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European University Market for 3D Printing and Business Plan of an Additive Manufacturing Laboratory

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Nonni, eredità di intenti,

speranze mai vanificate, sogni realizzati.

Ed oggi che ho raggiunto la grande meta ci siete anche Voi,

nel mio cuore, nella mia mente, per sempre.

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Table of Contents

List of Acronyms and Abbreviations 9
1 Introduction 11
1.1 Problem statement and derivation of research questions 12
1.2 Methodology 13
2 Additive Manufacturing Processes Categories 15
2.1 The Generic AM Process 15
2.2 Overview of AM technologies 19
2.2.1 Directed Energy Deposition 19
2.2.2 Binder Jetting 21
2.2.3 Sheet Lamination 23
2.2.4 Material Jetting 25
2.2.5 Material Extrusion 27
2.2.6 Photopolymerization Processes: SLA- Stereolithography 29
2.2.7 Powder Bed Fusion 32
3 Global Markets for 3D Printing 36
3.1 Global Market for 3D Printing by Technology 36
3.2 Summary 37
3.3 Market Breakdown by Components 38
3.3.1 Global Market for 3D printers: 39
3.3.2 Global Market of 3D Printing Services 41
3.3.3 Global Market for 3D Printing Software 43
3.3.4 Global Market for 3D Printing Material 44
3.4 Market Breakdown by Region 45
3.4.1 Europe 46
4 European Universities Market for 3D Printing 48
4.1 Data Acquisition 48
4.2 Data Analysis 56
4.2.1 National Geographic Distribution of the Universities investing in Additive Manufacturing 56
4.2.2 Classification of Laboratories according to TRL 62
4.3 Results 77

4.3.1 UK Results ... 79
4.3.2 German Results ... 92
4.3.3 Italian Results ... 102
4.3.4 French Results ... 109
4.4 University Market Research Conclusion ... 117
5 Ar-Lab’s Business Plan ... 121
5.1 Equipment ... 121
5.2 How to use the laboratory ... 124
5.3 Cost Structure ... 127
5.3.1 Principal Investigator Project Costs ... 128
5.3.2 Trinity College Costs ... 129
5.3.3 Ar-Lab - Additive Research Laboratory Costs ... 129
5.4 Revenue Structure ... 135
5.4.1 Academic hourly rate ... 136
5.4.2 Organization of events and courses based on Additive Manufacturing ... 137
5.4.3 Trinity College Revenue ... 140
5.5 Ar-Lab Financial Statement and its strategies ... 141
5.5.1 Income Statement 2019 ... 143
5.5.2 Income Statement 2020 ... 145
5.5.3 Income Statement 2021 ... 147
5.5.4 Income Statement 2022 ... 149
5.5.5 Results ... 150
6 Conclusion ... 153
References ... 155

Table Index

Table 1: Overview on the DCE Category 21
Table 2: Overview on the Binder Jetting category (30) 22
Table 3: Overview on the Sheet Lamination category 24
Table 4: Overview on the Material Jetting category (38) 26
Table 5: Overview on the Material Extrusion category 29
Table 6: Overview on the SLA category 31
Table 7: Overview on the Power Bed Fusion category 34
Table 8: Global Market for 3D Printers, by Technology, through 2023, (17) 37
Table 9: Global Market 3D Printing through 2023, (17) 39
Table 10: Global Market or 3D Printers by Printer Type (*17*) 39
Table 11: Global Market for Desktop 3D Printer through 2023 (17) 40
Table 12: Global Market for Industrial 3D Printer through 2023 (17) 41
Table 13: Global Market for 3D Printers through 2023, (17) 41
Table 14: Global Market for 3D Printing Service through 2023 (17) 42
Table 15: Global Market for 3D Printing Software through 2023, (17) 43
Table 16: Global Market for 3D Printing Materials, by type, through 2023, (17) 44
Table 17: Global Market for 3D Printing Materials, by Region, through 2023, (17) 45
Table 18: Global Market for 3D Printing, by Region, through 2023, (17) 46
Table 19: European Market for 3D Printers, by Country, through 2023, (17) 46
Table 20: UK Universities Analyzed 49
Table 21: German Universities Analyzed 49
Table 22: Italian Universities Analyzed 50
Table 23: French Universities Analyzed 51
Table 24: National Data Collection Excel Format 53
Table 25: Processing Estimates of 3D Printers Final Prices 54
Table 26: List of all UK Universities involved in the Additive Manufacturing (AM) academic diffusion 57
Table 27: List of all German Universities involved in the Additive Manufacturing (AM) academic diffusion 59
Table 28: List of all Italian Universities involved in the Additive Manufacturing (AM) academic diffusion 60
Table 29: List of all French Universities involved in the Additive Manufacturing (AM) academic diffusion 62
Table 30: Technology Readiness Level TRL (161) 63
Table 31: Incidence of the 3D Printers price in the revised global market (17) 65
Table 32 National Lab Classification 66
Table 33: Excel file used for Lab classification 68
Table 34: UK Laboratories Classification 68
Table 35: Results UK Laboratories Classification 70
Table 36: German Laboratories Classification 71
Table 37: Results Germany Laboratories Classification 72
Table 38: Italian Laboratories Classification 73

Table 39: Results Italian Laboratories Classification 74
Table 40: French Laboratories Classification 75
Table 41: Results French Laboratories Classification 76
Table 42: Excel format used to achieve the first two objectives 77
Table 43: Example show the format used to obtain the distribution of 3D Printers Manufacturers 78
Table 44: Format used to realize the distribution of technologies and investments made by each university in UK 79
Table 45: Format used to obtain the distribution of 3D Printers Manufacturers in UK 89
Table 46: Format used to realize the distribution of investments made by each university in Germany 92
Table 47: Format used to obtain the distribution of 3D Printers Manufacturers in Germany ... 100
Table 48: Format used to realize the distribution of technologies and investments made by each university in Italy 102
Table 49: Format used to obtain the distribution of 3D Printers Manufacturers in Italy........... 108
Table 50: Format used to realize the distribution of technologies and investments made by each university in French 110
Table 51: Format used to obtain the distribution of 3D Printers Manufacturers in French....... 115
Table 52: Market Research Conclusion 117
Table 53: Equipment Available in Ar-Lab 122
Table 54: Cost and Revenue Structure of main actors in Ar-Lab 127
Table 55: Ar-Lab's Cost Stucture 129
Table 56: Yearly Warranty Machines 131
Table 57: Hazardous Waste Removal Yearly Cost 134
Table 58: Total Usage Hours 136
Table 59: Financial analysis consisting of a single revenue stream 141
Table 60: Income Statement 2019 144
Table 61: Income Statement 2020 146
Table 62: Income Statement 2021 148
Table 63: Income Statement 2022 149
Table 64: Ar-Lab's Financial Analysis Results 150

Figure Index

Figure 1: Generic process of CAD to part, showing all 8 stages (12) 15
Figure 2: Schematic diagram of DED Process (203).. 19
Figure 3: Schematic over the Binder Jetting Process (12)... 22
Figure 4: Ultrasonic Additive manufacturing process (204) 24
Figure 5: Schematic of the material jetting 3D Printer (29) 26
Figure 6: Schematic of the FDM process (205)... 28
Figure 7: Photopolymerisation Process (206) 30
Figure 8: A basic schematic of the powder bed fusion process using the SLS technology. (29) 33
Figure 9: UK geographical distribution of identified universities; (created with https://it.batchgeo.com).. 57
Figure 10: German geographical distribution of identified universities; (created with https://it.batchgeo.com).. 58
Figure 11: Italian geographical distribution of identified universities; (created with https://it.batchgeo.com).. 60
Figure 12: French geographical distribution of identified universities; created with https://it.batchgeo.com 61
Figure 13: UK Total AM Investment Distribution 87
Figure 14: UK AM Technologies Distribution 89
Figure 15: UK AM Manufacturers Distribution 91
Figure 16: German Total AM Investment Distribution 98
Figure 17: German AM Technologies Distribution.. 99
Figure 18: German AM Manufacturers Distribution 101
Figure 19: Italian Total AM Investment Distribution... 106
Figure 20: Italian AM Technologies Distribution 107
Figure 21: Italian AM Manufacturers Distribution.. 109
Figure 22: French Total AM Investment Distribution.. 113
Figure 23: French AM Technologies Distribution 115
Figure 24: French AM Manufacturers Distribution.. 117
Figure 25: European University Market for 3D Printing... 118
Figure 26: European Market for 3D Printers 2018 (BCC Research) and European University Market for 3D Printers 120
Figure 27: Trinity College'Hazardous Material Centre Deliveries 133
Figure 28: Metal Powder life-cycle, (Phoenix Analysis & Design Technologies Inc) 133
Figure 29: ACAM in house modules 138
Figure 30: Ar-Lab Cash Flow 142
Figure 31: Ar-Lab's Profit Distribution Part 2 151
Figure 32: Comparison between Ar-Lab's current and probable future situation 151

List of Acronyms and Abbreviations

ABS acrylonitrile butadiene styrene

AM additive manufacturing

BJ binder jetting

CAD computer aided design

CAGR compound annual growth rate

CCD central composite design

CT computed tomography

DED directed energy deposition

DLP digital light processing

DMLS direct metal laser sintering

EBM electron beam melting

FDM fused deposition modeling

FPI fluorescent penetrating inspection

LCM Lithography Based Ceramic

MJ material jetting

PC polycarbonate

PI Principal Investigator

PIs Principal Investigators

PLA polylactic acid

PPE Personal Protective Equipment

RI radiographic inspection

RM rapid manufacturing, when AM is used for end products

RP rapid prototyping, when AM is used for prototyping

SL sheet lamination

SLA stereolithography apparatus

SLM selective laser melting

SLS selective laser sintering

TCD Trinity College Dublin

TPL Two-Photon lithography 2PL

1 Introduction

Various definitions and terminologies are used today to describe Additive Manufacturing (AM) (e.g. freeform fabrication, rapid prototyping, etc.). According to the official one, AM , or 3D printing Technology (3DPT) , refers to the "*process of joining materials to make parts from 3D model data usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies*" (1).

Under this perspective, AM represents the new technology whose birth dates back to the early 1980s, when it was conceived as a process known as Stereolithography: i.e., the application of lithographic techniques to the production of three dimensional objects, to simultaneously execute Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) in producing three-dimensional objects directly from computer instructions (2).

The AM history (3), shows that it *had a major impact on the development of various spheres of life; in* 1999 its first use was in medicine (4) and in 2000 the first parts of humans such as ears, fingers were made (5). In a few years, AM scope and its areas of research have progressed on a number of fronts; in 2006 it became Open source (6) and in 2009 Sculpteo, the world leader in digital manufacturing based in Paris ad San Francisco, was founded (7); in 2010 the first prototype car printed in 3D became a reality (8) and in 2014 NASA equipped itself with a 3D printer in space to make the first 3D printed object off the earth. (9); in 2014 there was the revolutionary ultra-fast continuous Liquid interface Production Technology 3D printer (10) and in 2016 the Trinity College's Professor, Daniel Kelly, announced the possibility of 3D printing both cartilage and bones using a "bio-ink" (11).

Nowadays, AM is focused in the context of the so-called "Digital Manufacturing" (DM): i.e. the use of additive manufacturing technologies for the production of end-use components (12).

Additionally, AM shows a strong and growing capacity for calculation and intelligence through the sharing of information between machines and people, made possible by digital information (3D Software) and mobile devices (13) (14).

AM, under several dimensions, represents the natural evolution that blends with computerized machines and algorithm codes. As a matter of fact, it is a concept in which various processes are used to physically replicate 3D objects created by computer – aided design (CAD) (15).

In conclusion, AM is regarded as the resolutive tool of the mathematics of the object to be worked: i.e. the way to catch the basic concepts of mathematics necessary for the effective development of computational methods for 3-D modelling and computer graphics in many fields of Science and Technology (16).

1.1 Problem statement and derivation of research questions

Trinity College Dublin has launched a new additive research laboratory called Ar-Lab and located on its campus in March 2018. The laboratory, composed by different types of 3D printers in order to cover the entire spectrum of materials from ceramics and polymers and biomaterials, is currently used only for academic and research purposes. As a matter of fact, until now, only research projects, managed by different professors belonging to the Trinity College's mechanical and manufacturing engineering department as Principal Investigator (PI), have been developed. Managing and maintaining an AM laboratory is very expensive due to the high cost of maintenance of the machinery and materials used to develop AM projects. For this reason, the purpose of this work is to support the laboratory by carrying out a financial analysis to study how the laboratory can operate independently over time without the financial support of third parties. The Ar-Lab's economic and financial analysis is based on the identification of the laboratory's cost and revenue structure and how these are distributed over time. Before tackling the analysis of the laboratory, it was decided to study how the other AM European laboratories are structured and managed in order to get some more ideas on how to implement the Ar-Lab's growth strategy. Thanks to the collaboration with the Market Research Center – Enterprise Ireland in Dublin, it was possible to obtain the approximate definition of the Global Market for 3D printing, through 2023. More in detail, according to BCC Research, the global market for 3D printing, including printers, software, material and services was 6.9 billion $ in 2017. Additionally, the market is expected to grow at a Compound Annual Growth Rate (CAGR) of 22.4% from 2018 to 2023, reaching nearly 23 billion $ by the end of the forecast period. (17) This information on the size of the 3D printing market allowed to introduce the second main work carried out within this thesis, that is the estimate of the European University Market for 3D printing, where for European it means the analysis developed in four different countries: UK, Germany, Italy and France. This dataset is an overview of the total amount of money invested by the public entities such as Universities, National Government, National Foundations, European founds and other entities, in the dissemination of AM within the European academic world. The data set contains information on 160 universities, consisting of innovative additive manufacturing centers for conducting applied research, academic laboratories for carrying out basic research, simple 3D printing services offered to students enrolled at the University and those engineering faculties without an AM Laboratory. After analyzing about 160 universities, more than half of these constituted by an AM laboratory, it was possible to define a support and growth strategy for Ar-Lab. In particular, new revenue streams have been identified that Ar-Lab will have to implement in the future to achieve the goal of being financially independent.

1.2 Methodology

The European University Market for 3D Printing was structured as follows:

1. *Data Acquisition*: Explanation of how all the data were collected.
2. *Data analysis*: Explanation of how all the data were analyzed.
   - 2.1 Execution of National Geographic Distribution of the Universities investing in Additive Manufacturing.
   - 2.2 Execution of classification of Laboratories according to TRL in order to estimate the National Universities Market for 3D Printing and to have further qualitative and more explanatory data on the level of national investment made in AM in each country considered.
3. *Results obtained for each country*:
   - 3.1 National distribution of the total investment made by each university in order to identify which universities have invested most in the diffusion of the AM within each country.
   - 3.2 National distribution of AM technologies used and studied in the AM Lab within each country.

3.3 National distribution of 3D printers Manufacturers to identify the AM manufacturers who have most sold 3D printers in the academic field.

4. *Conclusion*

4.1 Comparison of national data obtained between the 4 countries analyzed.

4.2 Comparison between the data obtained from the global market for 3D printing performed by BCC Research and the European University Market for 3D printers performed within this work.

Subsequently, thanks to the learning obtained in the execution of the market analysis and thanks to the support of Ar-Lab's technical staff, the financial analysis of the laboratory took place in the following way:

1. *Laboratory Description*: Presentation of the equipment currently in the laboratory and how the laboratory can run.
2. *Identification of Ar-Lab's cost structure*: Identification in detail of the cost structure of each actor, such as Principal Investigator, Trinity College and laboratory, involved in Ar-Lab projects.
3. *Identification of Ar-Lab's revenue structure:* Identification of existing revenue streams and strategy implementations for obtaining new revenue streams able to financially support the laboratory.
4. *Implementation of the Ar-Lab's financial statements* in the years 2019, 2020, 2021 and 2022.

2 Additive Manufacturing Processes Categories

This is a chapter of introduction to the basic concepts of Additive Manufacturing. More in detail, in this chapter an overview of the generic AM Process and a summary of the most common Additive Manufacturing methods will be presented. For each technology analyzed, it was highlighted the main fields of applications, the main materials used for the execution of the related process and its existing benefits and limitations. Some additive manufacturing methods like Stereolithography and Powder Bed Fusion have been analyzed more specifically because they represent methods implemented through various 3D printers at the Trinity College laboratory that will be the main topic of Chapter 5.

2.1 The Generic AM Process

AM involves several steps that move from the virtual CAD description to the physical resultant part. Depending on the complexity of the products, AM will be involved in several ways and degrees. As a matter of fact, these steps could be performed by some machines and at the same time some of these steps could be skipped by others. Although there are different AM methods and technologies, most of the AM processes are composed by steps shown in figure 1. (12)

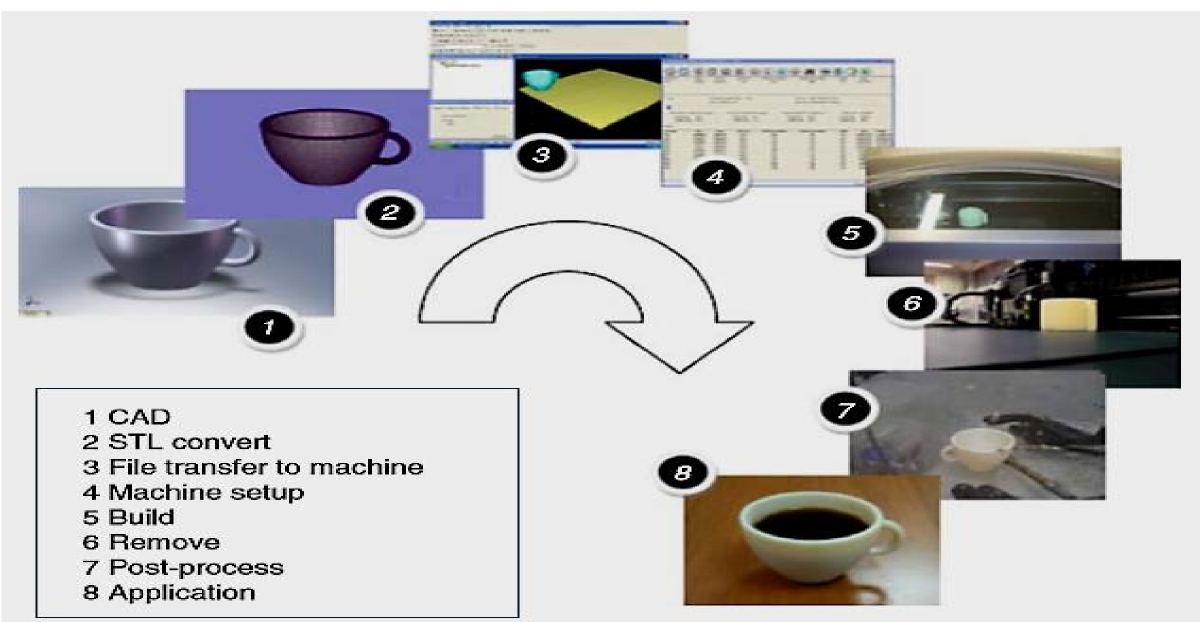

Figure 1: Generic process of CAD to part, showing all 8 stages (12)

In Step 1, each product development must begin with the definition of the product concept. If AM is to be used, the product description must be in a specific form that allows to create a 3D model of the object you would want to print. The 3D model can be designed with Computer Aided Design-CAD software that allows to clearly visualize the project and understand how the products work. More in detail, CAD program is a computer technology that designs a product and documents the design phase of the engineering process. This new kind of design, after that the 3D model has been created, enables to run simulations. CAD assist the developer in the creation, modification and optimization of design. The engineering software program can improve the quality of design, the productivity of the Engineer, communications through documentation and create a database for manufacturing. Moreover, CAD programs are used together with other tools such as:

- *Computer Aided Engineering* (CAE) tools are used to perform product simulation, validation, and optimization in order to analyse the robustness, performance components and assemblies. The main parameters that are typically considered for CAE simulations are: Temperature, Pressure, Component Interactions an Applied Forces. The aim of the simulations is to understand if the part could theoretically manage the design constraints.

Computer Aided Manufacturing (CAM) is the use of computer software for the control machine tools and related machinery in the manufacturing process. Cam may also use a computer to assist all operations of a manufacturing plant, including planning, management, transportation, and storage. Specifically, the CAM code is also used by Computer Numerical Control (CNC) for the production of products. CAM provides step by step instructions that the machine tools will follow to complete the manufacturing of the product, simplifying the machinist's work (18).

Additionally, in Step 2 is introduced the universal standard of the AM mathematics models called Standard Triangulation Language (STL). The file contains the object's geometry and additional information, such as material, texture and colour. (19) The 3D CAD model is converted into a SHELL model in which the external surface of the product is approximated to triangles of different sizes in order to follow the model profile. As a matter of fact, STL works by removing all construction data, model history and approximating the model surfaces with a series of triangular facets. Most of the CAD software are able automatically to perform the STL conversion process. During this phase, some errors may occur and so to identify and solve them, software tools like

MAGICS, that is used when there are some problems with the file generated by the CAD system, have been introduced (12).

Moreover, in Steps 3 and 4 the transfer of the STL file to the 3D Printers takes place and the machine will most likely need to be set-up. After that, the STL file has been created, the file is sliced into sections that define the thickness of each manufactured layer. In particular, the software that slices the STL file usually has an “add-in” from the AM machine provider that ensures the slice file contains the required machine specific commands. At this point, the sliced file can be transferred to the AM machine (19).
Additionally, before setting up the machine and starting printing, it is important to underline that, in order to avoid making mistakes, it is necessary to check the positioning, orientation and dimensioning of the object on the build platform (12). As a matter of fact, the machine operator selects the orientation of the build, applies support structures and inserts the relevant parameters for the build, according to the selected technologies (19).
Depending on the machine, it will be necessary to set up different specific parameters: machines that have been designed to work with a variety of materials and with variation of layer thickness or other build parameters, will require more set up time compared with less sophisticated machines.

Furthermore, during Steps 3 and 4, the feedstock purchased from a vendor must have been prepared for use. During the characterization of the raw material, which is a time and labor – intensive process, parameters such as material chemistry, particle size, shape and homogeneity are examined because all of these can affect the material properties of the parts produced.

Step 5 is the building phase that consists of a process of joining materials to create object, usually layer by layer, as opposed to subtractive manufacturing methodologies (20). Moreover, the building phase is performed by a controlled computer, unlike previous stages which are semi – automated and require considerable manual control, interaction and decision making (12). The steady monitoring of various manufacturing parameters takes place during the build process to prevent potentially dangerous situations such as excessive pressure or an overflowing of O2 inside the process chamber. Nowadays sensor information has been increasingly integrated into the process control, in order to improve the final quality of the construction and minimize time consuming and costly post processing steps (19).

At the end of the build process, the output should be ready for use. Clearly, the AM technologies still require support through manual finishing to get ready the products out of the previous stage. Step 6, representing the removal phase, is introduced. Whenever the final printed product must be either separated from a build plate on which the part was produced or removed from excess build material surrounding the part called supports. For some AM technologies this process could be performed easily, but for others it might require specific manual skills along with safety devices and controlled environments, because the use of a poor technique in removing the support could result in a low quality of the final product (12). It is common practice for service providers to recycle the excess build material or metal powder, this is done in order to minimizes manufacturing costs and reducing environmental impact (19).

After the removal phase, Step 7 is introduced through the post process phase. Depending on the AM technologies used, it’s necessary to perform post processing operations such as cleaning, painting and surface finishing which require a very careful handling of the parts to maintain a high precision and finish and to involve the use of other machines and tools.

With Step 8, the products are ready but before delivering them to customers, it is common to perform some tests to demonstrate that the final products will have the same properties as customers require. For instance, for functional parts, non-destructive tests are usually performed and composed by Fluorescent Penetrating Inspection (FPI), Radiographic Inspection (RI), and Computed Tomography (CT).

2.2 Overview of AM technologies

The ISO/ASTM 52900 Standard (1) was created in 2015 to standardize all terminology as well as classify each of the different methods of AM technologies whose roots lie in a total of seven process categories. As stated in the following paragraphs, any category differs from one another depending on the material and technology of the machine used.

2.2.1 Directed Energy Deposition

Direct Energy Deposition (DED) is an AM process used to create 3D models in a wide variety of material such as polymers and plastic, ceramics and others advanced materials.

In the general framework of AM, DED is specifically suitable for the production of metal products, through the deposition layer-by layer of molten metal powders, filament (for example, cobalt chrome, titanium, stainless steel, etc.) or also alloy. According to ASTM, a typical DED device, is an "AM process in which focused thermal energy is used to melt the materials when they are being deposited (21). As a matter of fact, DED consists of a concentrated heat source (a laser or an electron beam, an arc welding), which melts material (nickel-based alloy, aluminium etc.) in powder or wire, when they are deposited at a precise point.

A schematic description on how the laser powder beam and shielding gas are applied with DED, creating a melt pool on the workpiece, is shown in Figure 2.

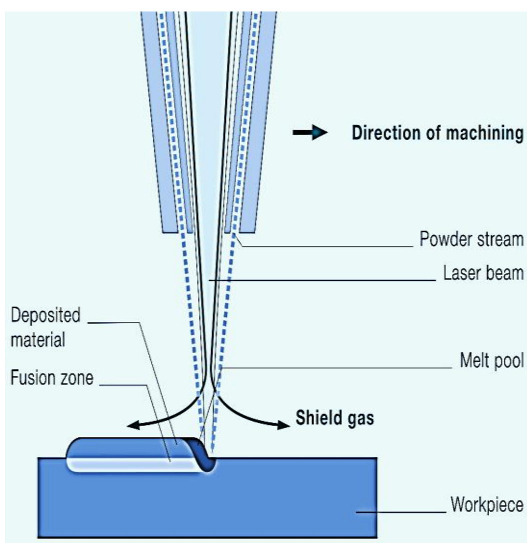

Figure 2: Schematic diagram of DED Process *(203)*

The energy-intensive source analyzes the surface, generating a fusion pool. This laser follows the specified routes to move forward and fill the top of the existing substrate and as a result, the solidification of small droplets of molten metal which strike the cold surface occurs (22). Additionally, the melting and diffusion processes produce a metal deposited with metallurgical bond to the substrate.

DED consists of two lower level processes:

- *Laser Engineered Net Shaping* (LENS), an additive layer manufacturing process that creates fully dense metal components using a laser, metal powder, and a solid computer model used to print metal parts through a printhead (23) . The printhead moves on all three axes. The laser is focused through the printhead and metal powder is injected into the printhead. Then, the powder is sintered when it comes out of the head and it is laid on the model. An inert protective gas is used inside the printhead to protect the metal from oxygen (so that the metal sintered correctly and can be controlled more accurately).
- *Electron Beam Freeform Fabrication* (EBF), an additive manufacturing technique developed over the past two years at NASA Langley Research Center. A computerized model of a component is created and translated into programmable machine code to drive the EBF system (24). A focused electron beam is used to create a molten pool on a metal substrate. Then, the wire to build the substrate is fed into the molten pool and the substrate is translated with respect to the electron beam. In conclusion, the final part is, thus, built up layer by layer.

Several studies discuss the DED outcome as a function of the processing parameters (25). The fundamental parameters of the DED process such as Laser Power, scanning speed and powder feeding speed can be modified by the operator and this has a strong impact on the quality of the process execution and therefore on the final product. Additionally, thanks to the functional properties of DED, surface treatments can be widely used in many industries to improve the corrosion resistance of sheet metal. Metal coatings can provide protection to steel sheet from environment attacks (26) and waste reduction is advantageous compared to subtractive technologies (12).

More generally, it is stated that in DED there are many advantages compared to conventional welding technologies for repair, such as inert tungsten gas or gas arc (27).

Table 1 offers an overview on them compared with other competing methods (i.e., Power Bed Fusion (28)) to build or repairing metal components:

Table 1: Overview on the DCE Category

Main applications	Build metal components from powder feedstock, Repairing, maintaining structural part and adding material to the existing components;
Materials	Polymers, ceramics, metals such as cobalt chrome, titanium, stainless steel in the form of either powder or wire.
Parameters	Print speed (Laser power), Layer Thickness, Estimated Build time, Price to build a size metal part with sample geometry
Benefits and limitations	BENEFITS: • Construction with rapid material deposition; • Reduction of material waste; • Reduction of thermal affects and residual stresses; • Improvement of precision and production flexibility; • New opportunities that allow parts of complex geometry; • Repair / coating and addition of high capacity functionality on 3D surfaces; • No need for supports; LIMITATIONS: • Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect; • Fusion processes require more research; • Speed benefits are costly • Significant post-processing requirement, usually in the form of secondary machining • Poor surface finish • Loss of wire precision, due to a preformed shape (12)

2.2.2 Binder Jetting

“Binder Jetting (BJ) is an AM process developed at MIT in the early 1990´s with the original name three-dimensional printing (3DP)”. Based on the two categories, sand printing and metal printing (29), BJ is an Additive manufacturing process in which a liquid bonding agent is selectively deposited to combine powdered materials (21)”. In BJ a liquid binder is deposited through a print head in the positions designated layer by layer for the manufacture of the part geometry. Even BJ, like many high AM techniques, is focused on building parts through a fusion or welding process to merge each layer together. As shown in Figure 3, the machine includes three main elements: a powder dispenser / diffuser, a powder bed and an inkjet print head with nozzles.

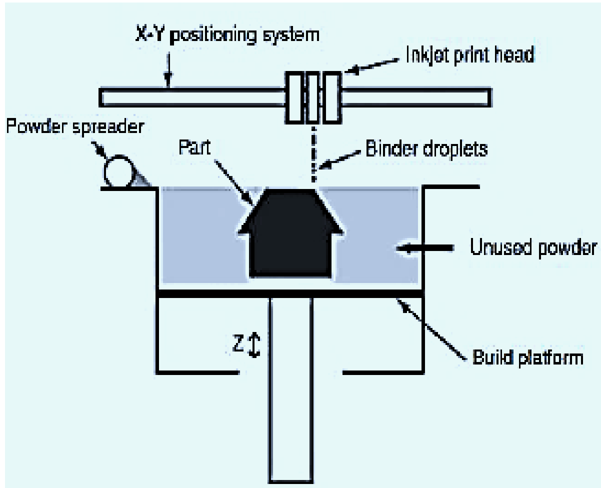

Figure 3: Schematic over the Binder Jetting Process *(12)*

As already seen, a software implements the CAD design and splits the component into several cross-section layers. Through the perceived 2D profile, a polymeric binder is then selectively sprayed from the inkjet printhead. Once the layer has been printed, the powder bed is reduced by the layer thickness and the powder spreader distributes a new thin layer on the powder bed. Then the process is repeated until all 2D layers have been formed and the desired 3D structure has been built up. In addition, the green body produced is surrounded by excess powder in the printing box. For this reason, during the refining process, the pressurized air blasting removes the excess powder whose unused part can be recycled and reused.

Table 2: Overview on the Binder Jetting category *(30)*

Main applications	It is used for wide a range of applications: Full color modelling and prototyping. Sand casting molds and cores. Functional metal parts when secondary processes are used in conjunction with BJ; (31)
Materials	Polymers, polymer blends, composites, metals and ceramics. Some examples are stainless steel, copper, tungsten, Inconel, nickel, ABS, PA, PC, glass; (31)
Benefits and limitations	BENEFITS: • Lack of support and supervisors; • Reduction of post-processing time; • Material savings; • Manufacturing of very large parts and complex metal geometries; • No limitation of thermal effects (eg Deformations); • Improvement of the quality of the surface finish compared to other additive production processes;

continued on the next page

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	• 100% powder reuse in future prints • Cost savings LIMITATIONS: • Limited material selection; • Higher porosity of the parts; • Weakness of mechanical resistance; • Lowering of the break/elongate force; • Not suitable for structural parts (31) • Printed components shrink during sintering; • The powder used in metal printing can significantly increase the cost of the process.

2.2.3 Sheet Lamination

Sheet lamination (SL) is one of the seven recognized 3D Printing methods in which sheets of material are bonded to form a part" (21) cut by laser or knife.

In SL the sheets are joined one after the other either by using an adhesive or by handling the laser cut sheets together to form the 3D object. When the building material used is made of metal sheets, the process is also called *Ultrasonic Additive manufacturing* (UAM), a solid-state manufacturing process that combines the additive joining of thin metal tapes with subtractive milling operations to generate metal parts of a net shape. (32)

The variation of the process in which the paper is used to make the 3D models is known by the name - *Laminated Object Manufacturing* (LOM), a low temperature manufacturing method involving layer-by-layer lamination of paper material sheets, cut using a CO2 laser, where each sheet represents one cross-sectional layer of the CAD model of the part (12) .

UAM, as can be seen in figure 4, combines sheets of metal with a sonotrode, a cylindrical head with a structured surface that flows in high frequencies causing the layers to melt (due to friction). In UAM, the sonotrode, driven by piezoelectric transducers, applies ultrasonic vibrations (>20 kHz) to a sheet, creating a washing and plastic deformation between the sheet and the material to which it is welded, often a metal baseplate, a part, or other sheets. The scrubbing action eliminates surface oxides and contaminants, while it collapses asperities, exposing nascent surfaces that instantly bind under a compressive force. At the end of the process, CNC allows the selective removal of the material and the final processing up to the final dimensions, even if the low thermal load in UAM implies that the finished parts are not always subject to distortion, and therefore no corrective processing is required. Other times, however, the UAM process may require further processing and removal of the unalloyed metal, often during the welding process. Consequently, to facilitate the post processing and to obtain better surface finish, it could be combined it with a mill head (33).

Regarding LOM, it develops a similar layer by layer approach but uses paper as material and adhesive instead of welding.

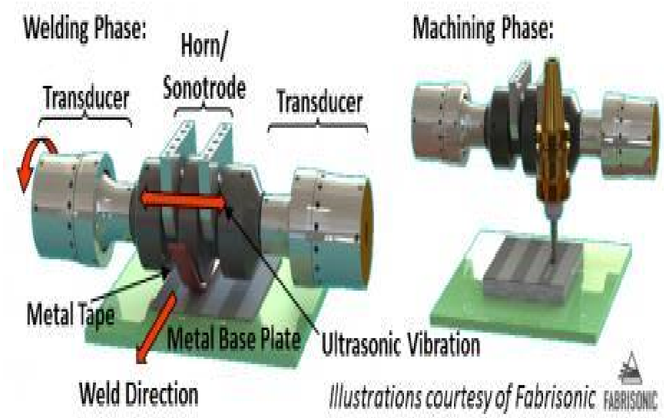

Figure 4: Ultrasonic Additive manufacturing process *(204)*

The LOM process uses a cross - hatch method during the printing process to allow easy removal at the end of the construction. Additionally, laminated objects are often used for aesthetic and visual models and are not suitable for structural use. As a matter of fact, LOM is mainly used not for production, but for prototyping. In conclusion, it is possible to observe an overview on the sheet lamination process in table 3:

Table 3:*Overview on the Sheet Lamination category*

Main applications	*LOM: It c*ould be a good substitute for wood models in sand casting. LOM is typically used for models or prototypes. *UAM:* is typically used for repairs. (31)
Materials	Polymers, polymer blends, metals and hybrid metals. Metals consolidated ultrasonically, craft paper coated with adhesives, standard sheets of papers with adhesives and carbon fibre fused with plastics. LOM could be integrated with colour (31)
Benefits and limitations	BENEFITS: • Speed improvement, cost reduction and ease of material management; • strength and integrity of the models dependent on the adhesive used (34); UAM: • Consolidations of UAM parts at bulk temperatures below 195°C; • Melting of avoided composite metals; • Incorporation of polymers and other heat-sensitive materials;

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	• High level of integration in fabrication of complex 3D externals and internal geometries for cooling channel applications or encapsulated features; LOM: • Components do not need support structures; • Only the circumference of the part is processed, whilst in most RP methods it is necessary to process the entire part area; • a potential for high manufacturing speeds LIMITATIONS: • Limited material use; • fusion processes require more research to further advance the process into a more mainstream positioning • Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect UAM: the limitation is that the strength and durability of the model created depends largely on the finish of the wielding; LOM: • Difficulty in producing good bonds between layers; • Poor surface finish; • Difficulty in the production of hollow parts;

2.2.4 Material Jetting

Material Jetting (MJ) is an additive manufacturing process, one of the most accurate 3D printing technologies, which works similarly to 2D printers. Through it, the droplets of material are selectively deposited" (21). As a matter of fact, a printhead (similar to the printheads used for standard inkjet printing) delivers tiny droplets of liquid photopolymer with different properties that solidifies under ultraviolet (UV) light, building a part layer-by-layer.

The materials used in MJ are thermosetting photopolymers (acrylics) which are in a liquid form.

Moreover, for this technology there are several printers and one of the best known is the Drop on Demand (DOD). This printer has two printing jets: one for depositing the build material and another for the dissolvable support material. Like all additive manufacturing machines, DOD 3D printer follows a pre-determined path and deposits the material precisely to build the cross-sectional area of a component. This machine uses a fly-cutter that skims the build area after each layer to ensure a perfectly flat surface before printing the next layer. Regarding the support material, it must be built under any overhanging surface (35) and can be removed by hand, by a sodium hydroxide solution, using a high-powered water jet station or by immersing the printed part in a water-based liquid (36).

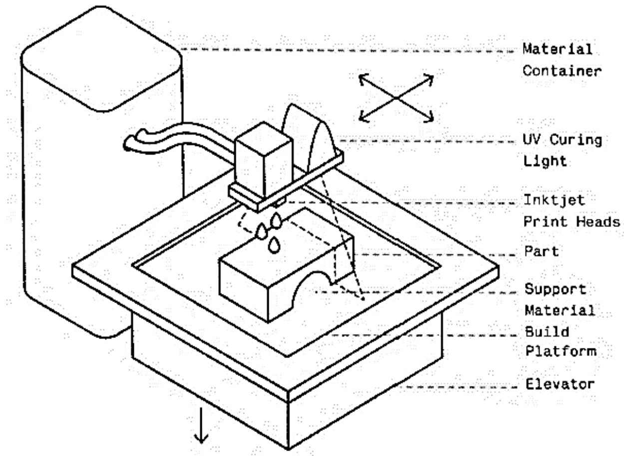

Figure 5: Schematic of the material jetting 3D Printer (29)

Additionally, DOD technology is typically used to produce wax models for lost-wax casting/investment casting and molding applications, making it an indirect 3D printing technique. Thanks to the high accuracy of the process technology, the printed part does not require manual finishing and process termination treatments and each machine is already equipped with jet cleaning systems and warns operators about the possible need for cleaning (37), (29)

The key advantages and disadvantages of the technology are summarised in table 4:

Table 4: Overview on the Material Jetting category *(38)*

Main applications	Typically, photopolymers and wax-like materials to use as investment casting patterns. it is also often used in direct part manufacturing for modelling and prototyping purposes, to print support structures from a different material during the build phase. Some machines also enable printing of electronic circuits (31)
Materials	Some types of polymers, polymer blends, composites and metals are possible. On some machines it is possible to print several but the number of materials available to use is limited and has a higher cost per kilogram (31) • Standard, (Rigid opaque plastic simulates injection molded parts etc.); • Flexible (Rubber-like Customizable hardness, poor elongation at break); • Simulated Polypropylene (Simulates PP parts, Good flexural strength, Brittle); • Simulated ABS (High temperature resistance, used for tooling & low run injection molds) • Castable, (no ash after burnout, optimized for investment casting) • High temperature (Good temperature stability (up to 80°C) High strength Brittle); • Transparent (Glass-like appearance can be post processed to 100% clear); • Medical grade (Sterilizable Short-term biocompatible Used in dental and medical applications

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Benefits and limitations	BENEFITS: • Low waste due to high accuracy droplets deposition • A process that allows multiplying the parts and colors of material; • Faster speed technology for production parts; • Multiple material can be printed in the same part and in a full color; LIMITATIONS: • Support material is often required; • A high accuracy can be achieved but materials are limited and only polymers and waxes can be used; • The parts produced have poor mechanical properties and are typically very brittle;

2.2.5 Material Extrusion

Generally, when we talk about extrusion we refer to the process used to create objects with a fixed cross-sectional profile. Within the seven additive manufacturing processes, the term Extrusion has a different and more specific meaning and refers to the involvement of a "Hot End" and a "Cold End" in the process. The extrusion process is considered the process in which the material contained in a tank is sucked through a nozzle and is then deposited layer by layer (21).

Its technology is known as *Fused Deposition Modelling* (FDM): the most popular material extrusion process, developed in the 1980s by Scott Crump, an engineer who had been working in the semiconductor industry and founded one of the most important AM companies called Stratasys (12), (39). FDM also includes another type of category such as *Fused filament fabrication* (FFF), developed by members of the RepRap project, an initiative aimed at creating a largely self-replicating machine that can be used for rapid prototyping (40) and manufacturing (41).

FDM process uses thermoplastic materials to produce both prototype and end-use parts and it is also ideal for concept models, functional prototypes manufacturing's aids and low volume end user parts. Compared to other 3D printing technologies, FDM produces very strong and dimensionally accurate parts and it is known to accurately produce features and details. As a matter of fact, it has an excellent strength-to-weight ratio.

As shown in figure 6, Material Extrusion includes the following steps:

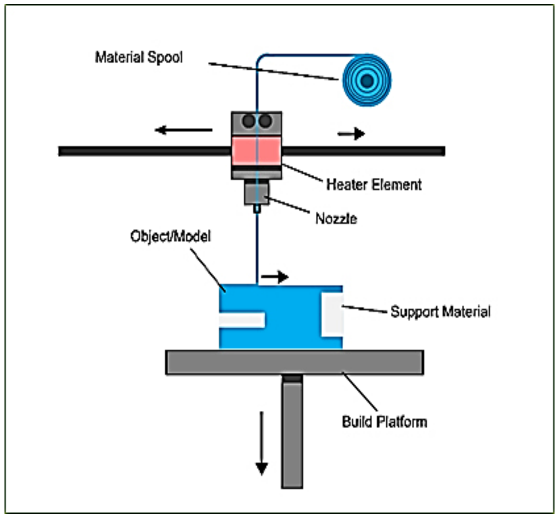

Figure 6: Schematic of the FDM process *(205)*

1. The FDM process begins by “slicing “3D CAD data into layers. The data is then transferred to the 3D printers which produces the object designed layer by layer on a build platform. Thin spools of thermoplastic and support material are used to create each cross section of the part. Through the extrusion nozzles the thermoplastic material protrudes and is positioned with precision both the support and the previous layers.
2. The extrusion nozzle continues to move in a horizontal X-Y plane and while the build platform moves down, building the part layer by layer.
3. The layers of material are fused together in a molten state and the finished part is removed from the build platform and cleaned from the support materials.

Most objects made using material extrusion technology do not need post-processing finishing. However, service providers offer multiple finishing options to create smooth and smooth parts, including manual sanding, assembly and cosmetic paint. In conclusion, since the FDM parts are made of thermoplastic material including ABS, polycarbonate and ULTEM, they are functional and durable (42). Although the materials used in FDM (polymers, composites, metals, ceramics, composites) are often more familiar to customers, the FDM market is much more dynamic and open than other markets. In this regard, FDM is used in a variety of industries, including automotive, commercial and medical industries.

Table 5: Overview on the Material Extrusion category

Main applications	Automotive; consumer goods manufacturing; biomedical and pharmaceutical applications
Materials	FDM can be used in 3D desktop printers and in parts intended for final production for a wide range of materials such as: polymers, composites, metals, ceramics, composites. In the filament there are several popular materials: the most common is Acrylonitrile butadiene styrene (ABS). Along with it some FDM machines also print in other thermoplastic, like Polycarbonate (PC) or polyetherimide (PEI)
Benefits and limitations	BENEFITS: • Multi materials on offer; • Low cost and above all efficient; • Strong, tough parts; • High dimensional stability; • Technology with the largest number of vendors of machines; and materials; • Easily understandable printing technique; • Simple and intuitive method of editing the print material; • Low initial and operating costs; • Faster printing time comparable for small and thin parts; • Printing tolerance of +/- 0.1 (+/- 0.005″); • No supervision required; • Small equipment size compared to another AM • Faster rate technology on produce parts; LIMITATIONS: • Vat polymerization and powder bed fusion have finer details; • Vat polymerization can produce smoother parts; • Visible layer lines; • The extrusion head must continue moving, or else material bumps up; • Supports may be required; • Poor part resistance of the part along the Z-axis (perpendicular to build platform); • Finer resolution and wider area increase the printing time; • Susceptible to deformation and other temperature fluctuation issues such as delamination; • Toxic printing materials

2.2.6 Photopolymerization Processes: SLA- Stereolithography

Stereolithography (SLA) is a rapid prototyping process that, in a matter of hours, convert liquid resins and translates CAD designs into solid objects (43).

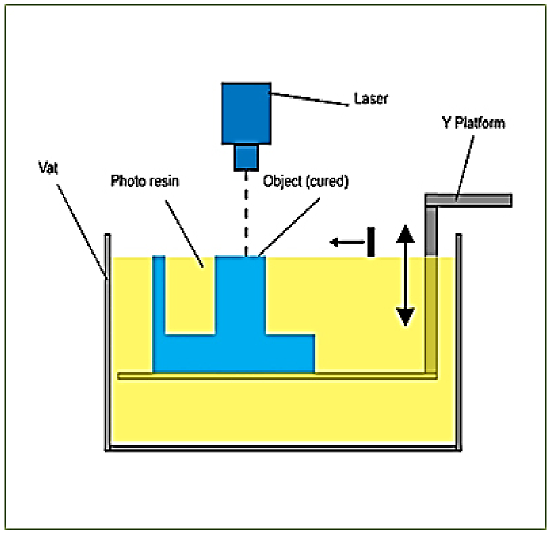

Figure 7: Photopolymerisation Process *(206)*

The combination of laser, photochemistry and software technologies with all forms of 3D Cad Data, including STEP, IGES and STL format as well as generic 3D CAD package files, makes SLA a highly accurate additive manufacturing (AM) process that may also be referred to as rapid prototyping or 3D printing. The way of creating three-dimensional objects from liquid materials using a light source is called photopolymerization: the process in which molecules called monomers bind to polymers under the influence of chemicals called light-sensitive photosynthesis. (12). In SLA, as shown in figure 7, the machine consists of the following units: a tank filled with liquid photopolymer, a perforated print, an ultraviolet laser and an STL file to direct the movement of the laser and the plane or printing platform. The adoption of the term " photopolymerization of the tank" derives from the need to describe the process by which a tank filled with a liquid photopolymer is used. Thin sections of liquid resin are cured or hardened in milliseconds by the selective activity exerted on them by the UV laser. Depending on the process used, the resin tank holds the Laser in its upper or lower part, even if the Upside-Down (SLA) is more used than SLA Right-Side Up (44).

During the curing process, the adjacent layers instantly join together and the platform is progressively lowered each time it creates a section. In this way, successive states are progressively printed through the laser, tracing the next section of the CAD model. Once the process is completed, the object is exposed by the operator who lowers the liquid resin tank and the liquid resin is removed with isopropyl alcohol. In case the need to further harden the object emerges, the use of an ultraviolet ray oven is often required. Furthermore, the supporting structures must be removed mechanically through pliers in the post-processing phase because they cannot be dissolved. This is because the SLA process uses only one type of resin at a time and the support structures are made using the same material applied in the production of the desired object (45).

Finally, talking about the advantages of SLA, it can be said that the wide range of liquid photopolymers compatible with the process makes stereolithography extremely advantageous. The flexibility, hardness and robustness of plastic production depend on the quality of the different resins used in the stereolithography process. As regards the applications of SLA, in the field of jewelery design, the qualities of the SLA process particularly appreciated by jewelers are the smooth surfaces and the highly accurate positioning of the pins (46). Finally, the use of the SLA process in the production of metal prototypes favors the creation of high-resolution objects with smooth surfaces, while in other sectors, such as biomedical engineering, the design using the SLA modeling systems has achieved important results thanks to the use of stereolithography for rapid prototyping related to the reconstruction of the head and neck. (47)

Table 6: Overview on the SLA category

Main applications	• Manufacturing; • Bio Medical Engineering; • Jewelry; • Automotive • Industrial Commercial • Investment Casting Patterns • Designer Models, snap-fit assemblies; • Optics, transparent covers
Materials	• Low viscosity liquid photopolymers; • ABS-like, liquid photopolymers; • stereolithography resins • ceramic-based materials
Benefits and limitations	BENEFITS: • complex modelling reduction; • Wide range of usable materials; • Low material consumption: non-hardened synthetic resin can be reused • No processing skills; • No communication error; • Possibility of continuous use; • Rapid prototyping; • Custom colouring; • Good accuracy and surface finish; • High resolution;

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	LIMITATIONS: • high cost of printers (compared to those using the FDM technique) and the materials (resin); • resin toxicity; • Limited resistance of components to the effects of UV radiation; • high maintenance costs; • Support need structure; • Existence of factors that limit the freedom of design; • Post-process phases, i.e. removal of supports and other manual steps; • Post-treatment, to solidify the entire structure and guarantee its integrity.

2.2.7 Powder Bed Fusion

Powder bed fusion (PBF) is the most popular AM method introduced into the market for producing a complex variety of components. According to ISO / ASTM 52900, PBF is an AM process in which heat energy selectively fuses the regions of a powder bed in which the raw materials are deposited and selectively melted by means of a heat source (48). PBF technologies use all the same basic techniques to produce parts layer by layer through a heat source that is most commonly a laser, but other methods are also available, including some using an electron beam or an infrared heater. The building process begins by laying a thin layer of metal powder on a substrate plate in a building chamber. After laying the powder, a high-energy density laser is used to fuse selected areas based on the processed data. Once the laser scan is completed, the building platform is lowered and a further layer of powder is deposited on the top and the laser scans a new layer. The process is then repeated until the components are complete. Additionally, during PBF process, due to the high temperatures required for melting, the parts are built in a controlled oxygen atmosphere using an inert gas, argon or nitrogen, to prevent oxidation and other problems that may affect the mechanical properties of the finished part. Moreover, PDB process is also known under terms as Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM). (49)

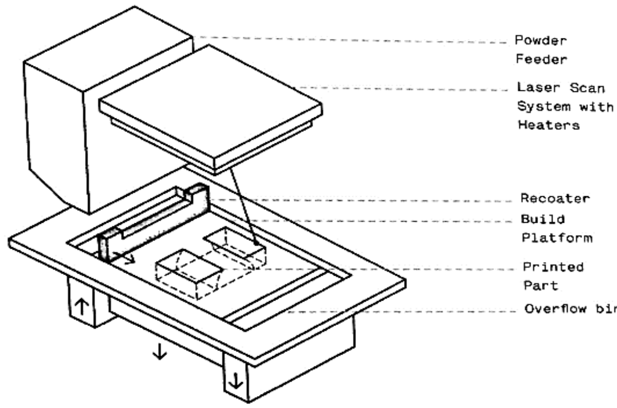

Figure 8: A basic schematic of the powder bed fusion process using the SLS technology. (29)

Selective Laser Sintering (SLS) is a rapid prototyping technology of choice for a wide range of functional prototype applications, including those with living hinges, snap couplings and other mechanical joints. The wide application of this process for the production of real parts and tools has influenced the creation of a wide selection of materials. (50) As a matter of fact, SLS technology uses a laser to harden and bind small grains of plastic, ceramic, glass, metal or other materials into layers in a three-dimensional structure. In addition, the laser sintering machine consists of a laser (such as Laser CO2, Yag and diode, Laser, Fiber), optical drive, XY scan head, process computer, construction chamber and inert gas (nitrogen) recirculating filter system that manages the building process. Various sensors are also available to monitor the process and to supervise machine components, calculation of scan patterns and scanner / laser communications. (51)

In regards to DMLS, it uses a variety of metal and alloy materials such as stainless steel and chromium-plated cobalt aluminium and inconel, stainless steel and titanium to create robust and durable parts and prototypes. (52) Moreover, it is an excellent choice for functional metal prototypes, high temperature applications and end-use parts and the typical uses of DMLS include tools and production aids, small integrated structures, dental components, surgical implants, aeronautical parts and aerospace.

In the SLM process, the volumetric density of the energy, the mechanical properties and the surface roughness of the parts produced are all factors optimized by a common set of parameters such as laser power, scanning speed, hatch distance, layer thickness. Furthermore, the laser energy is intense enough to allow full fusion (welding) of the particles to form solid metal. The process is repeated layer by layer until the part is completed. Greater control over the crystalline structure and reduced porosity are SLM factors which, more than in SLS, facilitate the production of stronger parts. In this perspective, the lower SLS speed must be assessed taking into account the higher energy costs of SLM and its poor energy efficiency. (12) Furthermore, although the SLM process parameters improve surface quality, it is usually lower than conventional production. For this reason, various post-processing techniques are used (for example, electropolishing, etching, plasma spraying, machining, sandblasting). Finally, it must be considered that for some complex parts it is not always possible to use SLM techniques. (53)

Electron beam melting (EBM) technology is similar to laser fusion, but it works with an electron beam instead of a laser. The machine distributes a layer of metal powder on a construction platform, which is melted by the electron beam. Furthermore, EBM produces less thermal stress in the parts and therefore requires less support structure than laser fusion. It also has a higher build speed and more uniform heat management than SLM, but at the same time it is an expensive process that works with limited metals and that requires a lot of post processing because it is not able to get good surface finishes. (54)

Table 7: Overview on the Power Bed Fusion category

Main applications	• Tools and fixitures; • Fuel tanks; • Light components for unmanned aerial vehicles; • Automotive designs • Air ducts • Architectural models • Artistic sculptures
Materials	• Large range of materials, including: - Metal and Polymers: SLM: Stainless Steel, Titainium, Aluminium, Cobalt Chrome, Steel; SHS: Nylon DMLS, SLS; EBM: titanum, Cobalt Chrome, ss, al and copper; • Glass and ceramics
Benefits and limitations	BENEFITS: • Low cost due to the drop of price in powder bed fusion machines. • Suitable for prototypes and visual models; • Wide selection of materials • Recycling of powders • SHS: Ability to integrate technology into small scale, office sized machine

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	LIMITATIONS: • Relatively slow speed (SHS) and long print time • Post-processing – Printed parts need.to be post-processed before use, adding time and cost • Lack of structural properties in materials; • High energy consumption; • Powder recycling;. • Thermal distortion that can cause shrinkage and deformation of manufactured parts. • The finish depends on the powder grain size;

3 Global Markets for 3D Printing

Thanks to the collaboration with the Market Research Center – Enterprise Ireland in Dublin, it was possible to obtain the approximate definition of the Global Market for 3D printing, through 2023. The data, subsequently presented in detail, were obtained from a market research carried out by BCC Research, a company who has been producing reliable market research reports and forecasts for more than 45 years. This information on the size of the 3D printing market allowed to introduce the main work carried out within this thesis, that is the estimate of the European University Market for 3D printing, where for European it means the analysis developed in four different countries: UK, Germany, Italy and France. As it will be analyzed more in detail later, some global market trends, such as the most widespread additive technology, were the same found in the European university market, others such as the European market for 3D printers market saw different results in the research presented here. In the next paragraphs, the results obtained by BCC Research will be presented in detail and can be summarized as follows:

- Global Market for 3D Printing Technology
- Global Market for 3D Printers
- Global Market for 3D Printing Services
- Global Market for 3D Printing Software
- Global Market for 3D Printing Material
- Market Breakdown by Region

3.1 Global Market for 3D Printing by Technology

Before plunging into the analysis of the global 3D printing market estimate conducted by BCC Research, the 3D printing technologies with their relative market estimate is reported below in table 8.

Table 8: Global Market for 3D Printers, by Technology, through 2023, (17)

Global Market for 3D Printers, by Technology, through 2023 (Millions $)				
Technology	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
Material extrusion	1460	1748.8	4590.7	21.3%
Vat photopolymerizatio	833.2	1008.6	2789.4	22.6%
Powder bed fusion	514.3	630.4	1855.8	24.1%
Jetting	436.6	528.7	1463.7	22.6%
Direct energy depositior	319.2	378.8	948.5	20.2%
Others	226.1	265.4	601.6	17.8%
Total	3789.4	4560.7	12249.7	21.8%

As you can see in table 1, the global market for 3D printers by technology was valued at 3.8 billion in 2017 and is expected to reach 12.2 billion in 2023 at a CAGR of 21.8%. Material extrusion is the most commonly used process in the 3D printing industry and is expected to hold the highest market share throughout the forecast period. (17) Subsequently, also in the European university market for 3D printing realized in this research, it will be demonstrated that extrusion technology, through the Fused Deposition Modeling technique, is the most widespread technology in the academic world in all four countries analyzed.

3.2 Summary

The global market for 3D printing, including printers, software, material and services was 6.9 billion $ in 2017. The market is expected to grow at a compound annual growth rate (CAGR) of 22.4% from 2018 to 2023, reaching nearly 23 billion $ by the end of the forecast period. The global 3D printing market has been segmented based on component, printer type, technology, material type, software and geography. Based on component, the market has been classified into 3D printers, 3D printing services, 3D printing software and 3D printing materials. Based on geography, the market has been segmented into North America, Europe, the Asia Pacific region and Rest of the World (RoW). (17) North America accounts for the largest market share of the global 3D printing market followed by the Asia-Pacific and European regions. Additionally, the Geographic breakdown of this report analyzes markets for the following geographic regions:

- North America: U.S, Canada and Mexico
- Europe: U.K, Germany, France, Italy and Rest of Europe
- Asia-Pacific: China, Japan, India, Australia and rest of Asia-Pacific
- Rest of the World: South America and Middle east and Africa (17)

3.3 Market Breakdown by Components

3D printing innovation is mainly about printers, materials and the printing methods. In the BCC report, the 3D printing market consists of components that include 3D printers, 3D printing services, 3D printing material and software. 3D printers account for the largest market share when compared to the other components. Software and materials also play significant role in the 3D printing process. (17)

- *3D printers:* They are sub-segmented into Desktop 3D printers and industrial / commercial 3D printers which dominate the segment when compared to Desktop 3D printers.
- *3D printing services:* The service types for 3D printing is classified into the following 2 segments: on demand services and other service. Having a plant constituted by additive technologies is a great investment for companies as the 3D printing requirements are very specialized and complex. Very often they are not able to satisfy these requirements by themselves and therefore decide to take advantage of a request for 3D manufacturing services offered by various suppliers. While, the other services segment includes printer maintenance, training and consulting services.
- *Materials:* Over the last 30 years a poor range of materials has been utilized for 3D printing. However, the range of materials printed in 3D has expanded rapidly. Materials currently in use include plastics, polymers, ceramic, metals and other metals.
- *Software:* Software is one of the essential components of the 3D printing system and plays a significant role in the process such as in sourcing design and ideas in three dimensions and in managing the printing process. (17)

Table 9: Global Market 3D Printing through 2023, (17)

Global Market 3D Printing through 2023 (Millions $)				
Component	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
3D printers	3789.5	4560.8	12249.7	21.8%
Services	1757.6	2164.2	6220	23.5%
Materials	697.1	845.7	2365.3	22.8%
Software	655.4	787.5	2149.9	22.2%
Total	6899.6	8358.2	22984.9	22.4%

The global market for 3D printing was valued at 6.9 billion $ in 2017 and is expected to reach nearly 23 billion $ in 2023. 3D printers and 3D printing services comprise of the largest market collectively for the global 3D printing market. The global market for 3D printers was valued at 3.8 billion $ in 2017 and is expected to reach 12.2 billion $ at a CAGR of 21.8% during the forecast period. Additionally, 3D printing services market is expected to grow at a CAGR of 23.5% from 2018 to 2023 more than the 3D printers grow, which means that due to the high prices of printers, commercial and industrial users are using printing services instead of buying 3D printers. (17)

3.3.1 Global Market for 3D printers:

There are two different types of 3D printer: Desktop 3D printers are also known as consumer 3D printers, while industrial printers are also referred to as commercial 3D printers. The global market for 3D printers was valued at 3.8 bill in 2017 and is expected to reach 12.2 billion $ by 2023. Industrial 3D printers accounted for the largest share of the global 3D printing market; the segment was valued at 2.9 billion $ in 2017 and is expected to reach 9.3 billion $ by 2023, for a CAGR of 21.5%. (17)

Table 10: Global Market or 3D Printers by Printer Type (*17*)

Global Market for 3D Printers by Printer Type through 2023 (Millions $)				
Printer Type	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
Commercial / Industrial	2930.4	3517.7	9325.7	21.5%
Desktop / Consumer	859	1043.1	2924	22.9%
Total	3789.4	4560.8	12249.7	21.8%

3.3.1.1 Desktop 3D printers

Consumer or Desktop 3D printers are low-cost printers, sold at affordable prices, mainly based on the Fused Deposition Modeling technique (FDM) and are used for 3D printing in home, schools, universities and offices. Users of this type of 3D printers used for the creation of objects for personal and creative use, are principally hobbyists, students, engineers, architects and game designers. As a matter of fact, 3D printer manufacturers are targeting their products toward home users, educational institutions and hobbyists. (17)

Table 11: Global Market for Desktop 3D Printer through 2023 (17)

Global Market for Desktop 3D Printer, by Region, through 2023 (Millions $)				
Region	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
North America	390.8	473.6	1315.9	22.7%
Asia - Pacific	239.2	295	892.9	24.8%
Europe	183.3	220.7	593.5	21.9%
ROW	45.8	53.8	121.7	17.7%
Total	859.1	1043.1	2924	22.9%

3.3.1.2 Industrial / Commercial 3D printers

Industrial 3D printing or commercial 3D printing is also known as advanced additive manufacturing and they produce parts with higher accuracy and in relatively less time with high efficiency when compared to Desktop 3D printers. As a matter of fact, these printers are more complex and more expensive because of their increased functionality and accuracy. Another important difference compared to Desktop 3D printers is that industrial printers are characterized by larger print area, so that they can produce bigger and larger parts or can simply print more objects at the same time. Additionally, they are mainly used for creating functional prototypes, concept modelling and manufacturing tooling, even if thanks recently technological advancements there has been a shift from prototyping to production of 3D printed products and spares. (17)

Table 12: Global Market for Industrial 3D Printer through 2023 (17)

Global Market for Industrial 3D Printer, by Region, through 2023 (Millions $)				
Region	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
North America	1215	1457.4	3839.7	21.4%
Asia - Pacific	905.4	1103.1	3147.9	23.3%
Europe	610.6	726.9	1850	20.5%
ROW	198.8	230.3	488.1	16.2%
Total	2929.8	3517.7	9325.7	21.5%

As we can see in table 12, North America is leading the market and is the primary user of the 3D printing technology, followed by the Asia-Pacific Region.

3.3.1.3 Global Market for 3D Printers by Region

The use of industrial 3D printers in the medical, industrial automotive and consumer electronics industries as well as the declining prices of Desktop 3D printers is driving the market in North America. The Asia-Pacific 3D printing market is growing at the highest CAGR, 24.6%, due to the increased use of 3D printing in the industrial manufacturing process instead of traditional and time-consuming additive manufacturing processes. (17)

Table 13: Global Market for 3D Printers through 2023, (17)

Global Market for 3D Printers, by Region, through 2023 (Millions $)				
Region	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
North America	1606.4	1931	5155.6	21.7%
Asia - Pacific	1144.6	1398.1	4040.8	23.6%
Europe	793.9	947.6	2443.5	20.9%
ROW	2444.6	284.1	609.8	16.5%
Total	5989.5	4560.8	12249.7	21.8%

3.3.2 Global Market of 3D Printing Services

Many manufacturers of 3D printing equipment and third parties provide services such as maintenance, training and other consulting services. As already seen, the service types for 3D printing is classified into 2 segments: on demand services and other service. (17)

- *On Demand Manufacturing:* There are several variations on the on - demand model. Some service providers outsource their actual 3D printing operations to a network of manufacturers and owners of 3D printers. Part of the attractiveness of this model is that the entity that makes the print can be located closer to the customer than the service provider. 3D Hub states that using its services, as many as 1 billion people can print something on the 3D printer within 10 miles of their homes. Users can upload their own 3D object files, choose the materials and choose the appropriate print locations near them and get their items printed and delivered, all typically within two days. Another variant of the 3D printing service provider model is managed by Shapeways. In addition to allowing the user to upload, choose the material and order the 3D printed object, the Shapeways website allows 3D designers to easily sell their work online. Customers who visit the website can browse through a catalog of available products, order and pay online. Designers receive royalties from sales while Shapeways manages finances, production, distribution and customer service. (17)
- *Other service types*: Other 3D printing service providers offer equipment maintenance, training and / or consulting services, either in addition to or in lieu of contract manufacturing services. Design, materials or other types of consulting services are the most frequent service offered, followed by training. (17)

3.3.2.1 Global Market for 3D Printing Service by Region

Following, as shown in table 14, is presented the global market for 3D printing services performed by BCC Research:

Table 14: Global Market for 3D Printing Service through 2023 (17)

Global Market for 3D Printing Service, by Region, through 2023 (Millions $)				
Region	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
North America	702.4	860.1	2404.6	22.8%
Asia - Pacific	533.7	669.1	2104.8	25.8%
Europe	402.8	490	1325.5	22.0%
ROW	118.7	145	385.1	21.6%
Total	1757.6	2164.2	6220	23.5%

The 3D printing services sector is expected to reach 6.2 billion $ in 2023 with a CAGR of 23.5% during the forecast period. The service market in North America has the highest market share followed by the Asia-Pacific region. Due to the fact that industrial 3D printers are very expensive, the service sector benefits from the economic advantages of owning a printer because the use of 3D printing services is often preferable to the purchase of a printer, especially in sectors such as manufacturing, automotive, medical, entertainment and construction. (17)

3.3.3 Global Market for 3D Printing Software

According to estimates by BCC Research, the global 3D printing software market was valued at 655.4M $ in 2017 and is estimated to grow at a compound annual growth rate (CAGR) of 22.2% to reach over 2.1 billion by 2023. Although there are growing trends in 3D printing software in the medical sector, in environmentally-friendly technology and an increase in demand from architects, lack of experience, skills and knowledge are one of the obstacles to the 3D printing software market on the road to mass adoption in consumer products and other applications.

Table 15: Global Market for 3D Printing Software through 2023, (17)

Global Market for 3D Printing Software, by Region, through 2023 (Millions $)				
Region	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
North America	322.1	381.1	963.1	20.4%
Asia - Pacific	175	212.4	609.5	23.5%
Europe	124.9	154.5	488.3	25.9%
ROW	2444.6	39.5	89	17.6%
Total	3066.6	787.5	2149.9	22.2%

Additionally, as shown in table 15, North America is expected to dominate the market with a share of 44.8% and will likely reach a market size of 963.1M $ by 2023. However, adoption of 3D printing software is expected to grow faster in the Asia-Pacific region due to the promising adoption of 3D printing software by countries such as China, Japan and South Korea and increasing government. (17)

3.3.4 Global Market for 3D Printing Material

There is a wide range of materials that can be used for 3D printing, from plastics to metals and even human cells. The 3D printing materials discussed in this paragraph include photopolymers, thermoplastics, polymers, metals and other materials. Photopolymers are the most used materials, followed by thermoplastic materials and polymers. Metal 3D printing is expected to grow at a CAGR of 34% during the forecast period. BCC Research estimated that the total global market for 3D printing materials was equal to 697.1 M $ in 2017. This figure is expected to increase to 845.7 M $ in 2018 and to nearly 2.4 billion $ in 2023, based on a CAGR of 22.8%. (17)

Table 16: Global Market for 3D Printing Materials, by type, through 2023, (17)

Global Market for 3D Printing Materials, by Type, through 2023 (Millions $)				
Material Type	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
Photopolymers	389.8	454.1	974.6	16.5%
Thermoplastic and polymers	181.3	220.7	589.1	21.7%
Metals	91.5	122.6	529.9	34.0%
Ceramics	3.9	4.5	10	17.3%
Other materials	30.6	43.8	261.7	43.0%
Total	697.1	845.7	2365.3	22.8%

As shown in table 16, photopolymers accounted for the largest share of the market (55.9%) in 2017, but they comprise the slowest growing segment, with a projected CAGR of 16.5%. As a result, this segment's market share should decline to roughly 41.2% by 2023. Meanwhile, thermoplastics will remain the second-largest segment, with between 26.0% and 24.9% of the market across the period under review. Ceramics account for less than 0.6% of the market across the forecast period, while the share of metals is projected to increase from 13.1% in 2017 to 22.4% in 2023. The market share of other materials (mainly wax in 2017, but also graphene and bio-inks by 2023) is expected to increase from under 4.4% in 2017 to 11.1% by 2023. (17)

3.3.4.1 Global Market for 3D Printing Materials by Region

Globally, the 3D printing materials industry is highly concentrated, with only four companies controlling around 75% of the market. The market leaders have protected and expanded their positions through a series of mergers and acquisitions. Analyzing the geographical distribution of the 3D materials market through table 17, North America is again the largest geographic market for 3D printing materials, accounting for about 38.9% of the global market in 2017. The Asia-

Pacific region is characterized by a more rapid growth, with an expected CAGR of 25.5% over the next five years. As a result, the Asia-Pacific market share is expected to increase from 32.7% to almost 37.2% between 2017 and 2023. Meanwhile, Europe is expected to experience somewhat slower growth than in North America or the Asia-Pacific region, showing a slight decline from 19.2% in 2017 to 18% in 2023. Other markets should also lose market shares. market, from around 9.2% in 2017 to 6.5% in 2023. (17)

Table 17: Global Market for 3D Printing Materials, by Region, through 2023, (17)

Global Market for 3D Printing Materials, by Region, through 2023 (Millions $)				
Region	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
North America	271.4	328.5	906	22.5%
Asia - Pacific	227.7	282.7	879.8	25.5%
Europe	133.9	161	425.5	21.5%
ROW	64.1	73.5	154	15.9%
Total	697.1	845.7	2365.3	22.8%

3.4 Market Breakdown by Region

Turning now from a breakdown of the market by component to geographical region, it is possible to notice that the global 3D printing market by region consists of North America, Europe, Asia-Pacific and Rest of the world. Globally, the 3D printing market was valued at 6.9 billion € in 2017 and is expected to reach 23 billion € in 2023 with a CAGR of 22.4%. It is important to underline the position of North America which holds the highest share of the global 3D printing market with 2.9 billion in 2017 and is expected to reach 9.4 billion in 2023 with a CAGR of 21.9%. This means that North America is a global market leader in terms of size, with around 40% in value, followed by Asia-Pacific and Europe. This growth in North America is due to the increase in technological advances, the personalization of products and the potential of regional companies to expand their investments in emerging technologies. Moreover, the growing trend in the use of 3D desktop printers by artists and students is driving the North American 3D printing market. (17)

Table 18: Global Market for 3D Printing, by Region, through 2023, (17)

Global Market for 3D Printing, by Region, through 2023 (Millions $)				
Region	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
North America	2902.3	3500.7	9429.4	21.9%
Asia - Pacific	2030.9	2504.5	7513.7	24.6%
Europe	1505.6	1811	4803.9	21.5%
ROW	460.8	542	1237.9	18.0%
Total	6899.6	8358.2	22984.9	22.4%

3.4.1 Europe

The European 3D printing technology market is supported by various initiatives and government support. The fact that 3D printing companies offer customized and improved products together with greater efficiency is contributing to the expansion of the market in the region. The trends estimate a considerable growth in the forecast period as there is a greater demand for 3D printers and an increase in AM investment. Regarding demand for 3D printers, it comes mainly from small and medium-sized companies that continuously need reliable and high-speed prototypes for testing and planting, while regarding the growth of the amount of investments made in the purchase of 3D printers, they are mainly made by some of the main players in the 3D printing industry, such as Materialize NV, Artc 3D, CADS Gmbh, etc. (17)

Table 19: European Market for 3D Printers, by Country, through 2023, (17)

European Market for 3D Printers, by Country, through 2023 (Millions $)				
Country	**2017**	**2018**	**2023**	**CAGR % 2018-2023**
U.K	473.5	560.5	1386.4	19.9%
Germany	168.7	202.5	537.5	21.6%
France	92.6	111.8	304.9	22.2%
Italy	42.2	51.1	142.3	22.7%
Rest of Europe	16.9	21.7	72.4	27.2%
Total	793.9	947.6	2443.5	20.9%

In addition, European countries are leaders in filing patents for emerging technologies such as 3D printing, robotics and nanotechnology. The region has a strong technical experience in 3D printing, a good knowledge of additive production and a growing general awareness. Finally, the growing number of start-ups in Germany, the United Kingdom, France and Spain is expanding the market's reach in the region. (17)

4 European Universities Market for 3D Printing

This dataset is an overview of the total amount of money invested by the public entities such as Universities, National Government, National Foundations, European founds and other entities, in the dissemination of AM within the European academic world. It is the description of a list of universities involved in additive manufacturing in four different European countries: UK, Germany, French and Italy. These countries were chosen to start from a collection of information collected and to obtain a comparison between the results obtained by the European Market for 3D printers conducted by BCC Research presented in table 11 and those obtained by the European University Market for 3D printers. All information in this chapter was obtained through an internet-based research and requests for private information by e-mail. The purpose of the realization of this data set is to provide a state-of-the-art information about the current situation of 3D Printing within the university academic environment in Europe. The data set contains information on 160 universities, consisting of innovative additive manufacturing centers for conducting applied research, academic laboratories for carrying out basic research, simple 3D printing services offered to students enrolled at the University and those engineering faculties without an AM Laboratory. Moreover, this information can be used by the same universities to identify possible collaborations with other nearby universities in the territory characterized by a common interest in the development of specific AM technologies and in the pursuit of similar objectives. Additionally, the structure of this overview was generated by an academic paper written by Felix W. Baumann and Dieter Roller belonging to the University of Stuttgart and TWT GmbH Science & Innovation in Germany and it is aimed at providing an overview of German AM Companies. This work is structured as follows: the following Sections 1 and 2 provide information on method and sources used in this research for the acquisition and compilation of data. (55) Section 3 provides the method of data analysis used to obtain the results and finally, Section 4 contains and illustrates the results obtained from this market research.

4.1 Data Acquisition

For each European country considered within the thesis approximately 42 engineering universities have been analyzed and identified through the use of rankings indicating the best engineering departments within each country. The list containing all the universities analyzed for each country considered will be presented below:

- UK

Table 20: UK Universities Analyzed

UK UNIVERSITIES ANALYZED	
University of Cambridge	Queen Mary, University of London
Imperial College London	University of Surrey
University of Sheffield	Queen's University Belfast
University of Nottingham	University of Edimburg
University of Birmingham	University of Glasgow- Strathclyde
Cardiff University	University of Liverpool
University of Bath	Newcastle University
University of Manchester	University of Leicester
Manchester Metropolitan University	University of Aberdeen
University of Leeds	Coventry University
Loughborough University	University College London UCL
University of Southampton	Sheffield Hallam University
University of Derby	University of West of Scotland
University College London	University of Bristol
Lancaster University	University of Huddersfield
University of Oxford	University of Loughborough
University of Durham	University of Heriot-Watt
University of Warwick	University of Ulster
Bournemouth University	University of Greenwich
University of Exeter	University of Dundee
Swansea University	University of Aston

- Germany

Table 21: German Universities Analyzed

GERMAN UNIVERSITIES ANALYZED	
Technical University of Munich	Ruhr University Bochum
RWTH Aachen University	University of Bremen-Fraunhofer Institute
Technical University of Berlin	University of Cologne
Karlsruhe Institute of Technology	University of Heidelberg
University of Stuttgart	University of Konstanz
TU Dresden-Fraunhofer IWS-	LMU Munich
Darmstadt University of Technology	University of Tübingen
TU Clausthal	TU Brandenburg
BTU Cottbus-Senffenberg	TU Chemnitz
Magdeburg University	TU Bergakademie Freiberg

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TU Ilmenau	Humboldt University of Berlin
Duisburg Essen University	University of Charitè Berlin
Saarlandes University	Free University of Berlin
Erlangen-Nuremberg University	University of Bonn
TU Kaiserlautern	University of Gottingen
ULM University	University of Mannheim
University of Hannover	University of Munster
Braunschweig University of Technology	University of Wurzburg
University of Freiburg	Bielefeld University
Dortmund University of Technology	University of Hohenheim
Hamburg University of Technology	University of Kiel

- Italy

Table 22: Italian Universities Analyzed

ITALIAN UNIVERSITIES ANALYZED	
Polytechnic of Milan	Polytechnic of Bari
Polytechnic of Turin	University of Pavia
University of Padua	University of Rome Tre
University of Modena and Reggio Emilia	Polytechnic of Marche
University of Trento	University of Catania
University of Genoa	University of Calabria
University of Brescia	University of Campania LV
University of Florence	University of Benevento
University of Pisa Sant'Anna Superiore	University of Cagliari
University of Bologna	University of Cassino
University of Parma	University of Perugia
University of Bergamo	University of Basilicata
University of Naples Federico II	University of Aquila
University of Naples Parthenope	University of Rome La Sapienza
University of Ferrara	University of Messina
University of Udine and Trieste	University of Reggio Calabria Mediterranea
University of Palermo	University of Camerino
University of Siena	University of Ca Foscari Venezia
University of Salerno	University of Molise
University of Verona	University of Catanzaro
University of Salento	University of Insubria - Varese

- French

Table 23: French Universities Analyzed

FRENCH UNIVERSITIES ANALYZED	
University of Paris Saclay	University of Cergy-Pontoise
University of Grenoble Alpes	Paris Nanterre University
University of Lorraine	University Paris Diderot - Paris 7
PSL Research University Paris	École des Ponts ParisTech
Federal university Toulouse	Telecom ParisTech
University of Lyon	University of Paris-Sud 11
University of Lille	Sciences Po
University Paris-Est	CentraleSupélec
National Institute de Lyon - INSA Lyon	Sorbonne University
University of Aix-Marseille	Ecole Polytechnique
University Toulouse III - Paul Sabatier	University of Strasbourg
University of Nantes	University of Montpellier
IMT Atlantique	University of Bordeaux
University of Rouen	University of Paris 2 Panthéon-Assas
University of Poitiers	Paris Descartes University
University Nice Sophia Antipolis	University Paris Nanterre
University de Rennes 1	National Institute Polytechnic of Toulouse
University of Technology of Compiegne	University of Clermont Auvergne
HeSam University	University of Orléans
Ecole Centrale de Lyon	University of Savoy
École Normale Supérieure of Cachan	University of Western Brittany

Furthermore, it is important to underline that for all the 168 European universities analyzed the following type of laboratories were considered within this research:

- Laboratories belonging to the university, mainly to the mechanical engineering departments.
- Laboratories belonging to Additive Manufacturing Center of which the university is a partner and with which the university conducts academic programs such as PhD, Post-Doctoral programs and thesis writing.
- Creation Lab aimed at students willing to expand their Additive Manufacturing knowledge through the use of 3D printing service.

Moreover, for each of these 168 European universities, the following information was sought:

- *Vision:* Brief excursus of the University and of the objectives pursued by the Laboratory.
- *Technologies currently in the Lab*: Collection of all available technologies related to the 3D printers owned by the Lab.
- *3D Printer currently in the Lab with their related price*: Identification of all 3D Printers available in the Lab.
- *3D Printer Manufacturers*: Collection of all 3D printer manufacturers chosen by the university for the purchase of 3D printers.
- *Other manufacturing machines currently in the Lab*: Identification of all the production machines available in the laboratory as a support for the development of the traditional production process and 3D printing.
- *Service and Activities carried out in the Lab*: Identification and classification of the main activities performed by the laboratory and the services offered to companies

All this information, excluding the prices for each 3D printers, were collected exclusively through Internet-based research and the data collection was done in the same way for all four countries. More in detail, this information have been obtained by analyzing mainly the websites of each engineering department analyzed and each website that had some information regarding the AM laboratories. Due to incomplete university websites characterized by missing specific information, especially in terms of 3D printers currently available in the Lab, it is right to warn the reader that the data collected may be incomplete. As an Internet research source, the Google search engine was used, browsing for information up to five pages in Google. Through the Google search engines, the following keywords and search phrases were used during the analysis of the single university:

- Name University + "Additive Manufacturing Laboratory"
- Name University + "3D Printing Laboratory"
- Name University + "3D Printers"
- Name University + "Additive Manufacturing course"

The English search phrases above mentioned were used for UK, Germany and France, while for Italy were used the same ones but in Italian language. Once the required information for each university in possession of an AM laboratory has been identified, these have been manually entered in the following national excel format:

Table 24: National Data Collection Excel Format

University Name	Website URL used for research	Vision Lab	Technologies related to 3D Printers	3D Printer with their related price	3D Printer Manufacturer	Other Manufacturing Machines	Service and Activities	Price Website URL

Identifying the price of 3D printers and therefore carrying out a precise market analysis on the national university market of 3D printers for the countries analyzed, has been very demanding. Many manufacturing companies have not made the prices available on the Web as a matter of business strategy. For the Desktop 3D printers, given their low selling price and being affordable for people with a medium income, there was no problem identifying the price. However, this has not been the case for industrial 3D printers, characterized by higher prices and performance than Desktop 3D printers and suitable either for use in industrial warehouses or innovative laboratories. In most cases, the prices of these types of 3D printers are never disclosed on the 3D Printers Manufacturers website, but only the possibility of directly contacting via e-mail or call phone with the company is indicated. For all those 3D printers in which it was not possible to identify their price on the website of their respective manufacturer, the following methods were used in order to obtain the best possible estimate:

- Search for prices on websites aimed at the approximate estimate of the Industrial 3D Printers prices or at the definition of price range. In this case, in the presence of the approximate estimate of the 3D Printer's sale price, this was assumed to be valid, while in the presence of a 3D printer's price range, it was always considered the average value. The main websites that were used in this case are Aniwaa, (https://www.aniwaa.com/)

whose aim is to compare the prices and technical characteristics of emerging technologies such as Additive Manufacturing, and 3D Hubs (https: // www.3dhubs.com/) that is an online 3D printing service and a 3D printing journal focused on 3D printers.

- With some 3D printers, however, it was impossible to find out their price even with the method presented above, so it was necessary to contact their producers directly via e-mail. Not all have found themselves available to provide their sales prices and as a result, it was necessary to make assumptions based on the other 3D printers price produced by themselves and based on the potential and performance of 3D printers. Following are all the manufacturers with their 3D printers that have been contacted via e-mail due to the uncertainty on the machines price or the absolute absence of the price information. As a result, the prices of 3D printers obtained by e-mail, the price assumptions made for the 3D printers for which the price was denied and the price information obtained via the web, after consulting up to the sixth page of Google, once not having obtained feedback from companies, are shown below:

Table 25: Processing Estimates of 3D Printers Final Prices

Range Price via Web	Approximate Price via Web	Prince Found via Website	Price obtained by E-mail
Estimated Price Resulting		Price not available	
Manufacturer	**3D Printers**	**Information Found**	**Price Chosen**
Renishaw	AM400	>250k$	$600,000
	AM250	$585,305	$585,305
	RenAM 500M	600K-700K$	$650,000
	Renishaw SLM 125	$300,000	$300,000
Arcam-General Electrics GE	Arcam A2X	$1,200,000	$1,200,000
	Arcam Q20Plus	$1,000,000	$1,000,000
	Arcam Q10	$1,000,000	$1,000,000
Optomec	Aerosol Jet HD(150kD)	$150,000	$150,000
	Aerosol Jet 200	$200,000	$200,000
	AerosolJet 300	$300,000	$300,000
	Lens MR-7	750-1000k$	$875,000
	AerosolJet 5X	$495,000	$495,000

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Stratasys Inc.	**Objet Eden 260VS**	$19,800	**$19,800**
	Fortus 900mc	$400,000	**$400,000**
	uPrint SE Plus	$28,000	**$28,000**
	Mojo-FDM	$5,000	**$5,000**
	Fortus 400mc	$185,000	**$185,000**
	F370-31kD	$31,000	**$31,000**
	Dimension Elite	$32,000	**$32,000**
	J750-300kD	$300,000	**$300,000**
	Dimension SST 768	$20,000	**$20,000**
	Fortus 360mc	$66,900	**$66,900**
	Fortus 250mc	$45,000	**$45,000**
	ObJet350 Connex2	$188,000	**$188,000**
DMG MORI	**Lasertec 65**	>990K$	$1,000,000
	Lasertec 30	$500,000	$500,000
Nanoscribe GmbH	**Two Photonic Professional GT**	$463,490	**$463,490**
Concept Laser GmbH-GE	**M2 Cusing**	750-950K$	**$850,000**
	Mlab Cusing R	$160,000	**$160,000**
	M1 Cusing	450-600k$	**$525,000**
SLM Solutions Group AG	**125 HL**	400-500k$	**$450,000**
	250 HL	750-1000k$	**$875,000**
	500 HL	1000-2000k$	**$1,500,000**
	280 HL	$950,000	**$950,000**
3D Systems	**Viper Pro SLA System**	$40,000	**$40,000**
SIJTechnology	**S030 SIJ**	$3,000	**$3,000**
nScrypt	**3Dn 450HP**	$600,000	**$600,000**
EOS-Electro Optical System	**EOSINT M280 DMLS**	$700,000	**$700,000**
	EOSINT P760	$250,000	**$250,000**
	Formiga p 110 EOS	$175,000	**$175,000**
	EOSINT M270	$600,000	**$600,000**
	EOS M100	$257,042	**$257,042**
	EOS M250	$325,000	**$325,000**

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	EOS M400	$1,526,000	**$1,526,000**
	EOS P396	$250,000	**$250,000**
	EOS M270	$450,000	**$450,000**
	EOS M290	$700,000	**$700,000**
	EOS M280	450-600k$	**$525,000**
VoxelJet AG	**VoxelJet VX500**	350-370k$	$360,000
Evo-Tech	**EVOlizer**	$22,785	$22,785
BeAM	**Module 400 BeAM-DED**	600-1000k$	$800,000
MicroLight Laser 3D	**Microlight 3D printer**	$100,000	$100,000

4.2 Data Analysis

The analysis of the data identified through the collection method presented above will be presented below. In detail, the geographical distribution of all AM laboratories identified in the academic field for each country and the classification of each laboratory will be presented.

4.2.1 National Geographic Distribution of the Universities investing in Additive Manufacturing

For each country considered, a list of all those universities among the 42 analyzed that have got an AM laboratory or that are partners of AM research centers has been compiled, in order to obtain also a geographical distribution of the universities. Additionally, in order to represent the geographic distribution of the Universities, the Batchgeo (https://it.batchgeo.com) website was used, which was able to map the Universities after manually entering the name, full address and website of each university.

4.2.1.1 UK Geographic Distribution

Figure 9: UK geographical distribution of identified universities; (created with https://it.batchgeo.com)

The United Kingdom is the most developed country with a larger number of universities involved in huge investments in additive manufacturing. 69% of the 42 universities analyzed, and therefore 29 universities out of 42, invested in the AM. Finally, it is useful to note that there are no geographical centralizations, but universities are distributed throughout the country.

The list of all UK universities queried for and included in this study are presented in table 26:

Table 26: List of all UK Universities involved in the Additive Manufacturing (AM) academic diffusion

Marker	Name	City	University Website URL
1	**University of Cambridge** (56), (57), (58)	Cambridge	https://www.cam.ac.uk/
2	**Imperial College London** (59)	London	https://www.imperial.ac.uk/
3	**University of Sheffield** (60), (61)	Sheffield	https://www.sheffield.ac.uk/
4	**University of Nottingham** (62)	Nottingham	https://www.nottingham.ac.uk/
5	**University of Birmingham** (63), (64)	Birmingham	https://www.birmingham.ac.uk
6	**Cardiff University** (65)	Cardiff	https://www.cardiff.ac.uk/
7	**University of Bath** (66)	Bath	https://www.bath.ac.uk/
8	**University of Manchester** (67)	Manchester	http://www.manchester.ac.uk/
9	**Manchester Metropolitan University** (68)	Manchester	https://www2.mmu.ac. uk/
10	**University of Leeds** (69)	Leeds	https://www.leeds.ac.uk/
11	**Loughborough University** (70)	Loughborough	https://www.lboro.ac.uk/

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12	**University of Southampton** (71), (72)	Southampton	https://www.southampton.ac.uk/
13	**University of Derby** (73)	Derby	https://www.derby.ac.uk/
14	**University College London**	London	https://www.ucl.ac.uk/
15	**Lancaster University** (74)	Lancaster	http://www.lancaster.ac.uk/
16	**University of Oxford** (75)	Oxford	http://www.ox.ac.uk/
17	**University of Durham** (76)	Durham	https://www.dur.ac.uk/
18	**University of Warwick** (77)	Warwick	https://warwick.ac.uk/
19	**Bournemouth University** (78)	Bournemouth	https://www.bournemouth.ac.uk/
20	**University of Exeter** (79)	Exeter	https://www.exeter.ac.uk/
21	**Swansea University** (80)	Swansea	https://www.swansea.ac.uk/
22	**Queen Mary, University of London** (81)	London	https://www.qmul.ac.uk/
23	**University of Surrey** (82)	Guildford	https://www.surrey.ac.uk/
24	**Queen's University Belfast** (83)	Belfast	http://www.qub.ac.uk/
25	**University of Edinburg** (84)	Edinburgh	https://www.ed.ac.uk/
26	**University of Glasgow- Strathclyde** (85)	Glasgow	https://www.strath.ac.uk/
27	**University of Liverpool** (86)	Liverpool	https://www.liverpool.ac.uk/
28	**Newcastle University** (87)	Newcastle	https://www.ncl.ac.uk/
29	**University of Leicester** (88)	Leicester	https://le.ac.uk/
30	**University of Aberdeen** (89)	Aberdeen	https://www.abdn.ac.uk/

4.2.1.2 Germany Geographic Distribution

Figure 10: German geographical distribution of identified universities; (created with https://it.batchgeo.com)

Germany is the second most developed country in terms of number of Universities investing in additive manufacturing with a number of 25 universities out of 42 (about 60%), uniformly distributed throughout Germany and protagonists in the academic dissemination of the AM

The list of all German universities queried for and included in this study follows in table 27:

Table 27: List of all German Universities involved in the Additive Manufacturing (AM) academic diffusion

Marker	Name	City	University Website URL
A	**TU Munich** (90)	München	https://www.tum.de/
B	**RWTH Aachen University** (91), (92)	Aachen	https://www.rwth-aachen.de/
C	**TU Berlin** (93)	Berlin	https://www.tu-berlin.de/
D	**University of Stuttgart** (94)	Stuttgart	https://www.uni-stuttgart.de/en/
E	**TU Dresden-Fraunhofer IWS** (95)	Dresden	https://www.iws.fraunhofer.de/
F	**TU Darmstadt** (96)	Darmstadt	https://www.tu-darmstadt.de/index.en.jsp
G	**Duisburg Essen University** (97)	Duisburg	https://www.uni-due.de/en/
H	**Erlangen-Nuremberg University** (98)	Erlangen	https://www.fau.eu/
I	**Ulm University** (99)	Ulm	https://www.uni-ulm.de/en/
J	**University of Hannover** (100), (101)	Hannover	https://www.uni-hannover.de/en/
K	**TU Braunschweig** (102)	Braunschweig	https://www.tu-braunschweig.de/
L	**University of Freiburg** (103)	Freiburg im Breisgau	https://www.uni-freiburg.de/
M	**TU Dortmund** (104)	Dortmund	https://www.tu-dortmund.de/en/?L=0
N	**TU Hamburg** (105), (106)	Hamburg	https://www.tuhh.de/alt/tuhh/university.html
O	**University of Heidelberg** (107)	Heidelberg	https://www.heidelberg.edu/
P	**LMU Munich** (108)	Munich	https://www.en.uni-muenchen.de/
Q	**University of Tübingen** (109)	Tübingen	https://uni-tuebingen.de/en/
R	**Charitè Universitätsmedizin Berlin** (110)	Berlin	https://www.charite.de/en/
S	**Free University of Berlin** (111)	Berlin	https://www.fu-berlin.de/en/index.html
T	**University of Bonn** (112)	Bonn	https://www.uni-bonn.de/
U	**University of Gottingen** (113)	Gottingen	https://www.uni-goettingen.de/en/1.html
V	**University of Mannheim** (114)	Mannheim	https://www.uni-mannheim.de/en/contact/
W	**University of Munster** (115)	Munster	https://www.uni-muenster.de/en/
X	**University of Kiel** (116)	Kiel	https://www.uni-kiel.de/en/?no_cache=1
Y	**TU Bremen-Fraunhofer IFAM** (117)	Bremen	https://www.ifam.fraunhofer.de/en.html

4.2.1.3 Italian Geographic Distribution

Figure 11: Italian geographical distribution of identified universities; (created with https://it.batchgeo.com)

Italy is the third most developed country in terms of the number of universities investing in additive manufacturing with a number of 21 universities out of 42 (about 50%), uniformly distributed throughout the country and protagonists in the academic dissemination of the AM. It is useful to note that there is not a great geographical difference between North and South.

The list of all Italian universities queried for and included in this study follows in table 28:

Table 28: List of all Italian Universities involved in the Additive Manufacturing (AM) academic diffusion

Marker	Name	City	University Website URL
A	**Polytechnic of Milan** (118)	Milano	http://www.polimi.it/
B	**University of Pavia** (119)	Pavia	http://webing.unipv.eu/
C	**Polytechnic of Turin** (120)	Torino	http://www.polito.it/
D	**University of Trento** (121), (122)	Trento	http://www.dii.unitn.it/
E	**University of Padua** (123)	Padova	http://www.ingegneria.unipd.it
F	**University of Brescia** (124)	Brescia	http://www.unibs.it/
G	**University of Florence** (125)	Firenze	http://www.ingegneria.unifi.it/
H	**University of Pisa Sant'Anna Superiore** (126)	Pisa	http://www.santannapisa.it/

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I	**University of Naples Federico II** (127)	Napoli	http:/ /www.unina.it/
J	**University of Udine and Trieste** (128)	Udine	http://www.lamafvg.it/
K	**University of Genoa** (129)	Genova	http://www.politecnica.unige.it/
L	**University of Bologna** (130)	Bologna	https://www.unibo.it/it
M	**University of Salerno** (131)	Salerno	http://www.diin.unisa.it/
N	**Polytechnic of Bari** (132)	Bari	http://www.poliba.it
O	**University of Salento** (133)	Lecce	http://www.dii.unisalento.it/
P	**University of Rome La Sapienza** (134)**,** (135)	Roma	http://www.ing.uniroma1.it
Q	**University of Cagliari** (136)	Pula	http://www.unica.it/
R	**University of Reggio Calabria** (137)	RC	http://www.unirc.it/
S	**University of Camerino** (138)	Camerino MC	https://www.unicam.it/
T	**University of Ca Foscari Venezia** (139)	Venezia	https://www.unive.it/
U	**University of Catanzaro**	Catanzaro	https://web.unicz.it/it/

4.2.1.4 French Geographic Distribution

Finally, France is the fourth most developed country in terms of the number of universities investing in additive manufacturing with a number of 20 universities out of 42 (about 48%), protagonists in the academic dissemination of the AM. It is useful to note, as in this case there is no equitable geographic distribution within the country, about 50% of the 20 universities identified are in Paris, this determines a high geographic concentration

.

Figure 12: French geographical distribution of identified universities; created with https://it.batchgeo.com

The list of all French universities queried for and included in this study are presented in Table 29:

Table 29: List of all French Universities involved in the Additive Manufacturing (AM) academic diffusion

Marker	Name	City	University Website URL
A	**University of Paris Saclay** (140), (141)	Saint-Aubin	https://www.universite-paris-saclay.fr/en
B	**University of Grenoble Alpes** (142)	Grenoble	https://www.univ-grenoble-alpes.fr/
C	**University of Lorraine**	Metz	http://welcome.univ-lorraine.fr/
D	**PSL Research University Paris** (143)	Paris	https://www.psl.eu/
E	**University of Lyon** (144)	Lyon	https://www.univ-lyon1.fr/
F	**Federal University Toulouse** (145)	Toulouse	https://en.univ-toulouse.fr/
G	**INSA Lyon** (146)	Villeurbanne	https://www.insa-lyon.fr/
H	**University of Nantes** (147)	Nantes	https://www.univ-nantes.fr/
I	**IMT Atlantique** (148)	Cesson-Sévigné	http://www.imt-atlantique.fr/en
J	**University of Cergy-Pontoise** (149)	Cergy-Pontoise	https://www.u-cergy.fr/en/index.html
K	**Lorraine Fab Living Lab** (150)	Nancy	http://lf2l.fr/
L	**University Paris Diderot - Paris 7** (151)	Paris	https://www.univ-paris-diderot.fr/
M	**École des Ponts ParisTech** (152)	Champs	http://www.enpc.fr/
N	**Telecom ParisTech** (153)	Paris	https://www.telecom-paristech.fr/
O	**CentraleSupélec** (154)	Gif-sur-Yvette	http://www.centralesupelec.fr/
P	**Sorbonne University** (155)	Paris	http://www.sorbonne-universite.fr/en
Q	**Ecole Polytechnique** (156), (157)	Paris	https://www.polytechnique.edu/
R	**University of Strasbourg** (158)	Strasbourg	https://www.unistra.fr/
S	**University of Montpellier** (159)	Montpellier	https://www.umontpellier.fr/
T	**University of Bordeaux** (160)	Bordeaux	https://www.u-bordeaux.fr/

4.2.2 Classification of Laboratories according to TRL

To estimate the National Universities Market for 3D Printing and to have further qualitative and more explanatory data on the level of national investment made in AM in each country considered, a classification of the Laboratories was performed. The classification follows the Technology Readiness Level - TRL index which is aimed at assessing the degree of maturity of a technology. It identifies the phases that start from the conceptualization of a new technology until its possible introduction into the market. As a matter of fact, its value varies in a scale from 1 to 9, where 1 corresponds to the first level of technological maturation, that is the incipit of the research, up to 9 which makes explicit the definitive integration of the technology in a production system (161).

90% of the total number of AM laboratories and research centers analyzed has a classification based on a TRL index between 1 and 4, in particular, as we will see later, in countries such as France the TRL level 1 is prevalent. The remaining laboratories instead can be considered large international research centers or innovative university laboratories where the TRL level can be even higher than 4 up to a maximum of 6. The explanation of the levels of the TRL index follows in the table 30:

Table 30: Technology Readiness Level TRL *(161)*

TRL 1- Basic Principles observed	Basic research begins its maturation through basic studies to evaluate the properties of the technology.
TRL 2 - Technology concept formulated	Study of the potential of the application. The main aspects have been observed and practical applications can now be hypothesized
TRL 3 - Experimental proof of concept	Active research and real developments begin at this stage and include "demonstration" with tests of parts created in the laboratory that are not integrated with each other
TRL 4 - Technology validated in Lab	Validation in the laboratory of components / assembled / integrated for an overall evaluation and explicit interaction and mutual influence
TRL 5 - Technology validated in relevant environment	The experimental components or assemblies created in the laboratory are validated in simulated or real environments.
TRL 6 - Technology demonstrated in relevant environment	In this phase there is the production of models / prototypes that are the result of the improvements applied.
TRL 7 - System prototype demonstration in operational environment	At this stage there is the demonstration of prototypes / models / pilot-line / pre-production in operating environments.
TRL 8 - System complete and qualified	End of the development phase and verification of all the product and process functionalities completing software and hardware integration
TRL 9 - Actual system proven in operational environment	Introduction of the product or process of the new technology in the operational environment.

The Lab classification have a dual purpose: to identify the size and level of technology of the existing laboratories in the national territory of all 4 countries analyzed and to obtain a rough estimate of the National University Market for 3D Printing. As will be better seen in detail later, first of all it was estimated the National University Market for 3D Printers, characterized by various assumptions related to the prices of 3D printers already presented in the Data Collection section, in order to identify the total investment made by each university for the purchase of 3D printers. Subsequently, to estimate the National University Market for 3D Printing and therefore to estimate the total investment made by the single University for the academic diffusion of Additive Manufacturing, the following and additional costs to be incurred were considered:

- *Operating machines used in traditional production processes:* During the study of the individual laboratories as previously seen, information was also collected on the machines operating in the laboratory. The following support machines have been identified, used for the development of traditional manufacturing process and for Additive Manufacturing: Milling machines, Turning machines, laser cutter machines, metal welding machines, material testing machines, non-destructive testing machines, surface finishing machines, etc. These are all machines mainly purchased before the investment supported by the university for the academic diffusion of Additive Manufacturing, in which we must consider a certain percentage of depreciation distributed on the development of additive manufacturing within the laboratory. These are machines that support traditional manufacturing process but can also be used to support the AM process.
- *Equipment and tools purchased for the development and implementation of advanced manufacturing process:* Additive manufacturing process needs special equipment for its operation. For those research centers characterized by 3D printers that are not exclusively 3D Printers Desktop, complementary machines are necessary for the realization of the final product. The following are some of the support machines for the AM process and fundamental to purchase for supply of an AM laboratory: 3D Scanner and reverse engineering, CAD work station with software 3D printing, 3D printing software license, support removal machine, special surface finishing machines and non-destructive testing machines.
- *Construction and Insurance of the academic laboratory:* A further cost, which is added to the total investment supported by the single university, is the construction of the building

and the purchase of an insurance for the safety of the entire laboratory and staff, especially for those laboratories that carry out projects through the use of reactive materials that also require a specific laboratory design.

- *Auxiliary systems of 3D Printers:* Generally, when a client buy an industrial 3D printers there are other costs to be incurred in addition to the selling price offered by the manufacturing company. If we consider a quote for the purchase of the metal 3D printer Renishaw AM 250, its sale price is $ 585305 to which it must be added a value of about $ 100000 representative of the following costs: auxiliary accessories of the 3D Printer (Separation vacuum system, chiller, sieving station, powder change kit, safe change filter housing, powder flask kit, ..), machine operation and processing training necessary to learn how to use the 3D printer independently, advanced materials training and the 3D printer installation. Maintenance costs are not included because one or two years free warranty are always included in the 3D printer sale price.

In the Global Market for 3D printing conducted by BCC Research, it can be seen that the cost of 3D printers represents the variable with the greatest impact on total investment. As already seen in table 9, in 2018 the price of 3D printers has an incidence of 54.6% of the total AM global market consisting of the following elements: 3D Printers, materials, services and software. Moreover, excluding the materials and services that are not considered in the estimate made, the incidence of 3D Printers increases up to 85.3% in 2018 as shown in the following table:

Table 31: Incidence of the 3D Printers price in the revised global market *(17)*

Global Market 3D Printing through 2023 (Millions $)				
Component	**2017**	**2018**	**2023**	**Market Share 2018 (%)**
3D Printers	3789.5	4560.8	12249.7	**85.3%**
Software	655.4	787.5	2149.9	14.7%
Total	3789.5	5348.3	14399.6	100%

Once justified the great impact of the cost of purchasing 3D printers in the total investment made by the single university, in order to make an approximate and qualitative estimate of the National University Market for 3D Printing and then to quantify the impact of the other variables presented above on the total value of the investment, strong assumptions were made. For each laboratory, based on the level of maturity of the technologies present in the laboratory defined by the type and number of 3D printers held and based on the total level of investment sustained for the purchase of 3D printers, the following classifications were made:

Table 32 National Lab Classification

Lab Classification	Total 3D Printers Investment- X ($)	Total Lab Investment	Total AM Investment
3D Printing Education Lab- TRL 1	X < 100k	**0%**	X
3D Printing Basic Research Lab - TRL 1-2	100k < X < 250k	**10%X**	X*1.1
3D Printing Basic Research Lab - TRL 1-3	250k < X < 500k	**15%X**	X*1.15
3D Printing Basic Research Lab - TRL 1-4	500k < X < 1000K	**25%X**	X*1.25
3D Printing Applied Research Lab - TRL 4-6	1000k < X < 2500k	**30%X**	X*1.30
3D Printing Applied Research Lab - TRL 4'-6'	X > 2500k	**35%X**	X*1.35

Below there is a detailed description of the laboratory classification used in the research and presented above:

- *3D Printing Education Lab - TRL 1:* This is a laboratory category composed mainly of very economical Desktop 3D printers, many of which do not exceed the purchase cost of 1k $. The role of this laboratory is not to carry out research projects, but to support teaching through the supply of Desktop 3D printers with which the students, independently or through a support from professors and assistants, can approach Additive Manufacturing. For these laboratories the total investment sustained by the single university is equal to the investment made for the purchase of 3D printers since no auxiliary tools are necessary, construction of new laboratories, etc.
- *3D Printing Basic Research Lab - TRL 1-2:* These laboratories consist mainly of large number of Desktop 3D printers, but also feature multiple professional 3D Printers based on material jetting or fused deposition modeling technologies. In this case the extra investment sustained by the university for the start-up of the laboratory was considered

to be about 10% of the total investment made for the purchase of 3D printers available in the laboratory, for an average value of 17k $.

- *3D Printing Basic Research Lab - TRL 1-3:* These laboratories, unlike those classified as TRL 1-2, start to have less Desktop 3D printers and 1 industrial 3D printers on which to run a larger project and also to build real research programs and projects.
- *3D Printing Basic Research Lab - TRL 1-4:* In this case the laboratory starts to own a vast number of 3D printers with different technologies and in particular at least one industrial metal printer characterized by high performance. This leads to an increase in investments no longer only 5% from the laboratory of the lower class, but 10% from a 15% to a total of 25%. This is because we have reached an important threshold of investment in 3D printers that also requires a greater complementary investment for the purchase of auxiliary equipment that are needed for the more professional 3D printers, for the purchase of complimentary machines, for the realization of the finished product, etc.
- *3D Printing Applied Research Lab - TRL 4-6:* In this case, more than a laboratory, they are research centers dedicated to additive manufacturing, characterized by large number of post-doctoral assistants and technical staff focused on the implementation of applied research projects. The number of metal machines or 3D printers characterized by directed energy deposition technology are beginning to increase and as a consequence the level of investment complementary to that of the purchase of 3D printers is growing to ensure the construction of a new building with a special insurance and the supply of an auxiliary machine park that support 3D printers for the production of the final product.
- *3D Printing Applied Research Lab - TRL 4'-6':* The latter classification mainly includes the international research centers of which the universities are partners who have contributed in part to the funding of these and which offer to doctoral candidates various work experience. These are research environments that are even made up of 10 high-performance metal machines specialized for the execution of research projects applied with large companies of world renown and can also achieve a total investment in the purchase of 3D printers of 7M $.

As we will see in detail, for each country analyzed, the following format of laboratory classification was used, considering the total investment level sustained for the purchase of 3D printers and collecting in an orderly manner the number of 3D printers owned by subdividing them for the following typologies: 3D Metal Printers, Desktop 3D printers (3DDP), 3D Fused Deposition Modeling Printers (FDM 3DP), 3D Material Jetting Printers (Jetting 3DP), 3D Stereolithography Printers (3D SLA), 3D Directed Energy Deposition Printers (3D DED):

Table 33: Excel file used for Lab classification

University Name	Total University Investment 3DP	Metal 3D Printers		Other 3D Printers				
		>200k$	<200K$	3DDP	FDM 3DP	Jetting 3DP	SLA 3DP	DED 3DP

4.2.2.1 UK Laboratories Classification

Table 34 shows the classification of AM laboratories belonging to universities in the United Kingdom:

Table 34: UK Laboratories Classification

University Name	Total University Investment 3D printers	Metal 3D Printers		Other 3D Printers				
		>200k$	<200k$	3DDP	FDM	Jetting	SLA	DED
University of Cambridge - IfM	$2,000	0	0	5	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Cambridge - 3D Printing Society	$4,598	0	0	2	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Cambridge - Dyson Centre	$5,070	0	0	0	5	0	0	0
		3D Printing Education Lab TRL 1						
University of Cambridge - Whittle Lab Printing	$188,000	0	0	0	0	1	0	0
		3D Printing Basic Research Lab TRL 1-2						
Imperial College London	$3,294	0	0	7	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Sheffield-AdAM	$5,764,800	5	1	0	0	2	1	0
		3D Printing Applied Research Lab TRL 4'-6'						

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University of Sheffield- AMRC	**$3,469,000**	1	0	1	2	0	1	2
		3D Printing Applied Research Lab TRL 4'-6'						
University of Nottingham- CfAM	**$2,559,983**	2	2	4	2	0	3	0
		3D Printing Applied Research Lab TRL 4'-6'						
University of Birmingham - AMPLab	**$2,350,000**	2	0	0	0	0	0	0
		3D Printing Applied Research Lab TRL 4-6						
University of Birmingham-CMD	**$1,300,000**	2	0	0	0	0	0	0
		3D Printing Applied Research Lab TRL 4-6						
Cardiff University- AM Laboratory	**$1,104,000**	1	0	0	1	2	0	0
		3D Printing Applied Research Lab TRL 4-6						
University of Bath- LASER Lab	**$650,000**	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Manchester	**$35,000**	0	0	2	0	1	0	0
		3D Printing Education Lab TRL 1						
Manchester Metropolitan University- Print City 3D	**$282,338**	0	0	26	2	3	0	0
		3D Printing Basic Research Lab TRL 1-3						
University of Leeds- Inst of Design, Robotics	**$504,999**	0	0	0	1	2	0	0
		3D Printing Basic Research Lab TRL 1-4						
Loughborough University-AMRG	**$282,852**	0	1	6	1	1	1	0
		3D Printing Basic Research Lab TRL 1-3						
University of Southampton- AM Lab	**$1,150,091**	1	1	6	0	3	0	0
		3D Printing Applied Research Lab TRL 4-6						
University of Southampton- 3D Service	**$43,405**	0	0	53	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Derby	**$410,900**	0	0	0	1	3	0	0
		3D Printing Basic Research Lab TRL 1-3						
Lancaster University- Mechanical Engineering	**$582,854**	0	2	3	1	1	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Oxford-3D Printing Service	**$51,893**	0	0	13	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Durham	**$81,290**	0	0	1	0	1	0	0
		3D Printing Education Lab TRL 1						
University of Warwick	**$2,031,000**	1	0	2	3	4	0	0
		3D Printing Applied Research Lab TRL 4-6						
Bournemouth University	**$79,759**	0	0	3	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Exeter- CALM	**$515,000**	1	2	0	2	0	0	0
		3D Printing Basic Research Lab TRL 1-4						

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Swansea University	**$650,000**	1	0	0	0	0	0	0	**3D Printing Basic Research Lab TRL 1-4**
Queen Mary, University of London	**$60,000**	0	0	0	0	2	0	0	**3D Printing Education Lab TRL 1**
University of Surrey	**$42,000**	0	0	0	0	2	0	0	**3D Printing Education Lab TRL 1**
Queen's University Belfast- Mechanical Engineering	**$19,900**	0	0	0	0	1	0	0	**3D Printing Education Lab TRL 1**
University of Edinburg- School of Engineering	**$45,000**	0	0	0	1	0	0	0	**3D Printing Education Lab TRL 1**
University of Edinburg- uCreateStudio	**$14,225**	0	0	6	0	0	0	0	**3D Printing Education Lab TRL 1**
University of Strathclyde Glasgow- Ulab	**$246,154**	0	0	6	2	0	1	1	**3D Printing Basic Research Lab TRL 1-2**
University of Liverpool- School of Architecture	**$9,807**	0	0	4	0	0	0	0	**3D Printing Education Lab TRL 1**
Newcastle University- School of Mechanical	**$656,737**		0	0	1	1	0	0	**3D Printing Basic Research Lab TRL 1-4**
University of Leicester	**$207,000**	0	1	0	1	0	0	0	**3D Printing Basic Research Lab TRL 1-2**
University of Aberdeen- 3D Printing Service	**$6,799**	0	0	2	0	0	0	0	**3D Printing Education Lab TRL 1**

The results can be summarized below in the table 35:

Table 35: Results UK Laboratories Classification

3D Printing Education Lab TRL 1	**16**	**44%**
3D Printing Basic Research Lab TRL 1-2	**3**	**8%**
3D Printing Basic Research Lab TRL 1-3	**3**	**8%**
3D Printing Basic Research Lab TRL 1-4	**6**	**17%**
3D Printing Applied Research Lab TRL 4-6	**5**	**14%**
3D Printing Applied Research Lab TRL 4'-6'	**3**	**8%**
Total UK Lab Number	**36**	**100%**

As already shown through the geographic distribution, UK consists of 36 AM laboratories distributed among 30 Universities. It is useful to underline that 39% of the total UK laboratories have an investment in 3D Printers exceeding 500k $ of which 20% of them is more than 1M $.

4.2.2.2 German Laboratories Classification

Table 36 shows the classification of AM laboratories belonging to universities in Germany:

Table 36: German Laboratories Classification

University Name	Total University Investment 3D printers	Metal 3D Printers		Other 3D Printers				
		>200k$	<200k$	3DDP	FDM	Jetting	SLA	DED
TU Munich	$4,039,701	5	2	4	1	1	0	0
		3D Printing Applied Research Lab TRL 4'-6'						
RWTH Aachen Centre for Additive Manufacturing	$3.361.451	6	0	3	0	2	0	0
		3D Printing Applied Research Lab TRL 4'-6'						
RWTH Aachen University	$87.853	0	0	4	0	1	0	0
		3D Printing Education Lab TRL 1						
TU Berlin-Institute of Mathematics	$94.800	0	0	0	1	1	0	0
		3D Printing Education Lab TRL 1						
University of Stuttgard-The Institute of Design	$196.300	0	0	2	1	0	0	0
		3D Printing Basic Research Lab TRL 1-2						
TU Dresden-Fraunhofer IWS	$2.207.026	2	0	7	0	0		
		3D Printing Applied Research Lab TRL 4-6						
TU Darmstadt- Institute of Printing Science IDD	$82.412	0	1	7	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Duisburg-Essen- 3D FabLab	$12.692	0	0	5	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Erlangen-Nuremberg- WTM	$2.200.000	3	0	0	0	0	0	0
		3D Printing Applied Research Lab TRL 4-6						
Ulm University- Institute of Chemical Engineering	$106.196	0	0	2	2	0	0	0
		3D Printing Basic Research Lab TRL 1-2						
University of Hannover-IPeG	$909.891	1	1	5	1	1	0	0
		3D Printing Basic Research Lab TRL 1-4						
Braunschweig University of Technology	$184.108	0	0	3	3	1	0	0
		3D Printing Basic Research Lab TRL 1-2						
University of Freiburg-FMF 3D Printing	$2.554.001	2	0	4	0	0	0	0
		3D Printing Applied Research Lab TRL 4'-6'						
TU Dortmund	$1.461.662	1	0	3	0	0	0	1
		3D Printing Applied Research Lab TRL 4-6						
TU Hamburg-Fraunhofer Research Institution AM	$6.526.008	10	0	3	0	0	0	0
		3D Printing Applied Research Lab TRL 4'-6'						

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TU Hamburg-TAMS	$196.506	0	0	3	2	1	0	0
		3D Printing Basic Research Lab TRL 1-2						
University of Heidelberg- Computing Centre	$58.353	0	0	3	0	1	0	0
		3D Printing Education Lab TRL 1						
LMU Munich-3D Printing Service	$7.064	0	0	2	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Tübingen-IIFIB	$2.798	0	0	2	0	0	0	0
		3D Printing Education Lab TRL 1						
Charitè Universitätsmedizin Berlin	$18.668	0	0	4	0	0	0	0
		3D Printing Education Lab TRL 1						
Free University of Berlin- Mathematics	$59.900	0	0	0	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Bonn-3D Printing Service	$4.508	0	0	1	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Gottingen-3D Printing Service	$3.654	0	0	1	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Munster-Nanofabrication Lab	$7.495	0	0	1	0	0	1	0
		3D Printing Education Lab TRL 1						
University of Mannheim-3D Printing Service	$2.000	0	0	1	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Kiel-Functional Nanomaterials	$21.900	0	0	2	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Bremen-Fraunhofer IFAM	$898.998	1	3	0	3	0	0	0
		3D Printing Basic Research Lab TRL 1-4						

Below the summary of analysis results:

Table 37: Results Germany Laboratories Classification

3D Printing Education Lab TRL 1	14	52%
3D Printing Basic Research Lab TRL 1-2	4	15%
3D Printing Basic Research Lab TRL 1-3	0	0%
3D Printing Basic Research Lab TRL 1-4	2	7%
3D Printing Applied Research Lab TRL 4-6	3	11%
3D Printing Applied Research Lab TRL 4'-6'	4	15%
Total German Lab Number	27	100%

Compared to UK, Germany present a type of laboratory that is less uniformly distributed. We can note that about 50% of its laboratories are those aimed at training and teaching support, but 26%

of the total number of laboratories represents that type of laboratory characterized by an investment in the purchase of 3D printers above 1M $, of which 15% of these are above 2.5M $ compared to 8% of UK.

4.2.2.3 Italian Laboratories Classification

Table 38 shows the classification of AM laboratories belonging to universities in Italy:

Table 38: Italian Laboratories Classification

University Name	Total University Investment 3D printers	Metal 3D Printers		Other 3D Printers				
		>200k$	<200k$	3DDP	FDM	Jetting	SLA	DED
Polytechnic of Milan-AM Laboratory	$585,305	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
Polytechnic of Turin - IAM	$2,826,000	4	1	0	3	0	0	0
		3D Printing Applied Research Lab TRL 4'-6'						
Polytechnic of Turin-3D Printing Service	$14,750	0	0	4	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Pavia-3DMetal Project	$600,000	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
Polytechnic of Genoa &IIS	$706,640	1	0	0	1	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Padua-TE.SI		0	0	0	0	0	1	0
University of Trento-Prom Facility	$1,916,300	1	1	2	0	1	0	1
		3D Printing Applied Research Lab TRL 4-6						
University of Trento-Prototyping Lab	$3,798	0	0	2	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Bologna-DIN	$192,500	0	1	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-2						
University of Brescia-LPA	$753,900	1	0	0	1	2	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Florence and CERTEMA Amlab	$850,000	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Pisa and CrossLab	$9,798	0	0	6	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Naples-Federico II- CREAMI	$6,242	0	0	3	0	0	0	0
		3D Printing Education Lab TRL 1						

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University of Udine and Trieste- LAMA FVG	$850,000	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Salerno-Academic Spinoff LIAM	$450,000	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-3						
Polytechnic of Bari-Rapid prototyping Lab	$15,359	0	0	3	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Rome Sapienza-Saperi&CO	$23,696	0	0	5	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Rome Sapienza- AM Lab DIMA	$700,000	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Cagliari-SardegnaRicerche	$351,742	1	0	0	1	3	0	0
		3D Printing Basic Research Lab TRL 1-3						
University of Salento-Lecce	$7,498	0	0	2	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Camerino-Faculty of Architecture	$19,800	0	0	0	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Ca' Foscari Venezia-DelFablab	$2,772	0	0	1	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Catanzaro-ImagEngLab	$2,794	0	0	1	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Reggio Calabria	$9,254	0	0	3	0	0	0	0
		3D Printing Education Lab TRL 1						

The Italian results can be summarized below in the Table 39:

Table 39: Results Italian Laboratories Classification

3D Printing Education Lab TRL 1	11	48%
3D Printing Basic Research Lab TRL 1-2	1	4%
3D Printing Basic Research Lab TRL 1-3	2	9%
3D Printing Basic Research Lab TRL 1-4	7	30%
3D Printing Applied Research Lab TRL 4-6	1	4%
3D Printing Applied Research Lab TRL 4'-6'	1	4%
Total Italian Lab Number	23	100%

Italy is the only country that compared to its total number of laboratories (23), only 48% is a TRL Education Lab 1. 38% of the total is characterized by a total investment in the purchase of 3D printers above $ 500k. This is because as we will see later, Italy is characterized by a high use of 3D metal printers which are the type of 3D printers more expensive than the others.

4.2.2.4 French Laboratories Classification

Table 40 shows the classification of AM laboratories belonging to universities in French:

Table 40: French Laboratories Classification

University Name	Total University Investment 3D printers	Metal 3D Printers		Other 3D Printers				
		>200k$	<200k$	3DDP	FDM	Jetting	SLA	DED
University of Paris Saclay - FABS	$775,000	1	0	0	0	0	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Paris Saclay -The Designspot	$10,794	0	0	2	0	1	0	0
		3D Printing Education Lab TRL 1						
University of Grenoble Alpes-SIMaP	$1,200,000	1	0	0	0	0	0	0
		3D Printing Applied Research Lab TRL 4-6						
PSL Research University Paris-Research Group	$75,000	0	0	0	0	0	1	0
		3D Printing Education Lab TRL 1						
Federal university Toulouse ICA	$509,900	1	0	0	0	1	0	0
		3D Printing Basic Research Lab TRL 1-4						
University of Lyon-3D Biology	$170,442	0	0	3	1	1	1	0
		3D Printing Basic Research Lab TRL 1-2						
Lyon INSA-MECA3D	$211,632	0	0	6	1	2	0	0
		3D Printing Basic Research Lab TRL 1-2						
IMT Atlantique-FabLab	$14,724	0	0	1	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Lorraine and Greater Nancy	$4,879	0	0	2	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Nantes-Yhnova Project	$450,000	0	0	0	1	0	0	0
		3D Printing Basic Research Lab TRL 1-3						
University of Cergy-Pontoise-FACLAB	$12,035	0	0	2	1	0	0	0
		3D Printing Education Lab TRL 1						
University of Paris Diderot - Paris 7	$45,000	0	0	0	1	0	0	0
		3D Printing Education Lab TRL 1						
Telecom ParisTech - FabLab TP	$25,199	0	0	3	0	1	0	0
		3D Printing Education Lab TRL 1						

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Ecole des Ponts ParisTech-FabLab	$26,594	0	0	6	1	0	0	0
		3D Printing Education Lab TRL 1						
CentraleSupélec-FabLab La Fabrique	$7,837	0	0	0	1	0	0	0
		3D Printing Education Lab TRL 1						
Ecole Polytechnique-FabLab	$14,205	0	0	5	0	0	0	0
		3D Printing Education Lab TRL 1						
Ecole Polytechnique-AM Centre	$830,000	0	0	0	0	1	0	1
		3D Printing Basic Research Lab TRL 1-4						
University of Strasbourg-FabLab	$4,500	0	0	3	0	0	0	0
		3D Printing Education Lab TRL 1						
Sorbonne University-FabLab	$12,699	0	0	7	0	0	0	0
		3D Printing Education Lab TRL 1						
University of Montpellier	$1,175,617	1	0	6	2	0	0	0
		3D Printing Applied Research Lab TRL 4-6						
University of Bordeaux-FabLab	$300	0	0	1	0	0	0	0
		3D Printing Education Lab TRL 1						

The French results can be summarized below in the Table 41:

Table 41: Results French Laboratories Classification

3D Printing Education Lab TRL 1	13	62%
3D Printing Basic Research Lab TRL 1-2	2	10%
3D Printing Basic Research Lab TRL 1-3	1	5%
3D Printing Basic Research Lab TRL 1-4	3	14%
3D Printing Applied Research Lab TRL 4-6	2	10%
3D Printing Applied Research Lab TRL 4'-6'	0	0%
Total French Lab Number	21	100%

France, compared to the other 3 countries analyzed, also exclusively from a qualitative point of view, it seems to be the least developed country in the field of additive manufacturing. We can see that of the 21 total laboratories present in France, only 5 of these exceed a total investment in the purchase of 3D printers over 500k $. This implies the absence of true AM research centers but a concentration of smaller laboratories characterized by non-industrial 3D printers with lower performance.

4.3 Results

The aim of this research, as previously discussed, was to determine the National University Market for 3D Printing for the UK, Germany, Italy and France. Additionally, before presenting the estimated total market value for each country, the following results will be also presented:

- *National distribution of the total investment made by each university* in order to identify which universities have invested most in the diffusion of the AM within each country.
- *National distribution of AM technologies* used and studied in the AM Lab within each country
- *National distribution of 3D printers Manufacturers* to identify the producers who have most sold 3D printers in the academic field

To obtain the first two results for each country, all the 3D printers owned by each laboratory were collected with their relative prices and technologies. Subsequently, at the total investment supported by each university for the purchase of 3D printers was added the amount of additional costs incurred for the start-up of the laboratory, calculated using the laboratory classification criterion explained above, in order to determine the total investment amount made by each university. Below is the format used to obtain these first two results, taking as an example the University of Technology Munich:

Table 42: Excel format used to achieve the first two objectives

University Name	3D Printers	Price	Technology
TU Munich-Institute of Machine Tools and Business Administration-AMLab	Concept Laser M1 Cusing	$525,000	DMLS
	EOSINT M270	$600,000	DMLS
	EOS M290	$700,000	DMLS
	SLM 250 HL	$875,000	SLM
	VoxelJet VX500	$360,000	MJP
	Formiga P 110 EOS	$175,000	SLS
	Sintratec KIT	$5,350	SLS
	Markforged Mark Two	$13,499	CFF
	Stratasys uPrint SE PLUS	$28,000	FDM
	Ultimaker 3	$3,654	FDM
	Ultimaker 2 Extended	$2,299	FDM
	Ultimaker 2	$1,899	FDM
	EOS M400	$750,000	DMLS

	Total 3D Printers Investment	**$4,039,701**
	Total Lab Investment (+35%)	**$5,453,596**
TU Munich	**Total AM Investment**	**$5,453,596**

As shown in the table 42, for each university have been identified the individual 3D printers held in the laboratory with their related technologies. Once the total investment made for the purchase of the 3D printers is calculated, which is the sum of the prices of all the 3D printers owned, the laboratory has been classified. Munich University is characterized by a total investment in 3D printers above 2.5 M $, therefore it has been considered as an "Applied Research Lab TRL 4'-6'" and to obtain the total investment supported by this university for the diffusion of the AM, it is added to the total investment made for the 3D printers as shown in the figure. Furthermore, to obtain the national distribution of the technologies used in the laboratory, this was achieved by considering all the technologies present in each university laboratory.

Moreover, to identify the national distribution of 3D Printer Manufacturers, through the collection of information on the 3D printers held in each university laboratory, the names of the manufacturers protagonists in the academic field have been identified. More in detail, after identifying all 3D Printers manufacturers, the goal was to identify the number of universities to which their machines were sold and the total number of machines sold in the country, as shown by example in the following table 43:

Table 43: Example show the format used to obtain the distribution of 3D Printers Manufacturers

Manufacturers	Total Number Universities	Total Number 3D Printers	Company Website URL
Concept Laser GmbH-GE	3	3	https://www.concept-laser.de/
EOS- Electro Optical Systems	6	13	https://www.eos.info/en
SLM Solutions Group AG	3	6	https://slm-solutions.com/

4.3.1 UK Results

Following are all the laboratories of the UK Universities indicating all the 3D printers held in the laboratory with their relative prices and technologies, identifying as previously explained, the total amount of investment in the AM made by each single university.

Table 44: Format used to realize the distribution of technologies and investments made by each university in UK

University Name	3D Printers	Price	Technology
University of Cambridge - Institute for Manufacturing IfM	x5 MakerBot Replicator	$2,000	FDM
	Total 3D Printers Investment	$2,000	
University of Cambridge - 3D Printing Society	x2 Ultimaker 2 Extended	$4,598	FDM
	Total 3D Printers Investment	$4,598	
University of Cambridge - Dyson Centre for Engineering Design	x5 RS IdeaWerk Pro	$5,070	FDM
	Total 3D Printers Investment	$5,070	
University of Cambridge - Whittle Lab Printing	Objet350 Connex2	$188,000	PolyJet
	Total 3D Printers Investment	$188,000	
	Total Lab Investment (+10%)	$206,800	
University of Cambridge Total AM Investment		$218,468	
Imperial College London - Advanced Hackspace Community	Ultimaker2	$1,899	FDM
	x6 UP Mini 2	$3,294	FDM
	Total 3D Printers Investment	$3,294	
Imperial College London Total AM Investment		$3,294	
University of Sheffield-Centre for Advanced Additive Manufacturing AdAM	x3 Arcam A2X	$3,600,000	EBM
	Renishaw SLM 125	$300,000	SLM
	Formiga P 110 EOS	$175,000	SLS
	Factum High Speed Sintering	$1,500,000	HSS
	Objet Eden260VS Stratasys	$19,800	PolyJet
	MicroFab Jetlab4	$20,000	InkJet
	Optomec Aerosol Jet HD	$150,000	Aerosol Jet
	Total 3D Printers Investment	$5,764,800	
	Total Lab Investment (+35%)	$7,782,480	

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University of Sheffield-Advanced Manufacturing Research Centre AMRC - The National Metals Technology Centre NAMTEC	Renishaw AM 250	$650,000	DMLS
	Optomec LENS MR-7	$875,000	DED
	3D System ProJet 6000 SD	$211,000	SLA
	Stratasys Fortus 900mc	$750,000	FDM
	Stratasys uPrint SE PLUS	$28,000	FDM
	Stratasys Mojo	$5,000	FDM
	Lasertec 65 3D DMG Mori	$950,000	DED
	Total 3D Printers Investment	**$3,469,000**	
	Total Lab Investment (+35%)	**$4,683,150**	
University of Sheffield Total AM Investment		**$12,465,630**	
University of Nottingham- Centre for Additive Manufacturing CfAM	Realizer SLM 250	$350,000	SLM
	Realizer SLM 50	$175,000	SLM
	Renishaw AM400	$600,000	DMLS
	Objet Eden260VS Stratasys	$19,800	PolyJet
	FujiFilm Dimatix DMP 2831	$30,000	InkJet
	Formiga P 110 EOS	$175,000	SLS
	Stratasys Fortus 400mc	$185,000	FDM
	Blueprinter SHS 3D Printer	$11,389	SHS
	MakerBot Replicator 2	$1,500	FDM
	Ultimaker2	$1,899	FDM
	Velleman K8200	$600	FDM
	Formlabs 1+	$2,300	SLA
	Ember	$7,495	DLP
	Two Photonic Professional GT		2PP
	PixdroToucan	$1,000,000	MJP
	Total 3D Printers Investment	**$2,559,983**	
	Total Lab Investment (+35%)	**$3,455,977**	
University of Nottingham Total AM Investment		**$3,455,977**	
University of Birmingham - Advanced Materials and Processing Laboratory AMPLab	Concept Laser M2 Cusing	$850,000	DMLS
	SLM 500 HL	$1,500,000	SLM
	Total 3D Printers Investment	**$2,350,000**	
	Total Lab Investment (+35%)	**$3,172,500**	
University of Birmingham-Centre for Custom Medical Devices CMD	x2 Renishaw RenAM 500M	$1,300,000	DMSL
	Total 3D Printers Investment	**$1,300,000**	
	Total Lab Investment (+30%)	**$1,690,000**	
University of Birmingham Total AM Investment		**$4,862,500**	

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Cardiff University-Additive Manufacturing Laboratory	Renishaw AM 250	$650,000	DMLS
	Stratasys Fortus 400mc	$185,000	FDM
	ProJET 5600 3D System	$239,000	MJP
	Battenfeld BA 750 CDK	$30,000	InkJet
	Total 3D Printers Investment	**$1,104,000**	
	Total Lab Investment (+30%)	**$1,435,200**	
Cardiff University Total AM Investment		**$1,435,200**	
University of Bath- Lab for Additive and Eng Research LASER	Renishaw AM 250	$650,000	DMLS
	Total 3D Printers Investment	**$650,000**	
	Total Lab Investment (+25%)	**$812,500**	
University of Bath Total AM Investment		**$812,500**	
University of Manchester- Centre for Digital Fabrication	FujiFilm Dimatix DMP 2800	$30,000	InkJet
	S030	$3,000	SIJ
	TX 1600 Mimaki Printer	$2,000	InkJet
	Total 3D Printers Investment	**$35,000**	
University of Manchester Total AM Investment		**$35,000**	
Manchester Metropolitan University- Print City 3D Printing Hub	x4 Robo R2	$6,000	FDM
	x8 Ultimaker 3	$29,232	FDM
	x2 Ultimaker 3 Extended	$9,016	FDM
	Ariwolf 3D HD printer	$1,800	FDM
	x2 3DP1000	$40,000	FDM
	x2 MakerBot Replicator 2	$3,000	FDM
	3D Systems ProJet 3510	$64,500	MJM
	x3 MarkOne	$15,000	CFF
	x6 FormLabs Form 2-	$21,000	SLA
	ProJet CJP 660Pro	$77,790	CJP
	ZPrinter150	$15,000	InkJet
	Total 3D Printers Investment	**$282,338**	
	Total Lab Investment (+15%)	**$324,689**	
Manchester Metropolitan University Total AM Investment		**$324,689**	
University of Leeds- Institute of Design, Robotics and Optimization	Objet1000 Stratasys	$99,999	PolyJet
	Objet500 Connex3 Stratasys	$330,000	PolyJet
	PerFactory 3 Mini Multi Lens	$75,000	DLP
	Total 3D Printers Investment	**$504,999**	
	Total Lab Investment (+25%)	**$631,249**	
University of Leeds Total AM Investment		**$631,249**	

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Loughborough University- Additive Manufacturing Research Group AMRG	FormLabs Form 2	$3,500	SLA
	Ultimaker 3	$3,654	FDM
	Ultimaker2	$1,899	FDM
	Ultimaker 2 Extended	$2,299	FDM
	MakerBot Replicator 2	$1,500	FDM
	MarkOne	$5,000	CFF
	Zprinter 450	$40,000	InkJet
	Dimension Elite	$32,000	FDM
	Formiga P 110 EOS	$175,000	SLS
	Viper Pro Sla System	$18,000	SLA
	Total 3D Printers Investment	**$282,852**	
	Total Lab Investment (+15%)	**$325,280**	
University of Loughborough Total AM Investment		**$325,280**	
University of Southampton- Advanced Manufacturing Laboratory	x4 FormLabs Form 2	$14,000	SLA
	ProJet 3600	$103,191	MJP
	Concept Laser M2 Cusing	$850,000	DMLS
	EnvisionTEC ULTRA 3SP HD	$75,000	SLS
	Z Printer 650	$59,900	InkJet
	Zprinter 450	$40,000	InkJet
	x2 BFB 3000	$8,000	RP Multicolor
	Total 3D Printers Investment	**$1,150,091**	
	Total Lab Investment (+30%)	**$1,495,118**	
University of Southampton-Printing Service	x20 Tiertime UP! Plus 2	$18,800	FDM
	x3 Tiertime UP!	$1,797	FDM
	x6 Six Tiertime UP Bo	$11,394	FDM
	x9 Monoprice Select Mini Pro	$2,250	FDM
	Metal Malyan M200	$230	FDM
	x6 Original Prusa i3 MK3	$5,280	FDM
	Ultimaker 3	$3,654	FDM
	Total 3D Printers Investment	**$43,405**	
University of Southampton Total AM Investment		**$1,538,523**	
University of Derby-Institute for Innovation in Sustainable Engineering IISE	Objet500 Connex3 Stratasys	$330,000	PolyJet
	ObJet 30	$19,900	PolyJet
	ObJet30 Prime	$30,000	PolyJet
	F370 Stratasys	$31,000	FDM
	Total 3D Printers Investment	**$410,900**	
	Total Lab Investment (+15%)	**$472,535**	
University of Derby Total AM Investment		**$472,535**	

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Lancaster University- Mechanical Engingeering Department	Ultimaker 3	$3,654	FDM
	FormLabs Form1	$2,800	SLA
	Stratasys Dimension Elite	$32,000	FDM
	Realizer SLM 100	$200,000	SLM
	DTM Sinterstation 2000	$40,000	SLS
	J750 Stratasys	$300,000	PolyJet
	ZMorph VX Multi-tool 3D Printer	$4,400	Multi-Tool
	Total 3D Printers Investment	**$582,854**	
	Total Lab Investment (+25%)	**$728,568**	
Lancaster University Total AM Investment		**$728,568**	
University of Oxford-3D Printing Service	Ultimaker 2 Extended	$2,299	FDM
	X4 MakerBot Replicator 2-	$6,000	FDM
	x2 3DP1000	$40,000	FDM
	x6 Tiertime UP!	$3,594	FDM
	Total 3D Printers Investment	**$51,893**	
University of Oxford Total AM Investment		**$51,893**	
University of Durham-Centre for Advanced Instrumentation	FormLabs Form2	$3,500	SLA
	ProJet CJP 660 Pro	$77,790	CJP
	Total 3D Printers Investment	**$81,290**	
University of Durham Total AM Investment		**$81,290**	
University of Warwick-Additive Technologies Capabilities Centre SLM	FormLabs Form2	$3,500	SLA
	FormLabs Form1	$2,800	SLA
	Stratasys Fortus 400mc	$185,000	FDM
	Stratasys Dimension SST 768	$20,000	FDM
	nScrypt 3Dn 450 HP	$600,000	FDM
	J750 Stratasys	$300,000	PolyJet
	ObJet260 Connex2 Stratasys	$150,000	PolyJet
	ProJet2500 3D Systems	$49,700	MJP
	ZPrinter 310	$20,000	InkJet
	EOS EOSINT M280	$700,000	DMLS
	Total 3D Printers Investment	**$2,031,000**	
	Total Lab Investment (+35%)	**$2,741,850**	
University of Warwick Total AM Investment		**$2,741,850**	
Bournemouth University- Design and Engineering Innovation Centre	MakerBot Replicator 5th Generation	$2,860	FDM
	MakerBot Replicator Z18	$6,499	FDM
	FormLabs Form2	$3,500	SLA
	Stratasys Fortus 360mc	$66,900	FDM
	Total 3D Printers Investment	**$79,759**	
Bournemouth University Total AM Investment		**$79,759**	

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University of Exeter- Centre for Additive Layer Manufacturing CALM	Formiga P 110 EOS	$175,000	SLS
	EOSINT P760 EOS	$250,000	SLS
	DTM Sinterstation 2000	$40,000	SLS
	Stratasys Dimension SST 768	$20,000	FDM
	ProJet HD3000 Plus	$30,000	FDM
	Total 3D Printers Investment	**$515,000**	
	Total Lab Investment (+25%)	**$643,750**	
University of Exeter Total AM Investment		**$643,750**	
Swansea University	Renishaw AM 250	$650,000	DMLS
	Total 3D Printers Investment	**$650,000**	
	Total Lab Investment (+25%)	**$812,500**	
Swansea University Total AM Investment		**$812,500**	
Queen Mary, University of London- School of Electronic Engineering and Computer Science	Objet30 Prime	$30,000	PolyJet
	FujiFilm Dimatix DMP 2831	$30,000	InkJet
	Total 3D Printers Investment	**$60,000**	
Queen Mary University Total AM Investment		**$60,000**	
University of Surrey- Centre for Engineering Materials	MicroFab Jetlab4	$20,000	InkJet
	MicroFab Jetlab 4xl	$22,000	InkJet
	Total 3D Printers Investment	**$42,000**	
University of Surrey Total AM Investment		**$42,000**	
Queen's University Belfast- Mechanical Engineering	ObJet 30	$19,900	PolyJet
	Total 3D Printers Investment	**$19,900**	
Queen's University BelfastTotal AM Investment		**$19,900**	
University of Edimburg-School of Engineering	Fortus 250 mc	$45,000	FDM
	Total 3D Printers Investment	**$45,000**	
University of Edimburg-uCreateStudio	Ultimaker 2 Extended	$2,299	FDM
	Ultimaker 3	$3,654	FDM
	Ultimaker2	$1,899	FDM
	Ultimaker 2 GO	$1,583	FDM
	Zortrax M200	$1,990	FDM
	FormLabs Form1	$2,800	SLA
	Total 3D Printers Investment	**$14,225**	
University of Edimburg Total AM Investment		**$59,225**	

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University of Strathclyde Glasgow- Ulab	x3 MakerBot Replicator 2	$4,500	FDM
	x2 MakerBot Replicator 5th Generation	$5,720	FDM
	Leapfrog Creatr HS	$8,274	FDM
	Stratasys Dimension SST 768	$20,000	FDM
	CEL Robox	$670	FDM
	Asiga PICO2 39	$6,990	SLA
	Aerosol Jet 200 Optomec	$200,000	Aerosol Jet
	Total 3D Printers Investment	**$246,154**	
	Total Lab Investment (+10%)	**$270,769**	
University of Strathclyde Glasgow Total AM Investment		**$270,769**	
University of Liverpool- School of Architecture	x2 MakerBot Replicator 2	$3,000	FDM
	Ultimaker 2 Extended	$2,299	FDM
	Ultimaker 3 Extended	$4,508	FDM
	Total 3D Printers Investment	**$9,807**	
University of Liverpool Total AM Investment		**$9,807**	
Newcastle University- School of Mechanical Systems Engineering	Ultimaker 3	$3,654	FDM
	Ultimaker2	$1,899	FDM
	FlashForge Dreamer	$899	FDM
	x2 BQ Witbox	$2,638	FDM
	x2 MakerBot Replicator 2X	$8,396	FDM
	FormLabs Form1	$2,800	SLA
	Ember	$7,495	DLP
	Photocentric Liquid Crystal 1.5	$3,056	SLA
	ZPrinter 350	$25,900	CJP
	nScrypt 3Dn 450 HP	$600,000	FDM
	Total 3D Printers Investment	**$656,737**	
	Total Lab Investment (+25%)	**$820,921**	
Newcastle University Total AM Investment		**$820,921**	
University of Leicester- Department of Physics & Astronomy	Dimension Elite	$32,000	FDM
	Formiga P 110 EOS	$175,000	SLS
	Total 3D Printers Investment	**$207,000**	
University of Leicester Total AM Investment		**$207,000**	
University of Aberdeen-3D Printing Service	Ultimaker2	$1,899	FDM
	ProJet1200 3D Systems	$4,900	MicroSla
	Total 3D Printers Investment	**$6,799**	
University of Aberdeen Total AM Investment		**$6,799**	

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As can be seen in the following Figure 13, the university that has invested most in the diffusion of the academic and research level of the AM is the University of Sheffield with about 12.5M $. The University of Sheffield consists of two main buildings dedicated to AM development: Centre for Advanced Additive Manufacturing AdAM and Advanced Manufacturing Research Centre AMRC within which it is placed the National Metals Technology Centre NAMTEC. More in details, AdAM is a Research Centre within the University of Sheffield and it is comprised of two technical staff and about 40 postgraduate researchers who work in a laboratory that hosts world-class manufacturing and testing facilities. The research center conducts worldwide research into the emerging field of additive manufacturing and most of the research carried out are published in high quality magazines. (162) While AMRC was established in 2001 as a 15M £ collaboration between the University of Sheffield and aerospace giant Boeing, with support from Yorkshire Forward and the European Regional Development Fund. Its aim is being a center of excellence that focus on making significant difference to the advanced manufacturing sector. The Research Centre is composed by 500 highly qualified researchers and engineers from around the globe. More specifically, it is useful to underline the existence of The National Metals Technology Centre NAMTEC that is a metals research group, joined AMRC with Boeing in 2012, that is focused on materials and processes for metal additive manufacturing. (163) Finally, regarding the University of Sheffield's effort in education programs, AdAM is also a training center. As a matter of fact, under the guidance of academics, part of the Masters in Additive Manufacturing and Advanced Manufacturing technologies, offered by the University of Sheffield for post-graduation, takes place in AdAM. This master lasts 12 months ans it is aimed at both new graduates and professional mechanical engineers. (164)

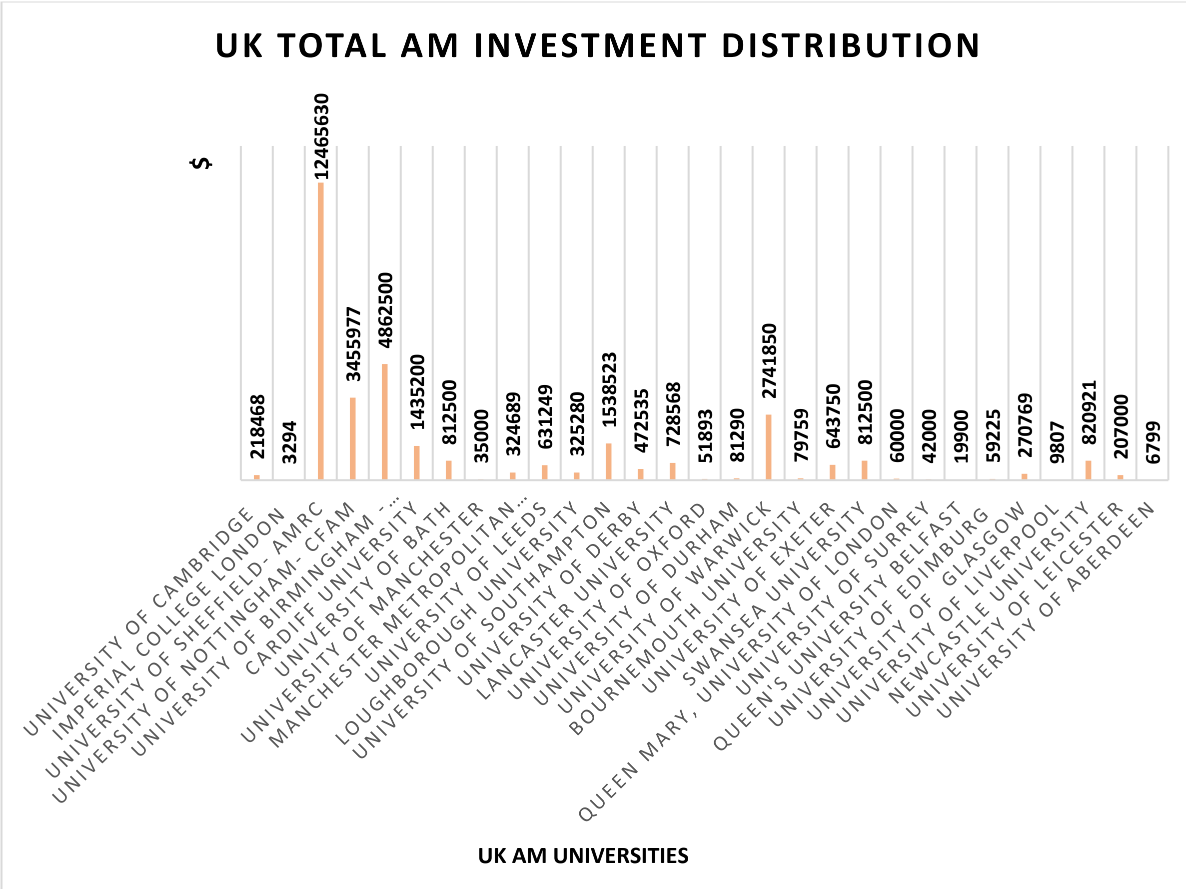

Figure 13: UK Total AM Investment Distribution

The second most developed university in AM is the University of Birmingham with about 4.9M $. The University of Birmingham consists of two main buildings dedicated to AM development: Advanced Materials and Processing Laboratory - AMPLab and Centre for Custom Medical Devices - CMD. The AMPLab aim is to understand the influence of advanced materials processing technique. Manufacturing processes and materials typically studied are selective laser melting SLM, direct laser fabrication DLF and friction joining for titanium, aluminum and ferrous alloys and nickel superalloys. (165) Moreover, the AMPlab located at the School of Metallurgy and Materials offers to its postgraduate students a Master in Metallurgy and Materials and to its Doctoral Researchers a 3 years full time PhD program. Nowadays, the school of Metallurgy and Materials has over 120 postgraduate research students carrying out various projects more than 100 PhD students. (166) While regarding Centre for Custom Medical Devices (CMD), located within the School of Metallurgy and Materials at the University of Birmingham, it wants to bring together multidisciplinary expertise to explore the full potential of additive manufacturing in the medical devices sector. CMD has important partnership with Healthcare Technologies Institute HTI, the Medical Devices Testing and Evaluation Centre MD-TEC and with Renishaw that is an engineering and scientific technology company in additive manufacturing. (167)

The third most developed university in AM is the University of Nottingham with about 3.5M $. The Centre for Additive Manufacturing at the University of Nottingham is renown as the world's leading Centre for Additive Manufacturing research and development and it is also the receiver of various large grants from the following funders: EPSRC, Innovate UK, Industry and other institutions. (168) Additionally, the University of Nottingham hosts the Centre for Doctoral Training (CDT) in Additive Manufacturing that is the most renown Education Centre of Europe and it is aimed at the talent who are able to face the major scientific and engineering Additive Manufacturing challenges. As a matter of fact, the CTD aim is to train and produce the best research leaders in Additive Manufacturing. (169) Finally, it is the 13^{th} year that the University of Nottingham hold the one of the most prestigious Additive Manufacturing Conference of the world. It is a two – days event that brings together more than 250 AM academics and industry professionals from all over the world, to share their knowledge and ideas. (170)

Regarding the UK AM technologies distribution, as shown in Figure 14, the most developed technology at the university level in the United Kingdom is the Fused Deposition Modeling (FDM) which is a common material extrusion process. Out of 233 total 3D printers currently in the academic and research fields in UK, 144 are material extrusion and in particular FDM. Another more used technology is material jetting that counts 13 3D printers based on InkJet Printing and 13 more on PolyJet Printing.

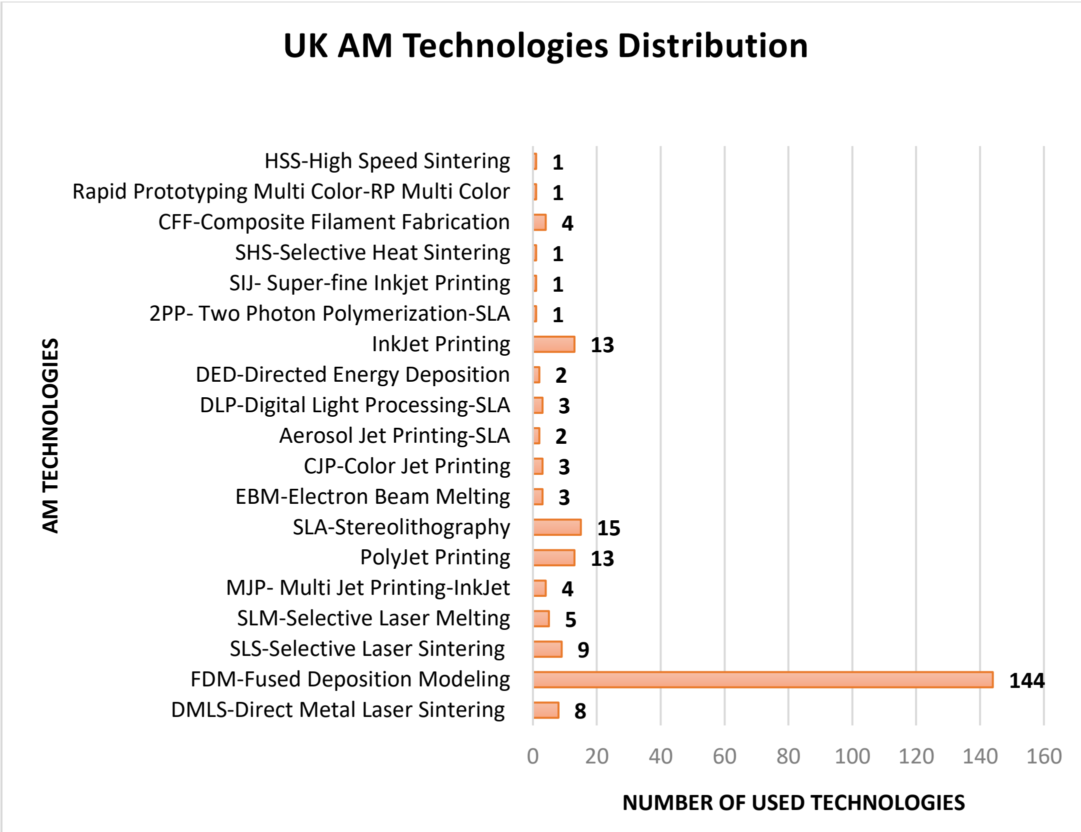

Figure 14: UK AM Technologies Distribution

The following is the format used for data collection and analysis to build a distribution of 3D printer manufacturers in UK in order to identify which 3D printer provider is the most developed in UK Universities.

Table 45: Format used to obtain the distribution of 3D Printers Manufacturers in UK

Manufacturers	Total Number Universities	Total Number 3D Printers	Company Website URL
Concept Laser GmbH-GE	2	2	https://www.concept-laser.de/
EOS- Electro Optical Systems	5	6	https://www.eos.info/en
SLM Solutions Group AG	1	1	https://slm-solutions.com/
Markforged	2	4	https://markforged.com/
Stratasys, Ltd	18	29	https://www.stratasys.com/
Ultimaker	12	29	https://ultimaker.com/
FormLabs	11	19	https://formlabs.com/
3D Systems	9	16	https://www.3dsystems.com/
Arcam- GE Company	1	3	http://www.arcam.com/
DMG Mori	1	1	https://it.dmgmori.com/

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Optomec	3	3	https://www.optomec.com/
MakerBot	9	21	https://www.makerbot.com/
FlashForge	1	1	http://www.flashforge.com/
Ember	2	2	https://ember.com/
Nanoscribe GmbH	1	1	https://www.nanoscribe.de/en/
RS	1	5	https://ie.rs-online.com/
Tiertime UP	3	41	https://www.tiertime.com/
ProBeam	1	1	http://www.probeam.com/
Renishaw	7	8	https://www.renishaw.com/shop/
MicroFab	2	3	http://www.microfab.com/
ReaLizer Gmbh	2	3	http://www.realizer.com/
FUJIFILM Dimatix, Inc.	3	3	http://www.fujifilm.com/
Meyer Burger	2	2	https://www.meyerburger.com/en/
BluePrinter	1	1	http://www.blueprinter.com/
Velleman	1	1	https://www.velleman.eu/
Autodesk	1	1	https://www.autodesk.com/
Wittman Battenfeld GmbH	1	1	https://www.wittmann-group.com/
Notion Systems GmbH	1	1	http://www.notion-systems.com/
ROBO 3D	1	1	https://robo3d.com/
Airwolf 3D	1	1	https://airwolf3d.com/
3D Platform	2	4	https://3dplatform.com/
EnvisionTec	1	1	https://envisiontec.com/
RapMan Pro	1	1	http://www.prototypeindia.com/
MonoPrice	1	1	https://www.monoprice.com/
Malyan	1	1	http://malyansys.com/en/
RepRap	1	1	https://reprap.org/
nScrypt	2	2	https://www.nscrypt.com/
Photocentric	1	1	https://www.photocentric3d.com/
BQ	1	1	https://www.bq.com/it/
Asiga	1	1	https://www.asiga.com/
Cel-Robox	1	1	http://www.cel-robox.com/
LeapFrog	1	1	https://www.lpfrg.com/
Zortrax	1	1	https://zortrax.com/
Total Number 3D Printers		**233**	

As shown in figure15, the manufacturers that have sold the largest number of 3D printers to UK Universities are those that offer 3D printers based on material extrusion technology such as Tiertime UP, Ultimaker, MakerBots that together with FormLabs, sell Desktop 3D printers. It also denotes an important diffusion of Stratasys that offers to the market both 3D Printers based on Material extrusion technology but also based on material jetting.

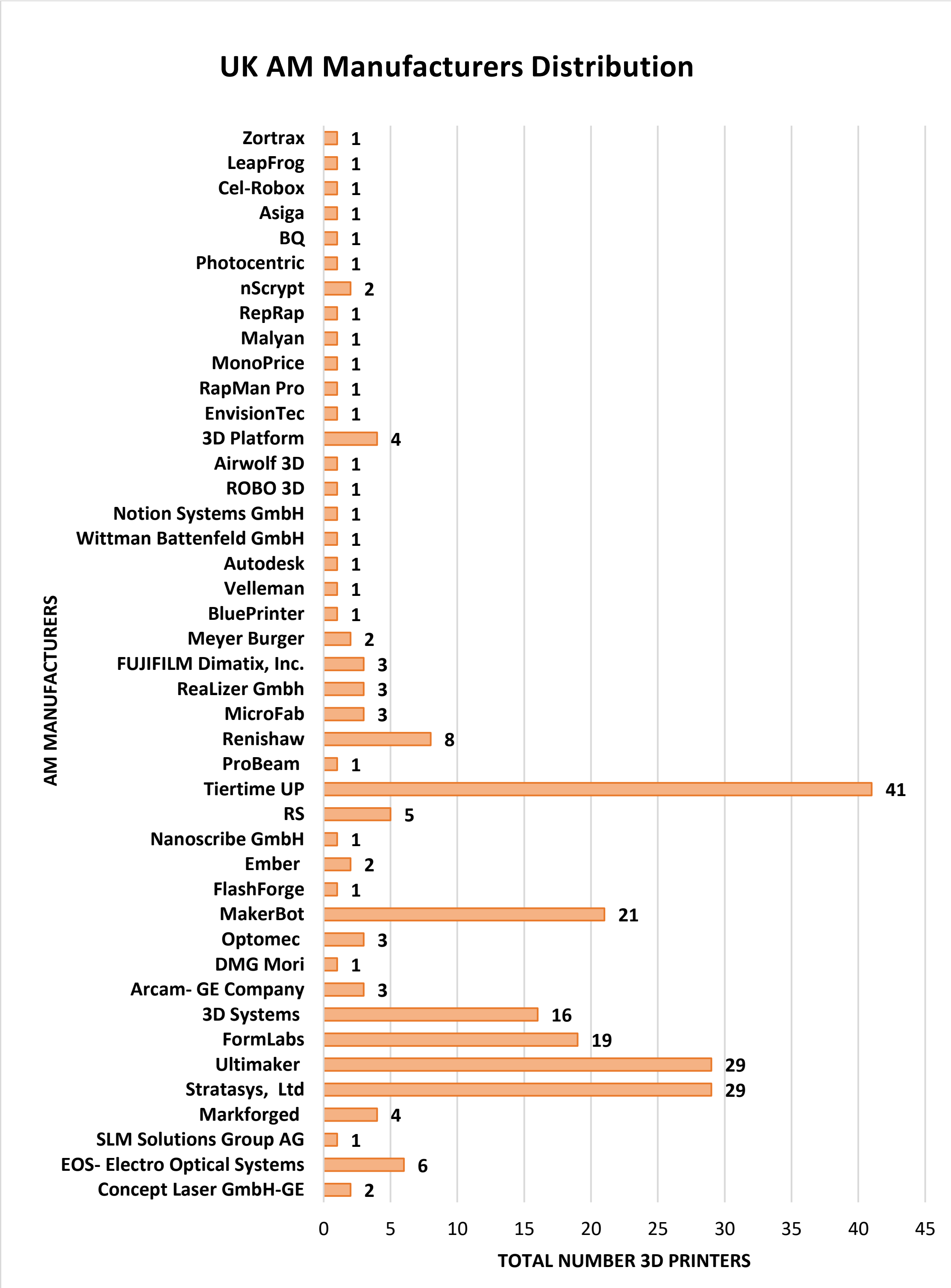

Figure 15: UK AM Manufacturers Distribution

4.3.2 German Results

Following there are all the laboratories belonging to the German universities indicating all the 3D printers held in their laboratory with their relative prices and technologies. As already previously explained, by following the classification criteria of the laboratories, it is possible to estimate the total amount of investment in the AM made by each single university.

Table 46: Format used to realize the distribution of investments made by each university in Germany

University Name	3D Printers	Price	Technology
TU Munich-Institute of Machine Tools and Business Administration-AMLab	Concept Laser M1 Cusing	€525,000	DMLS
	EOSINT M270	€600,000	DMLS
	EOS M290	€700,000	DMLS
	SLM 250 HL	€875,000	SLM
	VoxelJet VX500	€360,000	MJP
	Formiga P 110 EOS	€175,000	SLS
	Sintratec KIT	€5,350	SLS
	Markforged Mark Two	€13,499	CFF
	Stratasys uPrint SE PLUS	€28,000	FDM
	Ultimaker 3	€3,654	FDM
	Ultimaker 2 Extended	€2,299	FDM
	Ultimaker 2	€1,899	FDM
	EOS M400	€750,000	DMLS
	Total 3D Printers Investment	**€4,039,701**	
	Total Lab Investment (+35%)	**€5,453,596**	
TU Munich	**Total AM Investment**	**€5,453,596**	
RWTH Aachen University-Aachen Centre for Additive Manufacturing ACAM	Concept Laser M1 Cusing	€525,000	DMLS
	EOS M270	€450,000	DMLS
	EOS M250	€325,000	DMLS
	SLM 125 HL	€450,000	SLM
	SLM 280 HL	€950,000	SLS
	TruPrint 1000 Trumpf	€212,000	DMLS
	Objet500 Connex3 Stratasys	€330,000	PolyJet
	Objet1000 Stratasys	€99,999	PolyJet
	Ultimaker 3	€3,654	FDM
	Ultimaker 2 Extended	€2,299	FDM
	Markforged Mark Two	€13,499	CFF
	Total 3D Printers Investment	**€3,361,451**	
	Total Lab Investment (+35%)	**€4,537,959**	

RWTH Aachen University-Institute for Machine Elements and Systems Engineering MSE	Ultimaker 2	€1,899	FDM
	Ultimaker 2 Extended	€2,299	FDM
	Felix Pro 1	€2,365	FDM
	FormLabs Form2	€3,500	SLA
	ProJet CJP 660Pro	€77,790	CJP
	Total 3D Printers Investment	**€87,853**	
RWTH Aachen University	**Total AM Investment**	**€4,625,812**	
TU Berlin-Insitute of Mathematics	Zprinter 650	€59,900	InkJet
	Dimension SST1200	€34,900	FDM
	Total 3D Printers Investment	**€94,800**	
TU Berlin	**Total AM Investment**	**€94,800**	
University of Stuttgard-The Institute od Aircraft Design	Fortus 450mc Stratasys	€190,000	FDM
	FormLabs Form2	€3,500	SLA
	FormLabs Form1	€2,800	SLA
	Total 3D Printers Investment	**€196,300**	
	Total Lab Investment (+10%)	**€215,930**	
University of Stuttgard	**Total AM Investment**	**€215,930**	
TU Dresden-Fraunhofer Institute for Material and beam Technology IWS	Arcam A2X	€1,200,000	EBM
	Arcam Q10	€1,000,000	EBM
	x6 Renkforce RF 300	€4,200	FDM
	Renkforce RF 2000	€2,826	FDM
	Total 3D Printers Investment	**€2,207,026**	
	Total Lab Investment (+30%)	**€2,869,134**	
TU Dresden	**Total AM Investment**	**€2,869,134**	
TU Darmstadt- Institute of Printing Science and Technology IDD	MakerBot Thing O Matic	€1,225	FDM
	Evo Tech EVOlizer	€30,000	FDM
	System 30 Hyrel 3D	€3,995	FDM
	x4 Ultimaker 2+	€8,692	FDM
	FormLabs Form2	€3,500	SLA
	Sharebot Snowwhite	€35,000	SLS
	Total 3D Printers Investment	**€82,412**	
TU Darmstadt	**Total AM Investment**	**€82,412**	
University of Duisburg-Essen- 3D FabLab- Institute of Production Engineering	FormLabs Form2-SLA(3500D)	€3,500	SLA
	Ultimaker 2-FDM(1899D)	€1,899	FDM
	Ultimaker 2 Extended-FDM(2299D)	€2,299	FDM
	Ultimaker3-FDM(3654D)	€3,654	FDM
	Fabbster-FDM(1340)	€1,340	FDM
	Total 3D Printers Investment	**€12,692**	
University of Duisburg-Essen	**Total AM Investment**	**€12,692**	

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University of Erlangen-Nuremberg-Institute of Materials Science and Engineering for Metals WTM	Arcam A2X	€1,200,000	EBM
	Arcam Q10	€1,000,000	EBM
	Total 3D Printers Investment	**€2,200,000**	
	Total Lab Investment (+30%)	**€2,860,000**	
University of Erlangen-Nuremberg	**Total AM Investment**	**€2,860,000**	
Ulm University- Institute of Chemical Engineering- Laboratory of Photochemical Reaction Engineering	German RepRap X500	€41,999	FDM
	German RepRap X1000	€59,999	FDM
	Ultimaker 2	€1,899	FDM
	Ultimaker 2 Extended	€2,299	FDM
	Total 3D Printers Investment	**€106,196**	
	Total Lab Investment (+10%)	**€116,816**	
Ulm University	**Total AM Investment**	**€116,816**	
University of Hannover- Insitute of Product Development and Engineering Design (IPeG)	HP Designjet 3D Printer	€175,000	FDM
	Formiga P 110 EOS	€175,000	SLS
	EOSINT M280	€525,000	DMLS
	MakerBot Replicator	€2,000	FDM
	Object30 Stratasys	€19,900	PolyJet
	x3 Ultimaker3	€10,692	FDM
	Ultimaker2 Extended	€2,299	FDM
	Total 3D Printers Investment	**€909,891**	
	Total Lab Investment (+25%)	**€1,137,364**	
University of Hannover	**Total AM Investment**	**€1,137,364**	
TU Braunschweig -Institute for Engineering Design	Dimension SST1200	€34,900	FDM
	Zprinter 450	€40,000	InkJet
	Ultimaker original	€910	FDM
	GermanRepRap X500	€41,999	FDM
	GermanRepRap X1000	€59,999	FDM
	Formlabs Form1	€2,800	SLA
	Formlabs Form2	€3,500	SLA
	Total 3D Printers Investment	**€184,108**	
	Total Lab Investment (+10%)	**€202,519**	
TU Braunschweig	**Total AM Investment**	**€202,519**	
University of Freiburg-FMF Freiburger 3D Printing Alliance	EOS M400	€750,000	DMLS
	Arcam A2X	€1,200,000	EBM
	4x Ultimaker 3	€14,616	FDM
	Total 3D Printers Investment	**€1,964,616**	
	Total Lab Investment (+35%)	**€2,652,232**	
University of Freiburg	**Total AM Investment**	**€2,652,232**	

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TU Dortmund - Research Group on AM	Lasertec 65 3D DMG Mori	€950,000	DED
	Ultimaker 3	€3,654	FDM
	Ultimaker 3 Extended	€4,508	FDM
	Lasertec 30 SLM	€500,000	SLM
	FormLabs Form2	€3,500	SLA
	Total 3D Printers Investment	**€1,461,662**	
	Total Lab Investment (+30%)	**€1,900,161**	
TU Dortmund	**Total AM Investment**	**€1,900,161**	
TU Hamburg- Fraunhofer Research Institution for Additive Manufacturing Technologies IAPT	Concept Laser M2 Cusing	€850,000	SLS
	EOS M290	€225,000	DMLS
	EOS M270	€450,000	DMLS
	2x EOS P396	€500,000	SLS
	TruPrint 1000 Trumpf	€212,000	DMLS
	Arcam A2X	€1,200,000	EBM
	SLM 500 HL	€1,500,000	SLM
	SLM 250 HL	€875,000	SLM
	Ricoh AM s5500P	€700,000	SLS
	FormLabs Form2	€3,500	SLA
	Ultimaker 3 Extended	€4,508	FDM
	Intyamsys Funmat HT	€6,000	FDM
	Total 3D Printers Investment	**€6,526,008**	
	Total Lab Investment (+35%)	**€8,810,111**	
TU Hamburg-Technical Aspects of Multimodal Systems (TAMS)	2x German RepRap X500	€83,998	FDM
	3D Systems ProJet HD3600	€103,455	MJP
	Ultimaker 2	€1,899	FDM
	Ultimaker 3	€3,654	FDM
	Formlabs Form2	€3,500	SLA
	Total 3D Printers Investment	**€196,506**	
	Total Lab Investment (+10%)	**€216,157**	
TU Hamburg- Fraunhofer Institute	**Total AM Investment**	**€9,026,267**	
University of Heidelberg- Computing Centre	ProJet 460 Plus 3D Systems	€50,000	CJP
	Ultimaker 2	€1,899	FDM
	Ultimaker 3	€3,654	FDM
	Formlabs Form1	€2,800	SLA
	Total 3D Printers Investment	**€58,353**	
University of Heidelberg	**Total AM Investment**	**€58,353**	

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LMU Munich-3D Printing Service	Ultimaker 3	€3,564	FDM
	Formlabs Form2	€3,500	SLA
	Total 3D Printers Investment	**€7,064**	
LMU Munich	**Total AM Investment**	**€7,064**	
University of Tübingen-Interfaculty Institute of Biochimestry (IFIB)	Flashforge Creator Pro	€899	FDM
	Ultimaker 2	€1,899	FDM
	Total 3D Printers Investment	**€2,798**	
University of Tübingen	**Total AM Investment**	**€2,798**	
Charitè Universitätsmedizin Berlin-Centrum Scientific Workshops	Markforged OnyxPro	€7,000	CFF
	Ultimaker 5S	€5,995	FDM
	Ultimaker 2+	€2,173	FDM
	Formlabs Form2	€3,500	SLA
	Total 3D Printers Investment	**€18,668**	
Charitè Universitätsmedizin Berlin	**Total AM Investment**	**€18,668**	
Free University of Berlin-Department of Mathematics	Zprinter 650	€59,900	InkJet
	Total 3D Printers Investment	**€59,900**	
Free University of Berlin	**Total AM Investment**	**€59,900**	
University of Bonn-3D Printing Service	Ultimaker 3 Extended	€4,508	FDM
	Total 3D Printers Investment	**€4,508**	
University of Bonn	**Total AM Investment**	**€4,508**	
University of Gottingen-3D Printing Service	Ultimaker 3	€3,654	FDM
	Total 3D Printers Investment	**€3,654**	
University of Gottingen	**Total AM Investment**	**€3,654**	
University of Mannheim-3D Printing Service	MakerBot Replicator	€20,000	FDM
	Total 3D Printers Investment	**€2,000**	
University of Mannheim	**Total AM Investment**	**€2,000**	
University of Munster-Munster Nanofabrication Facility	Two Photonic Professional GT		2PP
	Ember	€7,495	DLP
	Total 3D Printers Investment	**€7,495**	
University of Monster	**Total AM Investment**	**€7,495**	
University of Kiel-Functional Nanomaterials Institute	German RepRap X400 Pro	€14,900	FDM
	German RepRap X350	€7,000	FDM
	Total 3D Printers Investment	**€21,900**	
University of Kiel	**Total AM Investment**	**€21,900**	

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University of Bremen-Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM	ExOne Innovent	€175,000	MBJ
	x2 ExOne Innovent+	€160,000	MBJ
	EOS M270	€450,000	DMLS
	x2 German RepRap X500	€83,998	FDM
	DLP Station 5	€30,000	FDM
	Total 3D Printers Investment	**€898,998**	
	Total Lab Investment (+25%)	**€1,123,748**	
University Bremen-Fraunhofer Ifam	**Total AM Investment**	**€1,123,748**	

As can be seen in Figure 16, the university that has invested most in the diffusion of the academic and research level of the AM in Germany is the University of Hamburg with about 9M $. The University of Hamburg consists of Research Group within the Department of Informatics and it is partner of the Fraunhofer Research Institution for Additive Manufacturing Technologies IAPT. There is a research group called TAMS that is aimed to develop methods and implement integrated real-time systems for acquiring, processing and applying information from multiple channels such as robotic vision, speech and sound, touch through action, etc. (171) The investment made by the University of Hamburg is very limited compared to that made by the Fraunhofer Research Institution, in fact the 9M $ attributed to the university of Hamburg only about 200k $ are those that are really independently supported by the university of Hamburg. On the other hand, The Fraunhofer IAPT was founded by the LZN Laser Zentrum Nord GmbH and parts of the Institute of Laser and System Technologies at the Hamburg University of Technology as one of the world's leading institution for scientific-industrial technology transfer in the area of 3D printing. Fraunhofer IAPT focuses on research and development of additive manufacturing technologies with main emphasis on design, process and factory with about 100 employees at the production sites in Hamburg and Lüneburg. The focus is on the application of additive technologies in the key fields of aerospace, ship & rail and machinery & tooling, as well as, polymers and medical technology for the serial production in terms of rapid and bionic manufacturing (172).

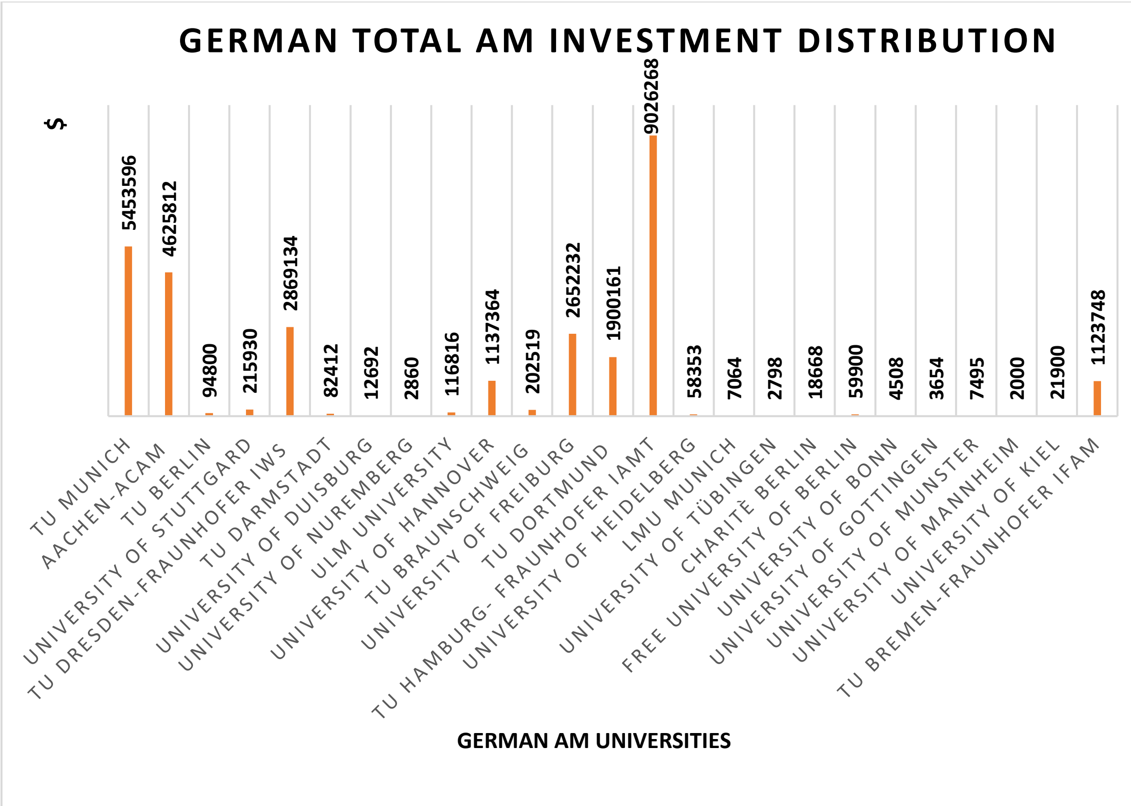

Figure 16: German Total AM Investment Distribution

The second most AM developed university in Germany is TU Munich with approximately 5,4M $. The TU Munich hosts the Institute of Machine tools and business administration AMLab. AMLab is an active technology transfer center composed by fourteen 3D printers based on six different technologies and aimed at embracing new collaborations with companies. It is available for short and medium-term projects for industrial customers with individual contracts. It is also ready to develop medium and long-term research projects in a network of research and industry partners for the search for joint solutions with industrial working groups. (173)

The third German University that has invested most in the diffusion of the AM is RWTH Aachen University with about 4.6M $. It consists of an Education Lab based mainly on Desktop 3D printers and dedicated to AM technologies in which research and academic courses are carried out (174). Additionally, it is also composed by a Centre for Additive Manufacturing ACAM. ACAM was founded by strategic partners such as RWH Aachen University. Its aims is to offer advanced training, feasibility studies and consultancy, as well as serving as a source of knowledge for the AM community. The University holds AM training offered to all employees of the partner companies which can use the laboratory as a training and research center. (175)

Regarding German AM technologies distribution. as shown in figure 17, it is possible to notice which are the differences between Germany and UK. As in the UK, also in Germany the material extrusion technology through the Fused Deposition Modeling process appears to be the most developed. As a matter of fact, out of 137 printers, 71 are material extrusion. But the big difference lies in the Powder Bed metal Fusion technology. Considering the following Powder Bed Fusion processes such as DMLS, SLS, SLM, EBM in total in German university laboratories there are 34 3D metallic printers out of 137 (25%), while in the UK 25 out of 233 (11%).

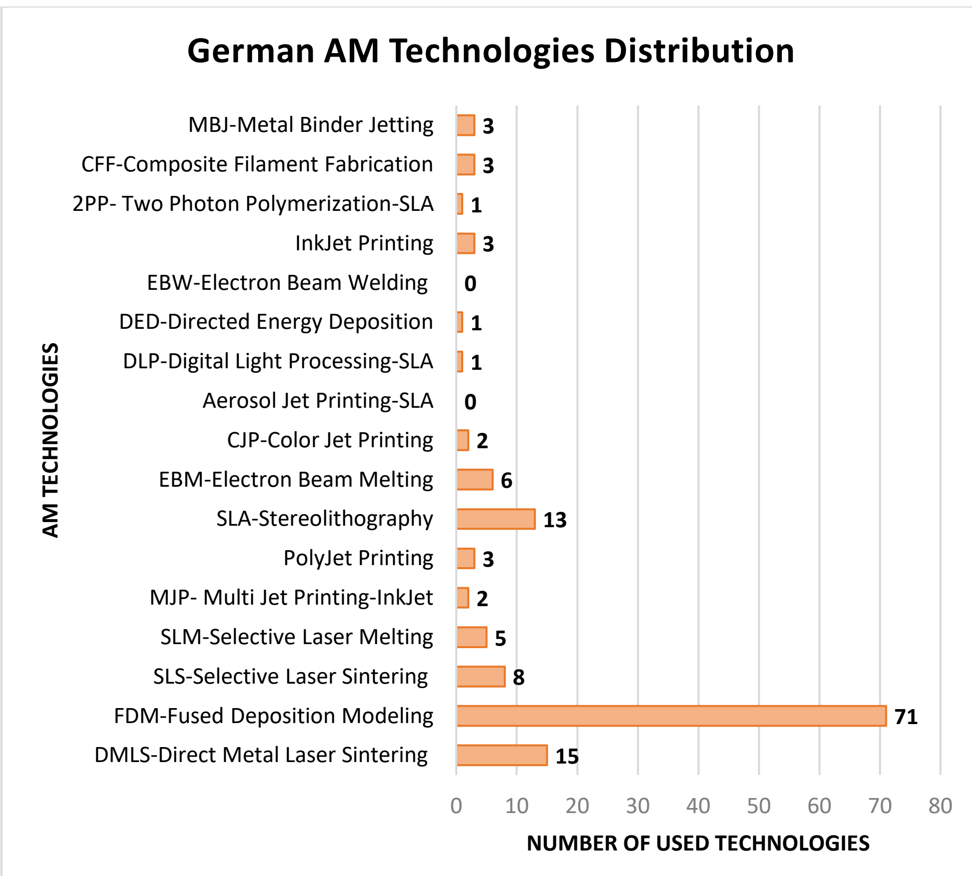

Figure 17: German AM Technologies Distribution

The following is the format used for data collection and analysis to build a distribution of 3D printer manufacturers in Germany in order to identify which 3D printer provider is the most developed in German Universities.

Table 47: Format used to obtain the distribution of 3D Printers Manufacturers in Germany

Manufacturers	Total Number Universities	Total Number 3D Printers	Company Website URL
Concept Laser GmbH-GE	3	3	https://www.concept-laser.de/
EOS- Electro Optical Systems	6	13	https://www.eos.info/en
SLM Solutions Group AG	3	6	https://slm-solutions.com/
Voxeljet AG	1	1	https://www.voxeljet.com/
Sintratec Ltd	1	1	https://sintratec.com/
Markforged	3	3	https://markforged.com/
Stratasys, Ltd	6	7	https://www.stratasys.com/
Ultimaker	18	39	https://ultimaker.com/
Trumpf	2	2	https://www.trumpf.com/de_INT/
Felixprinters	1	1	https://www.felixprinters.com/
FormLabs	11	15	https://formlabs.com/
3D Systems	5	4	https://www.3dsystems.com/
Arcam- GE Company	5	6	http://www.arcam.com/
DMG Mori	1	2	https://it.dmgmori.com/
MakerBot	3	3	https://www.makerbot.com/
Evotech s.r.l.	1	1	https://www.evotechsrl.com/
Hyrel 3D	1	1	http://www.hyrel3d.com/
Sharebot	1	1	http://sharebot.com/
Fabbster	1	1	http://www.fabbster.com/
German RepRap GmbH	5	9	https://www.germanreprap.com/
HP	1	1	http://www8.hp.com/us/en/
Ricoh	1	1	https://www.ricoh.com/
IntamSys	1	1	https://www.intamsys.com/
FlashForge	1	1	http://www.flashforge.com/
Ember	1	1	https://ember.com/
Nanoscribe GmbH	1	1	https://www.nanoscribe.de/en/
ProBeam	1	1	http://www.probeam.com/
ExOne	1	3	https://www.exone.com/
Atum3D	1	1	https://www.atum3d.com/
Renkforce	1	7	http://www.renkforce.com/
Total Number 3D Printers		**137**	

As can be seen from Figure 18, as in UK, also in Germany producers of Desktop 3D printers such as Ultimaker and FormLabs turn out to be those companies most present within the academic world due to the low cost of 3D printers sold. What is noteworthy because it differs from the UK distribution is that, on the basis of the German technologies distribution, the manufacturers of metal machines such as EOS-Electro Optical Systems, SLM Solutions Group AG and Arcam-GE Company are very influential in university laboratories, despite the high cost of 3D printers.

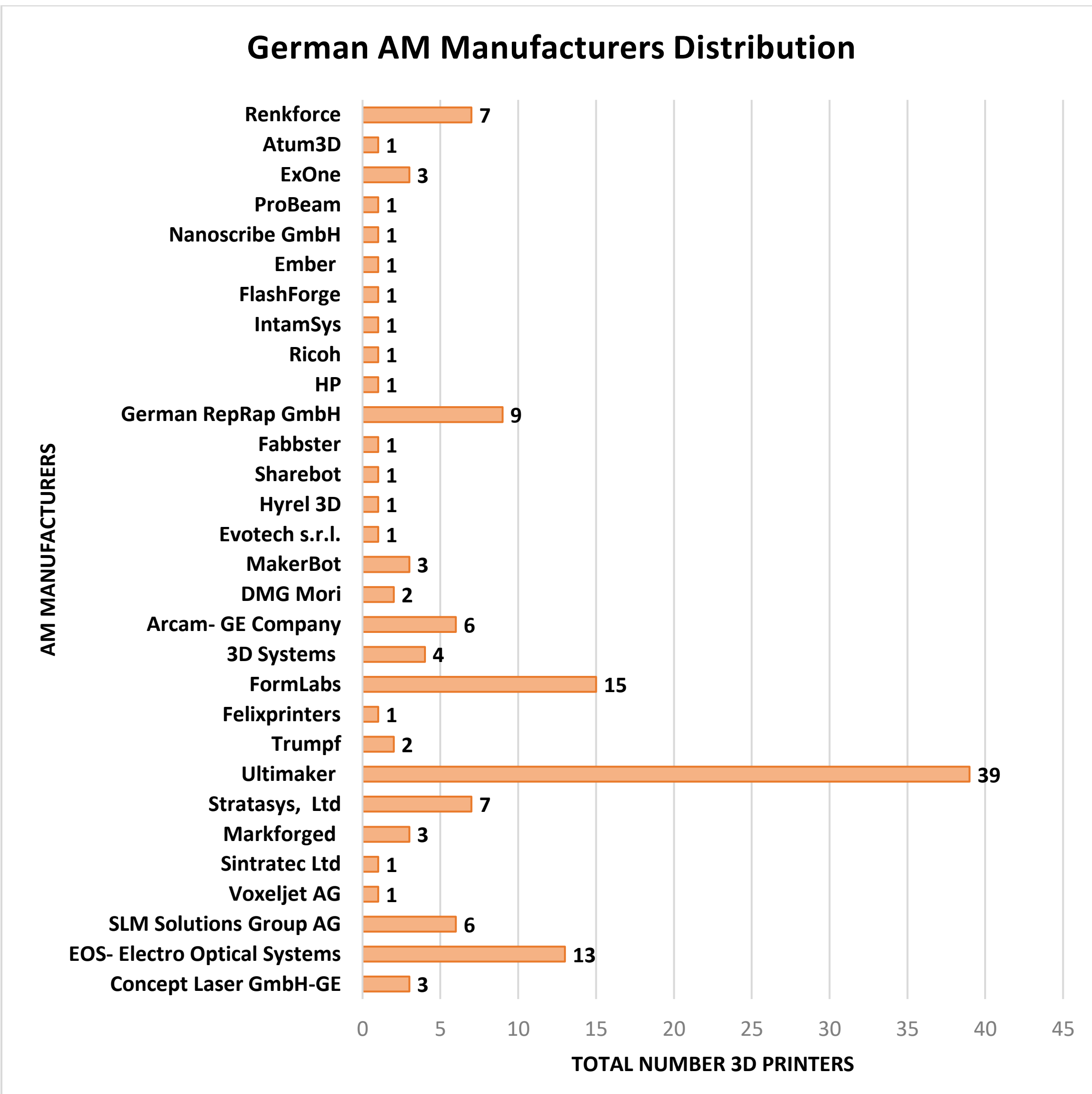

Figure 18: German AM Manufacturers Distribution

4.3.3 Italian Results

Following are all the laboratories of the Italian universities indicating all the 3D printers held in the laboratory with their relative prices and technologies. By following the classification criteria of the laboratories, it is possible to estimate the total amount of investment in the AM made by each university.

Table 48: Format used to realize the distribution of technologies and investments made by each university in Italy

University Name	3D Printers	Price	Technology
Polytechnic of Milan-AM Laboratory	Renishaw AM250	$585,305	DMLS
	Total 3D Printers Investment	**$585,305**	
	Total Lab Investment (+25%)	**$731,631**	
Polytechnic of Milan	**Total AM Investment**	**$731,631**	
Polytechnic of Turin - Integrated Additive Manufacturing IAM	M250 EOS	$325,000	DMLS
	M270 EOS	$450,000	DMLS
	EOSINT M270	$600,000	DMLS
	Arcam A2X	$1,200,000	EBM
	Dimension Elite	$32,000	FDM
	F370 Stratasys	$31,000	FDM
	EOS Formiga P110	$175,000	SLS
	Markforged Mark Two	$13,000	FDM
	Total 3D Printers Investment	**$2,826,000**	
	Total Lab Investment (+35%)	**$3,815,100**	
Polytechnic of Turin-3D Printing Service	x2 MakerBot Replicator	$7,510	FDM
	x2 MakerBot Replicator+	$7,240	FDM
	Total 3D Printers Investment	**$14,750**	
Polytechnic of Turin	**Total AM Investment**	**$3,829,850**	
University of Pavia-3DMetal Project	Renishaw AM400	$600,000	DMLS
	Total 3D Printers Investment	**$600,000**	
	Total Lab Investment (+25%)	**$750,000**	
University of Pavia	**Total AM Investment**	**$750,000**	
Polytechnic of Genoa &IIS Istituto Italiano della saldatura -Genoa Additive Manufacturing GeAM	EOS M290	$700,000	DMLS
	Wasp Delta 40x70	$6,640	FDM
	Total 3D Printers Investment	**$706,640**	
	Total Lab Investment (+25%)	**$883,300**	
Polytechnic of Genoa	**Total AM Investment**	**$883,300**	

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University of Padua-TE.SI	Two Photonic Professional GT Nanoscribe		2PP
	Total 3D Printers Investment	**$-00**	
University of Padua	**Total AM Investment**	**$-00**	
Prom Facility-Polo Meccatronic with University of Trento	Renishaw AM400	$600,000	DMLS
	Lasertec 65 3D DMG Mori	$950,000	DED
	FormLabs Form2	$3,500	SLA
	FormLabs Form1	$2,800	SLA
	HP Multi Jet Fusion 3D 4200	$200,000	Jet Fusion
	Concept Laser Mlab CUSING R	$160,000	SLS
	Total 3D Printers Investment	**$1,916,300**	
	Total Lab Investment (+30%)	**$2,491,190**	
University of Trento-Machine tools and prototyping Lab	x2 Ultimaker2	$3,798	FDM
	Total 3D Printers Investment	**$3,798**	
University of Trento	**Total AM Investment**	**$2,494,988**	
University of Bologna-Industrial Engineering department DIN	SISMA MySint100	$175,000	SLS
	Total 3D Printers Investment	**$175,000**	
	Total Lab Investment (+10%)	**$192,500**	
University of Bologna	**Total AM Investment**	**$192,500**	
University of Brescia- Advanced Prototyping Laboratory LPA	ProJet 2500 3D Systems	$435,000	MJP
	ProX 100	$250,000	DMLS
	ProJet 460Plus	$50,000	CJP
	Dimension 1200es	$18,900	FDM
	Total 3D Printers Investment	**$753,900**	
	Total Lab Investment (+25%)	**$942,375**	
University of Brescia	**Total AM Investment**	**$942,375**	
University of Florence and CERTEMA Amlab	Concept Laser M2 Cusing	$850,000	DMLS
	Total 3D Printers Investment	**$850,000**	
	Total Lab Investment (+25%)	**$1,062,500**	
University of Florence	**Total AM Investment**	**$1,062,500**	
University of Pisa and CrossLab	x2 Ultimaker 2	$3,798	FDM
	x4 MakerBot Replicator 2	$6,000	FDM
	Total 3D Printers Investment	**$9,798**	
University of Pisa	**Total AM Investment**	**$9,798**	

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University of Naples-Federico II- Centre of Reverse Engineering and Additive Manufacturing Innovation CREAMI	Ultimaker2	$1,899	FDM
	Prusa i3	$353	FDM
	CubeX Trio 3D Systems	$3,990	FDM
	Total 3D Printers Investment	**$6,242**	
University of Naples-Federico II	**Total AM Investment**	**$6,242**	
University of Udine and Trieste- Advanced Mechatronic LAMA FVG	Concept Laser M2 Cusing	$850,000	DMLS
	Total 3D Printers Investment	**$850,000**	
	Total Lab Investment (+25%)	**$1,062,500**	
University of Udine and Trieste	**Total AM Investment**	**$1,062,500**	
University of Salerno-Academic Spinoff LIAM-Laser Innovation	EOS M270	$450,000	DMLS
	Total 3D Printers Investment	**$450,000**	
	Total Lab Investment (+15%)	**$517,500**	
University of Salerno	**Total AM Investment**	**$517,500**	
Polytechnic of Bari- Rapid prototyping and Reverse Engineering Laboratory	Stratasys FDM 3000 3D Printer	$4,500	FDM
	Wasp Delta 40x70	$6,640	FDM
	Zortrax M200	$1,990	FDM
	MakeX M-One	$2,229	DLP
	Total 3D Printers Investment	**$15,359**	
Polytechnic of Bari	**Total AM Investment**	**$15,359**	
University of Rome Sapienza- Saperi&CO Project	Zortrax M200	$1,990	FDM
	FormLabs Form2	$3,500	SLA
	Wasp Delta 40x70	$6,640	FDM
	Wasp Delta 20x40	$2,772	FDM
	Ira3D Poetry Infinity	$2,794	FDM
	Xfab DWS	$6,000	SLA
	Total 3D Printers Investment	**$23,696**	
University of Rome Sapienza- AM Lab DIMA Department	EOS M290	$700,000	DMLS
	Total 3D Printers Investment	**$700,000**	
	Total Lab Investment (+25%)	**$875,000**	
University of Rome Sapienza	**Total AM Investment**	**$898,696**	
University of Cagliari- SardegnaRicerche	Dimension SST1200	$34,900	FDM
	ObJet EDEN 260	$19,800	PolyJet
	EOS M100	$257,042	DMLS
	Zprinter 450	$40,000	InkJet
	Total 3D Printers Investment	**$351,742**	
	Total Lab Investment (+15%)	**$404,503**	
University of Cagliari	**Total AM Investment**	**$404,503**	

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University of Salento-Lecce	x2 SLA 250/50 3D Systems	$7,498	SLA
	Total 3D Printers Investment	**$7,498**	
University of Salento	**Total AM Investment**	**$7,498**	
University of Camerino-Faculty of Architecture	ObJet EDEN 260	$19,800	PolyJet
	Total 3D Printers Investment	**$19,800**	
University of Camerino	**Total AM Investment**	**$19,800**	
University of Ca' Foscari Venezia-DelFablab	Wasp Delta 2040	$2,772	FDM
	Wasp Delta 60100	$30,000	FDM
	Total 3D Printers Investment	**$2,772**	
University of Ca' Foscari Venezia	**Total AM Investment**	**$2,772**	
University of Catanzaro-ImagEngLab	Poetry Infinity IRA3D	$2,794	FDM
	Total 3D Printers Investment	**$2,794**	
University of Catanzaro	**Total AM Investment**	**$2,794**	
University of Reggio Calabria-Multimedia Lab	x2 Sharebot Next Generation	$3,780	FDM
	Sharebot XXL	$5,474	FDM
	Total 3D Printers Investment	**$3,780**	
University of Reggio Calabria	**Total AM Investment**	**$3,780**	

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Turning now to analyze the distribution of total investments in AM made by Italian universities, as previously seen through the classification of laboratories, it is possible to analyze the great differences between countries such as UK and Germany and Italy and France. As we can see in figure 11, the university that has invested most in the diffusion of AM in Italy is the Polytechnic of Turin for a total of 3.9M $, unlike the 12M $ of the University of Sheffield in the UK. The Polytechnic of Turin hosts the Integrated Additive Manufacturing - IAM that is composed by five different departments: DIGEP- Department of Management and Production Engineering, DAUIN-Department of Control and Computer Engineering, DET-Department of Electronics and Telecommunications, DIMEAS- Department of Mechanical and Aerospace Engineering, DISAT-Department of Applied Science and Technology. IAM has three different aims: Developing projects with big companies such as FCA and GE Avio in order to carry out scouting and technology assessment; Supporting companies with consulting programs and execution of personalized projects and to allow them to access and use the infrastructures; Holding training programs by offering a second level master's degree in additive manufacturing. (176)

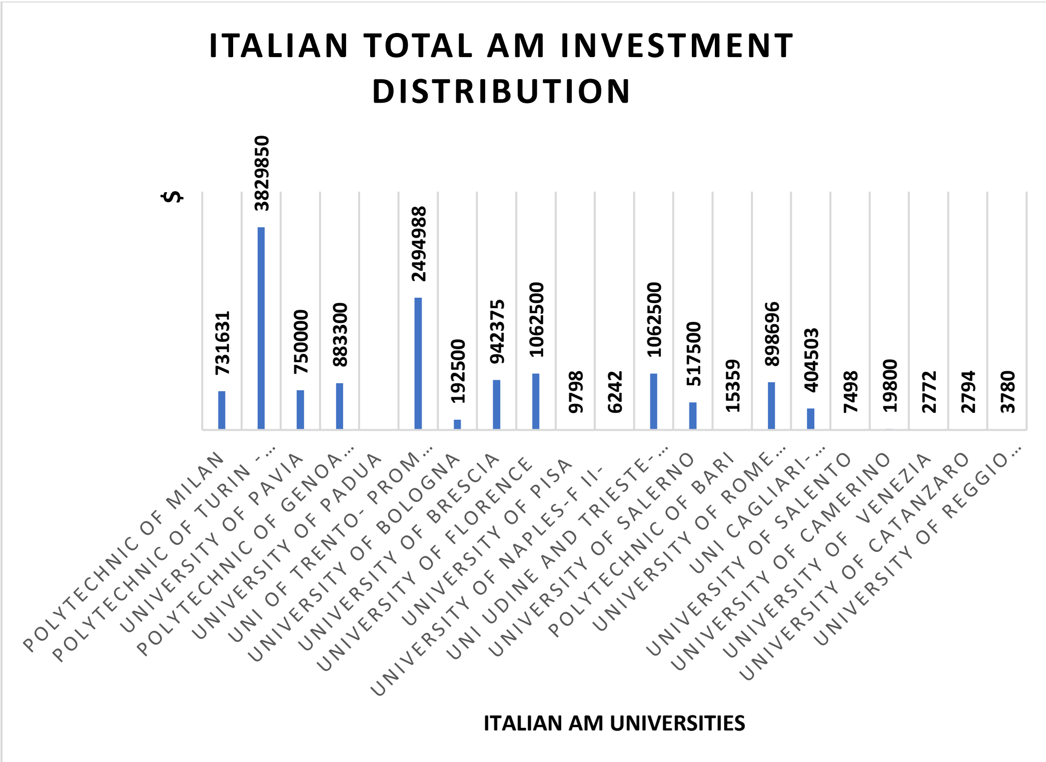

Figure 19: Italian Total AM Investment Distribution

The second university that has invested most in additive manufacturing is the University of Trento with 2.5M $, through its Mechatronics Centre- Prom Facility. Prom Facility is a network of companies, research centre and educational institutions contributing to the social and economic development of the entire Trentino production system. The most valuable aspect, supported by Prom Facility and that makes it at the forefront in Italy, is the existence of a “knowledge triangle” where research and innovation, business and training interact daily in an effective way. (177) Additionally, the collaboration among Marconi T.T.I, Veronesi V.I and University of Trento within Mechatronics Centre spreads innovative knowledge by performing and holding master degree and PhD programs but also secondary school programs and technical education. (178)

Finally, the union of synergies among three academic entities such as the University of Udine, the University of Trieste and the International Superior School for Advanced Studies-SISSA, represents the third largest investor in the AM in Italy with around 1M $. During the summer of 2016, it was launched the first Advanced Mechatronic Laboratory of the Friuli Venezia Giulia region - LAMA FVG. The laboratory aims to be the point of reference for the PhD students' experimental activities and for all those students who need to write their theses of master's degree courses with the collaboration of local companies. In conclusion, the objectives of the Laboratory are also to organize events and conferences to promote knowledge thanks to the availability of a large open space. (179)

Regarding the Italian technologies distribution used by the laboratories shown in figure 20, as for the other two countries previously analyzed, also in Italy, out of 67 3D Printers currently bought in the academic field, the most used technology is material extrusion through the Fused Deposition Modeling process. What is important to note is that, like Germany, Italy also has a high percentage of use of metal machines. As a matter of fact, considering the following Powder Bed Fusion processes such as DMLS, SLS, SLM, EBM in total in Italian university laboratories there are 17 3D metallic printers out of 67 total (25%), following the same percentage distribution of Germany.

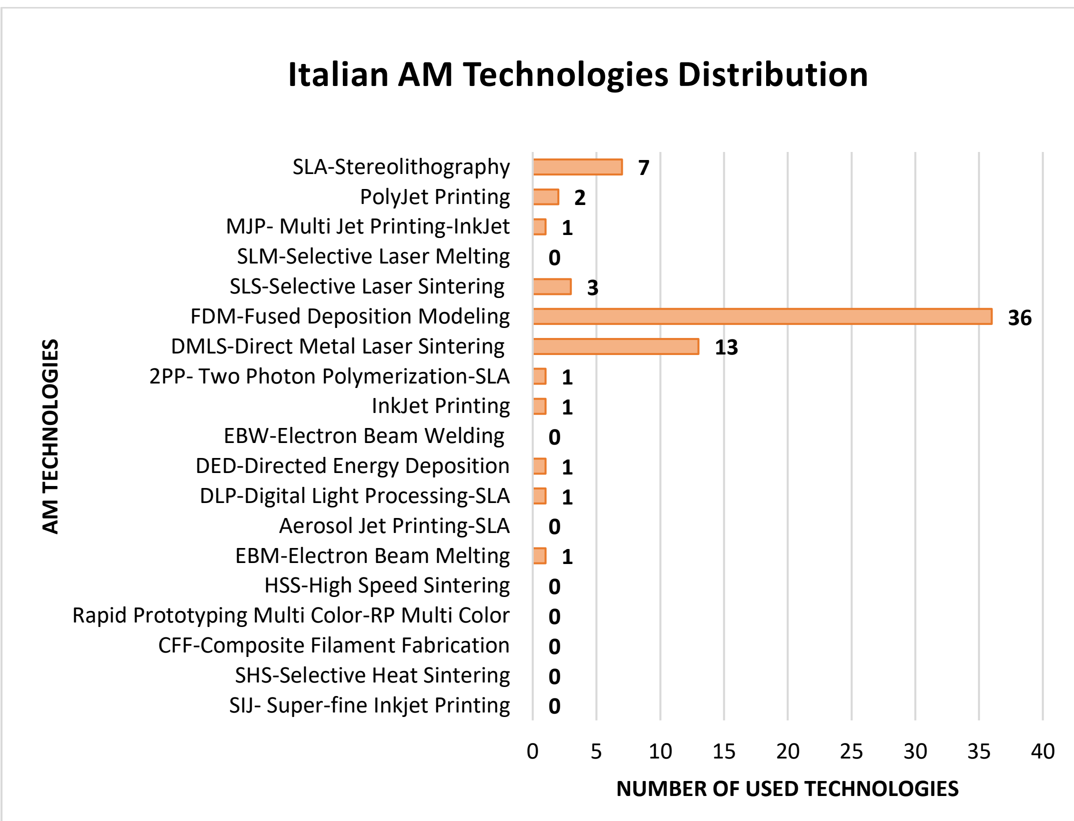

Figure 20: Italian AM Technologies Distribution

The following is the format used for data collection and analysis to build a distribution of 3D printer manufacturers in Italy in order to identify which 3D printer provider is the most developed in Italian Universities.

Table 49: Format used to obtain the distribution of 3D Printers Manufacturers in Italy

Manufacturers	Total Number Universities	Total Number 3D Printers	Company Website URL
EOS- Electro Optical Systems	5	8	https://www.eos.info/en
Arcam-GE Company	1	1	http://www.Arcam-GE Company.com/
Stratasys, Ltd	5	7	https://www.stratasys.com/
Renishaw	4	4	https://www.renishaw.it
WASP	4	6	https://www.3dwasp.com/
Nanoscribe GmbH	1	1	https://www.nanoscribe.de/en/
DMG Mori	2	2	https://it.dmgmori.com/
FormLabs	2	3	https://formlabs.com/it/
HP	1	1	https://www8.hp.com
Concept Laser GmbH-GE	4	4	https://www.concept-laser.de/
SISMA	1	1	https://www.sisma.com/
3D Systems	3	5	https://www.3dsystems.com/
RepRap	1	1	https://reprap.org/
DWS Systems	1	1	https://www.dwssystems.com/
Zortrax	2	2	https://zortrax.com/
MakeX	1	1	http://www.makex.com/
IRA3D	2	2	https://www.fablessy.com/
Markforged	1	1	https://markforged.com/
Ultimaker	3	5	https://ultimaker.com/
Sharebot	1	3	https://www.sharebot.it/
MakerBot	2	8	https://www.makerbot.com/
Total Number 3D Printers		67	

As can be seen from Figure 21, as in the UK and Germany, also in Italy, 3D desktop printer manufacturers turn out to be the most widespread companies in the academic world due to the low cost of 3D printers sold. But there is a difference: in Italy the manufacturer Ultimaker does not distribute its 3D printers unlike the other two countries previously analyzed, it is less popular in the choices made by Italian universities. Markforged, MakeX and HP are more common. Furthermore, as noted for Germany, on the basis of the German technologies distribution, manufacturers of metal machines such as EOS-Electro Optical Systems and Arcam-GE Company are very influential in university laboratories, despite the high cost of 3D printers.

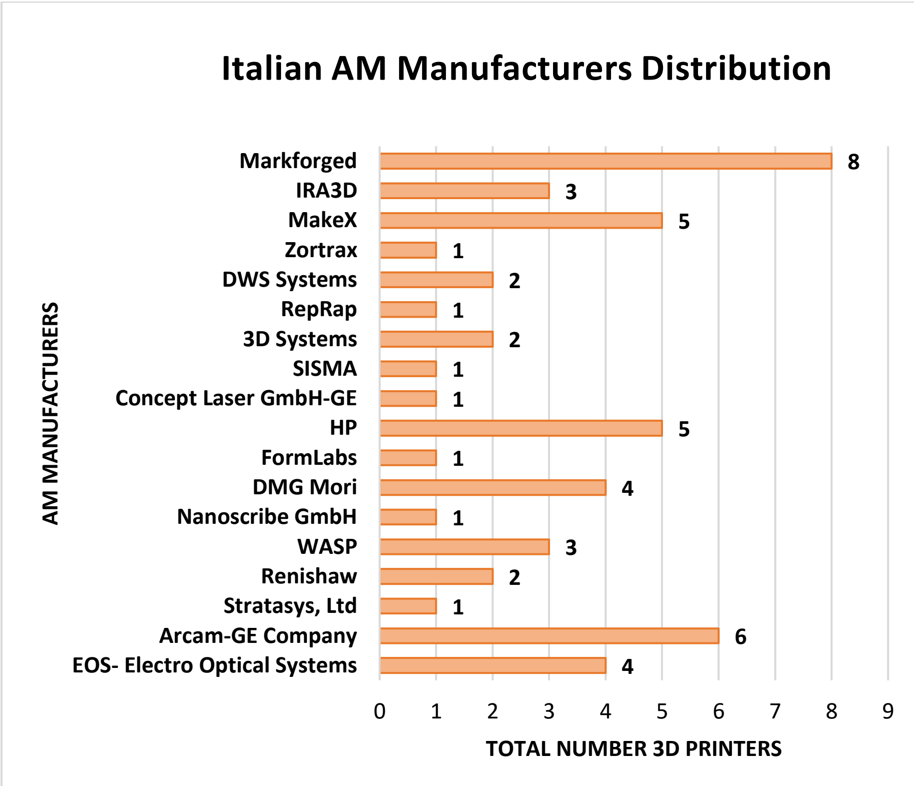

Figure 21: Italian AM Manufacturers Distribution

4.3.4 French Results

Following are all the information related to laboratories of the French universities composed by their 3D printers held in the laboratory with their relative prices and technologies, identifying as previously explained, the total amount of investment in the AM made by each single university.

Table 50: Format used to realize the distribution of technologies and investments made by each university in French

University Name	3D Printers	Price	Technology
University Paris Saclay - FABS-AM Research Project	FormUp 350 AddUp	$775,000	SLM
	Total 3D Printers Investment	**$775,000**	
	Total Lab Investment (+25%)	**$968,750**	
University Paris Saclay (ComUNE)- The Designspot	2x Ultimaker 2+ Extended	$2,299	FDM
	VersasStudio BN 20	$8,495	InkJet
	Total 3D Printers Investment	**$10,794**	
University Paris Saclay	**Total AM Investment**	**$979,544**	
University Grenoble Alpes- Engineering SIMaP	Arcam A2X	$1,200,000	EBM
	Total 3D Printers Investment	**$1,200,000**	
	Total Lab Investment (+30%)	**$1,560,000**	
University Grenoble Alpes	**Total AM Investment**	**$1,560,000**	
PSL Research University Paris- Research Group	DigitalWax 028K	$75,000	SLA
	Totale	**$75,000**	
PSL Research University Paris	**Total AM Investment**	**$75,000**	
Federal university Toulouse- Clement Ader Institute ICA	SLM 125HL	$450,000	SLM
	Zprinter 650	$59,900	InkJet
	Total 3D Printers Investment	**$509,900.00**	
	Total Lab Investment (+25%)	**$637,375**	
Federal University Toulouse	**Total AM Investment**	**$637,375**	
University of Lyon-3D Fabric if Adcanced Biology	Object 30	$19,900	PolyJet
	Tobeca1	$735	FDM
	Tobeca 3	$1,871	FDM
	x2 Tobeca 336	$44,446	FDM
	Microlight 3D micro printer	$100,000	2PP
	B9 Creator printer	$3,490	SLA
	Total 3D Printers Investment	**$170,442**	
	Total Lab Investment (+10%)	**$187,486**	
University of Lyon	**Total AM Investment**	**$187,486**	

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Institut National Des Sciences Appiquèes Lyon INSA-MECA3D	Zprinter 650	$59,900	InkJet
	3DTouch	$3,195	FDM
	Digital object Maker	$7,837	FDM
	FormLabs Form1	$2,800	SLA
	FormLabs Form2	$3,500	SLA
	Stratasys Fortus 360mc	$66,900	FDM
	x2 MakerBot Replicator 2X	$3,000	FDM
	ProJet 3510	$64,500	MJP
	Total 3D Printers Investment	**$211,632**	
	Total Lab Investment (+10%)	**$232,795**	
Lyon INSA	**Total AM Investment**	**$232,795**	
IMT Atlantique-FabLab	MakerBot Thing O Matic	$1,225	FDM
	MakerBot Mark Two	$13,499	FDM
	Total 3D Printers Investment	**$14,724**	
IMT Atlantique	**Total AM Investment**	**$14,724**	
University of Lorraine and Greater Nancy -Lorraine Fab Living Lab	Ultimaker 3	$3,654	FDM
	MakerBot Thing O Matic	$1,225	FDM
	Totale	**$4,879**	
University of Lorraine-Nancy	**Total AM Investment**	**$4,879**	
University of Nantes-Yhnova Project	BatiPrint 3D Printer Robot	$450,000	BatiPrint3D
	Total 3D Printers Investment	**$450,000**	
	Total Lab Investment (+15%)	**$517,500**	
University of Nantes	**Total AM Investment**	**$517,500**	
University of Cergy-Pontoise-FACLAB	Ultimaker 2	$1,899	FDM
	Ultimaker 2 Extended	$2,299	FDM
	Digital object Maker	$7,837	FDM
	Total 3D Printers Investment	**$12,035**	
University of Cergy-Pontoise	**Total AM Investment**	**$12,035**	
University of Paris Diderot - Paris 7	Fortus 250mc	$45,000	FDM
	Total 3D Printers Investment	**$45,000**	
Université Paris Diderot	**Total AM Investment**	**$45,000**	
Telecom ParisTech (École Nationale Supérieure des Télécommunications)-FabLab TP	Ultimaker 2	$1,899	FDM
	MakerBot Replicator 2X	$1,500	FDM
	Zortrax M200	$1,900	FDM
	Objet 30	$19,900	PolyJet
	Total 3D Printers Investment	**$25,199**	
Telecom ParisTech	**Total AM Investment**	**$25,199**	

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Ecole des Ponts ParisTech-FabLab	x3 Ultimaker 2	$5,697	FDM
	x2 Ultimaker 2 Extended	$4,598	FDM
	MakerBot Mark Two	$13,499	FDM
	FormLabs Form1	$2,800	SLA
	Total 3D Printers Investment	**$26,594**	
Ecole des Ponts ParisTech	**Total AM Investment**	**$26,594**	
CentraleSupélec-FabLab La Fabrique	Digital object Maker	$7,837	FDM
	Total 3D Printers Investment	**$7,837**	
CentraleSupélec	**Total AM Investment**	**$7,837**	
Ecole Polytechnique-FabLab	x3 Ultimaker 2 Extended	$6,897	FDM
	x2 Ultimaker 3	$7,308	FDM
	Total 3D Printers Investment	**$14,205**	
Ecole Polytechnique-Additive Manufacturing Centre	Objet30 Prime	$30,000	PolyJet
	Module 400 BeAM	$800,000	DED
	Total 3D Printers Investment	**$830,000**	
	Total Lab Investment (+25%)	**$1,037,500**	
Ecole Polytechnique	**Total AM Investment**	**$1,051,705**	
Sorbonne University-FabLab	2x Ultimaker 2	$1,899	FDM
	FormLabs Form1	$2,800	SLA
	FormLabs Form2	$3,500	SLA
	x3 MakerBot Replicator 2X	$4,500	FDM
	Total 3D Printers Investment	**$12,699**	
Sorbonne University	**Total AM Investment**	**$12,699**	
University of Strasbourg-FabLab	x3 MakerBot Replicator 2X	$4,500	FDM
	Total 3D Printers Investment	**$4,500**	
University Strasbourgh	**Total AM Investment**	**$4,500**	
University of Montpellier-Technological Platform for Research	Zortrax M200	$1,900	FDM
	FormLabs Form1	$2,800	SLA
	FormLabs Form2	$3,500	SLA
	Ultimaker 3	$3,654	FDM
	Dimension SST1200	$34,900	FDM
	Ultimaker 2+	$2,173	FDM
	HP Designjet 3D Printer	$175,000	FDM
	SLM 280HL	$950,000	SLM
	Witbox 2	$1,690	FDM
	Total 3D Printers Investment	**$1,175,617**	
	Total Lab Investment (+30%)	**$1,528,302**	
University of Montpellier	**Total AM Investment**	**$1,528,302**	

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University of Bordeaux-FabLab	iPrusa	$300	FDM
	Total 3D Printers Investment	**$300**	
University of Bordeaux	**Total AM Investment**	**$300**	

As shown in the figure 22, the university that has most invested in the diffusion of the AM in France is the university of Montpellier with about 1.5M $. PRO3D is a technology platform from the University of Montpellier dedicated to prototyping and additive manufacturing (polymer, metal). This center follows the three training / research / transfer axes and aims at structuring the forces involved in the field of additive manufacturing. Its range of services is from part production through additive manufacturing, to innovative product design and 3D print training tailored to individual needs. (180)

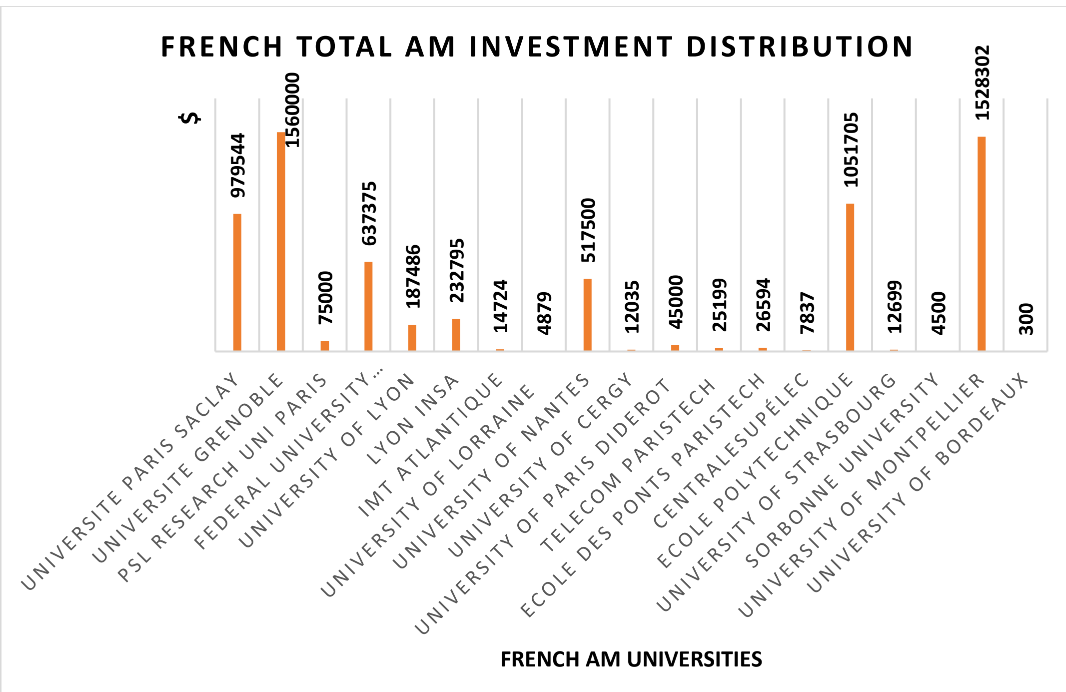

Figure 22: French Total AM Investment Distribution

On a par with the University of Montpellier, there is the University of Grenoble with about 1.5M $. The University of Grenoble hosts Materials and Process Science and Engineering Lab-SIMaP. The laboratory brings together physicists, mechanics and chemists of materials and fluids on objectives related to the design and development of materials and processes. Additionally, research activities around additive manufacturing at SIMaP rely mainly on the Electron Beam Melting

(EBM) technology and a significant part of the activity is devoted to material development and especially to materials that show a poor weldability. (181)

Finally, the third French university that has invested most in AM is the Ecole Polytechnique in Paris with about 1M $. The Ecole Polytechnique consists of an Education FabLab and an Additive Manufacturing Centre. FabLab is a high-tech prototyping space that is intended for entrepreneurs to create and develop innovative products (182). While regarding the Additive Manufacturing Center, it was inaugurated in December 2017 and it is aimed to benefit the students of École Polytechnique and ENSTA ParisTech who will be able to become aware of the challenges of the industry and develop their skills in innovative manufacturing processes. (183)

Regarding French 3D technologies distribution, as previously analyzed, France is predominantly constituted by small Education Labs with a purely academic purpose principally and characterized by Desktop 3D printers. Consequently, as can be seen in figure 15, out of 71 3D printers present in the academic field in France, 48 of these are based on material extrusion technology through the Fused Deposition Modeling process. Unlike Italy, French laboratories are not provided with high-cost 3D metal printers and, as we will see later, this will be the reason why Italy will have invested more in additive manufacturing than France.

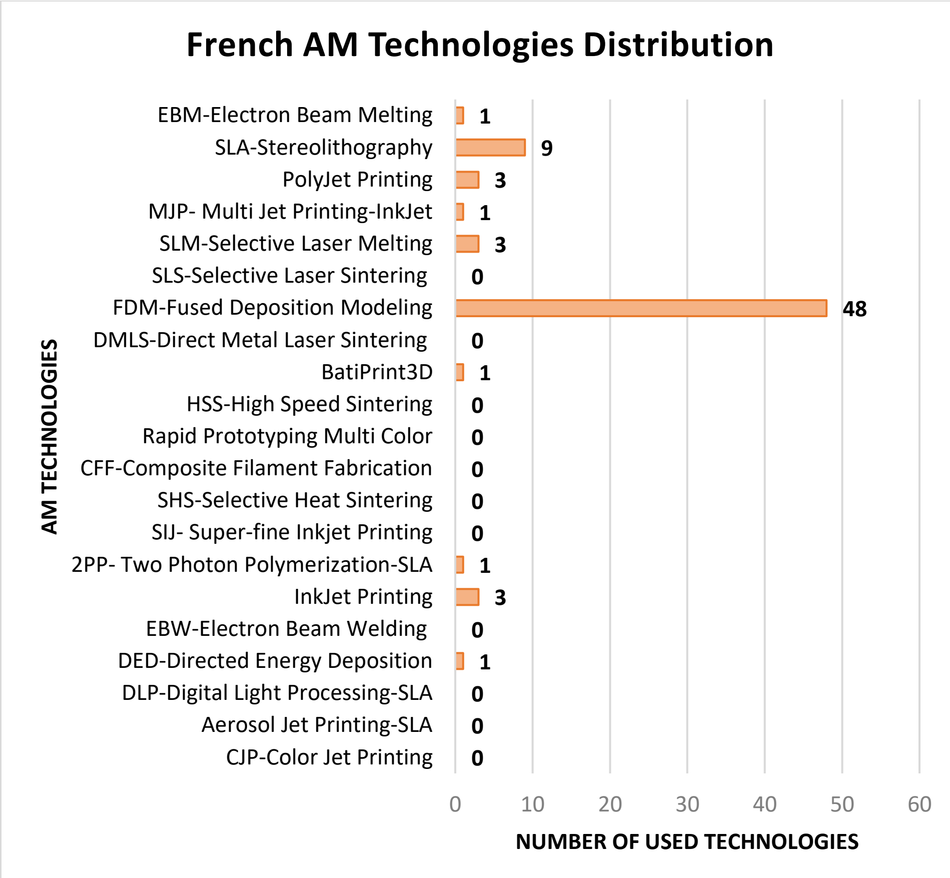

Figure 23: French AM Technologies Distribution

The following is the format used for data collection and analysis to build the distribution of 3D printer manufacturers in French in order to identify which 3D printer provider is the most developed in French Universities.

Table 51: Format used to obtain the distribution of 3D Printers Manufacturers in French

Manufacturers	Total Number Universiti es	Total Number 3D Printers	Company Website URL
AddUP	1	1	https://www.addupsolutions.com/en/
Ultimaker	8	21	https://ultimaker.com/
Roland DGA	1	0	https://www.rolanddga.com/
Arcam-GE Company	1	0	http://www.arcam.com/
DWS Systems	1	1	https://www.dwssystems.com/
SLM SolutionsGroup	2	2	https://slm-solutions.com/
3D Systems	2	4	https://www.3dsystems.com/
Stratasys	6	6	https://www.stratasys.com/

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Tobeca	3	4	http://www.tobeca.fr/
Microlight	1	1	http://www.microlight.fr/
B9 Creations	1	1	https://www.b9c.com/
DOOD	3	3	https://www.dood-studio.com/
FormLabs	4	7	https://formlabs.com/it/
MakerBot	7	13	https://www.makerbot.com/
BatiPrint LS2N	1	1	https://www.ls2n.fr/
Zortrax	2	2	https://zortrax.com/
BeAM	1	1	https://www.beam-machines.com/
HP	1	1	https://www8.hp.com
BQ	1	1	https://www.bq.com/it/
RepRap	1	1	https://reprap.org/
Total Number 3D Printers		**71**	

As regards the distribution of manufacturers in French, as a consequence of the distribution of the technologies used, the most widespread producers within the academic field are the producers of Desktop 3D printers based on material extrusion technology. Unlike Italy, the manufacturer Ultimaker appears to have the greatest influence in France, followed by MakerBot and FormLabs

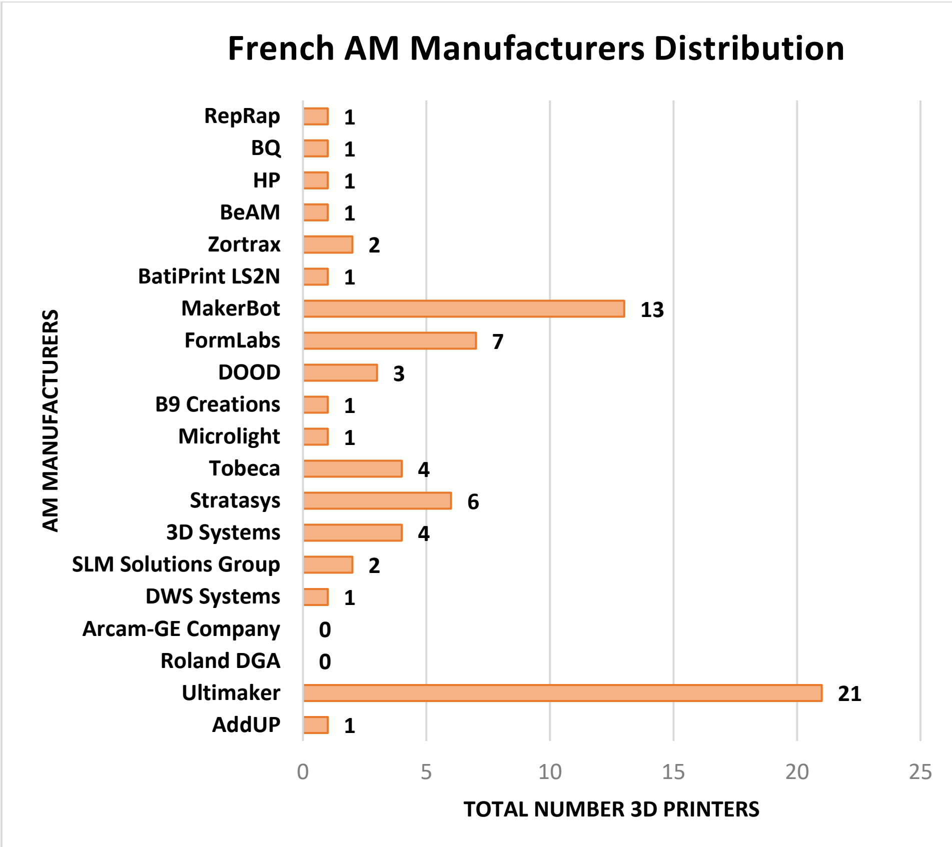

Figure 24: French AM Manufacturers Distribution

4.4 University Market Research Conclusion

To summarize the results obtained, as shown in the table 52, the following data were collected for each country analyzed.

Table 52: Market Research Conclusion

	UK	Germany	Italy	French
Total Number Universities	29	25	21	20
Total Number Laboratories	36	27	23	21
Total Number 3D Printers	233	137	67	71
University Market for 3D Printers	**$25.409.748**	**$24.716.560**	**$10.875.174**	**$5.576.357**
University Market for 3D Printing	**$33.174.876**	**$32.559.821**	**$13.838.387**	**$6.923.475**

- Number of universities within the country consisting of an AM laboratory or partner of an existing AM research center in the territory
- Number of total AM laboratories in the country related to the academic or research world
- Total number of 3D printers used in academic laboratories or research center in the country
- Total investment supported by the country for the purchase of 3D printers identified above
- Total investment made by the country for the diffusion of the AM in the academic and research world.

As shown in figure 25, there is a big difference between the AM development of UK and Germany compared to that of Italy and France. For this reason, a first comparison between UK and Germany will be presented. As already previously observed, 65% of the German and UK Universities analyzed owns an AM laboratory or are partners of some AM research center. Additionally, compared to a country like France, the diffusion of the AM has a uniform distribution throughout the country.

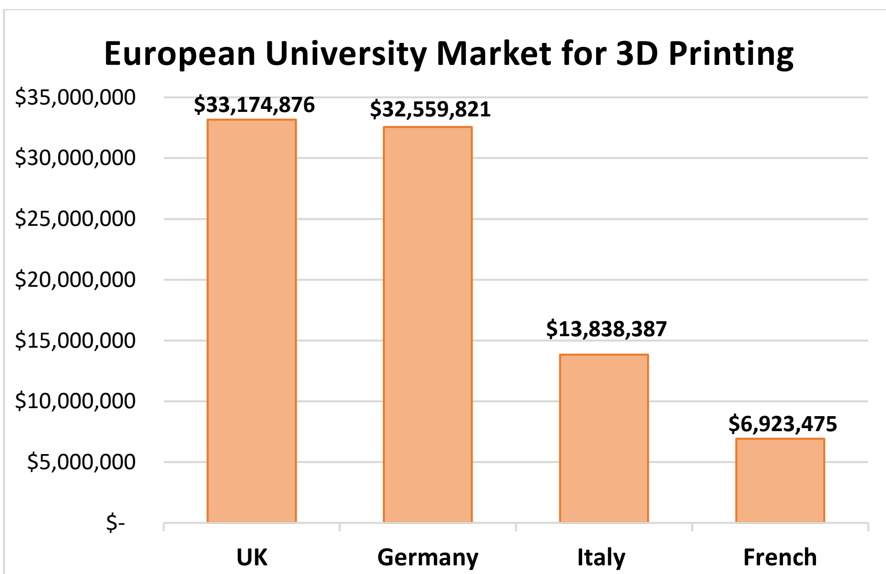

Figure 25: European University Market for 3D Printing

UK owns nine AM laboratories more than in Germany for a total of almost 100 3D printers more. Of the 233 3D printers owned by the UK, more than half of these are Desktop 3D printers with an average selling price of 1500 euros. This fact explains how it is possible that although UK owns almost 100 3D printers more than Germany, the UK investment in purchasing 3D printers is only about 700k $ higher. Consequently, it can be said that the two countries are characterized by a large investment in the purchase of 3D printers compared to the other two analyzed and that the UK has invested more than Germany in the purchase of Desktop 3D printers. These Desktop 3D Printers are characterized by the unique purpose of allowing students to approach Additive Manufacturing thanks to the presence of Laboratories aimed at training and teaching support and the presence of 3D printers on average not too expensive. As seen in the classification of Laboratories, Germany, compared to the UK, owns exclusively laboratories characterized by a high investment or laboratory aimed at student training. UK is much more characterized by laboratories consisting of a medium investment such as TRL 1-3 compared to Germany. This allows us to conclude that UK as in Germany, as well as pursuing the aim of making its contribution in increasing the performances related to AM, at the same time wants to give importance to small laboratories composed mainly by Desktop 3D printers to allow the dissemination of knowledge of AM to the largest number of student

On the other hand, making a comparison between Italy and France, it is surprising to note that although France is characterized by a higher number of 3D printers, Italy has invested twice as much in the purchase of 3D Printers. This is because as seen above, 25% of 3D printers purchased in Italy are 3D metal printers with an average selling price of more than 500k $, unlike the French laboratories that out of 71 3D printers, more than 65% are 3D printers desktops characterized by an average selling price of 1500 $. Furthermore, it can be noted that the difference between the two countries in the University Market for 3D Printers increases in the estimate of the University Market for 3D Printing from about 5M $ to 7M. This is because as previously analyzed, France is mainly constituted by Education Laboratories TRL 1 and only 5 laboratories exceeded total investment in the purchase of 3D printers over 500k $, unlike Italy which is constituted by a greater number of laboratories at high level also characterized by a TRL 4'-6' index.

Below is a comparison between the data obtained from the global market for 3D printing performed by BCC Research and the results obtained from the research presented.

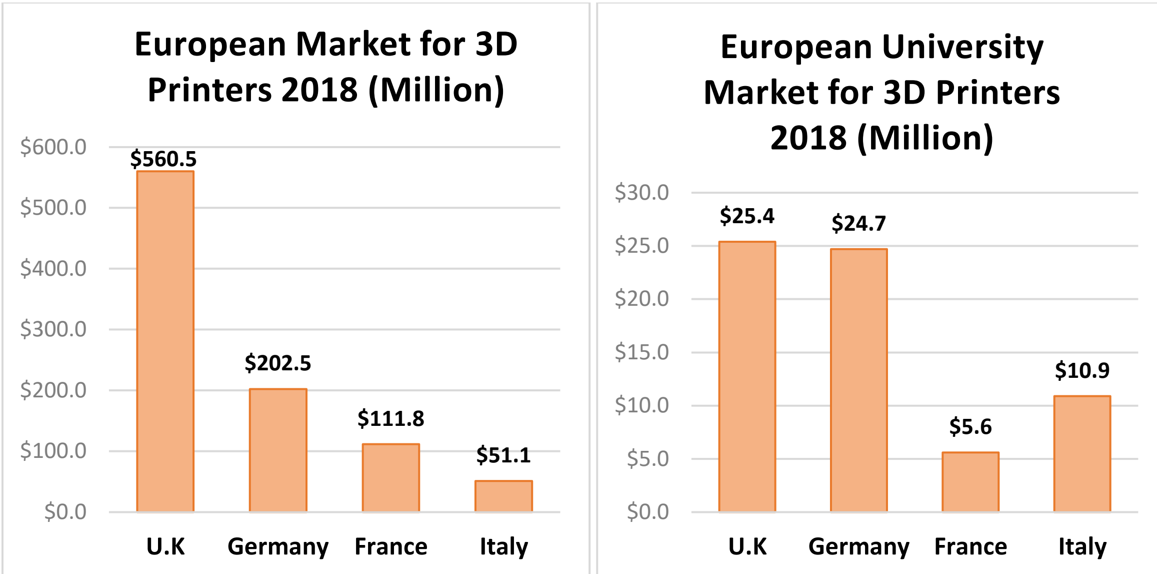

Figure 26: European Market for 3D Printers 2018 (BCC Research) and European University Market for 3D Printers

The BCC Research, as already seen, has carried out a Europe Market for 3D Printers going to consider all Desktop 3D printers and industrial 3D printers sold within the analyzed countries. The European University Market conduct does not show such a huge difference in investment in the purchase of 3D printers between the two UK and Germany countries compared to the European Market conducted by BCC Research. But the most important thing to underline is that while on the one hand France at a total level, considering not only the university-public sphere but also all the private sector made up of all those AM companies operating in different sectors, has invested twice as much Italy (111M $ vs 51M $), on the other hand, in the exclusively university context, the trend is the opposite.

5 Ar-Lab’s Business Plan

After trying to represent the European university landscape of 3D printing, the goal of this last part of the research is to analyze a real laboratory from the management point of view. More in detail, the Ar-Lab’s economic and financial analysis will be based on the identification of the laboratory's cost and revenue structure and how these are distributed over time. A further objective, based on the data provided by the laboratory, is to analyze if the laboratory can run independently over the time. The laboratory considered is the new Additive Research Lab - Ar-Lab currently built at Trinity College in Dublin. The Advanced Materials and Bio-Engineering Research - AMBER, the Science Foundation Ireland research center funded by Trinity College Dublin, launched a new additive research laboratory called Ar-Lab in March 2018. AMBER, working in collaboration with the Trinity College's Center for Research on adaptive nanostructures and nanodevices - CRANN, is a research center headquartered in Trinity's campus and it offers a partnership between leading researchers in materials science and industry for the development of new materials and devices for a wide range of industries (184). The AR-Lab is a fundamental component of AMBER in the research focused on fundamental material science challenges associated with 3D printing. It was decided to purchase different types of 3D printers and to be specialized, so as to cover the entire spectrum of materials from ceramics and polymers and biomaterials. The goal is to have a national impact on emerging 3D printing in the research ecosystem. (185) The laboratory is currently used only for academic and research purposes. Until now, only research projects, managed by different professors belonging to the Trinity College's mechanical and manufacturing engineering department as Principal Investigator (PI), have been developed. Specifically, PI is primarily responsible for the preparation, conduct and administration of a research grant for execution of a project. Additionally, the only people authorized to access and to use the Lab are: Ar-Lab’ technical staff, Principal Investigators and their students/researchers.

Finally, the Ar-Lab’s equipment, the assumptions on which the project is based, the cost and revenue structure of the laboratory will be introduced below.

5.1 Equipment

The laboratory is constituted by six industrial 3D printers. Specifically, there are two metal 3D printers characterized by Selective Laser Melting (SLM) technology, two stereolithography 3D printers that develop Lithography Based Ceramic (LCM), two-Photon lithography (2PL) technology and two 3D material jetting printers that develop the Inkjet printing and Aerosol Jet 3D printing technologies. Moreover, all the 3D Printers have been acquired through the funds granted by two Irish Foundations. As a matter of fact, Ar-Lab has been financed by Science Foundation Ireland for 3,3M € and by European Research Council for 1M €. Below. as shown in table 53, there are the machines currently in the laboratory with their short descriptions:

Table 53: Equipment Available in Ar-Lab

Equipment available in Ar-Lab				
Service	**Description**	**Machines**	**Technology**	**Applications**
Pre Process	Measure raw material quality in advance and quickly react to quality variations before the raw material is used in production. It allows to get materials ready to be printed. Specifically, it is a materials feedstock support platform for polymer fused filament fabrication AM capability (186)	Brabender Ketse 20/40 EC	Support Platform - Material testing on a lab scale	-
Process	It is capable to process ceramics into complex shapes, particularly at small dimension feature sizes and it is considered as the highest resolution tool of its type in the world. (187)	Lithoz CeraFab 7500	Stereolithography printing - Lithography based ceramic (LCM)	Bone implants, high temperature/wear/corrosive environments, space and aerospace and communications technologies (187)
	It is the world's highest resolution 3D printer. Characteristic key features are sub-micrometer resolution printing with feature sizes down to 200 nm and optical quality surface finishes. It is a turnkey system with an integrated user-friendly software package and offers a high degree of automation for ease-of -use but also great flexibility for expert users (188)	Nanoscribe Photonics Professional GT	Stereolithography printing - Two-photon lithography tool for polymers	Photonics and optics, bioengineering, bio-mimetics, micro-fluidics, interfacial surface interactions and metamaterials (187)

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	It is able to increase the flexibility of the tool for processing very fine and non regular metal powders. It offers reduced waste, greater speeds for productions, short set up times and the ability to produce very complex assemblies of very dense and complex metal parts manufactured. It also requires less post-processing due to its high quality surface finish (189)	3D Systems ProX 200	Power bed fusion - Selective Laser Melting (SLM)	Aerospace, energy and bio-engineering where the value propositions involves breaking form-function constraints (187)
	It is one of the highest resolution conventional metal powder bed SLM. It consists of an unusual laser configuration which enables a high degree of flexibility and control of alloy melt processing. (187) As a matter of fact, SLM 50 is designed for the production of small metal components requiring precision and excellent surface quality.	Realizer SLM 50	Power bed fusion - Selective Laser Melting (SLM)	Bone implants made of titanium and aluminum materials. Gold applications in both dental and jewelry industry (187)
	It provides the ability to print fine-feature electronic, structural and biological patterns onto almost any surface, with feature sizes as small as 10 µm. (190) It supports a wide variety of materials such as insulators, polymers, adhesives and also biological matter. (191)	Optomec Aerosol jet 300	Material Jetting printing - Aerosol Jet 3D printing	Electronics and biologics applications, devices for photovoltaic, touch screen displays and 3D interconnects (191)
	It is a new device for inkjet printing and material deposition. (192) It makes a higher degree of automated production processes and it has the capability of being a precision micro-fluidic instrument (187)	Microdop Gantry	Material Jetting printing - InkJet Printing	Biochips, pharmaceutical cartridges, solar cells, displays, gas sensors, fuel cells (192)

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Post Process1	Nikon's technology supports manufacturers with high-precision nondestructive inspection. Measure the complex internal structures of printed products and detect any defects within them, all without disassembling. (193) As a matter of fact, it evaluates the shape, structure and materials design properties in order to obtain qualitative and semi-qualitative information on defects, geometry, dimensional stability and microstructure. (187)	Nikon XTH225 ST	Support Platform – Non- destructive testing	-
Post Process2	Excetek is the large wire EDM (Electronic discharge machine) in the lab that research staff use for cutting parts printed in metal from their metal build plates. The Excetek is often used for an hour or 2 after a metal print is carried out as a post-process	Excetek 400 EDM	Wire Cutting Machine	

5.2 How to use the laboratory

Ar-Lab is able to satisfy and guarantee the use of the Lab in various ways defined as Case 1, Case 2 and Case 3:

- *Case 1- Long Project:* Access to the Lab is allowed exclusively to the researcher teams under the Principal Investigator's control. Undergraduate students, master students, PhD students and Post Doc students in order to use the machines and to access to the Lab must work on one of the Principal Investigator's projects. Generally, the Principal Investigator advertises and offers to the students the possibility to work on a specific project by explaining all the features of the project. The students interested in the project can apply and send their personal and academic information to the Professor in order to join the research team. In particular, the Principal Investigator can also point out which profile he is looking for. Otherwise, if a student wants to develop an own project, he can ask to the Professor if he was interested in finding a funds for that project and if he was willing to be the supervisor of the project. Moreover, Principal Investigators develop a long project with a team of specialized researchers who don’t need support during the use of the machines because they are completely independent. Perhaps, they would only need training at the beginning of the project to understand how to use the machine. The Ar-Lab, through the technical staffs, could be organize a training course at the beginning of each project. Additionally, Principal Investigators must estimate the project costs and they must find funds to pay the entire amount of money required to run the project.

- *Case 2 – Short Project:* It would be possible for the Principal Investigators or for some researchers to want to develop a small project. In this case the researcher could need a small amount of materials and a short period of training to be able to use the printing machine. This service offered by the Lab could help the researchers to not waste their time waiting for the arrival of the materials and for the equipment processed by the Principal Investigator and to not waste their money buying a big amount of materials if they only need a small one. This mechanism could be supported by the Lab and could allow to the Lab to build up economies of scale for materials. As matter of fact, the lab may buy a large amount of materials and pay them less than the fixed price per kilo. In this case the Lab should guarantee a service composed by materials, equipment / consumables, technical support and preliminary training.
- *Case 3-Additive Manufacturing Training Courses:* After analyzing more than 100 AM laboratories in the four studied European countries, it has emerged that Ar-Lab, as many other organizations already do, could hold basic, intermediate and advanced courses on Additive manufacturing through the support of its staff. This would give a very important source of income through only sharing knowledge and would give more international visibility to Ar-Lab. In the same way, one could think of organizing training events such as conferences aimed at promoting the spread of Additive Manufacturing.

Furthermore, a further application case (Case 4) will be presented below, identified during the university market research for 3D Printing in the larger AM laboratories, but which Ar-Lab is not able to satisfy due to its nature which is not oriented to commercial purposes.

- *Case 4 Not considered – Printing Service:* If the Lab was equipped with a much higher number of 3D printers with their related materials and was composed by a higher number of technical staff to run the Lab, it could satisfy the needs of the market. There could be some researchers or private companies in need of prints only. The lab could get the STL file previous sliced and ready to be print from the customers and then the Ar-Lab's technical staff could be print it, respecting the established agreement. This would be another service that the Lab could offer to the market by giving the possibility to use and to spread the innovative technologies present in the Lab all over the Ireland/Europe. However, this case was discarded because Ar-Lab is not a commercial lab but only for research purposes. As a matter of fact, the number of machines is insufficient to cover an on-demand service requested by the market, so this service will not be considered within the thesis and will not lead to any source of income.

Additionally, as we will see later in detail in all the cases presented, the following statements are valid:

1. In all the cases presented, the Trinity College must be incurred the following cost: Electricity and all the other utilities costs and Laboratory insurance cost.
2. In all the cases presented, Ar-Lab must be incurred the following cost: Technical staff labor costs, Waste disposal costs, Maintenance costs of the machines and all the direct costs necessary for the use of the machines and for the additive production (materials, equipment, solvents,..).
3. The cost incurred by the Principal Investigators depend on the cases analyzed: In Case 1 the Principal Investigator has to bear an hourly cost of using the 3D printers lower than Case 2. This is because, as previously explained, it will be the Principal Investigator who will take care of buying the equipment, the material and all that is necessary for the development of the project. In reverse, in Case 2 the Principal Investigator will pay more the use of the machine as to develop the short project, it will be necessary to ask for material, equipment, assistance from the staff and the use of the machines.
4. The payment system between the IP and the Ar-Lab takes place through a technological platform. Automatically, on the basis of the hours booked for the use of the machines (Case 1) or on the basis of the experiments carried out by the technical staff or the researcher using the laboratory materials (Case 2), at the end of the month the PI receives the charge of the total payment of the service used at the laboratory.

5. The booking process for the use of the machines takes place via a technological platform. Each researcher before using the machine must have pre-booked the machine by notifying the number of hours required

5.3 Cost Structure

As shown in table 54, the cost structure of each actor involved in the Ar-Lab project will be analyzed, and then focus exclusively on the Ar-Lab's future costs.

Table 54: Cost and Revenue Structure of main actors in Ar-Lab

Principal Investigator Project Costs	Trinity College Costs	Ar-Lab Costs
Researchers Labor Costs	Consumption expenses	Technical Staff Labor Costs
Materials	Laboratory Insurance Costs	Yearly Machines Warranty
Travel (Domestic and Overseas)	Building Constructions	Removal hazardous waste
Subcontract (Suppliers, consultants,..)		Miscellaneous and possible expenses
Consumables (Personal protective equipment, gloves, wipes, tools, items)		Materials available to Ar-Lab
Other (Training, analysis,..)		Consumables and Solvents available to Ar-Lab
Academic hourly Rate	**Revenue**	**Revenue**
Used laboratory materials	30% Total Project Costs	Academic hourly Rate + Used laboratory materials

5.3.1 Principal Investigator Project Costs

As previously explained, the PI turns out to be the manager of the project, the one who has to deal with the realization of a project budget and to obtain financing to cover entirely the following possible costs that a project can request:

- *Research Labor Costs:* The PIs can choose what kind of researcher to include in the Project. Depend on the researcher's qualification currently held, the salary could change according to the IUA salary scale (if applicable). The salary must also include employers PRSI contribution and pension costs.
- *Materials:* PIs must identify which materials the project needs and must estimate their quantities and costs. All materials must be supplied by the projects.
- *Travel (Domestic and Overseas):* PIs must list person travelling and reason for travel and quantify the related costs. Regarding to the international travel will only be allowed in circumstances where it is critical for the project deliverables and requires prior agreement.
- *Subcontract:* The PI must detail any costs relating to sub-contracting, consultancy, etc. The project could be supported by business and technical consultancy and joined by technical work.
- *Consumables (Personal protective equipment, gloves, wipes, tools, items):* The PI must identify and justify all the consumables that the project needs. Every Researchers have got their own equipment and all the tools (Personal protective equipment-PPE, gloves, wipes, tools such as Sensors, Specialized Extraction, Gas handling…) needed to be able to work. These variable costs vary from machine to machine. Most of the time, most machines just require nitrile gloves, while at other times more extensive protection is required. For example, it costs about €500-€700 for the metal printers PPE.
- *Other:* These may be specific costs that may vary from project to project.
- *Academic hourly rate:* The Principal Investigator must include in the project budget the cost related to the estimate of the total number of usage hours machines to be paid to Ar-Lab necessary to achieve the objective.

- *Laboratory material use:* PIs must take into consideration the possibility of needing, before starting to do the project, to carry out experiments or tests through the support of the laboratory's technical staff using the materials available to the laboratory. These extra costs must be taken into account in the budget.

5.3.2 Trinity College Costs

- *Building Constructions*: The TCD has provided and built the space in which Ar-Lab is located today.
- *Consumption expenses:* Being Ar-Lab located in a building that belongs to the TCD, consumption costs, such as water, electricity, air conditioning and local cleaning are considered to be borne by the University itself and therefore not considered in the Ar-Lab's cost structure.
- *Laboratory Insurance costs*: The laboratory insurance is under the Trinity policy and therefore it is not considered in the Ar-Lab's cost structure.

5.3.3 Ar-Lab - Additive Research Laboratory Costs

The costs that Ar-Lab must incur annually will be listed below in the following table 55 and will be analyzed more in detail in the next paragraphs:

Table 55: Ar-Lab's Cost Stucture

<table>
<tr><th>Ar-Lab Fixed Costs</th><th>Ar-Lab Variable Costs</th></tr>
<tr><td>Technical Staff Labor Costs</td><td rowspan="2">Materials available to Lab</td></tr>
<tr><td>Yearly Machines Warranty</td></tr>
<tr><td>Removal hazardous waste</td><td rowspan="2">Consumables and Solvents available to Lab</td></tr>
<tr><td>Miscellaneous and possible expenses</td></tr>
</table>

5.3.3.1 Technical Staff Labor Costs:

The laboratory will be managed by people who can operate on both mechanical and electronic technological priorities with skills coming mainly from the engineering area. The presence of complex equipment within the laboratory requires specific skills for their correct operation and therefore the presence of a technical reference figure, that can be permanently dedicated as a support to the management and use of the instrumentation, is essential. The main activities carried out by this technical figure are presented below:

- Coordinating the activities and therefore the projects promoted by the Principal Investigators both in relation to the expectations of the partners and stakeholders, and with reference to the integration needs of the different disciplinary areas involved in each project, also promoting the technology transfer activities.
- Promote interdisciplinary aggregations to access local funding, national and European.
- Support the drafting of both scientific, educational and financial parts of project proposals.
- Organize events and courses based on additive manufacturing to obtain new revenue streams and to strengthen the brand positioning both nationally and internationally.

To carry out all these activities, the presence of other staff is necessary to support the technical and economic management of the laboratory together with the technical manager. Research grant holders and post graduate students are the figures considered for this role. Unlike the technician, they are not hired through a full-time contract of around 50,000 €, but they are paid through research grants received from funds and projects. Currently, there is a technician and a research fellow at Ar-Lab.

5.3.3.2 Yearly Machines Warranty

Once the TCD made the investment for the purchase of all the machines currently in the laboratory, the goal would be that Ar-Lab independently has to be able to guarantee the maintenance of all these machines. Some machines currently in the laboratory have a warranty already expired, others instead as purchased new, are still under free purchase guarantee. Once Ar-Lab will have to start paying the warranty for these machines, the laboratory's fixed and indirect costs will increase. This must be taken into account, prior to sustaining these new future costs, by slowly increasing the cost of using the machines from the beginning of the model in order to save money to cover the maintenance of the machine in the future and not to increase the hourly cost of using the machine sudden.

Table 56: Yearly Warranty Machines

			Warranty price	
Machine	**Warranty Free Period**	**Warranty expiration Year**	**1 Year Full**	**1 Year Servicing**
Lithoz Cerafab 7500	5 Years full	Dec 2021	€ 10,000	€ 4,000
Photonics Professional GT	5 Years full	Dec 2021	€ 20,000	€ 5,000
3D Systems ProX 200	3 Years full	Jan 2020	€ 25,000	-
Realizer SLM 50	3 full + 1 servicing	Jan 2021	€ 10,000	
Optomec Aerosol Jet 300	-	already expired	€ 22,938	-
Microdop Gantry	No - Necessary	-	560€ to 1500€ for each dispenser heads and pipettes replacement	
Nikon Xray CT	2 full + 1 servicing	Jan 2020	€ 25,055	€ 3,696
Excetek 400 EDM	2 Years Full	Aug 2021	€ 3,847	

As shown in table 56, it has been identified the free warranty period guaranteed by the 3D printer manufacturers since these were purchased new, the year of expiry of the free warranty guaranteed by the 3D printer manufacturers and the warranty price that the laboratory will have to support annually once the free warranty will be expired. Moreover, the difference between the 1 year full and 1 year servicing warranty type is that the full includes repair or replace the product during the specified warranty period, while the 1 year servicing is limited to just the specified parts, certain types of defects, or other conditions established by the manufacturer. (194) The majority of the warranty prices were obtained on request to the company involved via e-mail excluding those of Bradenber and Realizer SLM 50 which due to the lack of information it was impossible to recover them and therefore they were roughly estimated. Finally, it can be noted that Optomec Aerosol Jet 300 3D Printer has set a base price of 22938 € but by agreement with the university, the real price supported by Ar-Lab is 12900 €, exactly 10,000 € less. This is because with the signing of long-term guarantee contracts and having the laboratory exclusively for research purposes the price made by the manufacturers has decreased.

5.3.3.3 Disposal hazardous waste

Disposing of the waste from separator vacuums is costly. Large companies adhere to the appropriate hazardous waste procedures by placing the remains of the wet separator in a 55-gallon drum, weighing it and disposing of it as hazardous waste at up to $44.00 per pound. Considering the number of machines and amount of materials that may be present on the shop floor quickly reveals how the numbers can add up. (195) There is a chemical temporary and transition storage inside the Ar-Lab where the barrels wait for being picked up and moved to the Trinity College where there is a specific center called Hazard Department. The Trinity College's Hazardous Materials Facility offers a suite of services for the supply, disposal and transport of dangerous goods and laboratory supplies. All its services are delivered according to safety and environmental legislative requirements and best practice principles. Moreover, Hazardous Materials Facility offers a comprehensive hazardous waste disposal service for all wastes including biohazard waste, chemical waste and lab smalls (LabCup). Each area is charged for the service based on the amount disposed and all hazardous waste is consigned to authorized facilities only for treatment or disposal. Approximately 50 tons of hazardous waste is produced by laboratories in Trinity each year. All of this is tracked by HMF until final destruction in Irish and European facilities (195). Both liquid and solid wastes, such as organic solvent waste and toxic and corrosive liquids, are transported using a certified driver for the carriage of dangerous goods. HMF van is equipped with a tail lift and a long wheel base and high roof. (196) Moreover, the hazardous waste collections have an expense that depends on the distance between the Trinity College's hazardous waste center and the waste collection building. The Ar-Lab building is located in the Green Zone, therefore only for the pick up service of all the barrels to be collected there is a service charge of 35 €.

Zone	Hazardous waste collection
Blue	€25
Green	€35
Yellow	€45

Figure 27: Trinity College'Hazardous Material Centre Deliveries

Additionally, to clarify from what types of barrels is generally composed of a laboratory consisting of 3D metal printers, we report the following example of Phoenix Analysis & Design Technologies, Inc (197):

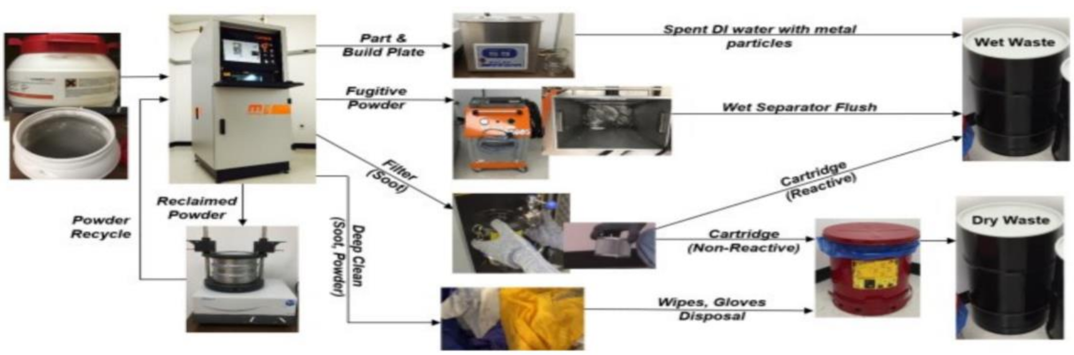


Figure 28: Metal Powder life-cycle, (Phoenix Analysis & Design Technologies Inc)

As shown in figure 28, the metal powder used in the process ends up in dry and wet waste.

- The *dry waste (White Drum)* can be composed of wipes and gloves with powder and soot.
- The *wet waste (Blue Drum)* is mostly composed of water and suspended metal particles (from the wet separator and ultrasonic cleaner), and for reactive alloys, can also consist of

filter cartridges that need to be suspended in water throughout. For instance, to remove from the metal machine the remaining powder, it is necessary to use specific solvents. There is an internal shop in the Trinity College who sell these materials and in which Ar-Lab supplies itself.

Regarding Ar-Lab currently uses three Wet waste (White tubs) and three Dry waste (Blue Drums). The cost of disposal of each of white tubs is 99,64 €, while that of the blue drums is 99.37 €. The model assumes that Ar-Lab will have 4 blue drums to have picked up once a month for a total of 12 times per year. While it assumes that Ar-Lab will have 1.5 White barrels to have picked up once a week for a total of 50 times per year. It assumes that for 2 weeks per year, it won't be necessary to pick barrels up. As shown in the table 57, the total annual cost that Ar-Lab must support for the removal of hazardous waste is approximately 13,624 €.

Table 57: Hazardous Waste Removal Yearly Cost

Hazardous Waste Removal Yearly Cost		
Number **Wet Waste buckets** picked up per week		1.5
Number **Dry Waste drums** picked up per week		1
Expected Number of **buckets** pickups needed per month		4
Expected number of **drums** pickups needed per month		1
Removal Unit Cost	**Wet** waste bucket removal unit cost	€ 99.64
	Dry waste drum removal unit cost	€ 99.37
Transport Unit Cost	Pickup unit cost	€ 35.00
Removal Monthly Cost	**Wet** waste bucket removal monthly cost	€ 597.84
	Dry waste drum removal monthly cost	€ 397.48
Transport Monthly Cost	Pickups monthly total number	4
	Transport monthly cost	€ 140.00
Hazardous Waste Removal Monthly Total Cost		**€ 1,135.32**
Hazardous Waste Removal Yearly Total Cost		**€ 13,623.84**

5.3.3.4 Miscellaneous and possible expenses

Marketing expenses and events organizational expenses were included in the financial planning events aimed at increasing the visibility of the Ar-Labs nationally and internationally, to attract orders from the outside and allow collaborations with possible research partners, including universities. These activities include the production of brochures, advertising activities and the organization of meetings and events. Moreover, if one of the future revenue stream is to organize

AM courses aimed at companies, professionals and students, Ar-Lab must increase its visibility by creating content and strengthening its brand. These expenses have been quantified at 5500 € for the first year and 8000 € for the second year and beyond. Expenses were also foreseen for the development and management of a dedicated website of about € 500 / year.

5.3.3.5 Materials available to Lab

It has already been previously defined that any expenditure deriving from the materials used in the construction of prototypes realized in research projects, contracts and / or third parties will be activities of the projects themselves and therefore not considered in the project cost plan. In this case we are talking about all those materials that the laboratory needs. These materials could be used during the training carried out by the technical staff for the researchers who have to start a project and have to learn how to use the machine, for training events for the laboratory sponsorship, for the experiments required by the Principal Investigator for the feasibility analysis of a project, for all those occasions that can be presented and listed in Case 2. Through the support of the technical staff, for each machine in the laboratory, approximately the amount of material that must be present in the laboratory for any use by the staff was estimated and the total cost of material related to each machine was reported in the financial document.

5.3.3.6 Consumables and Solvents available to Lab

Inside the laboratory must also be present the consumables necessary for the use of the machines and its cleaning. Possible consumables can be nitrile gloves, sterile, serological pipettes, syringes, tubes, flasks, miscellaneous and biological substances, while solvents used primarily for cleaning machines are acetone, absolute alcohol, industrial methylated, HPCL grade ethanol, HPCL grade methanol and propanol, etc. Finally, it is important to point out that the amount of the cost that Ar-Lab will incur for the purchase of materials, consumables and solvents has been collected in a single item within the financial plan drawn up.

5.4 Revenue Structure

Before analyzing the Ar-Lab's revenue structure, the estimate of annual usage hours for each machine currently in the laboratory, is presented below as shown in table 48. Considering a number of national working days equal to 253, each of them composed by 8 hours per day, a maximum number of usage hours of each machine is 2024 hours a year. For 2019, on the basis of active projects and those that take place in the future, it has been estimated that 3D printers consisting of a percentage of usage hours greater than all the others are metallic ones. In conclusion, it can be seen that the Nikon machine, having the ability to work independently without the assistance of the human being for more than a few hours in a row, will be able to work for more than 8 hours a day

Table 58: Total Usage Hours

Annual Working Days: 253 Daily Working Hours: 8	Lithoz Cerafab 7500	Nanoscribe Photonics Professional GT	3D Systems ProX 200	Realizer SLM 50	Optomec Aerosol Jet 300	Microdop Autodrop Gantry	Nikon XTH225 ST	Excetek 400 EDM
Estimated usage hours	**910**	**1400**	**1920**	**1920**	**1400**	**490**	**2400**	**700**
Available usage hours per year	2024	2024	2024	2024	2024	2024	2024	2024
% of use of available usage hours	45%	69%	95%	95%	69%	24%	119%	35%
Estimated working days	113.75	175	240	240	175	61.25	300	87.5

5.4.1 Academic hourly rate

To ensure that the laboratory could be managed independently, net of the investments made for the purchase of the equipment in the laboratory and the construction of the building, it was decided to include a cost of use associated with each machine currently in the lab. Academic hourly usage represents the cost that each Principal Investigator must support to carry out the project. As already explained, through a technological platform and the online booking system of 3D printers, at the end of the month the PI can find a charge of the usage total cost of the machines used to run the project in that month on the current account of the project. This revenue stream is key to balancing the huge expenditures related to staff labor costs and the maintenance of the machines that will become increasingly expensive over time. The hours of academic use have been calculated taking into account the related costs associated with the machines in terms of materials and consumables, the annual warranty of the machine and based on the estimated total usage hours. The unit price is higher for those machines characterized by a lower number of uses and higher costs.

5.4.2 Organization of events and courses based on Additive Manufacturing

After having had the opportunity to study how the AM laboratories in the four analyzed countries are organized and managed, it has been observed that most of the laboratories, developed in terms of investments made for the diffusion of the AM in the academic field, hold and offer courses of various kinds to increase their revenue streams. These courses vary in length, knowledge level and audience. As a matter of fact, there are courses that can last more than a month and others a few days more, they are based from basic to advanced level and in terms of audience, from the company to the private professional up to the students. Following will be presented different types of courses offered by different European universities identified during the market analysis previously presented.

5.4.2.1 Long-term Additive Manufacturing course aimed at Companies

Rwth Aachen German University offers customized seminars to companies allowing them to choose to follow those topics in which they are most interested. These are seminars and courses that can be organized according to the needs of the company and are exclusively aimed at a professional education in Additive Manufacturing. In particular, they are seminars for company employees such as technology and corporate managers, product developers and members of the R&D department, based on their specific needs and individual level of knowledge. ACAM offers different types of courses, from beginner to expert, through the execution of different modules chosen by the same company according to their needs. (198) The following are the different types of modules, as show in figure 29:

- *Basic Modules:* The basic modules transmit the theoretical approaches and describe them as the fundamental AM applications of a specific topic and are primarily aimed at those new-comers companies to AM. They provide a deepening of the existing AM technologies, on the AM market with its cost structure and its business models, followed by a deepening of the Design and the AM software. (198)
- *Advance Modules:* After acquiring a foundation on AM knowledge, the university offers advanced courses aimed at extending the qualification of participants around a specific AM topic. The main topics covered are the materials used in the AM production processes, tests

for the use of AM software for the design of final products and further information on post processing for AM. (198)

- *Experience Modules:* These modules provide the opportunity for participants to acquire an even deeper understanding of specific topics. As a matter of fact, we move from theory to practice in the laboratory, having the opportunity to see live the application of technologies or by carrying out the design of projects with AM software. Finally, they provide an opportunity to explore the particular aspects of production processes, to know the best practices and communicate directly with the machine operators. (198)

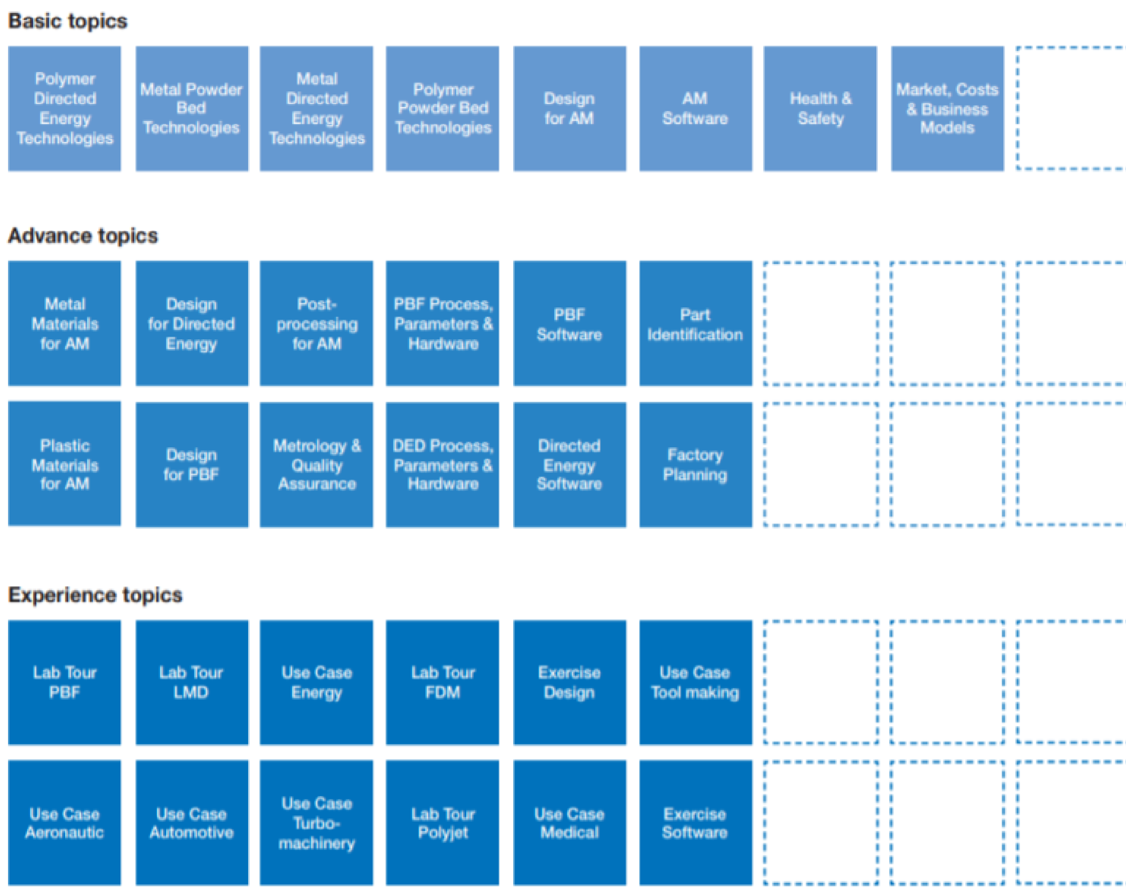


Figure 29: ACAM in house modules

5.4.2.2 Additive Manufacturing Summer University course aimed at students

The TU Berlin every 6 months organizes a 4-weeks intensive course with 18 hours per week for up to 15 students, mainly coming from the faculty of engineering but also faculties such as design and fine art, who want to approach and deepen their knowledge related to Additive Manufacturing. Specifically, the course is aimed at all those students interested in 3D scanning, printing technologies and those who want to explore the work with professional 3D printing technologies and learn about current applications. (199) The course price is around 2300 € and includes exclusively the course. The prerequisites for attending the course are as follows: at least having attended a university year, having a level of English B2 or equivalent and a basic knowledge of CAD software in order to be able to handle 3D modelling software. The course is mainly structured as follows:

- Introduction to manufacturing 3D printed objects with the laser sintering system and the powder printer of the 3D Lab. (199)
- Data generation and preparation for these technologies
- Application in the Lab by gaining basic knowledge of the use of two professional 3D printers based on two different AM technologies, structured light scanners and related software. (199)

5.4.2.3 Short-term Additive Manufacturing course aimed at professionals

The AM course organized in collaboration with Aconity3D and Xilloc in the Fraunhofer Institute of Research in Aachen is a state-of-the-art 2 days+ 3 days Lab experience, from 9AM to 17 PM, once a week. It costs 3245 € and includes a 5-days flexible course and lunch. Furthermore, the course is mainly aimed at manufacturers, product engineers, project leaders and design products and designers. (200) The main contents of the course divided into 5 days are shown below:

- *Day 1 State of the Art Additive Manufacturing and its Materials:* introduction of AM technologies and global developments; View of most important metal AM processes; View of common metal Materials for AM and their mechanical properties; Identification of business cases and economic potential for AM. (200)
- *Day 2 Process deep dive and Design for Additive Manufacturing:* Introduction of most important Process Parameters; Understand major process possibilities and restrictions; Deducing of Design rules from acquired knowledge; Interactive Design study on exemplified part; Future prospects of AM. (200)

- *Day 3 Xilloc Factory:* Introduction in Polymer AM and its technologies; Understand major process possibilities and restrictions; Deducing of Design rules from acquired knowledge; Guided tour through the Xilloc Factory; Introduction of post processing possibilities and Quality assurance; Understand the cost structure for polymer AM processes; Future of Polymer AM processes. (200)
- *Day 4 Software solutions and job preparation:* Understanding the possibilities and limitations of the STL file format; Get to know supporting Design tools: Topology Optimization; Hands- On Software Training on market leading Software Magics; Prepare individualized part for Lab Day; Understand the cost structure for AM processes. (200)
- *Day 5 Lab Day in Aachen:* Preparing a metal AM job: Do's and don'ts; Start a job with self-prepared parts; Guided Lab Tour Aconity3D and Fraunhofer Research Institute; Introduction of post processing possibilities and Quality assurance; Unpacking your own manufactured part. (200)

5.4.3 Trinity College Revenue

The TCD for each project launched through the allocation of funds by entities such as Enterprise Ireland or Science Foundation Ireland, receives an amount of money that is equal to 30% of the total costs of the project to support the indirect costs of the Lab incurred to develop projects such as utilities and assurance Lab. In this way, Trinity College is able to sustain all consumption costs and the amortization of the investment made for the construction of the laboratory and the buildings available to Amber. To make a small parenthesis, in this case there will be a contraposition of interests as in this case the IP to the project investors will request a 30% reimbursement of the total indirect costs of the project for the use of the laboratory that will be received by the TCD and a reimbursement of the costs for using the machines necessary for the execution of the project. It might be thought that some investors might reply that the total cost of using the machines is already included in the reimbursement of 30% of the total indirect costs of the project.

5.5 Ar-Lab Financial Statement and its strategies

After having seen in detail the structure of the costs and revenues of Ar-Lab, the following is the estimate financial statement of the period from the current year 2019 up to 2022, on the basis of all the information gathered through the help of Ar-Lab's researchers and based on strategies designed to make Ar-Lab profitable and able to sustain itself independently. As shown in Table 59, if Ar-Lab does not diversify its revenue stream but is based exclusively on a single revenue stream equal to academic hourly rate, paid by the Principal Investigators for the use of the machines, as early as 2021, the laboratory will be at a loss. From 2019 to 2022 the fixed maintenance costs will increase more and more and from 2021 the laboratory, without considering the possible extra unplanned costs that Ar-Lab should incur and considering a single technical staff hired for an annual labor cost of 50,000 €, will start to have a negative budget profit.

Table 59: Financial analysis consisting of a single revenue stream

2019	Total
Estimated Academic Income	€ 199,940
Total Net Operating Costs	€ 144,524
Profit 2019	€ 55,416
Total Revenue Reserves 2019	€ 55,416

2020	Total
Estimated Academic Income	€ 199,940
Total Net Operating Costs	€ 196,079
Profit 2020	€ 3,861
Total Revenue Reserves 2020	€ 59,277

2021	Total
Estimated Academic Income	€ 199,940
Total Net Operating Costs	€ 206,503
Profit (loss) 2021	€ (6,563)
Total Revenue Reserves 2021	€ 52,715

2022	Total
Estimated Academic Income	€ 199,940
Total Net Operating Costs	€ 216,503
Profit (loss) 2022	€ (16,563)
Total Revenue Reserves 2022	€ 36,152

As a matter of fact, as shown in figure 30, in 2022, the year in which Ar-Lab will incur maintenance costs for all the machines present in the laboratory, the laboratory will close the year in loss of 16563 €, bringing the total cash flow to only 36152 €. In the following year only, the laboratory will have run out of reserves and from there will close the years both with an operating profit insufficient to cover all the Ar-Lab cost structure and with negative reserves, that means the laboratory from 2023 onwards will no longer be able to remain independent.

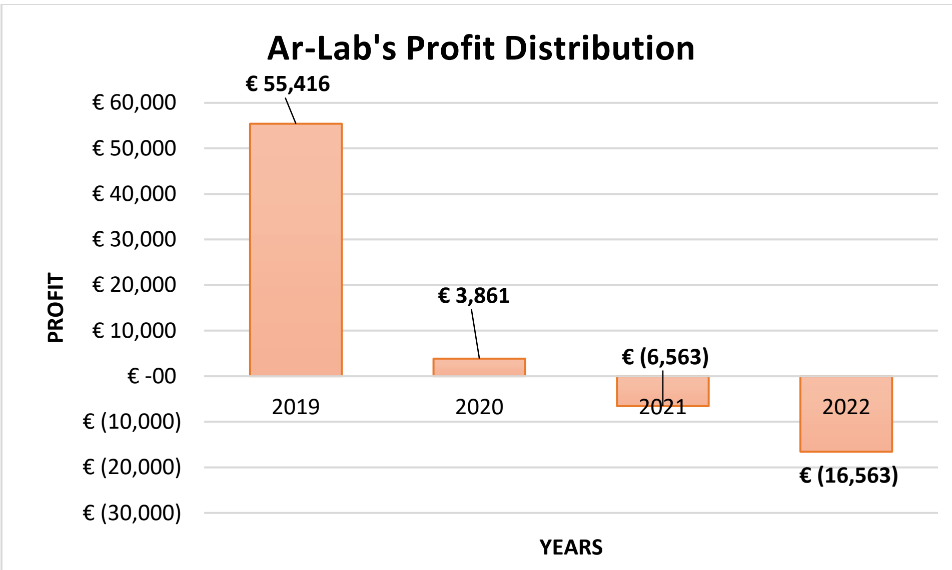


Figure 30: Ar-Lab Cash Flow

Consequently, on the basis of the capabilities that Ar-Lab can perform as a research laboratory, it was decided to introduce additional revenue sources into the model that could allow the laboratory to run independently without any financial support from third parties. As will be introduced later in the specific, the three additional sources of revenue introduced are the following:

- *University Summer AM Course*: Like TU Berlin, Ar-Lab could organize an international course based on the AM technologies of a month in the summer. Dublin during the summertime is a very frequented city by students who come to Ireland to improve their English skills. If it was launched an AM course aimed at all those students fond of these technologies, there are all the conditions that make this course successful. The course will last one month and will cost 2300 € for up to 15 students. The total revenue obtained from an event of this type will be 34500 € per course.

- *University Winter AM Course:* It is a course structured in the same way as the summer course but made up only of a smaller number of contents for a total duration of 2 weeks. This could be a cheaper and shorter course to reach those students who have less money and time to spend for their personal training. Finally, it costs 1100 € for up to 15 students and as a consequence, the total revenue expected from this type of event is 16500 €.

- *Short-term AM Course:* As Fraunhofer Research Institute, Ar-Lab could also organize a short-term course for professionals at a low price of 1100 € for 5 days a week for up to 12 professionals. The price compared to that offered by Fraunhofer is 75% lower (1100 € vs 3245 €). This is because to make it international and not oriented exclusively to local professionals, it was decided to organize the course of 5 consecutive days and not at the choice of the professional. Moreover, for the fact that these are the first years since the launch of the project, the goal is to realize sales volumes and therefore focusing on quantity rather than price will make the laboratory profitable.

In conclusion, in the financial analysis the prices of the guarantee contracts, and therefore the total annual cost that Ar-Lab must support for the maintenance of the machine, have been reduced by 20%. This was done to consider the possibility that some companies such as Optomec may be favorable to discount the base price of the warranty while other companies, after granting a long free warranty service, could request the basic price list offered to all customers without reach an agreement with Ar-Lab to reduce the price.

5.5.1 Income Statement 2019

As shown in table 60, in 2019 the profit generated by Ar-Lab is very high and equal to 71516 €. This essentially for two reasons: compared to the other years, taken into account the fixed costs, these are lower and there is the introduction of a further source of revenue. The fixed costs are lower because, apart from Optomec Aerosol Jet 300, all the other machines currently in the lab are still covered by the free purchase guarantee. While for the new revenue source, it has been estimated that Ar-Lab, and therefore the technical staff and the research grant holders who currently working in the management of the laboratory, will be able to organize a summer course. In this case, since there are only few months available to organize the event, Ar-Lab will be able to launch a two-week event for a maximum of 7 students at a price of 1100 €.

Table 60: Income Statement 2019

2019	Lithoz Cerafab 7500	Nanoscribe Photonics Professional GT	3D Systems ProX 200	Realizer SLM 50	Optomec Aerosol Jet 300	Microdop Autodrop Gantry	Nikon XTH225 ST	Brabender KETSE 20/40 EC	Total
Total Usage Hours	910	1400	1920	1920	1400	490	2400	700	/
Academic hourly rate	€ 15	€ 13	€ 14	€ 16	€ 17	€ 21	€ 19	€ 44	/
Estimated Academic Income	€ 13,650	€ 18,200	€ 26,880	€ 30,720	€ 23,800	€ 10,290	€ 45,600	€ 30,800	€ 199,940
AM Summer University Course Income (2 weeks)	€ 7,700								€ 7,700
Materials&Consumables	€ 2,500	€ 7,500	€ 3,500	€ 7,000	€ 3,500	€ 3,500	€ 20,000	€ 15,000	€ 62,500
Yearly Machines Warranty	/	/	/	/	€ 12,900	/	/	/	€ 12,900
Technical Staff Labor Costs	€ 50,000								
Removal hazardous waste	€ 13,624								
Michellaneous and possible expenses	€ 5,500								
Total Net Operating Costs	€ 144,524								
Profit 2019	€ 63,116								
Total Revenue Reserves 2019	€ 63,116								

5.5.2 Income Statement 2020

In 2020 the final profit turns out to be only 2752 € with a total cash flow of the year before equals to 71516 € that will be able to cope with any unforeseen cost that Ar-Lab should bear. The profit is about zero as it has been estimated that in 2020 there will be an increase in net operating costs of about 51% compared to 2019 and this for the following reasons:

- Increased machine maintenance costs by around 3 times: Lithoz and Nikon warranties have expired and Microdop will need to change its head pippets
- Adding a new technical staff: it has already been seen how the laboratory, in order to run independently, has to organize and hold AM courses. In the summer of 2019, a two-week test course was planned, which once revised and taking the feedback received from the participants of the first summer edition, it will be reorganized during the winter in the academic year 2019/2020 based on the same duration (2 weeks) and on the contests for a maximum of 15 students at a price of 1100 €. Moreover, in order to be able to organize the one-month summer course in the summer of 2020 and to improve the brand positioning of the laboratory, it was fundamental to hire a new technical staff from the existing team. This new technical staff will have to support the staff team in the management of the laboratory, focusing mainly on organizing the summer course and launching marketing campaigns to increase the brand of the laboratory. To do this, the costs for marketing expenses defined under the name "Miscellaneous and possible expenses" have been increased by 60%. Additionally, the summer course will be structured for a maximum of 15 students, lasting 18 hours per week for 4 weeks at a cost of 2300 € per each student.
- Increase in costs of materials used by the laboratory by 20%: the events in order to stay in line with the program offered by the other competing universities will have to provide

practical sessions in the laboratory. To do this, the students taking part in the course will have at their disposal 3D printing materials to be used to conduct their experiments.

Table 61: Income Statement 2020

2020	Lithoz Cerafab 7500	Nanoscribe Photonics Professional GT	3D Systems ProX 200	Realizer SLM 50	Optomec Aerosol Jet 300	Microdop Autodrop Gantry	Nikon XTH225 ST	Brabender KETSE 20/40 EC	Total
Total Usage Hours	910	1400	1920	1920	1400	490	2400	700	/
Academic hourly rate	€15	€ 13	€ 14	€16	€ 17	€21	€19	€44	/
Estimated Academic Income	€ 13,650	€ 18,200	€ 26,880	€ 30,720	€ 23,800	€ 10,290	€ 45,600	€ 30,800	€ 199,940
University Summer AM Courses Income (4 weeks)	€ 34,500								€ 34,500
AM University Winter Courses Income (2 weeks)	€ 16,500								€ 16,500
Materials&Consumables	€ 2,500	€ 7,500	€ 3,500	€ 7,000	€ 3,500	€ 3,500	€ 20,000	€ 15,000	€ 75,000
Yearly Machines Warranty	/	/	€ 25,000	/	€ 12,900	€ 1,500	€ 25,055	/	€ 51,564
Technical Staff Labor Costs	€ 100,000								
Removal hazardous waste	€ 13,624								
Michellaneous and possible expenses	€ 8,000								
Total Net Operating Costs	€ 248,188								
Profit 2020	€ 2,752								
Total Revenue Reserves 2019	€ 63,116								
Total Revenue Reserves 2020	€ 65,868								

5.5.3 Income Statement 2021

In 2021 what is relevant to indicate is that the increase in profits derives from an increase in revenues due to two factors:

- Increase in the number of usage hours of machines: thanks to the presence of the second technical staff and thanks to the improvement of the brand positioning that will take place at an international level, the laboratory will receive a greater number of orders for the execution of projects. This implies that the number of hours used with the machines will be increased by 20%, with a consequent increase by 20% of the "Estimated Academic Income" based on the decision to keep the "Academic hourly Rate" fixed in order not to result in an increase project costs for the Principal Investigators.
- Introduction short-term course for 12 professionals: once the intensive courses aimed at students will be designed, the laboratory will not only still develop the summer and winter course, but also will increase its target audience by offering a course for professionals such as product manager, designer, engineering, etc. Thanks to the continuous investment in marketing activities for the dissemination and enhancement of the brand of the laboratory, 2021 will be the first year in which a 12-week course will be launched at a cost of 1100 €.

Moreover, this increase in revenues will have an impact on the cost structure determining an increase. Specifically, as a result of the growth of the increase in the number of usage hours of the machines, there will be an increase in removal hazardous waste costs. Additionally, following an increase in the events held by the laboratory, there will be a further increase of 10% compared to 2020 of the materials costs available to the laboratory, for a total increase of 30% from 2019.

Table 62: Income Statement 2021

2021	Lithoz Cerafab 7500	Nanoscribe Photonics Professional GT	3D Systems ProX 200	Realizer SLM 50	Optomec Aerosol Jet 300	Microdop Autodrop Gantry	Nikon XTH225 ST	Brabender KETSE 20/40 EC	Total
Total Usage Hours	1092	1680	2304	2304	1680	588	2880	840	/
Academic hourly rate	€1 5	€ 13	€14	€16	€17	€21	€19	€44	/
Estimated Academic Income	€ 16,380	€ 21,840	€ 32,256	€ 36,864	€ 28,560	€ 12,348	€ 54,720	€ 36,960	€ 239,928
AM University Summer Courses Income (4 weeks)	€ 34,500								€ 34,500
AM University Winter Courses Income (2 weeks)	€ 16,500								€ 16,500
Short-term AM Courses Income (1 week)	€ 13,200								€ 11,000
Materials&Consumables	€ 2,500	€ 7,500	€ 3,500	€ 7,000	€ 3,500	€ 3,500	€ 20,000	€ 15,000	€ 81,250
Yearly Machines Warranty	/	/	€ 25,000	€ 10,000	€ 12,900	/	€ 25,055	€ 1,924	€ 59,903
Technical Staff Labor Costs	€ 100,000								
Removal hazardous waste	€ 17,711								
Michellaneous and possible expenses	€ 8,000								
Total Net Operating Costs	€ 266,864								
Profit 2021	€ 35,064								
Total Revenue Reserves 2020	€ 65,868								
Total Revenue Reserves 2021	€ 100,932								

5.5.4 Income Statement 2022

2022 is that year in which the fixed costs related to the maintenance of the machines will be the highest of all because for all the machines the free purchase guarantee will be expired.

Table 63: Income Statement 2022

2022	Lithoz Cerafab 7500	Nanoscribe Photonics Professional GT	3D Systems ProX 200	Realizer SLM 50	Optomec Aerosol Jet 300	Microdop Autodrop Gantry	Nikon XTH225 ST	Brabender KETSE 20/40 EC	Total
Total Usage Hours	1092	1680	2304	2304	1680	588	2880	840	/
Academic hourly rate	€15	€ 13	€ 14	€16	€ 17	€21	€ 19	€ 44	/
Estimated Academic Income	€ 16,380	€ 21,840	€ 32,256	€ 36,864	€ 28,560	€ 12,348	€ 54,720	€ 36,960	€ 239,928
AM University Summer Course Income (4 weeks)	€ 34,500								€ 34,500
AM University Winter Course Income (2 weeks)	€ 16,500								€ 16,500
Short-term AM Courses Income (1 week)	€ 26,400								€ 22,000
Materials&Consumables	€ 2,500	€ 7,500	€ 3,500	€ 7,000	€ 3,500	€ 3,500	€ 20,000	€ 15,000	€ 84,375
Yearly Machines Warranty	€ 10,000	€ 20,000	€ 25,000	€ 10,000	€ 12,900	/	€ 25,055	€ 1,924	€ 83,903
Technical Staff Labor Costs	€ 100,000								
Removal hazardous waste	€ 17,711								
Michellaneous and possible expenses	€ 8,000								
Total Net Operating Costs	€ 293,989								
Profit 2022	€ 18,939								
Total Revenue Reserves 2021	€ 100,932								
Total Revenue Reserves 2022	€ 119,871								

In addition, the laboratory, which has reached the fourth year of organization of AM courses, will offer twice a year a one-week course for professionals and two courses aimed at students, respectively of one month and two weeks, in summer and winter. For having added the organization of a further course held by Ar-Lab, the costs related to the materials used and available to the laboratory have increased by 5% compared to 2021. The annual profit is positive and the laboratory is well organized.

5.5.5 Results

Table 64 shows the results obtained from this financial analysis projected up to 2022.

Table 64: Ar-Lab's Financial Analysis Results

2019	Total
Estimated Total Income	€ 207,640
Total Net Operating Costs	€ 144,524
Profit 2019	€ 63,116
Total Revenue Reserves 2019	€ 63,116

2020	Total
Estimated Total Income	€ 250,940
Total Net Operating Costs	€ 248,188
Profit 2020	€ 2,752
Total Revenue Reserves 2020	€ 65,868

2021	Total
Estimated Total Income	€ 301,928
Total Net Operating Costs	€ 266,864
Profit 2021	€ 35,064
Total Revenue Reserves 2021	€ 100,932

2022	Total
Estimated Total Income	€ 312,928
Total Net Operating Costs	€ 293,989
Profit 2022	€ 18,939
Total Revenue Reserves 2022	€ 119,871

Unlike what is shown in figure 30, with the implementation of this strategy of organizing different types of courses for the dissemination of the AM knowledge, in figure 31, Ar-Lab's annual profits are always positive.

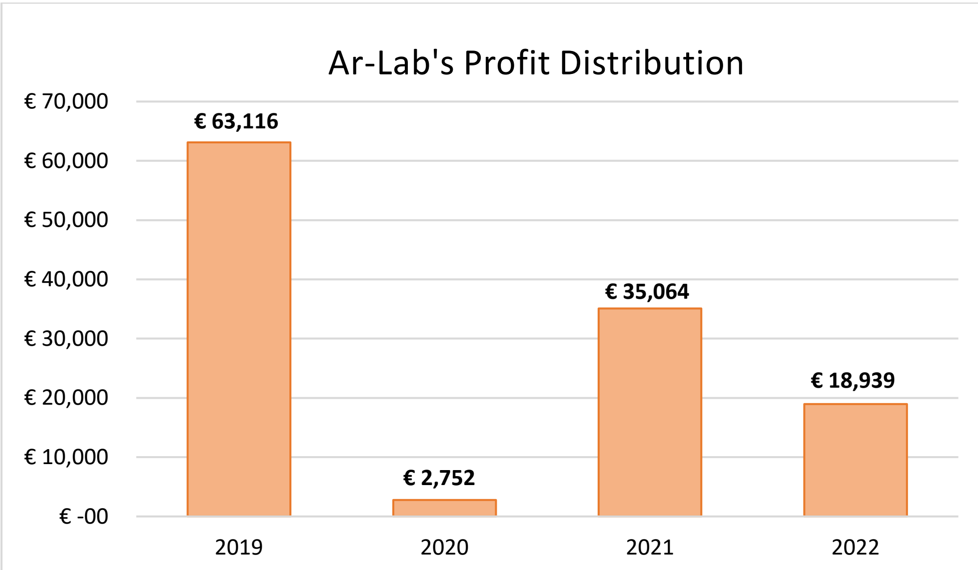
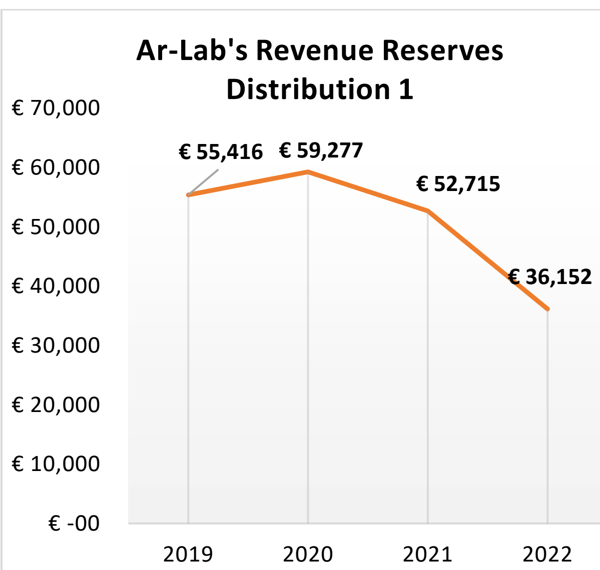


Figure 31: Ar-Lab's Profit Distribution Part 2

The important conclusion to keep in mind is shown in figure 32.



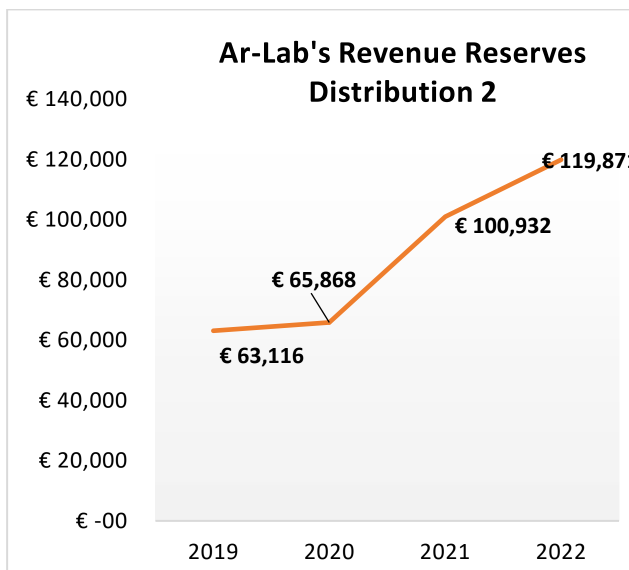


Figure 32: Comparison between Ar-Lab's current and probable future situation

If Ar-Lab does not add to its growth strategy additional revenue streams, in 5 years as shown in the figure on the left, because of the negative profits will exhaust all its resources and will not work independently. On the contrary, if Ar-Lab will increase its revenue streams through, for example, the organization of courses and events based on the spread of additive manufacturing, then the laboratory will expand, will have a structure capable of sustaining the huge costs and will be able to represent an important point reference for all the other international laboratories previously seen.

6 Conclusion

This thesis presents the implementation of the European University Market Analysis for 3D Printing and the execution of business plan for the Trinity College's Additive Manufacturing laboratory.

Thanks to the support of the Market Research Centre - Enterprise Ireland in Dublin, it has been possible to access the European Market for 3D Printers estimated by BCC Research considering all desktop and industrial 3D printers sold in four analyzed countries: UK, Germany, France and Italy. As in the market estimate conducted by BCC Research, even within this thesis it has been found that the country that invested the most in the purchase of 3D printers for the spread of Additive Manufacturing at university level was UK followed by Germany. The only difference compared to what was found by BCC Research, at university level, has been that the investments made by the UK and Germany in the purchase of 3D Printers differ only by about 1 M $ to the advantage of the UK, respectively 25.4 M $ for UK and 24.7 M $ for Germany. Furthermore, another important result has been to figure out that Italy invested twice as much as France, respectively 10.9 ML $ for Italy against 5.6 ML $ for France, unlike what was estimated by BCC Research which at the level of the overall market it has the opposite trend (111.8 M $ for France compared to 51.1 M $ for Italy). More in detail the results obtained from the estimate of the European University Market for 3D Printing conducted within this thesis were the following:

- Number of universities within the country consisting of an AM laboratory or partner of an existing AM research center in the territory
- Number of total AM laboratories in the country related to the academic or research world
- Total number of 3D printers used in academic laboratories or research center in the country
- Total investment supported by the country and by the single university for the purchase of 3D printers identified above
- Distribution of AM technologies used at university level
- Distribution of 3D printers manufacturers at university level in terms of total 3D printers sold to universities for each country
- Total investment made by the country and the single university for the diffusion of the AM in the academic and research world

These results could be used by universities to identify 3D printers owned by other universities in order to start collaborations aimed at carrying out projects, while the distribution of technologies used at university level and the distribution of 3D printers manufacturers, indicating production companies more widespread within each country, it could be useful information for existing players operating in the 3D printers market.

The analysis of about 97 Additive Manufacturing laboratories, distributed among the four countries analyzed, has allowed to execute a business plan for the Trinity College's AM laboratory with better awareness of the management and organization of an Additive Manufacturing laboratory. After identifying the current revenue structure that was not able, after around 4 years, to support the current laboratory's cost structure, it has been decided to apply a strategy that would make the laboratory profitable independently, without any financial support from third parties. As a result, revenue based strategy has been applied: it has been observed that most of the laboratories, developed in terms of investments made for the diffusion of the AM in the academic field, hold and offer AM courses of various kinds to increase their revenue streams. These courses vary in length, knowledge level and audience. As a matter of fact, there are courses that can last more than a month and others a few days more, they are based from basic to advanced level and in terms of audience, from the company to the private professional up to the students. Consequently, based on the capabilities that Ar-Lab can perform as a research laboratory and to allow the laboratory to run independently, three additional sources of revenues have been introduced, such as:

- *University Summer AM Course*: International course based on the AM technologies of a month in the summer that costs 2300 € for up 15 students and it is aimed at students.
- *University Winter AM Course:* International course structured in the same way as the summer course but made up only of a smaller number of contents for a total duration of 2 weeks that costs 1100 € for up to 15 students.
- *Short-term AM Course:* Short-term course for professionals at a low price of 1100 € for 5 days a week for up to 12 professionals.

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