This variety in the AM revolution provides a range of advantages over conventional manufacturing methods, such as: freedom of design (complex shapes), seamlessness (reduction of process steps), reduced costs (optimization in material, as it avoids moulds, hand carving and forming techniques) and high accuracy (tens of microns).

"*Many times across history a new technology has transformed our lives. Today, the latest revolution of the internet is settling into a gentle pattern of 'evolution', and as* *this is occurring, the next revolution of 'additive manufacturing' or '3D Printing' is waiting in the wings.*"

3D Printing: Second Edition, Christopher Barnatt

The main development in this research project is based upon the study of the AM technology and several of its most common and revolutionary techniques. After understanding the industrial revolution that this technology is creating, there should be sufficient theoretical context in order to introduce the practical development of the project. In that section previous research will be used to apply the AM technology practically, testing it by putting to use a 3D printer that must evaluate the hypothesis which is being proposed. In this practical development a design for a one-off production (single product is designed and made to a client's specification) will be, prior to being printed sustainably from recycled filament, experimentally analysed through the computational framework.

Thus the hypothesis I will evaluate with this research is:

- The additive manufacturing technology can be used to help the strand of society with limited resources in a sustainable way.

I have chosen to research on this topic because ever since I first made contact with the 3D technology I was fascinated. The concept of materialising what was originally an idea at such a low cost and with so much independence from Multinational Companies (MCs) has revolutionised design at a consumer and manufacturer level. The potential of the technology in social applications is also high and I found it should be harnessed; this is why I chose to evaluate this hypothesis.

Another force that is driving me to develop this project is the motive to fight the wealth gap that is increasing between countries. As technology thrives, so do the Developed Countries (DC), but it is always at the cost of others: the developing countries (dC). With 3D printing being a revolutionary technology with lots of practical applications that could enable a better development in many deprived areas of the world, there is currently little work being done with that objective. That is why I chose to research the former hypothesis, and some more specific ones mentioned later on.

I undertook a work experience program in June 2016 at the International Centre for Numerical Methods in Engineering (CIMNE) where I worked with the master's student Tomás Varona in a project entitled "Sensitivity analysis and experimental calibration for the Additive Manufacturing computational framework". It consisted in the analysis of 3D prints previous to being printed in order to test the restraints it could withstand and how the printer would cope with the design. This placement encouraged me to apply the knowledge I had gained to try and apply it with relation to my project and hypothesis.

Finally, I acquired my eagerness for sustainability at a volunteering community service project I carried out in Costa Rica in July 2016, where I helped with conservation efforts to protect the Pacific Ocean. I learned about the poor preservation efforts the human race is doing towards the planet by mass manufacturing plastics at a higher rate than they are decomposed or recycled. However, I found that through 3D printing technologies and the industrial revolution it is driving the world into, a change could be made.

In order to prove my understanding of the theoretical research of AM and what I will learn from building a 3D printer, I will simulate the capacity of adoption of the technology in an environment where it is new. To do that I will carry out a class to a selected group of students with very basic knowledge on the matter in order to, both, prove my personal understanding on the topic by the capability of divulgating my knowledge and test whether AM technologies could be understood by someone who sees it for the first time.

This research project is therefore going to be based on a theoretical research which will then be extensively applied to fully understand the potential of the AM technology and 3D printing in an unknown environment for the technology.

2. OBJECTIVES

With this research project I aim at completing a set of objectives that will lead me to successfully evaluating my initial hypothesis. These objectives have been organised into more specific sub-headings in order to pin-point their importance in the development of the project in its different perspectives. More specific hypothesis will be formulated in relation to the different objectives in order to complement the initial, slightly broader and generic, hypothesis.

2.1. CONCEPTUAL OBJECTIVES

With this research project I am aiming at reaching a full understanding in the AM technologies. I am going to analyse several printing techniques in order to evaluate a broader spectrum of applications the 3D printing technologies are used in. However the main focus of the theoretical research will be based on the current AM industry and how this one will develop in a near future to create the next industrial revolution. Finally I will also focus on the sustainability of 3D printing as a developing technology as I find it is a very important aspect in a world where plastics are being abused and overproduced.

In order to build a 3D printer and a filament extruder[1] (in order to recycle plastic) I must also research the structure of a low-cost 3D printer to understand the engineering behind it. This will require basic construction and programming skills that I will develop with an Arduino and basic hand tools.

Finally, my research will also entail the ability to be able to use several programs in order to design, orientate, calibrate and transform ".STL" files (STereo Lithography/Standard Triangle Language – files that describe the surface geometry of a 3D object) into G-codes (a Numerical Control (NC) programming language –

[1] A device for making 3D printing filament (material used in conventional 3D printers) out of plastic pellets or recycled plastic pieces (possibly from unwanted prints).

what controls the printer's movements to build the object). The programs I will have to work with and deepen my knowledge in are:

As to the design of parts: FreeCAD, SolidWorks and Thingiverse.com.

As to the calibration and transformation of the STL into G-code: GiD, NetFabb, Slic3r and Cura-BCN3D.

2.2. PRACTICAL OBJECTIVES

The objectives for the practical development are to be able to apply the knowledge gained in the theoretical framework in order to build a 3D printer, a filament extruder, test the properties of a 3D design through the computational framework (on the computer), print the piece and finally teach a group of people the basic concepts and how to work with a 3D printers to print pieces themselves.

Once the printer and filament extruder are built they must be calibrated to suit a specific plastic and programs that will enable me to successfully print in 3D. The testing of the properties of the design on the computational framework will require me the knowledge on the program GiD. Then will then print the design of a prosthetic arm in order to test the customizability for one-off batches in this manufacturing process, and, finally, test the capability of inclusion of the AM technology by instructing all of my findings to a group of people.

Therefore, in order to sustain my practical development, I formulated a hypothesis in relation to it:

- I will be able to build a 3D printer and print a prosthetic hand with it, and be able to teach a group of 7 people how to do that too.

2.3. SOCIAL OBJECTIVES

In order to give this research project a greater repercussion when applied to the real world I decided to develop a social purpose. This idea consists in introducing the AM technology in a dC, or in a city/town within that country, which would help in the production of very specific components that would otherwise be too expensive to produce.

I will therefore collaborate with a well-established social project, called “Cyborg Beast”, for which low-cost hand prosthetics printed in 3D have been developed at 1,25% of the average price for a normal hand prosthetic. I will attempt to print and assemble a 3D printed prosthetic hand and, moreover, my objective will also be to be able to teach a group of people with no knowledge of 3D printing whatsoever (simulating a group of people from a poorly developed town, that will have no knowledge of AM technologies) to be able to understand the practical developments undertaken in this project.

Although these objectives are tightly linked to the practical development, I also formulated a hypothesis in relation to it:

- A group of 7 people will prove to be able to sustainably print a prosthetic hand for 1,25% of the average price for a conventional hand prosthetic.

2.4. ENVIRONMENTAL OBJECTIVES

We currently live in an unsustainable world, as we use resources up at a faster pace than they are produced. This means that we are facing a need to become sustainable with the manufacturing processes, especially those involving plastics, since most take thousands of years to decompose and they are polluting and affecting many natural processes.

3D printing proves to already be far more sustainable than other manufacturing processes, but one of the big problems is that they too use plastic. Since there is a lot of waste produced in the AM: support material, failed prints, brims and waste produced from calibration errors; I focused on being environmentally sustainable in my research project. To do this I will build a filament extruder, which can re-melt failed 3D printed material into re-useable filament.

This will also make the process of printing cheaper. I hypothesise that:

- Plastic from 3D printing can be successfully recycled, thus making the manufacturing process 100% sustainable and 50% more inexpensive.

3. METHODOLOGY

The hardest task I encountered in the development of my research project was finding the appropriate hypothesis, for the topic I was going to base it on was always very clear: 3D printing. I wanted to develop a project that could be favourable to those with fewer resources, sustainable and containing the AM technology as a pillar for it and that is how I came up with the main hypothesis:

- The additive manufacturing technology can be used to help the strand of society with limited resources in a sustainable way.

My development then consisted of an initial research on what 3D printing was. I had a rough idea of this manufacturing method before I started the project, but I needed to fully understand it before I started my research.

The methodology to finding most of the information was mainly through the internet, where I found many articles and webpages that talked about the many aspects of this technology. I also found two books written by the same author, Christopher Barnatt, who is an activist in the development of 3D printing as he believes it will revolutionize the world, which I read in order to deepen my understanding on the topic. I also had the chance to visit the HP (Hewlett Packard) 3D printing headquarters (based in Barcelona) to witness the next generation of 3D printers which will most likely be the revolution in the future. Moreover, since Barcelona is a fairly active and pioneer city in 3D technology I was also able to visit several conventions, such as the “IN3DUSTRY” where the AM technologies were being showcased for investment and partnership in business, or a visit to IAAC (Institute of Advanced Architecture of Catalonia) which gave me a good understanding of how the technology can be applied directly in projects.

The research on most of the conceptual information was relatively easy as it is very well documented online and I had a good access to other sources.

The real challenge of the project came with the practical development. In order to build a 3D printer I had to contact BCN3D (an AM company developed in Barcelona) to assist me with the mechanical and circuits building of the printer. I also found many videos and pages online very helpful in this process.

Once I had built the printer I also had to use it, so I printed and built a functional prosthetic hand from a social, open sourced enterprise. With the printing process I had to develop the skills to handle the programs that control the printer with research online and with some help from BCN3D. Since the design I was printing I downloaded it online (due to a lack of time, as I would have designed it instead) it was much simpler to handle with the several programs that process the STL design.

I then also had to build the filament extruder, which was a harder task as I found very little help and it is not extensively documented online. I was able to acquire the pieces to build it and, working from circuit plans and vlogs online I was able to build it and successfully test it with the help of my tutor. I also contacted via email several companies and creators that had worked with filament extruders to share my concerns in hope of a useful response.

Finally, after documenting the development of the project, I was able to carry out a lesson that would simulate the introduction of my research project in a strand of society with limited resources. To do that I was able to select a set of students and plan a lesson to teach them basic knowledge on AM technologies and evaluate the level of adoption through a survey after the presentation.

4. PROJECT BODY

4.1. THEORETICAL DEVELOPMENT

4.1.1. ADDITIVE MANUFACTURING: STATE-OF-THE-ART

As I have said before, the additive manufacturing (AM) technology, most commonly known as 3D printing, consist of building parts, layer upon layer, directly from 3D model data in order to make a three dimensional solid object. AM was founded as a Rapid Prototyping (RP) technique in the 1980s by 3D Systems primarily used to quickly fabricate conceptual models of new products for form and fit evaluation, to test the prototype's properties in a quick and inexpensive way. The *status quo*[2] of the AM technology has developed into producing increasingly final products instead of simply prototypes. The techniques have been evolving for over more than three decades, broadening the spectre of materials available and the possibilities, slowly driving away from its original purpose of RP.

In the last few years, 3D printing has started to evolve into a next-generation manufacturing technology that has the potential to allow the local, on-demand production of final products or parts thereof.

The name AM defines this technology as it consists of adding layers of materials to build up a desired part, as opposed to the conventional computer aided manufacture (CAM) which consists of subtracting material from an initial block of material, and thus giving it the name of subtractive manufacturing (SM).

SM has been the most common way of manufacture for decades, and still is.

However AM shows a series of advantages over this conventional manufacturing method which are likely to cause a manufacturing revolution.

[2] Current state.

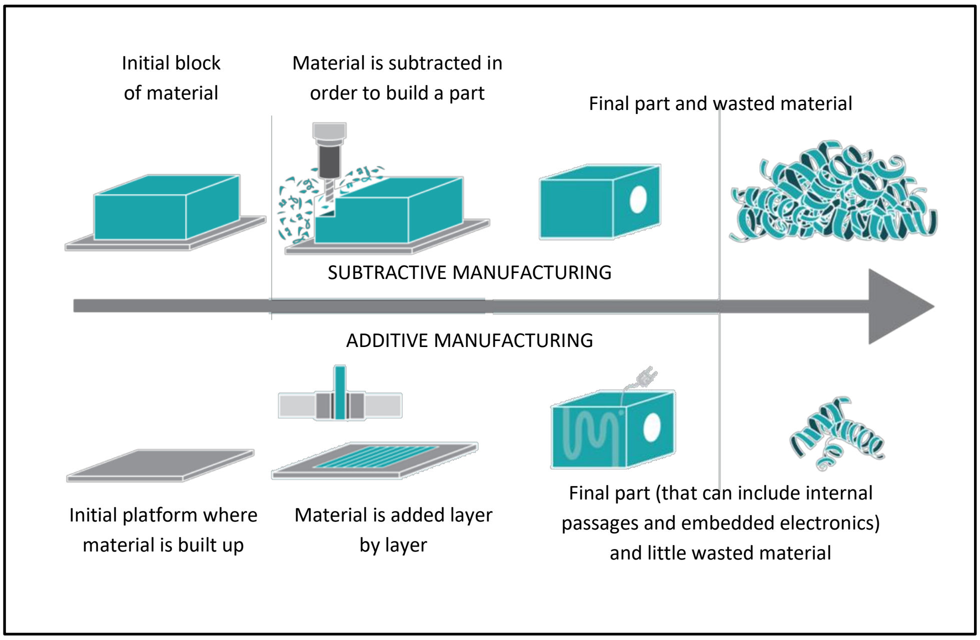


Figure 4.1. – Subtractive manufacturing vs. Additive manufacturing

3D printing encompasses a wide range of AM technologies, which will be analysed later on in the project.

4.1.1.1. ADVANTAGES AND DISADVANTAGES

AM gives 3D printing many advantages over conventional, SM processes. However, there are still certain restraints with the capabilities of 3D printers, and that is why SM and other methods are still being used. For example, the sizes of objects that can be printed are restricted by the size of the printable surface.

One of the advantages of the AM over the SM is that fewer waste products are produced (as seen in **Fig. 4.1.**), which can also be fully recycled into useful building material. However, AM shows an extensive list of advantages over SM which are driving this revolution:

EFFICIENCY & SUSTAINABILITY

3D printing has become a far more efficient alternative for conventional SM methods since they produce substantially less waste. Moreover, in 3D printing, even if any material is wasted (like the support material[3]) it can be recycled and reused, whereas in the latter process there is a lot of waste produced which is very difficult to reuse.

AM is also widely used in rapid prototyping, so it offers a faster and cheap way for designers/companies to produce prototypes quickly and with high precision.

Other manufacturing methods require the creation of expensive tools and moulds to produce prototypes and objects to the same standards as 3D printers are able to, but 3D printing enables flexibility in the design without having to alter the functioning of the machine which is unprecedented in the world of manufacturing.

CREATIVITY & COMPLEXITY

The inexpensive nature of the AM technologies offer lots of creativity for designers as producing intricate designs is still low cost. Since AM builds layers upon layers, internal properties (such as internal passages or infill percentages[4]) or embedded electronics can be printed to offer possibilities that cannot be obtained with conventional manufacturing methods. Furthermore, AM technologies have the accuracy of tens of microns in their designs, which enable greater detail and complexity in the designs.

In machining, several tools changes are usually needed to create the final product. The 3D printer is a single tool which can cope with any possible design.

[3] Refer to 4.1.2.1. MATERIAL EXTRUSION.
[4] Material density of the design.

ACCESSIBILITY

The 3D printing industry has grown considerably in recent years due to the decreasing price of consumer 3D printers. This lower price causes a greater part of the population to have access to the technology, thus creating an advantage over SM as more people can use this technology in their favour.

Furthermore, since the products in AM are digital files, there is an ability to share them at a global scale so that anyone can have access to it and simply have to edit a few parameters of the design to be able to print it.

CUSTOMIZABILITY

With the AM technology a piece can be easily edited and reproduced if, say, an error was found in the design. That flexibility in conventional production methods would be highly priced as the whole chain of production could be changed for a single design flaw.

For example, when producing limb prosthesis, the measurements and data from the person’s body will define how the piece will be designed. There must be a different design for every individual limb, as the needs of each individual will never be the same. In conventional manufacturing processes, these changes in the design mean that new tools and moulds have to be produced, resulting in an excessively expensive limb.

In the AM a design can be changed as many times as wanted and the cost will still be the same. Therefore rapid prototyping and one off batches show an advantage in the pace of production and the cost.

On the other hand, there are also other disadvantages when printing in 3D:

MASS PRODUCTION:

When producing one-off batches AM shows a clear advantage over conventional manufacturing methods, however, once the moulds and tools are produced with the SM, mass producing something is far more efficient.

In their current embodiments, usual 3D printers can print around 25 cm^3 of plastic per hour. On the other hand, an injection moulding machine (conventional manufacture) can make several parts that are the same in under a minute.

To print a prosthetic limb, 3D printers may take around 10-20 hours. Injection moulds and other conventional methods can produce the same one in seconds, of course, only once the mould has been formed.

MECHANICAL PROPERTIES:

Another disadvantage of the AM is the varying strength of the pieces produced. Due to the layer-by-layer fabrication process, parts are often weak in the direction of the build, as layers don’t always form a full bond between them as a continuous surface would.

Most AM processes also use polymers that do not provide the properties of conventional materials. For example, most 3D printed plastic pieces will not be able to handle high temperatures as their melting point is usually quite low (which is the property that enables them to be printed).

However, there are several methods of manufacture within AM which favour certain properties in the manufacture. In my research I will study four of those methods in depth by investigating their workings, applications and advantages over other AM methods.

4.1.2. PRINTING TECHNIQUES

As I previously said, there are many different printing techniques available in the AM world nowadays; however I am going to study the four main processes which will take part in most of the current applications of AM in the industry.

Although the processes might be completely different, they all have the same basis of AM, which is building the piece layer by layer which are typically about 0.1mm thick, but can be as accurate as tens of microns.

They all start with a CAD model (shown in **Fig. 4.1.2.** on the left) which is processed, sliced into the several layers and cross-sections and then outputted through the printer.

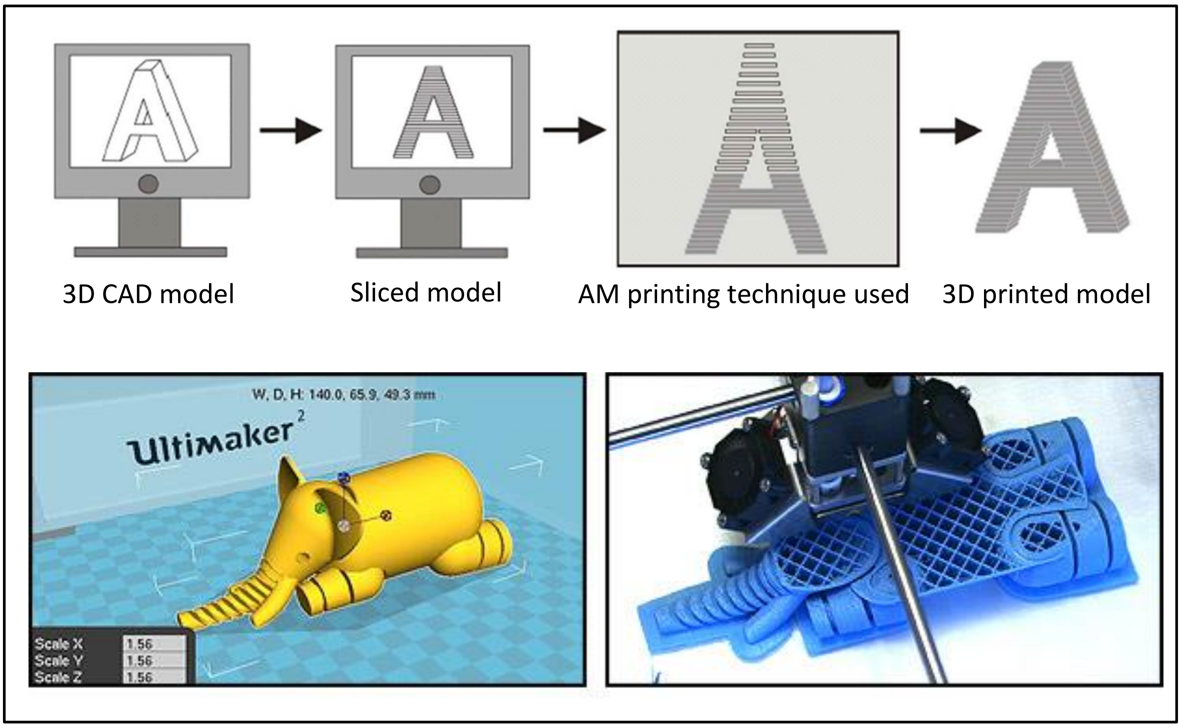


Figure 4.1.2. – CAD model on the left being printed (through material extrusion on the picture) on the right.

Many companies are now manufacturing 3D printers and countless techniques have been developed differently by different companies; however, more than once, we can find several names for a same technique (as different companies develop it in parallel and attempt to claim it their own with a different name). However, in 2015, the International Organization for Standardization (ISO) defined the seven main printing processes and summarized the standards to give the development of the technology an order.

In my research project I will be looking at the four (standardized) most relevant printing techniques at the moment.

4.1.2.1. MATERIAL EXTRUSION

The most commonly known and widely used 3D printing method when it comes to RP and printing low-cost 3D objects is material extrusion.

This refers to any 3D printing process that builds up objects in layers by outputting a semi-liquid material from a computer-controlled nozzle (also known as hot-end).

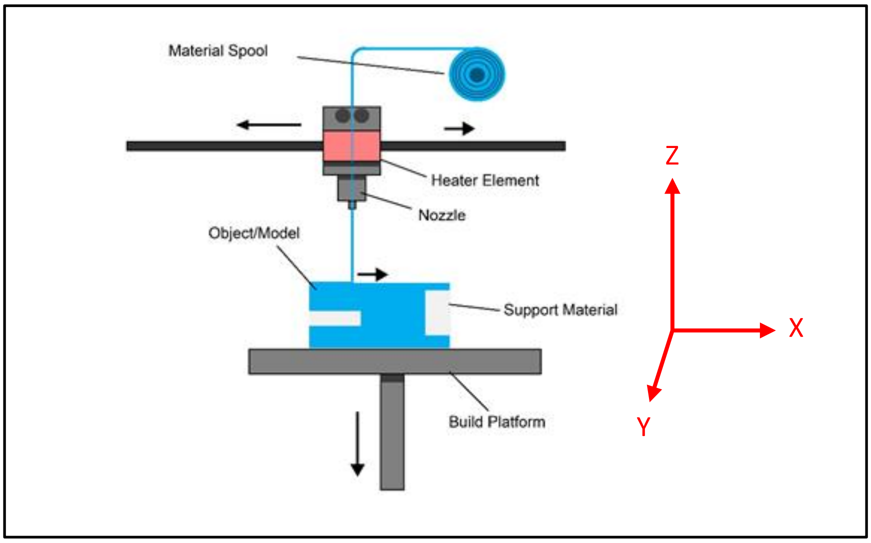


Figure 4.1.2.1. (a) – An example of material extrusion showing the axes that control the movement of the nozzle.

As the material is deposited on the build platform, there are some structures that are overhanging the rest of the piece, so when the printer tries to deposit the plastic it will fall due to gravity and the print will be failed. In order to prevent this, material extrusion uses support material in order to be able to print overhangs.

For example, if we were trying to print the letter 'T', it would start from the bottom and once it reached the top the perpendicular line would not be able to be printed as there would be no other material to be deposited on. However, if support material is used, the ‘T’ can be successfully printed, as shown on **Fig. 4.1.2.1. (b)**. Of course, the best way to print a letter ‘T’ would be to rotate it, as shown on the last diagram, to optimize the amount of plastic used (no need for support material).

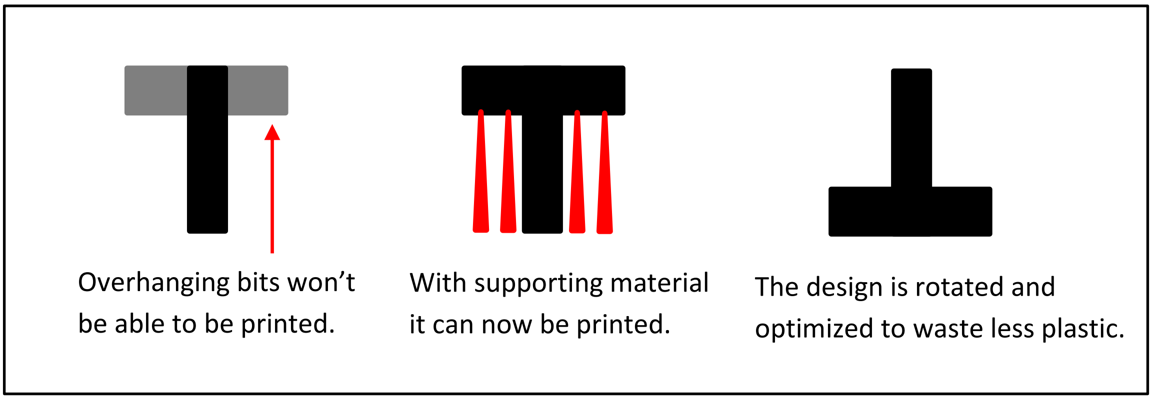


Figure 4.1.2.1. (b) – Overhangs and optimization

Most usually, the build material used is a thermoplastic such as Acrylontirile Butadiene Styrene (ABS) or Polylactic Acid (PLA).

However, through materials science, printing techniques have been heavily developed and other materials such as clay and concrete or even food can now be extruded using this method.

I will study the possible applications of the 3D printing revolution in the chapter for the industrial revolution in more detail.

The above picture shows the 3D printing of food (chocolate).

4.1.2.2. VAT PHOTO-POLYMERIZATION

The next printing technique is called vat photo-polymerization, and it consists on using a laser (or other light sources) in order to solidify successive layers on the surface of a liquid photo-polymer (vat).

Although this sounds like a very specific and complex technique, it is extensively commercialised, most commonly to the name of 'Stereo-lithography'. This technique was the first ever 3D printing process.

This process uses a photopolymer resin as a material. A laser is inflicted upon the resin in order to solidify it and deposit it on the build platform. Once a whole layer has been solidified, the build platform sinks into the resin (it sinks the same height as the height of the next layer) and the laser solidifies the next layer on top of the previous one and it binds them.

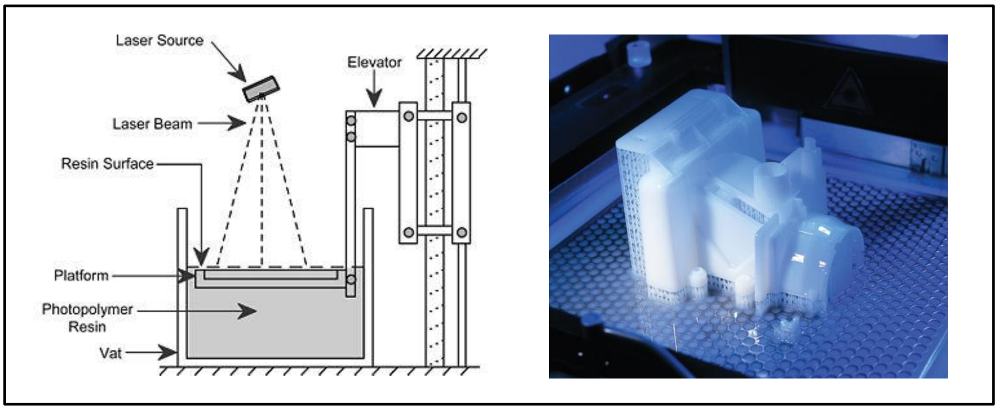


Figure 4.1.2.2. – Process of stereo-lithography in building a part.

The advantage of vat photo-polymerization over material extrusion is that it uses up less material because there are less supports needed in the overhangs. It also produces a more accurate and aesthetically pleasing product. On the other hand, vat photo-polymerization is a far slower process than material extrusion, which means that the latter is more likely to be used for RP whereas final products could be produced by vat photo-polymerization.

Another vat photo-polymerization technique is DLP projection, which consists of projecting the light of the whole layer onto the resin to solidify it completely with one go and make it more efficient.

4.1.2.3. SELECTIVE LASER SINTERING

Selective Laser Sintering (SLS) is a similar printing technique to the vat photo-polymerization as it uses a laser (or heat source) to selectively bind the layers of material; however, instead of using resin it uses powder.

This technique enables the printing of any material that can be fused from powder, so it enables the use of metals, ceramics, sand, wax and plastics such as nylon.

It uses the selective application of heat to bond adjacent powder granules. Once the layer is finished, it is all covered with powder so that the next layer can be printed over it.

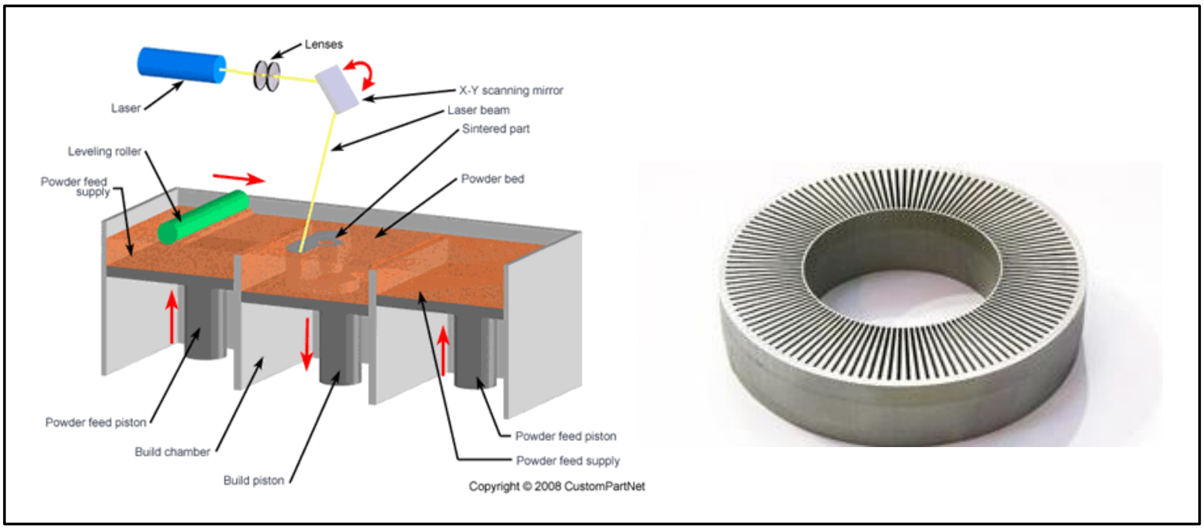


Figure 4.1.2.3. – SLS process and a metal component formed with that technique.

With my visit to the Hewlett and Packard (HP) headquarters in Barcelona I was able to learn further about the SLS printing technique since HP were developing a printer that consisted on this technique.

The picture above shows the SLS printer that is currently under development at the HP headquarters.

4.1.2.4. DIRECT ENERGY DEPOSITION

The technique of Direct Energy Deposition (DED) is similar to the SLS because it also uses heat to fuse powder and deposit the material. However, in this method the powder is selectively fed into the laser beam so that less of it is wasted and only the amount that is fed will melt.

Unlike with SLS, the metal powder being fed in DED can be altered continuously during the printout, therefore enabling the fabrication of objects with properties that can’t be matched with other manufacturing processes.

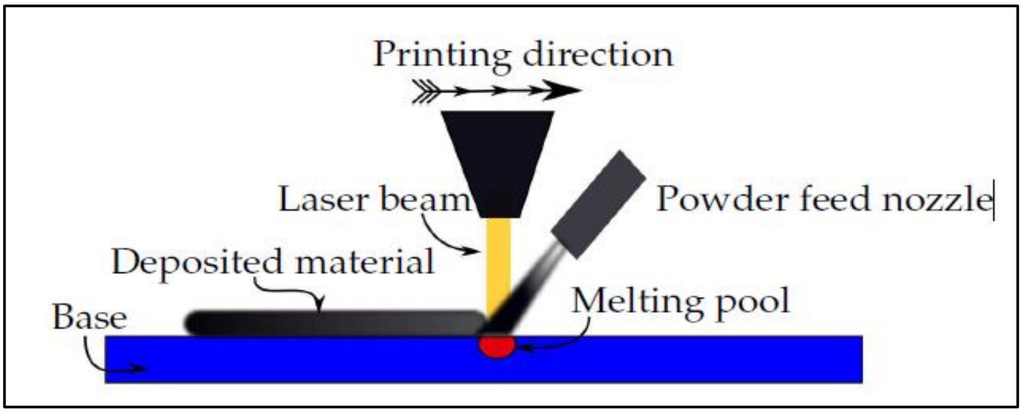


Figure 4.1.2.4. – Schematic diagram for the use of a DED technique.

4.1.3. THE ADDITIVE MANUFACTURING INDUSTRY

3D printing is an industry on the rise. Most of the technology created over a year ago is starting to be obsolete, and this means that it is in constant development and very hard to keep up with.

Given its potential, it is incredibly difficult to predict how rapidly the industry will grow. However, according to leading analysts, 3D printing is expected to reach a global market worth 30,19 billion $ (USD) by 2020.

The market this industry is creating is extremely wide, as the technology is reaching every corner of the manufacturing industry. Nonetheless, it is developing at a different rate in different aspects.

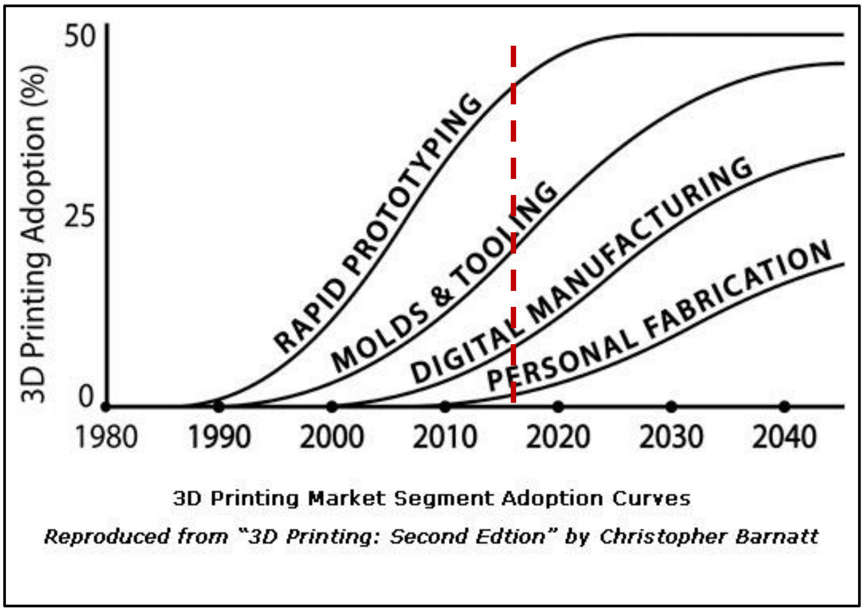


Figure 4.1.3. – Adoption curves of the 3D printing uses (*3D Printing: Second Edition, Christopher Barnatt*)

As the graph shows, 3D printing was born as an idea of rapid prototyping in the 1980s but it has developed into several other sectors of manufacture as time went by. The graph simulates the adoption of each of the uses the 3D printing industries will offer, by showing the percentage of adoption over time. It shows exponential growth from 0, developing into a consistent growth that falls away as the applications approach market saturation[5].

As we can see from the graph, we currently are living through the most thriving moment for 3D printing, as most industry sectors haven't developed substantially yet but are about to.

Each of the different industries that the technology is currently creating is going to affect the world in a very different way (some more and some less), but in order to understand the full impact of 3D printing on the industry we must understand every sector of application.

4.1.3.1. RAPID PROTOTYPING (RP)

As I have previously said, 3D printing was born with the idea of RP in 1980s by 3D Systems. The nature of 3D printing propitiates the production of prototypes as it allows customizability at a very fast speed. It can result in companies saving significant amounts of money from pre-production processes.

For example, Ford Motor Company has claimed to print 500,000 prototypes in prototyping alone and saved billions of dollars and hours of work in the process. They use techniques such as SLS due to the level of accuracy it can obtain.

To a smaller scale, material extrusion printers costing a few thousand or even just hundreds of dollars can now make very decent prototypes in hours, whereas conventionally, prototypes were either very expensive to produce or not of a great quality.

Although this is the most widely spread application of 3D printers that we might currently find, it is not one that will cause the next industrial revolution. As we can see from '**Fig. 4.1.3.'** rapid prototyping is close to saturating the market and letting through the next substantial AM industry: the production of tools and moulds.

[5] When the application of a product is fulfilled and no further growth is achieved.

4.1.3.2. PRODUCING TOOLS AND MOULDS

Currently, the fastest growing area of 3D printing application is the additive manufacture of production tools.

Traditionally, moulds, jigs and tools used in the production of final products, for example moulds used in injection moulding, are hand-crafted and can often cost up to tens of thousands of dollars.

In contrast, it is now possible to use 3D printers to produce injection moulds which, although they may last for a shorter period of time, are considerably cheaper and still deliver the result of production.

For example, in August of 2016, the Oak Ridge National Laboratory in the United States printed a 5m drill tool to build a Boeing plane. It was 3D printed in carbon reinforced plastic in around 30 hours. In comparison, the existing traditional tooling option would have taken three months to manufacture.

Figure 4.1.3.2. – Functional 3D printed injection mould.

The AM therefore shows a very important opportunity for development in this sector of the manufacturing industry.

4.1.3.3. DIRECT DIGITAL MANUFACTURING (DDM)

Direct Digital Manufacturing (DDM) refers to the process of going directly from an electronic digital representation of a part to the final product via AM. On occasions, the final destination for 3D printed pieces might be a simple prototype or a mould. However many industrial sectors are already adopting 3D printed pieces in their final products, such as the automotive and aerospace manufacture or the fashion industry.

The idea that a 3D printed object would be a final product (or be used in one) when 3D printing was invented was unthought-of. This clearly shows the improvement that this technology has seen over the last few decades and is letting through the development of the DDM industry's sector.

With the constant development of the AM technologies, the possibilities that they offer are constantly increasing, so it is always hard to define what can and what cannot be printed in 3D. Currently, 3D printed pieces are being widely used in the automotive manufacturing sector. This can enable companies to produce components with very specific properties can often only be achieved with AM processes.

Many other direct applications are being seeked for AM methods, and the customizability is enabling unique components, such as prosthetics or even full-functioning, organic, body organs, to be produced at low costs as a final product.

4.1.3.4. PERSONAL FABRICATION

Finally, the last industrial sector that AM will induce is going to be personal fabrication. This is possibly the most considerable factor that will make a trend to a manufacturing industrial revolution.

The idea of personal fabrication means that people print for themselves the DDM products that they need with 3D printers they have easy access to. There are already hundreds of personal 3D printers being sold for prices around 200$. Moreover, there is an increasing provision of free (or paid) 3D models that can be downloaded online for consumers to print for themselves. For example, websites like Thingiverse (hosting over 1,000,000 3D objects), which are open source platforms, where people can upload their designs and share them with anyone wishing to download it and print it with their own printer, even allowing the user to edit the design to exactly deliver the use they were wishing for.

This trend will ultimately change the current centralized and exporting manufacture into a tendency to Local Digital Manufacturing (LDM), where individuals fabricate the objects they need, both in the right proportion and quantity.

This exciting development that AM is inducing will lead the world into the industrial revolution and can increase the sustainability of the product manufacture. I will study these effects next in the theoretical research and later on with the practical development.

4.1.4. INDUSTRIAL REVOLUTION

The industrial revolution that I have been relating the AM with is defined by the applications that 3D printing will bring to the world. Of course, the applications that were thought of for this technology initially have nothing to do with what it is being done now, so there is no way we can know for sure where this technology can take us next. The two main ideas that are driving this revolution in the present are Local Digital Manufacturing (LDM) and the revolutionary applications that are being developed for use with 3D printers.

4.1.4.1. LOCAL DIGITAL MANUFACTURING (LDM)

LDM is defined as a manufacturing trend in which products are produced locally where they are used instead of being produced at a centralized location from which they are exported to the users.

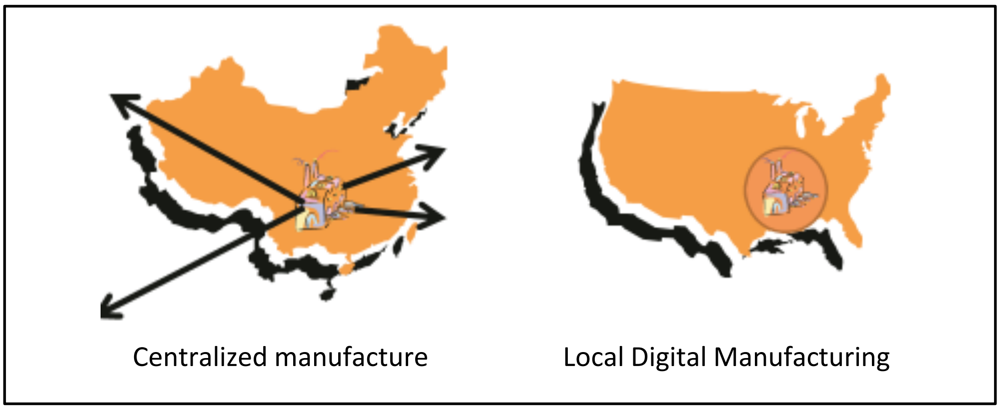


Figure 4.1.4.1. – Centralized manufacture vs LDM.

LDM can only be achieved with AM and the personal fabrication industry towards which 3D printing is creating a trend. Through LDM, in a utopian society, everyone would have a 3D printer at home, with which they would be able to print everything they would need in the right amount, from clothes and electronic equipment to food and new organs.

Although the idea that everyone has a 3D printer at home that is sophisticated enough to be able to print anything is rather difficult, the tendency that is being developed is of printing centres where people can take their CAD model and, for a moderate price, they can print it for them.

The LDM tendency has many positive effects towards some of humanity's biggest problems. For example, the pollution from the exportation of thousands cargo containers every day could be reduced with LDM, as there is no need for manufacturing products abroad when you can do it locally for the same price.

Moreover, it would have a great effect on sustainability. When producing products the traditional way like, let's say, a lamp, there is always a great stock of them produced so that the elevated manufacturing cost is justified. Let's say 1,000,000 lamps are manufactured. Very often, only 2/3 of the stock is actually sold, and 1/3 of it is gone to waste, so 333,000 perfect lamps would be thrown away because they had not been sold. With LDM, products are produced on demand, which means that only if a consumer shows an interest in the product will it be manufactured. AM enables this due to the low costs of production it provides, whereas for conventional manufacturing methods it would be extremely costly and unsustainable.

4.1.4.2. REVOLUTIONARY APPLICATIONS

The other side of the AM industrial revolution will be leaded by the applications that are constantly being found for 3D printing. Of course, with the constant developing nature of this technology it is impossible to describe all of the applications that are currently being found. I will attempt to describe a couple of the most revolutionary ones at the moment.

4.1.4.2.1. BIOPRINTING

Bioprinting is the process of 3D printing organic tissues which can build up organs, for use in medical applications, through AM technologies.

Bioprinting consists of building up layers of cells in order to build three dimensional living tissues, which can later on be developed as organs. Currently, complete organs have not been able to be printed successfully as the technology hasn't been developed fully; however, companies like 'Organovo' have already recreated kidney and liver tissues which have the ability to be used in testing for new drugs and cures for different diseases affecting these organs.

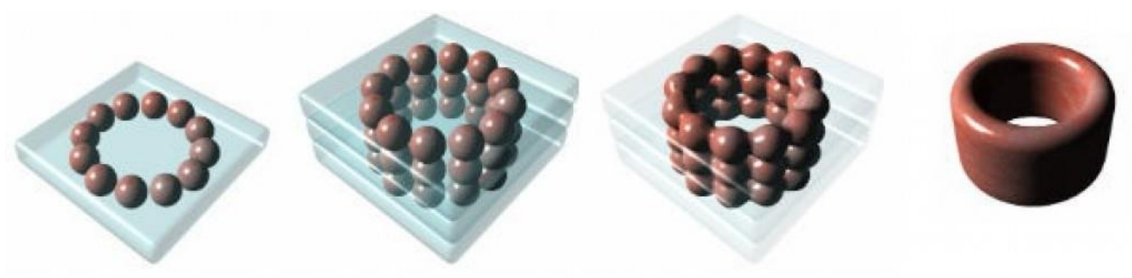


Figure 4.1.4.2.1. – These diagrams show the succession of steps in building a living tissue.

The Bioprinting process consists on placing a bio-paper gel medium where cells and bio-ink spheroids can be deposited. As layers and layers of cells are being built up, the bio-ink spheroids (containing cells) are able to fuse together, finally creating a living tissue.

There are also more applications to Bioprinting than creating organs: there is the possibility to create new materials by printing molecules with different structures and even the capability of printing *in vivo* during an operation so that diseased tissues inside the body can be regenerated directly with 3D printers.

4.1.4.2.2. PRINTING ON THE MOON

Finally, one of the greatest human challenges is to be able to settle down in a different planet for we may not have a chance to live in this world for much longer.

In order to settle down in different planets we must first build a structure that can withstand human life. The idea of building a base on the moon has been around for some decades, but the complication is to have to take all the materials and tools to the moon in order to build a settlement.

With the potential of 3D printing, it would be much simpler to construct it from local materials and print the building *in situ*[6]. Material extrusion 3D printers have been developed to be able to print real sized houses by extruding a semi-liquid concrete which solidifies when deposited. In order to print on the moon, the local resources would be used in order to produce a similar material to concrete which could also be used to print buildings.

This would save time and costs to companies like the National (American) Aeronautics and Space Administration (NASA) which would otherwise have to transport all of the construction materials and tools from the Earth.

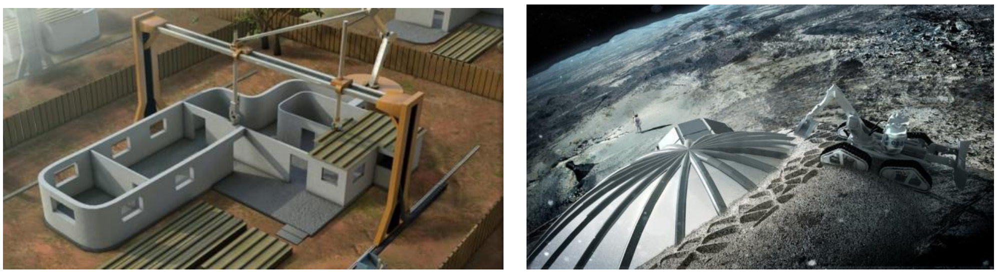


Figure 4.1.4.2.2. – Printing buildings through material extrusion (right) and settling the moon (left).

[6] In the same place where the action elapses.

4.1.5. SUSTAINABILITY

Some of the greatest benefits of 3D printing arise from material savings and the sustainable aspect this entails. Nowadays, most manufacturing is SM, and AM clearly shows an advantage over that technology in saving material.

Another key development of the AM industry that will impact positively on sustainability is LDM. Through this process less material is wasted as the products are manufactured on demand. There is no need to transport and store products and, with the increasing climate change the ability to cut on the transportation will affect positively on the world.

Moreover, the ability to recycle most components to their original material, which can then be reused in 3D printers to produce new parts, means that not much waste is being produced with AM technologies.

For example, plastic recycling is currently a big issue with the pollution of oceans and landfill. In a close future, material science is going to allow different kinds of plastics to be decomposed and reused in 3D printing through DDM in order to create final products from waste.

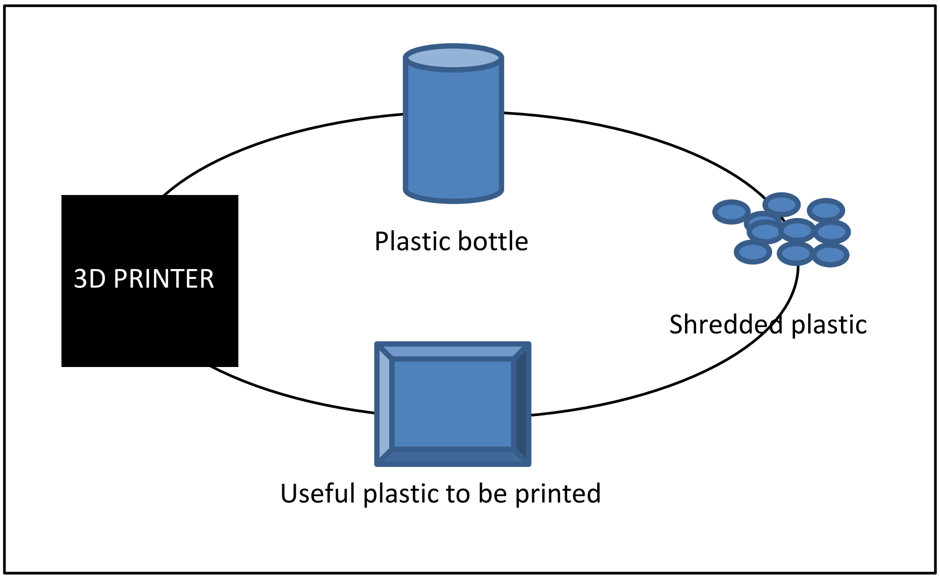


Figure 4.1.5. – Recycling process of a 3D printed object.

AM therefore shows a great potential in order to change the manufacturing process by creating a LDM culture and enabling recycling of its products to create a sustainable manufacture.

4.2. PRACTICAL DEVELOPMENT

4.2.1. INTRODUCTION

With the theoretical knowledge I have developed throughout the first section of this research project, I am now able to endeavour the practical development and research, which will justify my hypothesis:

- The additive manufacturing technology can be used to help the strand of society with limited resources in a sustainable way.

In order to do so I will simulate the introduction of the AM technology in a society with limited resources and evaluate the sustainability and efficiency to justify whether it will result in a positive development.

I carried out several practical developments in order to test this, including:

- The building of a 3D printer, which will prove my theoretical knowledge on the different printing techniques and put them into practice.

- The creation of a filament extruder, which recycles the plastic and will attain my environmental and sustainable objectives.

- The social application of both AM machines (the printer and the filament extruder) which will be evaluated economically and compared with other methods when manufacturing a prosthetic hand.

- The experimental calibration and testing of the printed parts through the computational framework.

- Finally, a simulation of the ease of implementation of the 3D printing technologies in a dC through a lesson and an evaluation form.

4.2.2. BUILDING A 3D PRINTER

My main practical development during this project was the building of a 3D printer, as it is the basis of the AM technologies.

Subsequent to the theoretical development, I could understand the functioning and the potential of the 3D printers a lot better than at the start of this project; however, to fully understand how it worked and test its capabilities I had to build one. As we have seen in the theory, personal fabrication is already present and a big sector of the 3D industry, as more than half a million personal printers had been sold by 2015. It enables individuals to print customized objects independently from big manufacturers: that is what building a personal fabrication printer will enable me to do in my project.

In order to build a 3D printer I had to research a lot of web pages that talked about the essential qualities of a printer, which are the controls and the different types of printers. I decided to build a material extrusion printer because it is the most commonly used in personal fabrication as it is also the cheapest and easiest to use.

To start building my printer I had to contact BCN3D, a local company in Barcelona that produces retail 3D printers. They would sell the printers as a kit that you could assemble, so during the development of the project I went in to their headquarters and built the printer with their help and tutoring.

It was a long process; however I got to understand exactly how the printer worked as I was putting the pieces together.

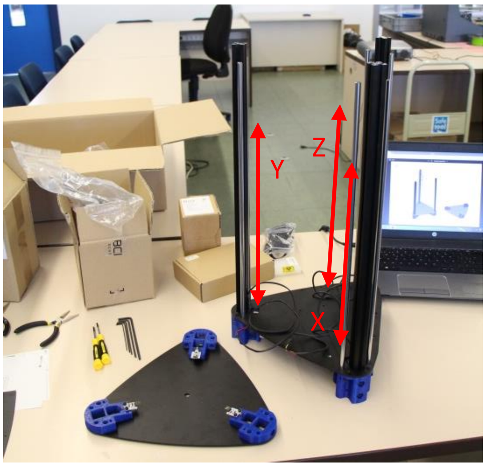
I documented the whole process with pictures in order to be able to show the development that I carried out.

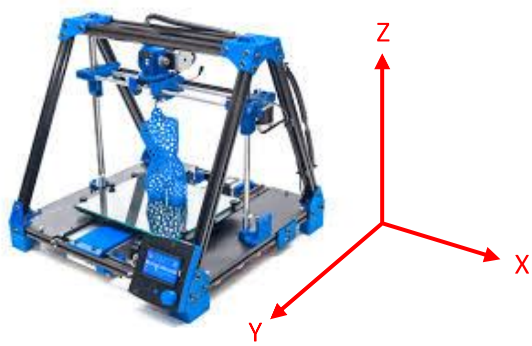
4.2.2.1. CONSTRUCTION PROCESS

When I started, all of the materials were inside labelled boxes ready to be assembled and calibrated.

The first day of construction consisted on the structural and mechanical construction, and the second day I connected the circuit and had to calibrate the machine. Some of the pieces which I used to build this printer (the ones that appear to be blue) were 3D printed, which is an example of DDM as printed pieces are being used in final products.

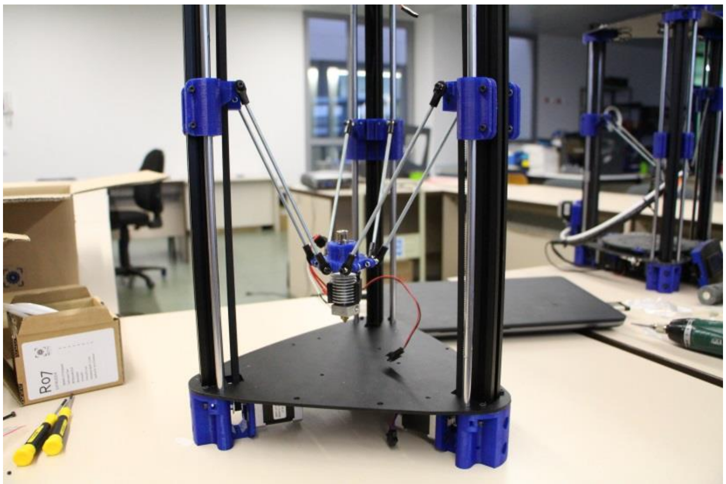
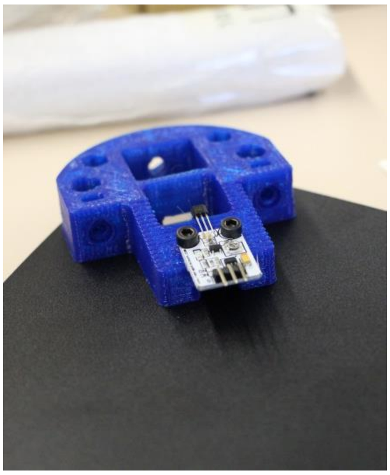
1) The 3D printer I was building (model: BCN3DR) consisted of three columns which controlled the x, y and z axes by complementing each other with the movements (not a conventional printer where each axis was controlled separately), so the first step in the construction was to build the structure with the motors.





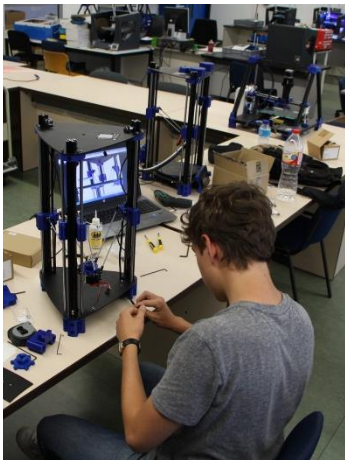
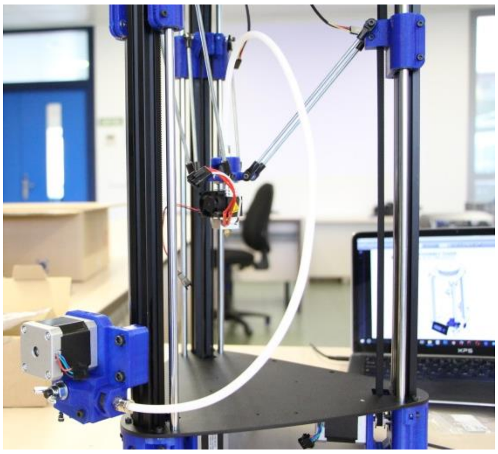
Comparison between conventional 3D printer's axes and BCN3DR's.

2) After assembling the initial structure I had to assemble the calibration devices (at the top of each axis) that would ensure the printer could be calibrated properly later on, and I then had to assemble the filament hot-end (where the plastic is melted and deposited) with the axes' bearings.

Filament hot-end on the left and calibration devices on the right.

3) After that, I installed the motor that would control the pace at which the filament would be fed to the printer's hot-end to ensure that it was always being fed and the printer would never run out of plastic in the middle of a print.

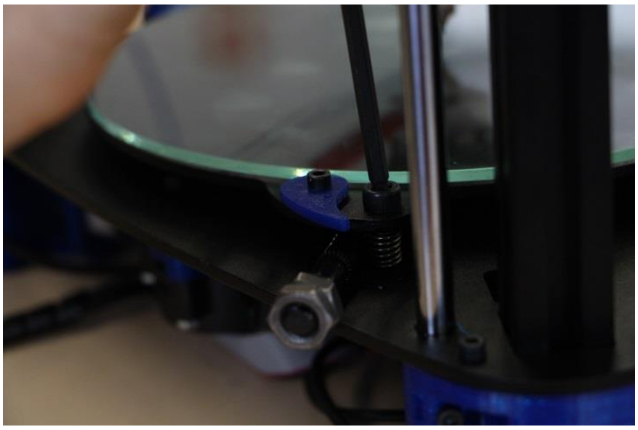
The motor pictured on the right and myself installing it on the left.

4) The next step was to install the electronics that would control the 3D printer. This consisted of two chips and a monitor display to be able to control the

printer's settings. The two chips that we used were the Arduino and Rep-Rap[7] chip (the most commonly used in retail printers).

The Rep-Rap chip on top of the Arduino pictured above.

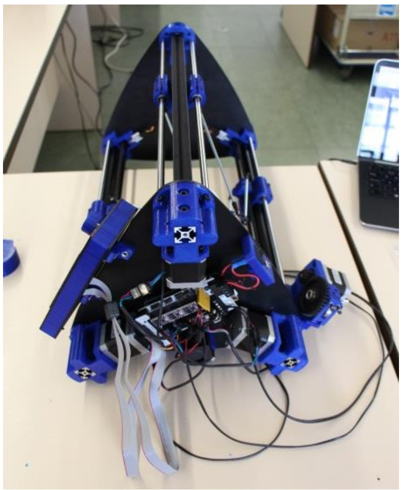
5) Once the chips were installed, I had to place the platform where the printed piece would be deposited. I had to calibrate it with 3 screws to ensure it was completely flat so that when the printer was working the printing surface wasn't uneven.

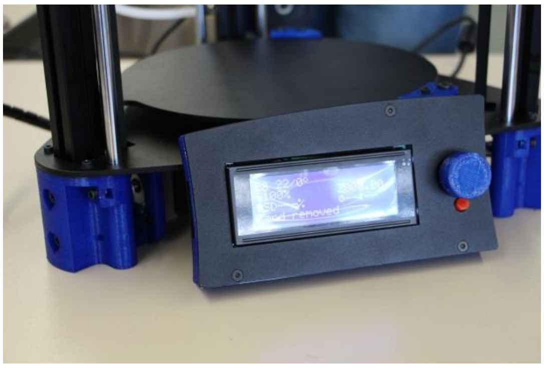


Controlling the height of the platform with a bolt in the picture above.

[7] A free desktop 3D printer interface developed as a community project to be able to expand the reaches of low-cost material extrusion personal fabrication printers.

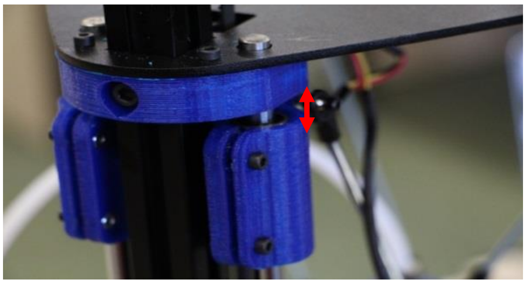
6) Finally, I finished the circuits by connecting the fans and the motors to the Rep-Rap chip (which will control their power) and I then started the machine in order to calibrate the axes.



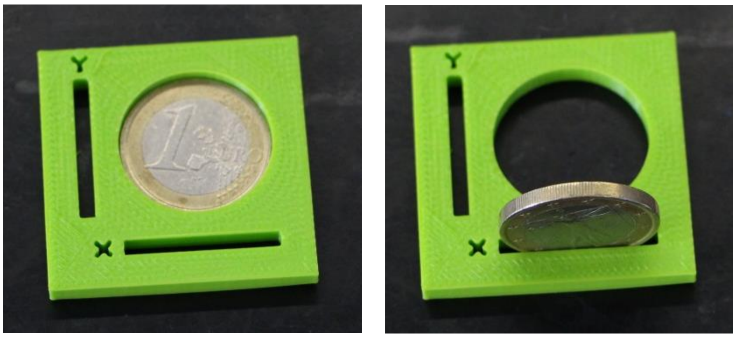


The monitor display turned on (right) and the finished circuit (left).

7) When calibrating the axes, I had to make sure that the distance between the pieces that controlled the hot-end and the top of the printer were all the same. To do this, the calibrating devices would sensor a magnet (which was on the pieces that controlled the hot-end on the axes) at a certain distance, at which I had to set the Rep-Rap as origin. I repeated the process with the three axes using the same distance to make sure that the origin point was even with the printing surface.



8) It was finally time for testing the printer by printing a calibration piece. We printed a coin model, which, if the coin fitted properly, meant that the printer had been successfully calibrated.



The calibration showing it was successful when the coin fitted in the slots.

Once I had built the 3D printer I could go on with my other practical developments. I would later on use the 3D printer I built to produce a 3D printed prosthetic hand to evaluate the hypothesis and to link it to the customizability that the AM technology enables.

4.2.3. CREATING A FILAMENT EXTRUDER

After the construction of the 3D printer my aim was to make it fully sustainable (as I hypothesised in my environmental objective and in my main hypothesis). In order to do so, I came up with the idea of making a filament extruder.

This consists of a machine which can turn plastic waste from the Material Extrusion 3D printer (the one I built) back into 3D filament that can be reused in the printer to print more, fully recycled, 3D objects.

The filament extruder would use waste such as the support material from overhangs in prints, or even failed prints which don't come out the way expected, which have imperfections in the design.

A filament extruder consists of a 12mm screw that pushes the plastic, that is introduced through the hopper, towards the heater, where it melts. The pressure of the plastic which is constantly being pushed by the screw causes the melted plastic to be forced through the feedpipe into the nozzle at the end, which extrudes the, initially waste plastic, filament which can be reused in 3D printers.

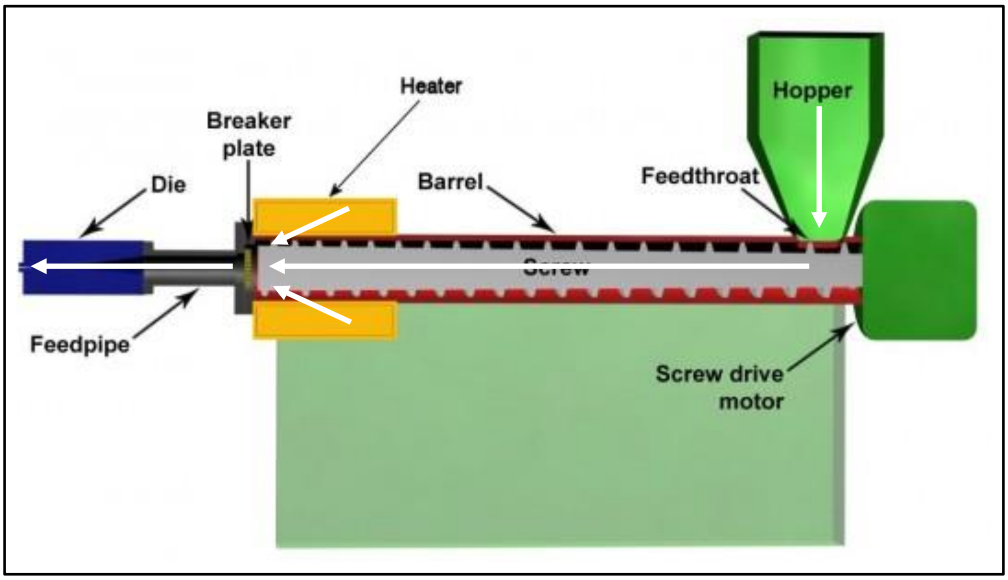


Figure 4.2.3. – Parts of a filament extruder.

The process to build the filament extruder was much harder than the 3D printer as the resources and access to information was far more limited. Filament extruders are not a common device in personal fabrication, as they are usually used at a mass production scale to produce the retail plastic filaments (of course, the plastic those extruders use are not recycled nor sustainable).

The development of the filament extruder allowed me to ensure the sustainability in the project as the printer could now reuse 100% of the filament, making the print far more inexpensive as well (as less (even no) retail filament has to be purchased).

I documented the whole process with pictures in order to be able to show the development that I carried out.

4.2.3.1. CONSTRUCTION PROCESS

To be able to build the machine I also, similarly to the 3D printer, had to acquire a kit with all of the pieces I needed to build it. The only difference was that I wasn't able to contact the company providing me with the pieces (called 'Filastruder') so I had to build it using resources online and a few schematic drawings.

The process of assembly was also fairly similar to the printer's: it was separated into the assembly of the mechanical structure followed by the electronic assembly and calibration.

1) The first thing I did when the parts arrived was to lay them out in order to try and understand how to assemble it. I then started the mechanical build of the filament extruder, which was placing the bearing on the screw so that it was able to turn.

Screw with the bearings on the right and all of the materials on the left.

2) I then put the screw together with the motor, which would turn it, and the metal structure of the filament extruder.

3) To finish the mechanical build I had to install the barrel around the screw and finally the nozzle at the end with the heating component (it heats up the nozzle and barrel).

4) I guided my electronic assembly with a schematic diagram for the circuit that described all of the connections between the components. The circuit was controlled by the Proportional-Integral-Derivate controller (PID), which worked as the central computer for the heating system as it controlled the limit at which the nozzle should be heated up. The other key component was the Stall Protection Board, which controlled the pace at which the motor should turn the screw to push the plastic. Finally there were two fans to keep the motor cool and a Thermostat Couple (T/Couple) which measured the temperature at the nozzle to ensure the PID was working correctly.

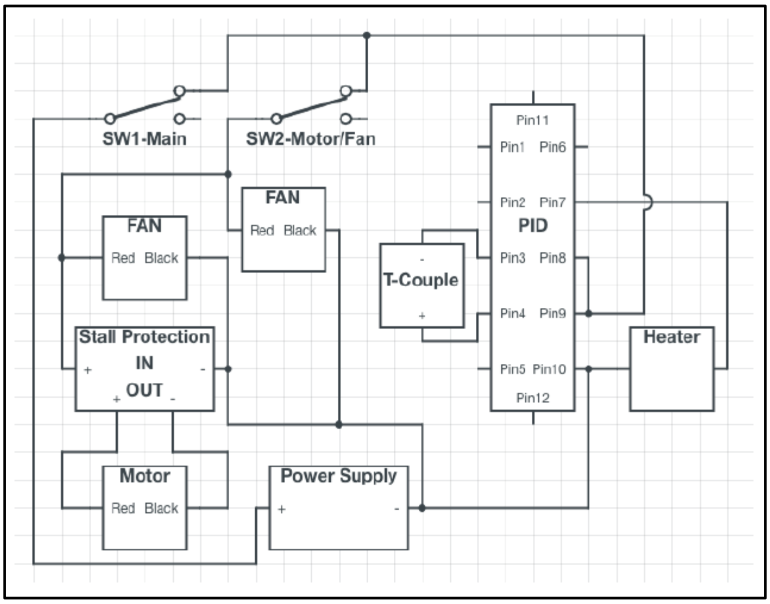
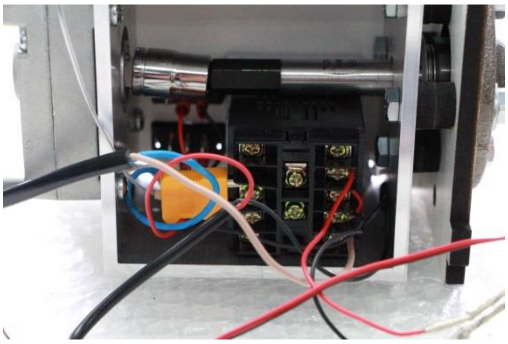
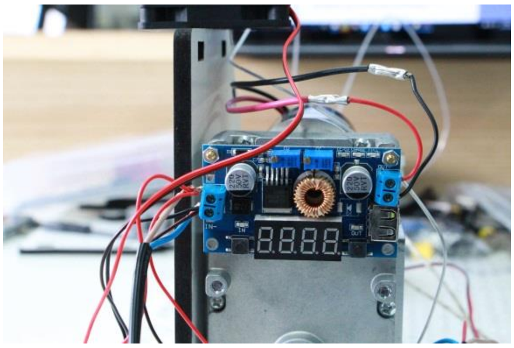


Figure 4.2.3.1. – Schematic diagram for the filament extruder's circuit

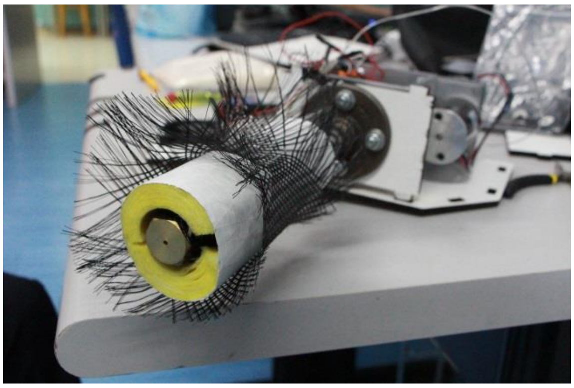


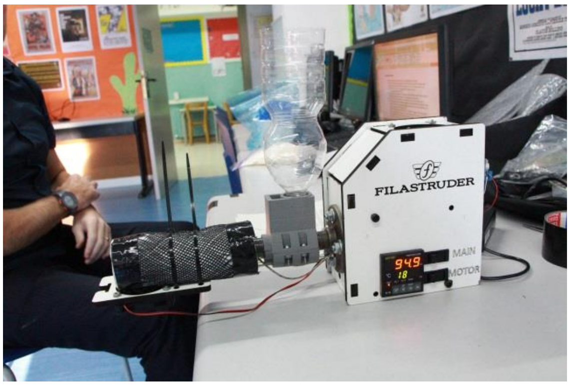


The PID controller connected as shown on the schematics on the left, and the Stall Protector on the right.

5) Finally, the stall protector’s current and voltage had to be set to the right amount so that the motor would turn at an appropriate speed (Voltage = roughly 12 volts (V); Current = 1.4 – 1.6 amps (A)).

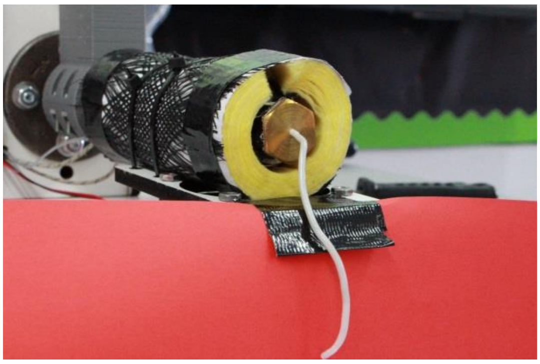
6) The last step before the construction process was finished was to insulate the nozzle and barrel with a foam (as they heat up to around 180ºC) and to install both fans (one by the nozzle and one by the motor) before enclosing the metal structure encasing the motor with another piece of wood on the opposite side.

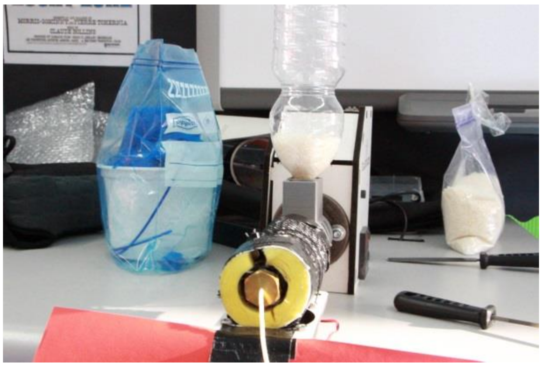


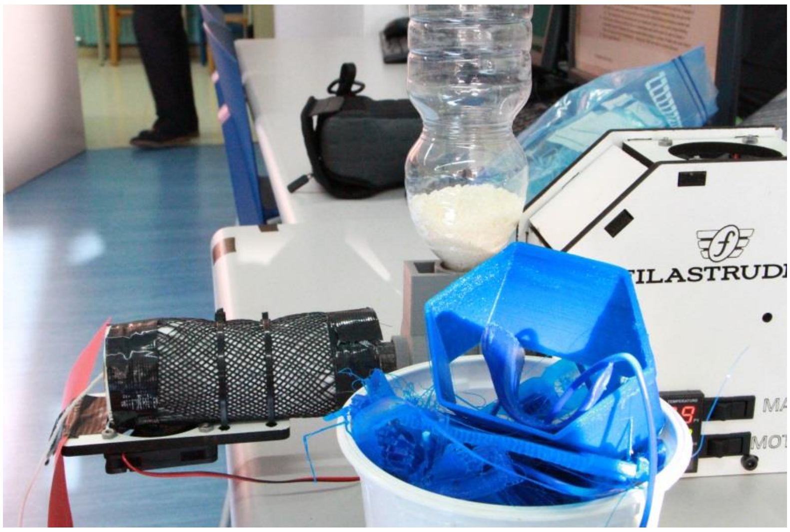


In order to test the filament extruder we had to set the temperature at 180ºC (temperature at which ABS melts) and wait around 10 minutes until it heated up. Then we placed some plastic pellets inside the hopper and turned on the motor so that the pellets would start to be pushed through to the nozzle.

The filament extruder had to run for 6 hours with plastic pellets in order to clean the barrel and screw from any metal bits or dust that might have been left inside. Once that had finished, it could be used to recycle waste plastic from the 3D printer: its original purpose.







The images on the top show the filament extruder creating an ABS filament with the pellets and the one on the bottom shows the machine next to a pile of wasted plastic from the 3D printer ready to be recycled.

4.2.4. PROJECT APPLICATION

Now that both the 3D Printer and the Filament Extruder have been built I can carry out the final practical development of the project.

It will consist on the application of the 3D printer to print a one-off batch for a specific and customized design that must be sustainably produced using the filament extruder. I will print and build a prosthetic hand as it is a piece that requires customization for every individual one that is produced.

Once I have produced the design sustainably, I will compare the price of the production with a conventional manufacturing method in order to evaluate economically the AM.

Finally, I will simulate the introduction of the whole practical development (from using a printer to sustainably printing a prosthetic hand for a notoriously reduced cost) into an appropriate dC where a strand of society with limited resources could benefit from the AM technology. I will do this by carrying out a lesson with seven pupils with very basic knowledge on 3D printing and evaluating the progress and capability of implementation with a questionnaire following the teaching practice.

4.2.4.1. 3D PRINT DESIGN

Through the several platforms personal fabrication offers, I was able to find an open sourced design for a prosthetic hand on Thingiverse.

Figure 4.2.4.1. – Cyborg beast rendered model

This design, called 'Cyborg Beast', was based a social enterprise that has as a mission to create customized, low-cost, prosthetic solutions for underserved populations. Their design consists of an easy to assemble and low-cost prosthetic for children from the age of 3 to 16 year olds.

I was able to directly download the STL files for the design off the open source designs sharing website (Thingiverse) which I then had to fix and transform into a G-code file so that the 3D material extrusion printer could interpret the design.

4.2.4.1.1. LOCAL DIGITAL MANUFACTURING AND CUSTOMIZABILITY

With the LDM nature that 3D printing technologies enables its users to use, I was able to print the 'Cyborg Beast' prosthetic hand to match the certain specifications I needed.

Since I was printing the replacement hand for myself (so I could test it) I had to scale the original size of all of the parts so that it would become the correct size.

In order to know which percentage to scale it by, I was able to use a scaling chart that defined the scale percentage needed depending on the age of the patient.

This meant that we were using set anthropometric data[8] to print the piece, although AM technologies enable a far more specific customizability to match the individual's needs.

[8] Collections of measurements for the 50th percentile, average, human dimensions.

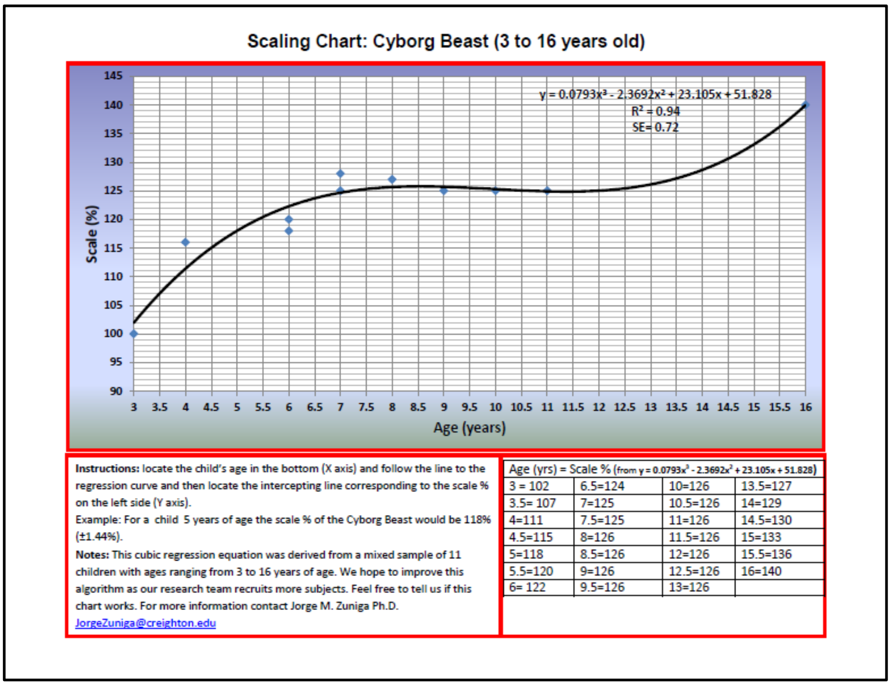


Figure 4.2.4.1.1. – Scaling chart by age for prosthetic hand

Since I am currently 16 years old, we can deduct from the chart that we must scale the design by 140%.

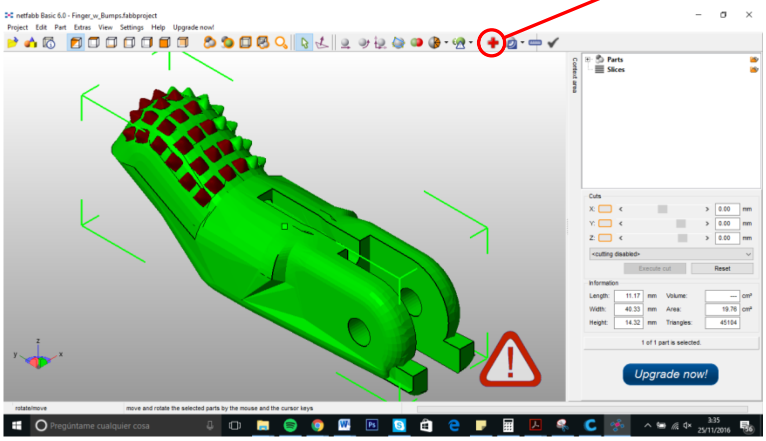
SM technologies or overseas traditional manufacturing would make the ability to customize freely the design extremely costly and unsustainable, showing the advantageous nature of AM in this aspect of manufacture.

4.2.4.1.2. DESIGN DEVELOPMENT

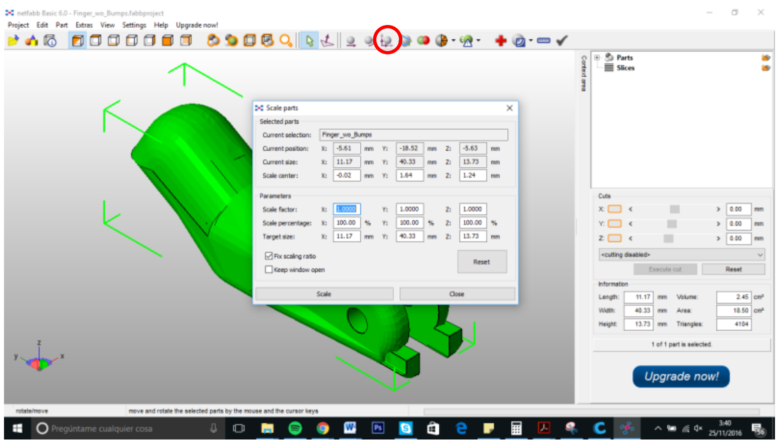
Once the STL file has been downloaded online, there is a process that must be carried out in order to change the STL file into a G-code, which the printer will be able to interpret and print.

The first program that must be used is called ‘Net-Fabb’. This program will enable us to fix the surface STL if there are any imperfections present, and we will then use the program to scale the piece to the desired size and orientate it in space so that we can choose which side will be bottom first (in order to optimize material use and minimize support material).

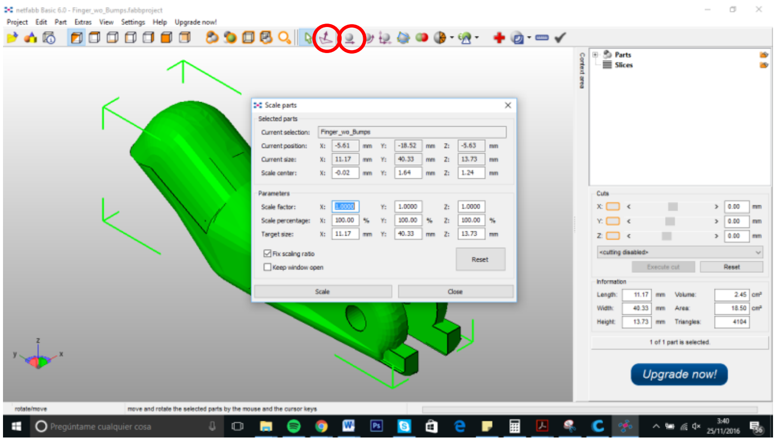
1) As we can see on the screenshot of the ‘Net-Fabb’ program, if we encounter a warning sign at the bottom right of the screen it means that the surface geometry of the part has a few errors, so we must fix it with the ‘Fix’ function.



2) Next, we can scale the part with the ‘Scale Part’ function, which will enable us to enlarge the piece to the size we desire. Scales can be applied to exclusively different axis (x, y or z) or to the part in general so that it all enlarges or reduces in proportion.

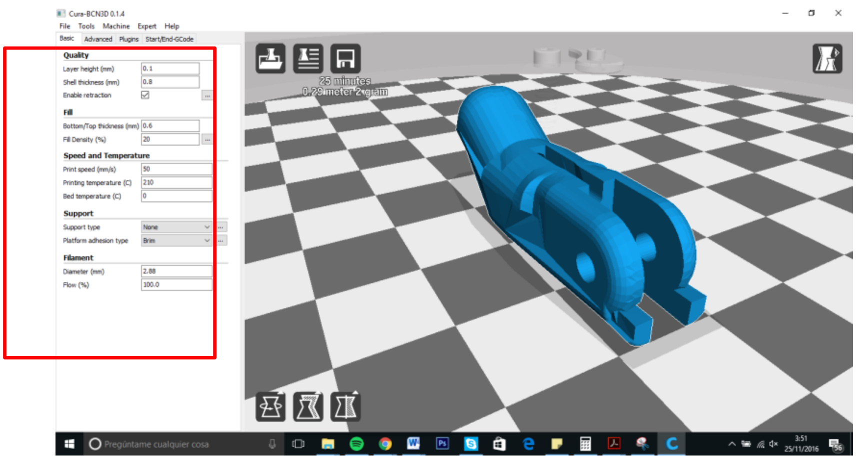


3) Finally, we can ‘Align’ the desired area to be the first layer of the 3d print and we can ‘Move the Part’ around the plane freely, although we usually want to bring it to the origin so that when it is printed it will start in the centre (ensuring all of the piece will fit on the printing surface).

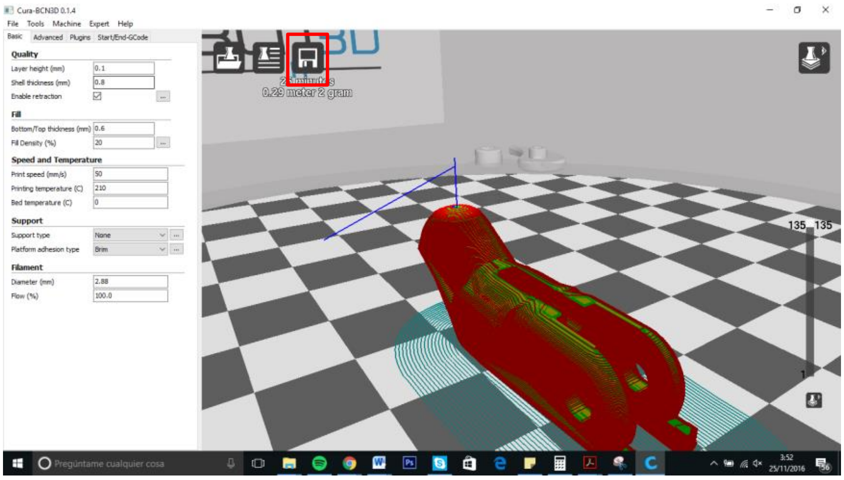


Then, in order to slice the part into different layers so that we can print the piece, we must create a G-code file. This will be done with the Cura BCN3D program, which has inbuilt settings of the BCN3DR printer (the one we are using to print the pieces) and makes it easier in order to carry out the process.

1) The fixed, aligned and scaled STL files from Net-Fabb are imported to Cura, where the printing settings can be controlled. For example, the height of every layer, the % of material infill and the support material used.



2) Once all of the settings are chosen, the program enables you to form the G-code, which will control the movements of the 3D printer as it prints, layer by layer, the piece.



Once the G-code has been generated, the piece is ready to be sent to the printer and to start the print.

4.2.4.1.3. SENSITIVITY ANALYSIS AND EXPERIMENTAL CALIBRATION

A sensitivity analysis is a simulation of the printing of a part carried out computationally. It gives you data about the temperature at which the part heats up when it is being printed and that enables you to deduce how successful the production of a print would be.

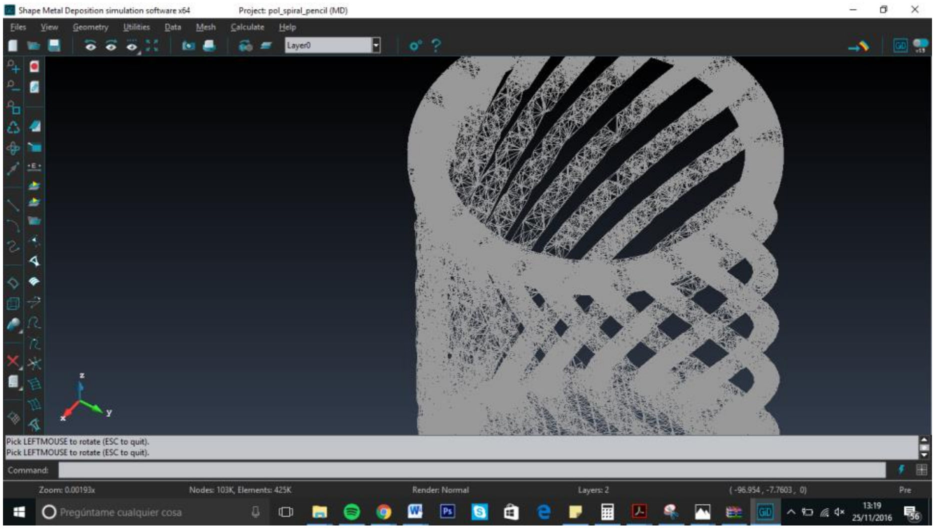
When 3D printing using material extrusion, an experimental calibration is not really needed as the temperatures are not that elevated and the printing method is really cheap.

Being able to carry out experimental calibrations and sensitivity analysis becomes beneficial when printing with materials like metals, as there is a lot of energy and resources needed to produce a piece, so the design must be ensured to withstand the temperatures and not have any errors in the printing.

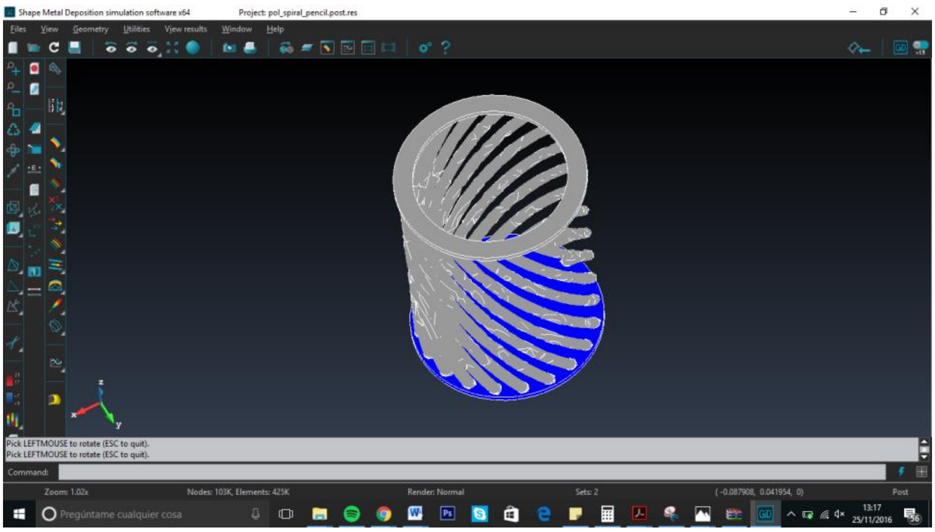
Therefore, although the experimental calibration is not directly applicable to the design development I am carrying out with the plastic prosthetic hand, it is very useful for printing with metals, a technology that will soon be equally available as the printing of plastics nowadays.

Working at CIMNE with the Master's student Tomás Varona I was able to carry out a set of analysis and calibrations of a complex STL file when being printed with the SLS printing technique (Printing techniques: 4.1.2.3.).

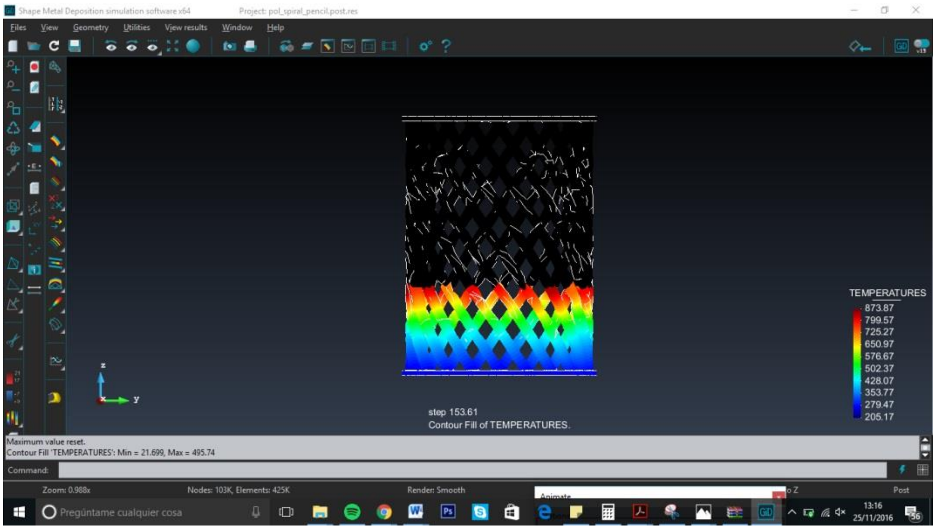
Once the design was loaded on the program GiD (the one that enables to carry out the simulations), it had to form a mesh around it to define the volume of the shape.



Then, the settings of the print were selected, such as the height of each layer and the power of the beam fusing the powder to form the shape.



Finally, I analysed the results by watching the print simulation layer by layer and looking out for any temperature inconsistencies that would mean that the design had flaws that should be solved before carrying out the print.



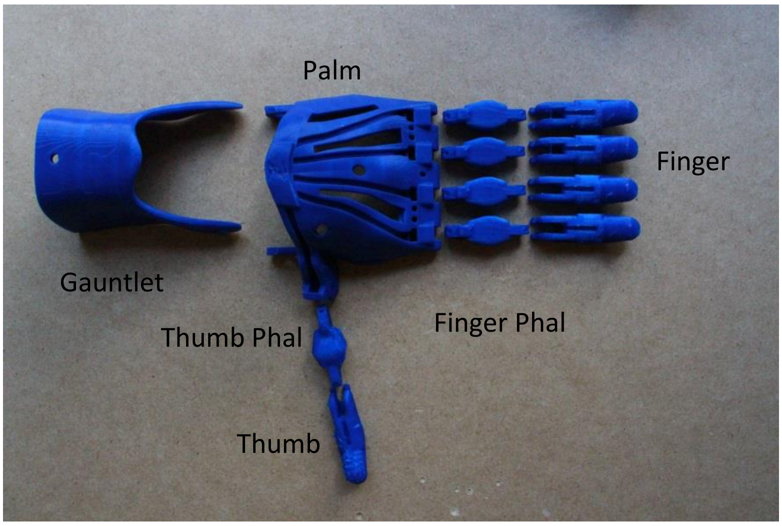
4.2.4.1.4. CONSTRUCTION PROCESS

Once the proper G-code file is ready, the design is sent to the printer and the print is started. The 'Cyborg Beast' consisted of 12 pieces which had to be printed in a way that the printing time was optimized (as a printer takes shorter to print more pieces at one go than several ones separately).

I wasn't able to print the biggest piece of the prosthetic hand on my printer, as it was too big, and so I had to resort to a LDM personal fabricator who produced DDM of the 3D printed pieces that you chose.

Once the printing had finished, it had to be assembled:

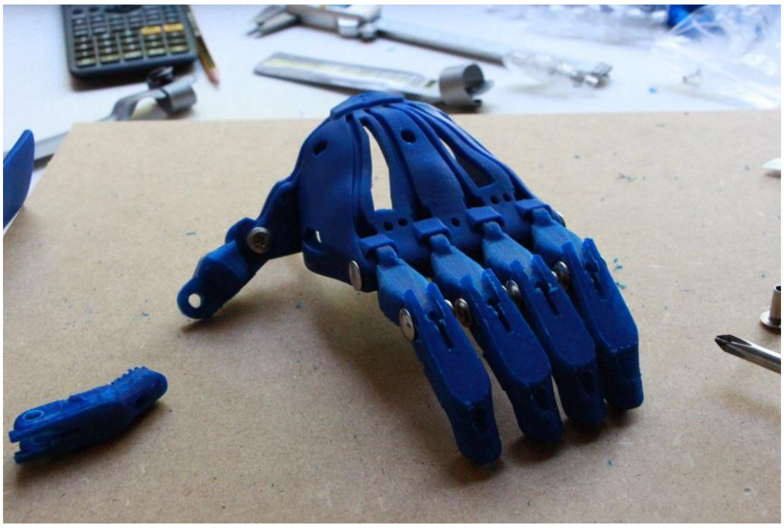
1) Firstly, I put together all of the pieces to ensure that the order and orientation I was placing them in was the correct one.



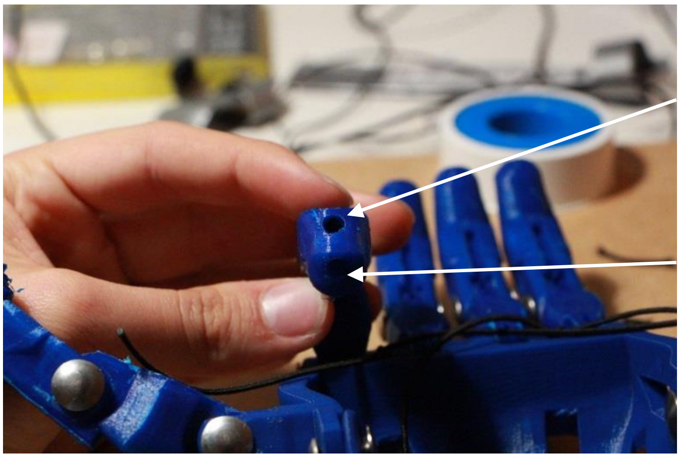
This picture shows the exploded view of all of the pieces in the 'Cyborg Beast'.

2) Then, I checked the measurements of the holes in the joints of the hand through where 5mm screws had to go through. I realised that most joints didn't have the wholes, so I had to drill them one by one.

3) Once I had enlarged all of the holes I was able to fit the screws in all of the joints and I assembled the pieces.



4) Finally, I had to insert elastic chords and rigid chords through every single finger. The rigid chords made fingers to close up when the wrist was bent, and when it went back into position, the elastic chords would bring the fingers back up to the original position.



4.2.4.2. IMPLEMENTATION OF THE PROJECT

The task of developing a sustainable method to print a customized prosthetic hand now had to be implemented into an underserved society with limited resources in order to test the hypothesis.

In order to fully implement the project I first had to evaluate if, economically, the production of the customized prosthetic hand had been considerably cheaper than a prosthetic hand that is being manufactured with a conventional, injection moulding method.

I found that the average cost of a prosthetic hand with limited functionality (like the 'Cyborg Beast') being manufactured in a conventional way would cost around 10000$ (USD).

I then calculated the price of the 3D printed prosthetic hand by calculating the price of each piece using the average price per kilogram for a PLA 3.00mm blue filament, which was 29.64$ (USD) / kg.

Piece	Mass of Piece	Mass of Support Material
Gauntlet	39g	17g
Finger (x4)	5g	1g
Finger Phal (x4)	4g	0g
Palm	60g	21g
Thumb	5g	1g
Thumb Phal	5g	1g
TOTAL	144g	(minus) 43g
	101g	

I subtracted the weight of the support material as, using the filament extruder, I would be able to recycle 100% of the unused plastic, meaning that it is recycled and made cheaper.

In conclusion, the total price for the materials used to build the Prosthetic hand is:

$$0.101\text{kg} \cdot 29.64\$/\text{kg} = 2.99\$$$

$$2.99\$ + 30\$ = 32.99\$$$

(Thirty dollars are added for the screws and different strings that are used to enable the functionality in the hand).

With this comparison I am not taking into account the manual labour needed in 3D printing, which is the designing of the part and the preparation of the printer. These two factors would increase the price of the print by around 22$ (considering that the prosthetic hand takes 16 hours to print (only a few minutes to prepare the machine) and that a low pay for this kind of job would be 10$/day; I also assumed that the depreciation[9] of the machine would be of 2$ since it can print at least 360 prosthetic hands and it only costs 700$). However, for the purposes of this project I will be considering that the manufacture is being carried out by a Non-Governmental Organization (NGO), meaning that the cost of labour is deleted as volunteers are carrying out the job.

In conclusion, the prosthetic hand's cost of production is, in average, 0.4% of the production price of one made through conventional processes.

$$(32.99\$ / 10000\$) \cdot 100 = \underline{0.4\%}$$

Once I had proved that the production of a prosthetic hand sustainably is showing to be advantageous economically for a strand of society with limited resources, I could go on with the implementation of the project in a specific location.

4.2.4.2.1. SPECIFIC LOCALIZATION

I would chose to implement my project in the dC of Angola, in the South West of Africa, because I find it is a developing country with poor resources and a need

[9] The allocation of the costs of the machine towards every product that it prints.

for 3D printing technologies, and especially the ability of customization of prosthetics.

This is because Angola is the second country in the world with most bombs hidden within the ground (antipersonnel mines). There are at least 9 million mines in the country, and at least one out of every 470 people in Angola is missing a limb.

Figure 4.2.4.2.1. – Flag of Angola

This is the result of the civil war they suffered in 2002, and it has been causing very frequent serious injuries and deaths.

The introduction of AM and 3D technologies in this country would provide very affordable and fast producing solutions for many people who see their lives gravely affected by the consequences that can bring living without a limb.

4.2.4.2.2. SIMULATION OF A LESSON

The last practical development that I had to carry out in order to test the implementation of the practical research in a selected location was the simulation of a lesson in which I would explain the whole development.

In order to prove that the AM could be used to help the strand of society with limited resources in a sustainable way, I had to prove that I could teach the essence of AM and explain how to 3D print a prosthetic hand sustainably.

In order to carry out a fair test to fully simulate the divulgation of my practical development as if it were in the selected location of Angola, I selected a group of 7 students who, although they knew what 3D printing was, they didn't know how it worked.

During my lesson, I taught the students, initially, what 3D printing was, I gave them a couple of examples of the industry it is creating and I described the two basic printing techniques.

That basic knowledge gave enough information for the students to already understand the matter, so we could now apply it practically.

I taught them how to find an STL off the internet and convert it into a G-code (the same way I did with my prosthetic hand) to be able to customize it and print it to their please.

Finally, in order to test the success of the lesson, I gave out a survey at the end of the lesson so that they could answer the questions I proposed, which will give me data that I can analyse in order to draw conclusions about the success of the lesson.

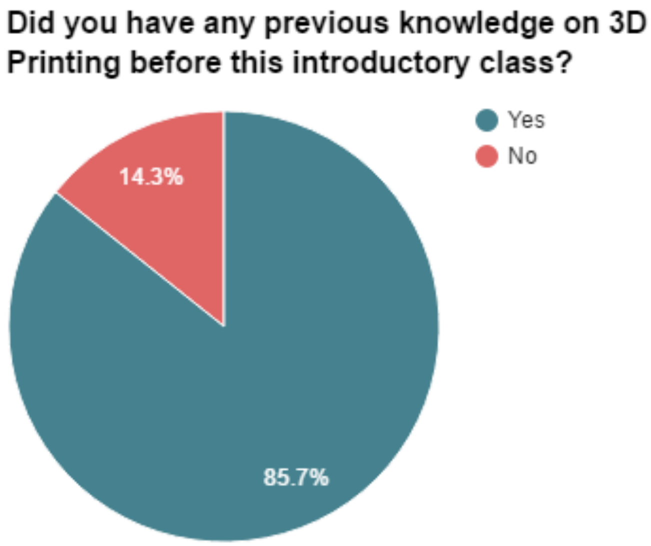
4.2.4.2.3. EVALUATION FORM

After the simulation of a lesson, I was able to draw data about the attainment of the objective through an evaluation form with questions on it.

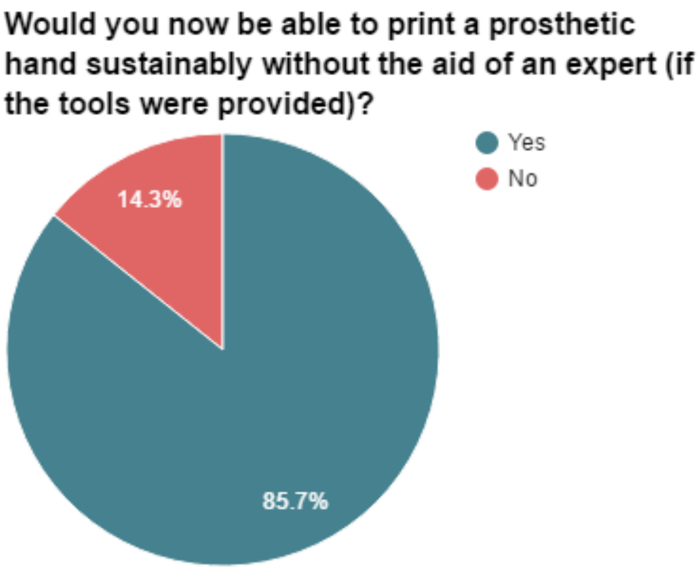
I plotted the results I drew from the survey on graphs so that the analysis of the results would be more visual.

Through this form I was able to draw conclusions on the success of the lesson, therefore of the simulation of implementation of my practical development.

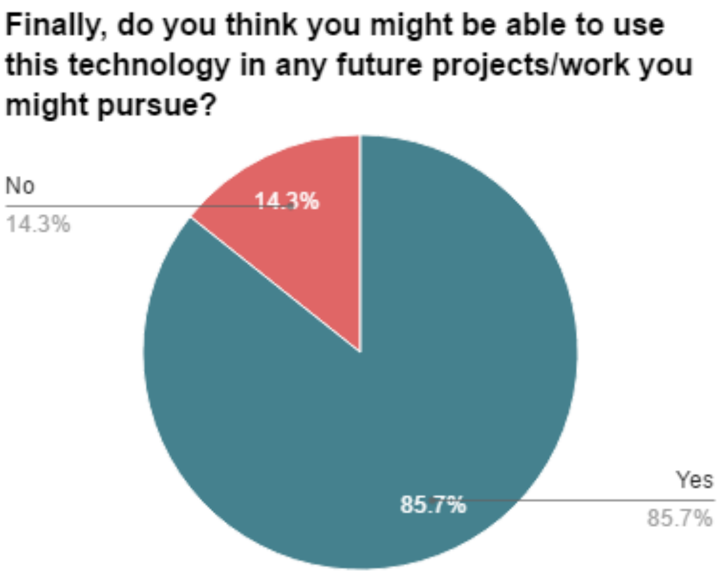
The first question asked whether the students had any previous knowledge on 3D printing. 6 out of 7 marked yes, meaning that the grand majority had heard about the technology before. Since the question is not too specific, no real conclusions can be drawn from it.



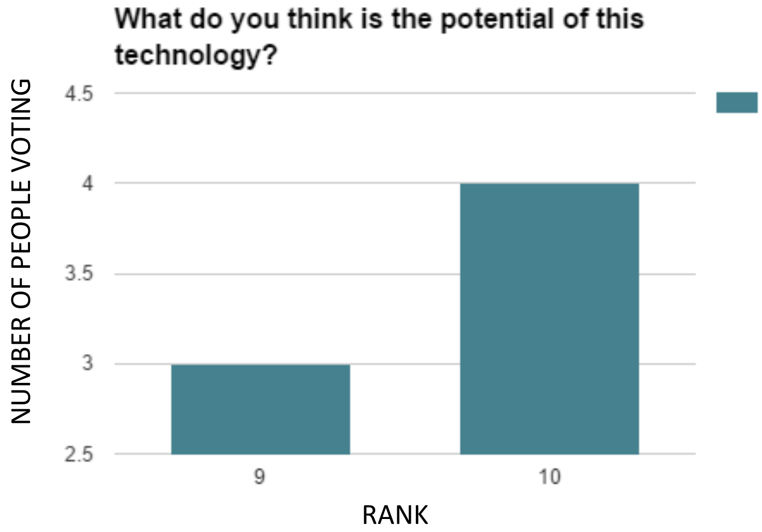
The next question asked the students whether, after the lesson, they could 3D print a prosthetic hand or not. Again, 6 out of 7 of the students marked yes. The important factor is that one marked no. This means that the lesson maybe should have been more focused on the practical development rather than the theoretical introduction.



The next question was checking whether or not the students thought they would actually use the technology in the future. Yet again, the same number of people said yes and no. This could mean that the grand majority of the class see the AM technologies as something that could be useful in a future.



Finally, the last question allowed the students to rank the potential of the technology from 0 through to 10 (0 meaning it has no potential and 10 meaning it has an obvious potential).



These results demonstrate that the basic theoretical knowledge and the practical methodology and functioning of the AM technology and a Material Extrusion 3D printer can be easily taught and divulgated in order to allow its implementation in a strand of society with limited resources that would be benefitted by sustainable AM.

5. HYPOTHESIS EVALUATION

In order to evaluate my development project on the Additive Manufacturing technology I had to refer back to my initial hypothesis that led me to this development and consider whether I was able to attain it or not:

- The additive manufacturing technology can be used to help the strand of society with limited resources in a sustainable way.

With my theoretical research I proved the many advantages that the AM technology showed over other manufacturing methods, such as customizability and lower costs.

The practical development then proved the capability of being able to develop the technology sustainably, by producing the filament extruder to recycle the wasted plastic when creating a customized prosthetic hand.

Finally, with the implementation of the project and the simulation of a lesson, the AM technology proved to be suitable for divulgation and proved economically the positive impact it would have on a strand of society with limited resources.

In conclusion, we could consider this hypothesis as true, as the additive manufacturing technology can be used to help the strand of society with limited resources in a sustainable way.

5.1. SPECIFIC HYPOTHESIS EVALUATION

Aside from the development of my main hypothesis I also clarified a set of more specific hypothesis, tightly linked to a group of objectives I aimed to attain with the research project.

PRACTICAL HYPOTHESIS:

- I will be able to build a 3D printer and print a prosthetic hand with it, and be able to teach a group of 7 people how to do that too.

With my design development I was able to build a 3D printer, with which I was able to print a prosthetic hand. I then carried out a lesson in which I taught 7 students the process from a computer design to a physical object, a prosthetic hand.

Since the evaluation following the lesson indicated that the vast majority of the students had learnt how to carry out the process, I am able to positively evaluate this hypothesis and say that it was successfully fulfilled.

SOCIAL HYPOTHESIS:

- A group of 7 people will prove to be able to sustainably print a prosthetic hand for 1,25% of the average price for a conventional hand prosthetic.

The social objective of the project was to be able to produce a low-cost prosthetic hand for underserved people. I was able to attain the purpose by producing it at 0.4% of the average cost, greatly improving the hypothesised cost.

ENVIRONMENTAL HYPOTHESIS:

- Plastic from 3D printing can be successfully recycled, thus making the manufacturing process 100% sustainable and 50% more inexpensive.

Finally, with the production of the filament extruder I was able to prove that 100% of the products could be directly recycled into useful material again.

However, it didn’t prove to be necessarily 50% more inexpensive (although it definitely made the 3D printing process cheaper).

6. CONCLUSION

After delving with the AM technology and this research project for months, I was able to come to several positive conclusions.

At the start of the research, I was quite lost in regards to the motive I was giving my development on 3D printing. After being able to acquire my goal, my hypothesis, I started the theoretical development to have a solid conceptual background. As I applied the theory in my practical development, I was able to draw several conclusions:

- The Additive Manufacturing technologies will have the power to revolutionize our manufacturing processes and, although it might never completely take over conventional methods, it will certainly revolutionize the world.

- I was able to find easily most resources online, which means that the development of the technology is being well documented in order to enable open source accessibility to the greatest number of people.

- When I exposed the practical development and simulated the implementation of my project, although most of the students did not initially know how 3D printing worked, I was able to easily transmit the basis of how it worked, showing the growing sector of personal fabrication in 3D printing.

In conclusion, this project taught me how to understand the new technology and advancements that we face with AM, and the practical development demonstrated the truth of my hypothesis (that the AM technology can be used to help the strand of society with limited resources in a sustainable way) which will result in an industrial revolution in which all of the levels of society could be and will be benefitted from.

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