الجمهورية الجزائرية الديمقراطية الشعبية

REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE

وزارة التعليم العالي والبحث العلمي

Ministère de l’Enseignement Supérieur et de la Recherche Scientifique

جامعة أبي بكر بلقايد – تلمسان –

Université Aboubakr Belkaïd – Tlemcen –

Faculté de TECHNOLOGIE

MEMOIRE

Présenté pour l’obtention du **diplôme** de **MASTER**

En : Génie Mécanique

Spécialité : Construction Mécanique

Par: Atmani Madjida

Sujet

State of the Art of Additive Manufacturing and Techno-Economic Comparative Study of Different Mechanical 3D Printing Technologies

Soutenu publiquement, le 17/06/2025, devant le jury composé de :

M. SEBAA Fethi	Pr	Université de Tlemcen	Président
M. RAHOU Mohammed	Pr	IS2M, Univ-Tlemcen	Examinateur
M. CHEIKH Abdelmadjid	Pr	Université de Tlemcen	Encadreur

Année universitaire :2024 /2025

Acknowledgements

First and foremost, full praise and profound gratitude to the Almighty Allah who granted me with strength, patience and willingness to undertake and accomplish this study.

- I would like to express my deepest gratitude and respect to my supervisor **M. CHEIKH Abdelmadjid** for his constant help, his patience, precious suggestions and valuable advices. Thank you for your encouragement.

- I am extremely grateful to the members of the jury: **M. SEBAA Fethi** and **M. RAHOU Mohammed** for their valuable remarks and doing me the honor of examining and reviewing this humble work.

- I would also like to thank my source of strength and motivation in life, my parents for all the love, care and support. Thank you so much mom and dad.

- I want to give special thanks to my siblings especially my sisters; Fatima Zohra and Samia for always being by my side.

Dedication

I dedicate this work

To little me, the quite dreamer girl, I carry you with me. I am becoming everything you wished we would be and I am still reaching for more, for us.

To whom I owe my life, to my beloved parents, my source of inspiration, strength and motivation; to the ones whose hopes I embraced and carried like a seed in my heart, especially to my mother, whose dream was passed onto me and became my own. Forever grateful.

Abstract

This dissertation presents a structured study of additive manufacturing (AM) from both a technological and economic perspective. The first part reviews the development of AM technologies, focusing on the main processes, materials used and costs. This section establishes a foundation for evaluating the relevance of different AM techniques for industrial uses.

The second part presents a comparative analysis of the seven established AM processes. The comparison is based on practical variables, including process complexity, material availability, setup requirements, maintenance demands, and suitability for small and medium-sized enterprises (SMEs). A cost and investment evaluation are also included to support realistic assessments of technology adoption in various real-world applications.

The study results are presented in a series of comparative tables, a visual organizational chart and decision-making algorithms in order to assist with process selection based on functional needs. The outcomes of this work can support further development of a computer-based AM technology selection tool that serves as a reference for engineers, researchers, and businesses that rely on additive manufacturing technologies.

Key words: Additive Manufacturing (AM), AM Manufacturing Processes, Comparative Study, Decision Making Framework, AM Selection Tools.

Résumé

Ce mémoire présente une étude structurée de la fabrication additive (AM) d'un point de vue technologique et économique. La première partie passe en revue le développement des technologies AM, en se concentrant sur les principaux processus, les matériaux utilisés et les coûts. Cette section jette les bases d'une évaluation de la pertinence des différentes techniques de fabrication additive pour des utilisations industrielles.

La deuxième partie présente une analyse comparative des sept processus d'AM établis. La comparaison est basée sur des variables pratiques, notamment la complexité du processus, la disponibilité des matériaux, les exigences en matière de configuration, les exigences en matière de maintenance et l'adéquation avec les petites et moyennes entreprises. Une évaluation des coûts et des investissements est également incluse pour soutenir des évaluations réalistes de l'adoption de la technologie dans diverses applications du monde réel.

Les résultats de l'étude sont présentés dans une série de tableaux comparatifs, un organigramme visuel et des algorithmes de prise de décision afin d'aider à la sélection des processus en fonction des besoins fonctionnels. Les résultats de ce travail peuvent contribuer à la poursuite du développement d'un outil informatique de sélection des technologies de fabrication additive qui servira de référence aux ingénieurs, aux chercheurs et aux entreprises qui dépendent de ces technologies.

Mots clés : Fabrication Additive (AM), Processus de Fabrication AM, Etude Comparative, Cadre de Prise de Décision, Outils de Sélection AM.

ملخص

تقدم هذه الأطروحة دراسة منظمة للتصنيع الإضافي (AM) من منظور تكنولوجي واقتصادي. يستعرض الجزء الأول تطور تقنيات التصنيع الاضافي مع التركيز على العمليات الرئيسية والمواد المستخدمة والتكاليف. يضع هذا القسم أساسًا لتقييم مدى ملاءمة تقنيات التصنيع الاضافي المختلفة للاستخدامات الصناعية.

يتضمن الجزء الثاني تحليلاً مقارنًا لعمليات التصنيع الإضافي السبعة القائمة. وتعتمد المقارنة على المتغيرات العملية، بما في ذلك مدى تعقيد العملية، وتوفر المواد، ومتطلبات الإعداد، ومتطلبات الصيانة، ومدى ملاءمتها للشركات الصغيرة والمتوسطة الحجم. كما تم إدراج تقييم للتكاليف والاستثمار لدعم التقييمات الواقعية لتبني التكنولوجيا في مختلف التطبيقات الواقعية.

ينتج عن هذه الدراسة سلسلة من جداول المقارنة ومخطط تنظيمي مرئي وخوارزميات اتخاذ القرار للمساعدة في اختيار العملية بناءً على الاحتياجات الوظيفية. يمكن لنتائج هذا العمل دعم تطوير المزيد من أدوات الاختيار لتقنيات التصنيع الإضافي المعتمدة على الكمبيوتر والتي تعد بمثابة مرجع للمهندسين والباحثين والشركات التي تعتمد على تقنيات التصنيع الإضافي.

الكلمات المفتاحية: التصنيع الإضافي (AM)، عمليات التصنيع الإضافي، دراسة المقارنة، إطار عمل لاتخاذ القرار، أدوات انتقاء عمليات التصنيع الإضافي.

Table of Contents

Chapter I: History and Evolution of Additive Manufacturing

Chapter II: Additive Manufacturing Technologies

Chapter III: Techno-Economic Comparative Study of Additive Manufacturing Processes

List of Figures

List of Tables

General Introduction

Additive Manufacturing, has rapidly transformed from a niche prototyping tool into a powerful manufacturing solution across multiple industries. As technological progress accelerates and digital production becomes more dominant, AM is increasingly recognized for its capacity to revolutionize how parts are designed, fabricated, and optimized. This transformation is not limited to technological innovation alone, it also brings out new economic models, investment considerations, and strategic decisions for manufacturers and investors.

This dissertation aims to explore additive manufacturing from both a technical and economic perspective, beginning with an in-depth review of its evolution, processes, materials and applications. It investigates the strengths and limitations of various AM technologies, providing a clear understanding of their operational mechanisms and suitability for different use cases. As the landscape of manufacturing shifts, so does the need to evaluate the practicality of each technology, not only in terms of performance but also in cost effectiveness and accessibility.

In the later part of this research, a comparative analysis is conducted to evaluate AM technologies based on factors such as process complexity, material availability, setup, maintenance requirements and investment needs. By focusing on both functional performance and economic feasibility, this study offers valuable insight for businesses, researchers and engineers considering the adoption or expansion of additive manufacturing solutions.

This dissertation is structed to first provide the necessary historical and technological background, followed by a detailed comparison of processes and concludes with a Techno-Economic evaluation that supports informed decision making in the field of modern manufacturing.

Chapter I: History and Evolution of Additive Manufacturing

I.1 Introduction

Additive Manufacturing (AM), often referred to as 3D printing, has evolved from niche prototyping technology into a cornerstone of modern manufacturing. This chapter aims to trace the origins, technological advancements and the factors that shaped the journey of additive manufacturing.

I.2 Early Beginnings

I.2.1 Foundations of AM technology

In the early years of 1970s, the basis foundation of a layer-by-layer technology was first introduced by the Japanese engineer Dr. Hideo Kodama. His works laid the base for what was later developed into what we known now as 3D printing [1].

I.2.2 Additive manufacturing in the 1980s

The first rapid prototyping system (Figure I.1), stereolithography (SLA), was invented in the year of 1986, by Chuck Hull. Hull developed a way to solidify liquid resin using a UV laser to build the first 3d printed object (Figure I.2) [2].

Another AM technology was developed after Hull's invention, by Carl Deckard, Selective Laser Sintering (SLS). SLS technology uses a laser to fuse small particles of plastics, metals, or ceramics to create the printed parts.

Fused Deposition Modelling (FDM) process, was invented in 1989 by Scott Crump. FDM technology works by extruding a filament of melted plastic material, which solidifies creating the 3D object.

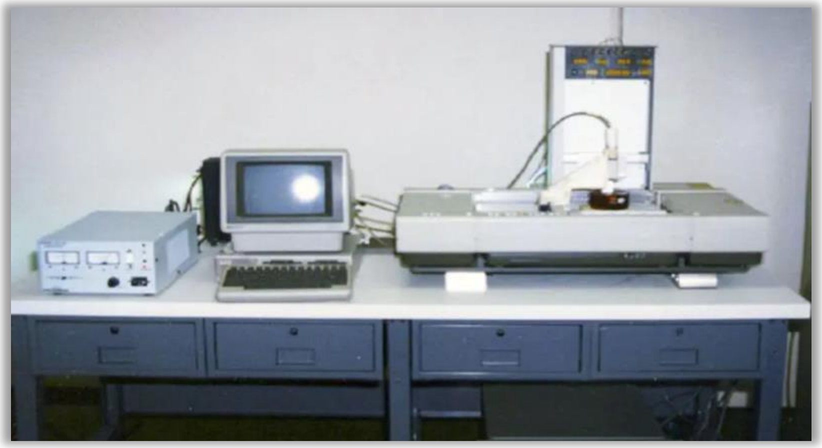


Figure I.1: The first SLA machine [3]

Figure I.2: First 3D printed part produced by Chuck Hull [4]

I.3 Milestones in the evolution of AM

I.3.1 Main 3D printing manufacturers and dedicated CAD programs

The period of the 1990s marked a significant expansion of the early 3D printing industry characterized by the establishment of new companies and the exploration of new technologies bringing additive manufacturing to the next level. 3D systems which had introduced SLA has continued to develop the technology expanding its market.

Stratasys an American company, brought fused deposition modeling (FDM) to the market, making AM more accessible for industrial prototyping purposes. Meanwhile, EOS GmbH, founded in Germany, made significant advancements in Selective Laser Sintering (SLS), which became a crucial technology for high performance applications.

At the same time, we can see that newer and freer dedicated CAD and CAM tools, allowing to create and print 3D models, are becoming available, for hobbyist and small project developers, for example: Autodesk Fusion 360, Tinkercad, Blender, Sketchup, SolidWorks.

Collectively, these companies played a vital role in transitioning AM from a phase of experimental research to commercial and industrial adoptions.

I.3.2 Additive manufacturing in the 2000s and beyond

In the early 2000s Direct Metal Deposition (DMD) was introduced. This process was also initially known as Direct Energy Deposition (DED). DMD was initially used to repair damaged parts by adding a certain amount of metal. The expansion of 3D printing into the production of end-use 3D printed parts has led to create entire parts and objects (Figure I.3). Lately a Spurre of metal AM have been introduced into the market. This has shown a significant growth and development of MAM [5].

Recently based on a combination of MAM with traditional metal cutting techniques and the use of multiple thermal energy sources, metal hybrid additive manufacturing was developed. These developments enhanced both the productivity and the quality of the manufactured parts. These innovations paved the way for the first commercial hybrid metal additive manufacturing systems.

Figure I.3: Printed metal gear parts

The first desktop 3D printer, RepRap was invented in 2005 by Prof. Adrian Bowyer. The RepRap using an open-source firmware, allowed the accessibility of the 3D printing technology to the general public.

The first multi-material 3D printer was released in 2007 by Objet, a 3D printing manufacturer. This developed technology allowed the creation of printed parts with different material properties.

MakerBot, another 3D printing manufacturer. Released the first consumer-grade 3D printer, in 2009. This company allowed 3D printing to be more accessible for amateurs and hobbyists to use for their home or office.

In 2010, as AM started taking more space in the automative field. The creation of the first 3D printed car was possible, using a large 3D printer to fully print the car's body. The integration of AM in automative industry allowed more development and growth in the field, taking it to another level [3].

In 2011, Prusa Research was founded. This company used the RepRap principal to develop the Prusa i3. This 3D printer has become popular due to its low price and easy to use design.

In 2016, the term "3D printed jewelry" was introduced to the market by the Indian company Melorra. This approach involves creating intricate wax or resin models through 3D printing, which are then used to produce molds as shown in (Figure I.4) for traditional casting and expert finishing. Although direct 3D printing in precious metals is technically possible, the use of digital design and modeling offers great creative freedom. It allows jewelers to produce highly unique pieces while significantly reducing the time, effort and cost typically associated with manual carving.

Figure I.4: 3D printed wax jewelry models [6]

New 3D printing materials are being explored continuously, expanding the possibilities of additive manufacturing. One notable example is the French startup XtreeE, a construction tech company that designs and manufactures large scale, multi material, 3D printers for the construction industry. The application of 3D printing in the architecture industry has led to realization of habitable 3D built homes. The first habitable house as presented in (Figure I.5) was built in 2018, the house was 1022 square feet and took two days to print [3].

Figure I.5: First 3D printed house [3]

The 21st century has seen remarkable advancements in additive manufacturing technologies. A Compound Annual Growth Rate (CAGR) of 15% has been registered between the years 2015 to 2025, with an increasing number of companies entering the field, contributing to the wider acceptance and integration of this technology into mainstream manufacturing practices.

I.4 Additive manufacturing in the future

I.4.1 Bioprinting

One of the most impactful applications of additive manufacturing lies in the medical field. Researchers are actively developing 3D printed organs to be used for transplants. For example, hip implants built using 3D printing are now used in the replacement of damaged hip joints. Another example is the use of printed parts as prosthetic body parts for handicapped people as shown in (Figure I.6).

Figure I.6: 3D printed prosthetic leg implant [3]

I.4.2 Aerospace field

Additive Manufacturing plays a crucial role in the aerospace field. 3D printed parts are currently used in aircrafts, as they are lighter and stronger than the traditionally manufactured parts.

I.4.3 Automobile field

The automobile industry relies on the use of AM Technologies. 3D printing is now used to build prototypes and low-volume production runs, as it makes it both time and cost efficient compared to the traditional manufacturing processes.

As predictable, AM is seen to be widely adopted across the industries. As the technology continues to evolve, new applications will emerge, further driving the growth and integration of additive manufacturing in the years to come.

I.5 Conclusion:

A comprehensive examination of the history and development of additive manufacturing establishes a basis for exploring its processes, materials, and applications.

The historical insight lays the groundwork for an extensive analysis of the different additive manufacturing techniques, the variety of materials employed, and the extensive applications that remain at the forefront of innovation across various sectors.

Chapter 2: Additive Manufacturing Technologies

II.1 Introduction

The term AM, refers to a range of techniques that fabricate objects through a layer-by-layer approach, this chapter analyzes main AM process chain, the fundamental AM methods, the materials utilized and their effects on performance. It also addresses the limitations of AM emphasizing the challenges that need to be overcome for wider industrial integration.

II.2 Generalized additive manufacturing process chain

When it comes to manufacturing any type of product involving the utilization of an AM machine it requires the operator to go through a set of tasks.

II.2.1 The eight key steps in additive manufacturing [7]

The eight essential steps of AM (Figure II.1) may still see some changes in the post build part of the process, depending on the AM technologies used and the choice of the machine.

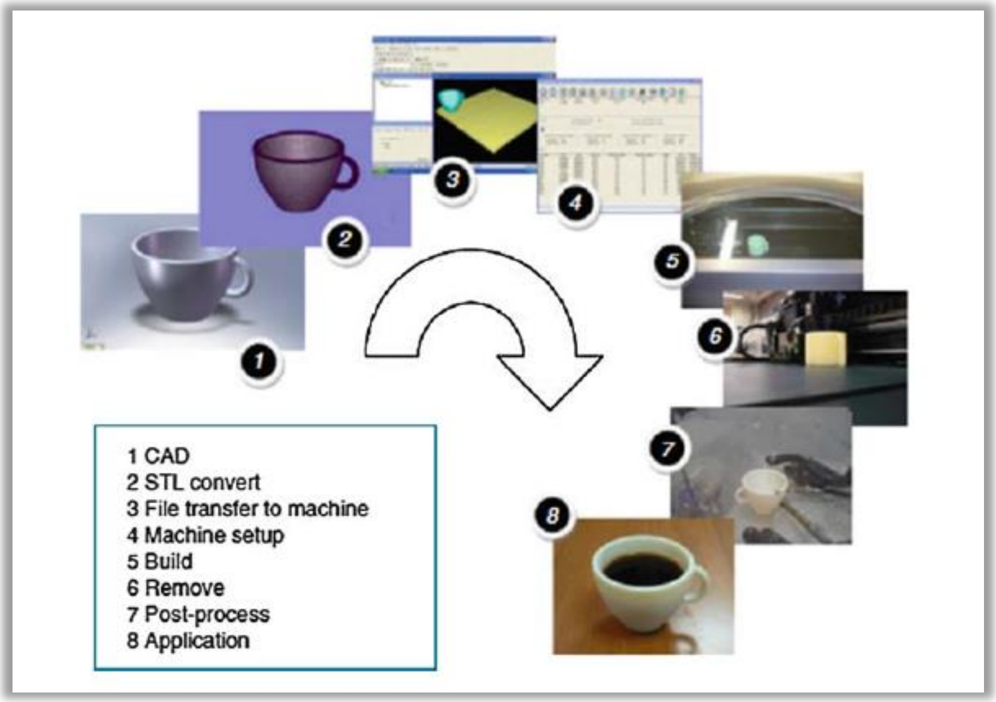


Figure II.1: The eight steps in AM process [7]

Step 1: Conceptualization and CAD

To be able to use AM, the product description needs to be in digital form. In developing a product first, we need to conceive an idea of how the product will look and function, using a CAD system.

Step 2: Conversion to STL/AMF

An STL file has no units, color, material, or other feature information. On the other hand, AMF file format is now international ASTM/ISO standard format which extends the STL format to include dimensions, color, material, and many other useful features. This process is automatic in most CAD systems.

Step 3: Slicing and Upload to AM Machine

Once the STL/AMF file has been created and repaired, the first task would be to verify that the part is correct. Then the AM system software: usually a dedicated Computer Aided Manufacturing (CAM) slicing system allows the user through a visualization tool to view and manipulate the slicing (layer-by-layer) process and G-code final program generation and transfer to the Machine.

Step 4: Machine Setup

All AM machines will have at least some setup parameters that are specific to that machine or process. Some machines are only designed to run a few specific materials. Other machines are designed to run with a variety of materials and may also have some parameters that require optimization to suit the type of part that is to be built.

Step 5: Build

Once the previous steps are completed, this is where the layer-based manufacturing takes place. All AM machines will have a similar sequence of layering. As long as no errors are detected during the build, AM machines will repeat the layering process until the build is complete.

Step 6: Removal and Cleanup

While sometimes the output from the AM machines should be ready for use with minimal manual intervention, more often than not parts require a significant amount of post processing before they are ready for use.

Step 7: Post processing

Post processing refers to the manual stages of finishing the parts for application purposes. Since different AM processes have different results in terms of accuracy, this stage in the process is very application specific.

Step 8: Application

Following post processing stage, parts are ready for use. Although parts may be made from similar materials to those other parts available from other manufacturing processes, parts may not behave according to standard materials specifications. Some AM processes may cause the material to not bound, link, or crystallize in a proper way. AM processes and materials are improving rapidly, and thus designers must be aware of the recent advancements to best determine how to use AM for their needs.

II.3 Additive Manufacturing Processes [8]

AM processes mainly consist of seven main technologies. Choosing the right procedure needs an appropriate understanding of each method, to meet the specifications of the manufactured project.

II.3.1 Vat Photopolymerization

Vat photopolymerization works by exposing a light activated polymer resin to a specific wavelength, so solidifies due to a chemical reaction with light.

This technique uses a recipient of liquid photopolymer resin. Within this tank the object is constructed layer by layer, and a UV light is used to solidify the resin. After each new layer is worked, a platform moves the object being made downwards, and the process begins again. This process uses liquid to create objects and so there is no structural support during the build phase. This often means that support structure will need to be added separately and later removed.

The liquid resins get cured using a process of photopolymerization, this means UV light is directed across the surface of the resin using mirrors. As the light gets in contact with the resin is hardens creating the desired object.

Materials: This process relies on the use of plastics, polymers and UV curable resin.

When using this process there are three different techniques that uses different heat sources available:

- SLA melts and cures the liquid plastic using a laser, building up the part layer by layer as shown in (Figure II.2).

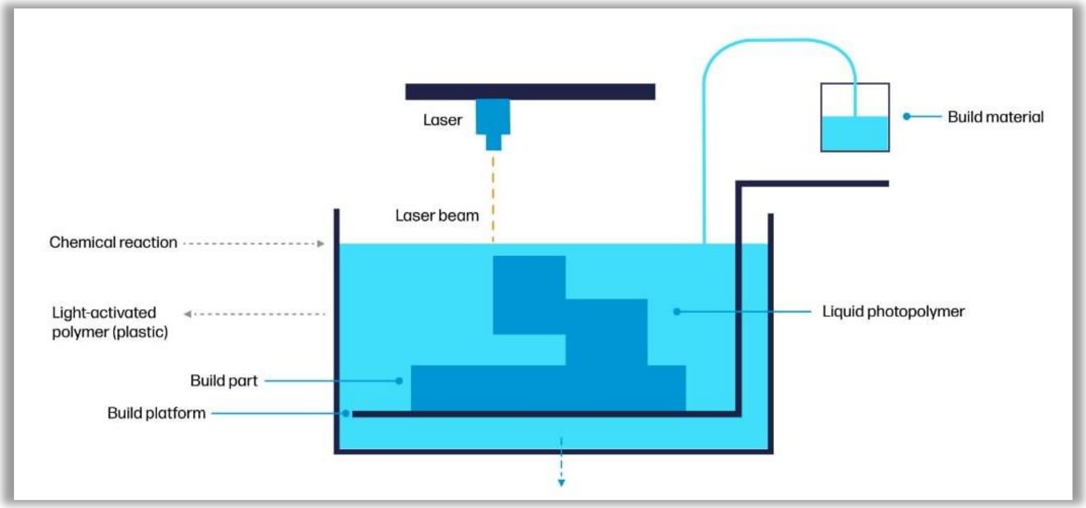


Figure II.2: Stereolithography (SLA)

- Direct light processing (DLP) uses a DLP projector to flash all voxels of the layer at the same time (Figure II.3).

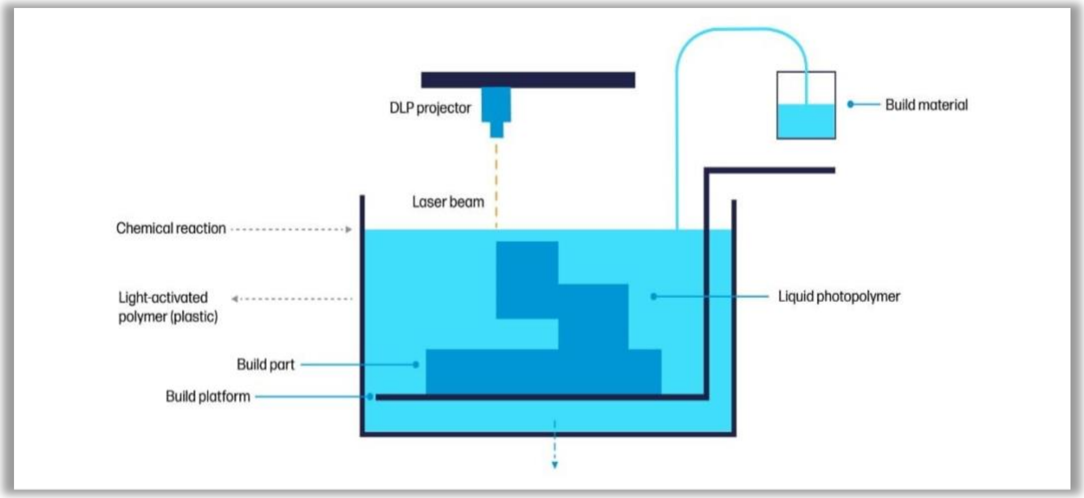


Figure II.3: Direct light Processing (DLP)

- Continuous Direct Light Processing (CDLP), also known as Continuous Liquid Interface Production (CLIP), influences the continuous motion of the build plate in Z direction to flash melt the layer (Figure II.4).

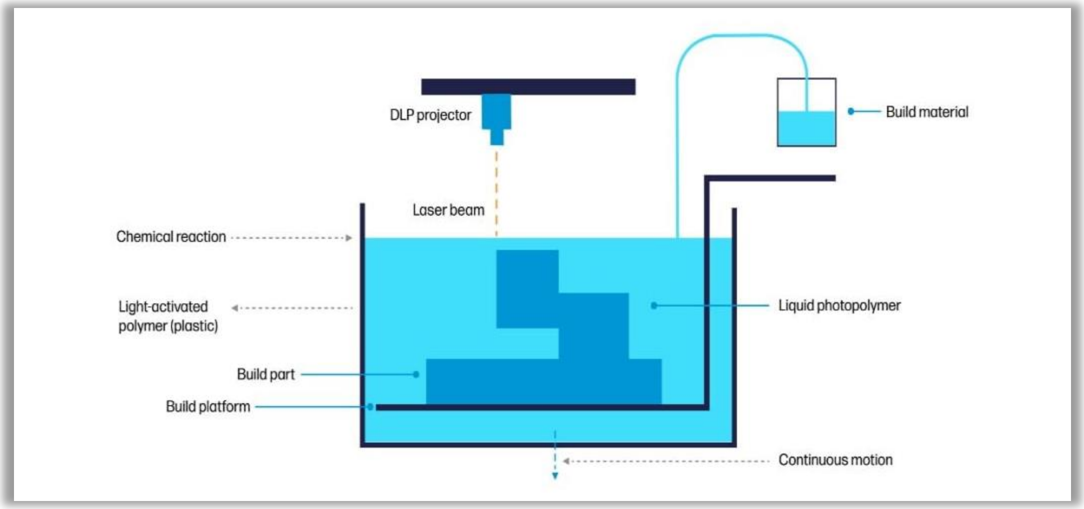


Figure II.4: Continuous Direct Light Processing (CDLP)

Photopolymerization and due to its high accuracy, fast process and good finish, is mainly used in the medical field particularly in the dental practices which includes 3D printed dental implants.

II.3.2 Powder Bed Fusion

The powder bed fusion (PBF) process, uses heat or light energy either in laser form or electron beam energy to melt the powdered material.

There are different techniques that falls under this process including, Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), Selective Laser Melting (SLM), Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF).

These techniques use different mechanisms when it comes to spreading the powder layers. SLS uses laser to sinter powder plastics into a single three-dimensional shape. After each section is melted, the powder bed is lowered by one layer thickness and a new layer is applied on top and the process is repeated ass shown in (Figure II.5). DMLS is similar to SLS but uses powder metals instead of plastics, it also uses a powerful laser beam to melt the metal powder just enough for making a solid part. It is also important to note that the solid mass is formed by heating and applying pressure to the metal material, but not fully melting to a point of liquefaction. On the other hand, SLM uses laser beam to fully melt the material.

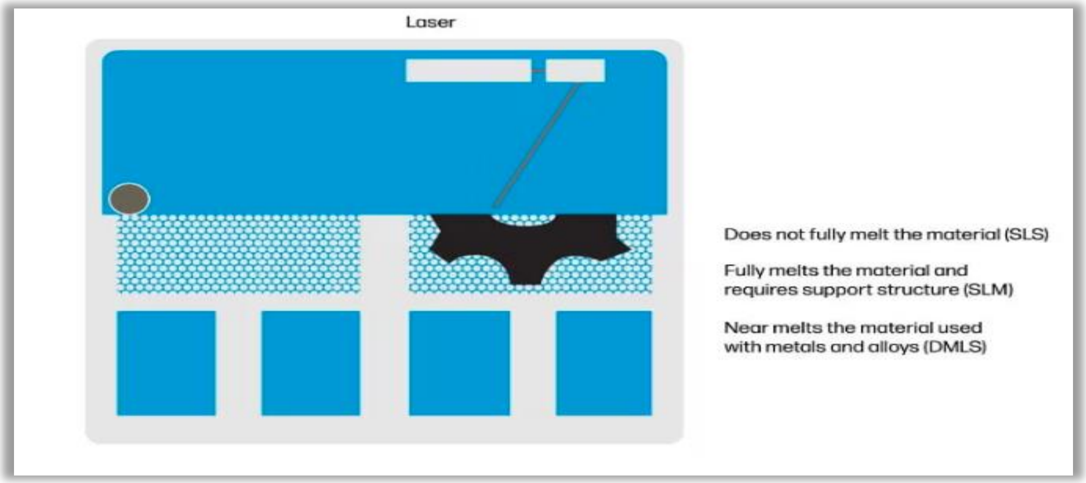


Figure II.5: Powder bed fusion

Unlike the other techniques, EBM as shown in (Figure II.6**)** uses a high energy electron beam and can only be used with conductive materials. It also requires a vacuum build environment in order to fuse metals and alloys to create a variety of functional parts.

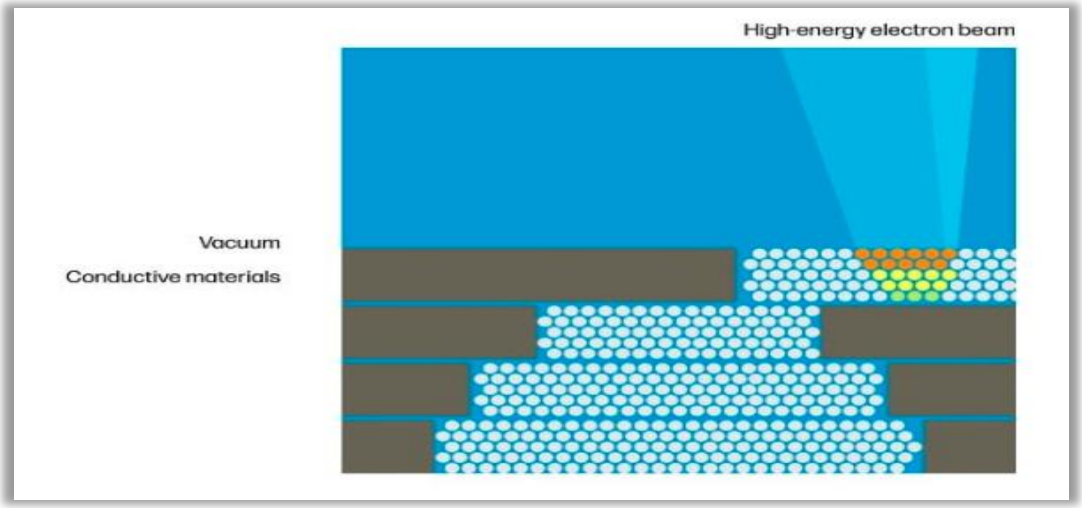


Figure II.6: Electron Beam Melting (EBM)

Materials: Powder based polymers and metals including, stainless steel, titanium, cobalt chrome, and copper.

Powder Bed Fusion is considered a main contributor in many key manufacturing industries due to its cost effectiveness and wide range material options, from the automative industry and the ability to produce lightweight components, to the medical field as a major adopter of this process as it produces a variety of complex implants such as knee replacement and hip joint.

II.3.3 Material Extrusion

Material Extrusion is the most familiar form of Fused Deposition Modeling (FDM) that relies on the use of plastic filament fed through a heated nozzle. The melted material is deposited layer by layer using a moving remote-controlled mechanism. The extruded melted material is formed into layers that are bounded with temperature or chemical agents, as it cools down and hardens. In some machines another nozzle is used at the same time to extrude a dissolvable secondary material as a support for the main part as shown in (Figure II.7).

Materials: Plastics and polymers, besides ABS, Nylon, PC and AB.

The term FDM is proprietary technology that is trademarked meanwhile the equivalent used term, Fused Filament Fabrication (FFF) is not owned or trademarked, and thus it is used more freely.

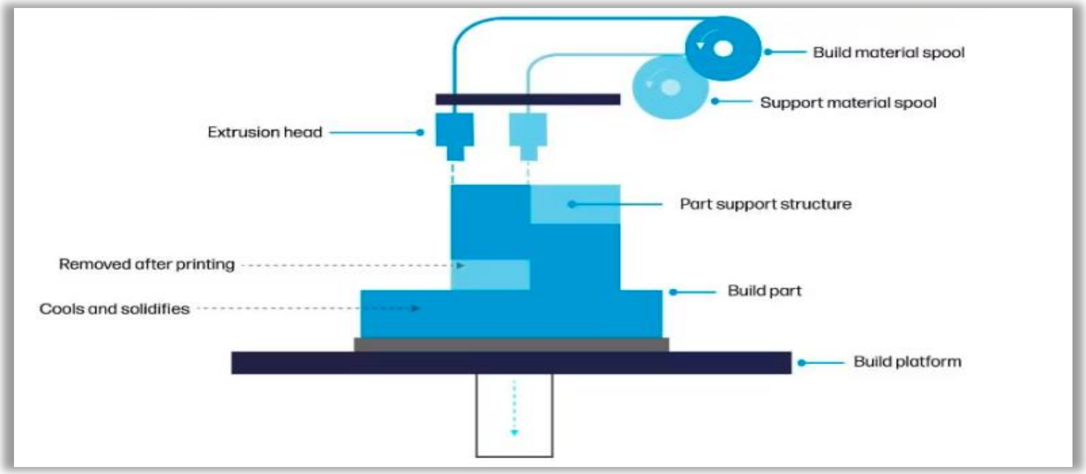


Figure II.7: Fused Deposition Medeling (FDM)

Material extrusion is a widely used technology through various industries but it is also very common among hobbyists, due to its inexpensive cost and easily accessible materials. It is used for making either quick fit up or functional prototypes, jigs, fixates, tooling and molding patterns.

II.3.4 Binder Jetting

Binder Jetting is process that relies on the use of powder-based materials and a liquid binder, that is selectively used as an adhesive between layers. In this process an inkjet printhead moves horizontally along the X and Y axes depositing the binding material alternately with the powder spreader depositing the powder material creating layers. After each layer the build platform lowers by the same thickness as the printed layer as shown in (Figure II.8). Similar to the other powder-based printing processes, binder jetting does not require any support structures as the printed parts are supported by the powder bed, except in most cases where metal or sand are used it requires a significant post processing, where the printed parts need to be subjected to sintering using a furnace to enhance and increase the mechanical properties of the material.

Materials: Polymers, Metals, Ceramics and Sand (Glass).

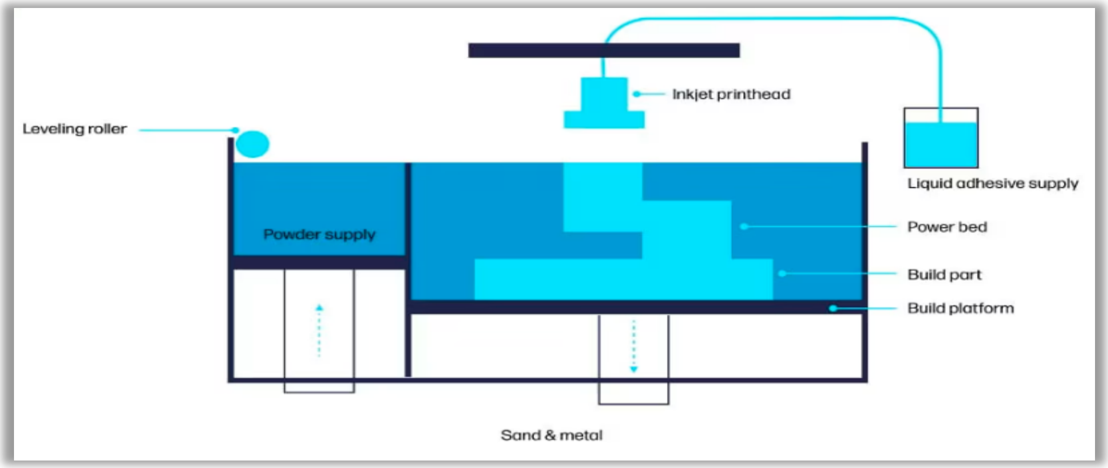


Figure II.8: Binder Jetting (BJ)

Binder Jetting is a process that is considered generally fast white a wide range of materials and the two-material method that allows different binder powder combination, making it more suitable for certain applications then others such as printing lightweighted durable parts in large numbers and short period of times, making it a practical technology in the both the automative and aerospace industries.

II.3.5 Sheet Lamination

Also referred to as Laminated Object Manufacturing (LOM) is a process where large sheets are bounded together using an external force. The bounding varies from material to another, for paper or plastic sheets, heat and a type of adhesive is used to join the sheets before cutting it into a precise form as shown in (Figure II.9**)**. For hard materials the sheets are bounded together using ultrasonic welding then milled into the desired shape, this technique is also named Ultrasonic Additive Manufacturing (UAM), this process requires an additional step using CNC machining usually to remove the unbounded metal.

Materials: Paper, Plastic, Metal.

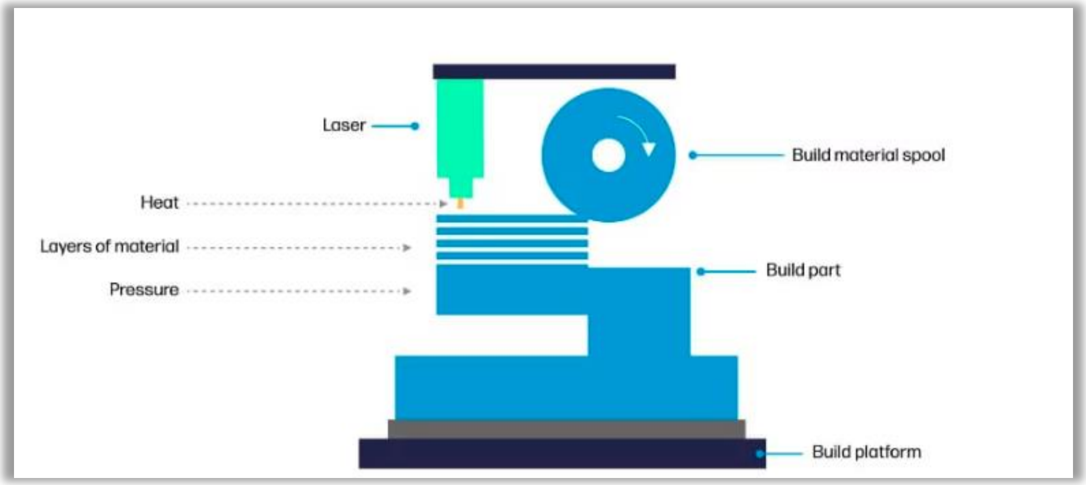


Figure II.9: Sheet Lamination

Although this technique is both cost and time effective with easy material handling, it is mostly used for aesthetic or visual models such as topography visualization and architecture models, but it is still adopted by the automative and aerospace industries as it allows the creation of lightweight technical components at a very competitive cost.

II.3.6 Direct Energy Deposition

Direct Energy Deposition (DED) also referred to as Direct Metal Deposition (DMD), enables the creation of parts by melting metal powder or wire as it deposits onto a surface. The metal is fused by either a laser, electron beam or plasma arc, which forms the solid part layer by layer as shown in (Figure II.10**)**. With this process the nozzle is not fixed to a certain axis, allowing it to move in multiple directions, which means that the material can be deposited from any angle while melted upon deposition.

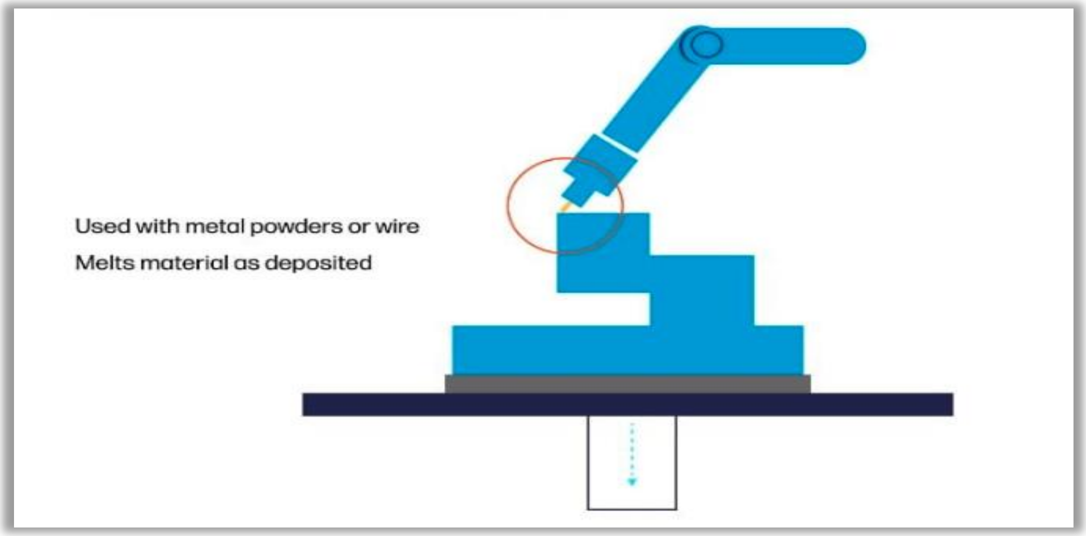


Figure II.10: Direct Energy Deposition (DED)

Materials: Metals including cobalt, chrome and titanium.

The high level of control of DED and the ability to perform high quality repair work on functional parts allows it to be adopted mainly by aeronautics. As it allows the repairing of expensive and complex components instead of completely replacing them. This technique is considered to be superb for tooling processes as it is the only existing method that allows the repair, resurface and reinforcement of components.

II.3.7 Material jetting

Material Jetting (MJ) is a process that uses the same principle as photopolymerization to cure the material. The chosen material is deposited in droplets through a small nozzle using either continuous or Drop on Demand (DOD) technique, the material is extruded into a building platform and then hardened using UV light. This process requires support structure, which is printed along side with the main part, and then separated after it hardens as shown in (Figure II.11**)**. Although the material is deposited in droplets form and it might limit the material availability allowing mainly polymers and waxes to be used but metals are still functional with this process.

Materials: Plastics, polymers, resins and metals.

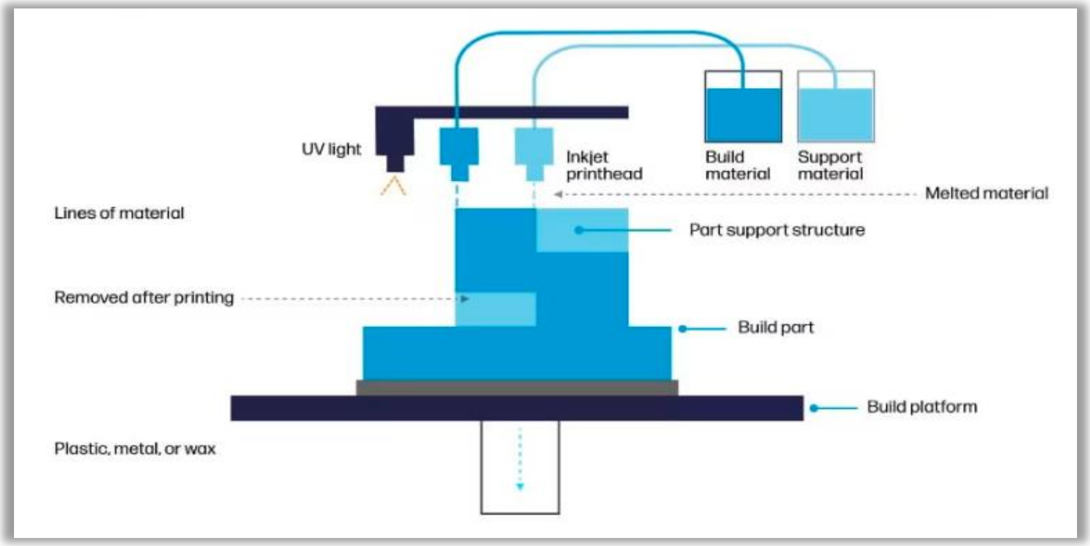


Figure II.11: Material Jetting

Material jetting process offers very high resolution and accuracy for the printed parts while still maintaining low waste, making it widely used in variety of fields such as producing visual prototypes for medical uses as well as engineering test pieces. It is also used in the jewelry making industry for making highly detailed patterns for limited production runs.

II.4 Emerging and Advanced Additive Manufacturing Technologies

In addition to the main AM processes, several next generation techniques are being explored to take additive manufacturing to the next level, expanding its capabilities and potential applications.

- **Hybrid Additive Manufacturing**

  This process combines the benefits of additive and traditional manufacturing techniques, such as CNC machining, within the same process. It allows both the creation of complex structures and the precision finishing of parts, improving efficiency and versatility in manufacturing.

- **4d printing**
  Think of it as next step from 3D printing that creates items that can transform with the passage of time upon exposure to environmental stimuli such as light, heat, or moisture. It has promising potential for creating smart materials and responsive structures that can adapt to their surroundings.
- **Multi material and multi process printing**
  These systems can combine different materials, such as metals, polymers and ceramics, or even merge additive and subtractive processes such as CNC machining and additive manufacturing. This integration boosts the functionality, accuracy, and complexity of the parts being manufactured.
- **High speed sintering**
  A fast powder bed fusion method using infrared radiation in conjunction with inkjet printed detail agents to fuse the powder. The method has high production rates and is especially useful for mass production of polymer components.
- **Microscale and nanoscale printing**
  These extremely accurate methods are used to construct minute structures, usually intended for biomedical devices, sensors and electronic parts. They enable improvements at a level that was hard to accomplish before using traditional techniques.
- **Cold spray AM**
  An advanced AM process in which metal particles are propelled at high velocities and bonded by impact but not melted. It is especially useful for remanufacturing components and producing parts with minimal thermal stress.
- **AI driven generative design**
  A new technology where artificial intelligence comes in to automatically design and optimize structures. This process results in lightweight, high-performance parts that are tailored specifically for additive manufacturing.

II.5 Conclusion

This chapter provides an overview of key additive manufacturing processes, their materials and limitations. It highlights the strengths and weaknesses of each process as well as setup and post processing requirements. The chapter also touches on new and advanced AM technologies that are shaping the future of the field.

Chapter 3: Techno-Economic Comparative Study of Additive Manufacturing Processes

III.1 Introduction

As each additive manufacturing technology vary significantly from one another, it allows each process to be included in a verity of industries based on their needs. This chapter offers a comparative study based on two main practical criteria, the technical and economic aspects. The purpose of this study is to offer a guide that allows decision makers to select the suitable technology based on their work requirements and financial limits.

III.2 Technical comparison

The technical comparison study of AM technologies builds a deep understanding of its practical qualifications and limitations, this includes the complexity of each process, material handling as well as maintenance requirements.

III.2.1 Processes complexity level

We present the variation of the complexity of the AM processes including other requirements that impact the production workflow as shown in (Table III-1). In this table we present a general comparison between AM processes depending on complexity/simplicity of use, level of operator skills required, setup requirements and post processing requirements.

Complexity/Simplicity is the overall difficulty of the AM process from a technical and operational standpoint. This includes the number of steps involved, the precision and control required during printing.

Operator Skill Level indicates how much training or expertise is required to operate and monitor the AM process. It ranges from low to very high skill level.

Setup Requirements covers machine calibration, material preparation, environmental controls (like gas flow or UV safety). Simpler processes involve fewer setup steps, whereas complex processes require advanced infrastructure and time intensive calibration.

Post Processing is an essential phase in AM, often necessary to achieve the final mechanical properties, surface finish and dimensional accuracy of the printed parts. The extent and nature of post processing vary depending on the technology used.

Table III-1: Processes complexity level comparison

AM process	**Process Complexity (see chapter 2)**	**Required Skills Level**	**Setup Requirements**	**Post Processing Requirements**
Material Extrusion	Simple	Low	Minimal (Basic alignment)	Minimal (Support structure removal, surface finish)
Vat Photopolymerization	Medium	Medium	Moderate (resin calibration, leveling)	Moderate (Support removal, UV curing)
Powder Bed Fusion	Very complex	Very high	Maximal (Powder handling, inert gas, laser/ beam)	Maximal (Powder removal, heat treatment, surface finish)
Material Jetting	Complex	High	Minimal (printhead calibration)	Maximal (Support removal, UV curing)
Binder Jetting	Medium	Medium	Moderate (binder, powder prep)	Maximal (Sintering)
Sheet Lamination	Medium	Low	Minimal (sheet feed setup)	Moderate (Trimming)
Direct Energy Deposition	Very complex	Very high	Maximal (multi axis setup, material feed)	Maximal (Machining, surface finish)

III.2.2 Material handling

From the point of view of materials used, (Table III-2) gives a comparison of the process compatibility with the materials, their different raw forms and their availability as well as their storage requirements.

Raw Forms of the materials refer to the physical state and structure in which the material is supplied to the AM machine-generally filament, powder, liquid or wire. This form influences how the material is stored, transported, loaded into the system and how it behaves during the printing process.

Material Availability describes how readily the materials are on the commercial market. It is expressed in quantitative terms ranging from low to high. It depends on factors such as supplier networks, regional availability, variety of materials and cost. It is expressed in a value ranging from low (inaccessible materials) to high (easily accessible materials).

Material Handling reflects the level of operational complexity when working with the material during production. This includes how easy or difficult it is to load, feed, process the material and the safety or cleaning procedures required. It is ranked on a scale from easy to very difficult.

Storage and Manipulation Requirements involves the environmental and procedural conditions necessary to safely store and manipulate the material without degrading its quality or posing risks. These considerations include:

- Moisture sensitivity: Some powders and filaments absorb moisture from the air, which can affect print quality.
- Light sensitivity: Resins for example are UV sensitive and require light protected storage spaces.
- Temperature control: Certain materials need to be kept within a specific temperature range to maintain their stability.
- Toxicity and reactivity: Metal powders, reactive polymers or chemical binders may require fume extraction, sealed systems or inert environments.

Table III-2: Material handling requirements of AM processes

AM process	Different Raw Forms of the material	Material Availability	Material Handling	Material Storage Requirements
Material Extrusion	Thermoplastic filaments	High	Easy	Dry, room temperature space
Vat Photopolymerization	Liquid – Photopolymer resin	Medium	Moderate	Light protected, room temperature space
Powder Bed Fusion	Powder – Polymers/Metals	Low to Moderate	Difficult	Dry, sealed, inert environment
Material Jetting	Liquid – Photopolymer resin, wax	Medium	Moderate	UV protected, humidity-controlled space
Binder Jetting	Powder (metal, sand, ceramic, composites) + liquid binder	Medium	Moderate	Dry, light protected, room temperature space
Sheet Lamination	Solid – Sheets (paper, plastic, metal)	High (paper, plastic), low (metal)	Easy	Humidity protected
Direct Energy Deposition	Powder /Wire – Metal	Low	Very Difficult	Inert gas or vacuumed environment

III.2.3 Maintenance requirements

We present an overview of the main maintenance requirements for various AM processes, including maintenance frequency, required skill level and maintenance cost as shown below in (Table III-3).

Maintenance Frequency refers to how often routine or corrective maintenance must be performed to ensure the smooth operation of the AM system. Tasks may include cleaning, recalibrating and resolving mechanical or software issues. It is expressed in a value ranging from low to high.

Maintenance Skill Level refers to the technical expertise necessary to perform maintenance operations. It includes the ability to diagnose issues, replace components and manage system specific requirements. It is expressed in a value ranging from low (basic skills) to very high (advanced technical skills).

Maintenance Cost encompasses all costs related to maintaining the equipment, including spare parts, service time, consumables and machine downtime. It is expressed in a value ranging from low (minimal cost) to high (significant investments in parts and services).

Table III-3: Maintenance requirements for AM processes

AM process	**Maintenance Frequency**	**Required Skill Level**	**Maintenance Requirements Cost**
Material Extrusion	Low (weekly to monthly)	Low	Low
Vat Photopolymerization	Medium (monthly)	Medium	Medium
Powder Bed Fusion	High (daily)	High	High
Material Jetting	High	High	High
Binder Jetting	Medium	Medium to high	Medium
Sheet Lamination	Low	Low	Low
Direct Energy Deposition	High	Very high	High

III.3 Suitability for practical use cases

As AM is being included in a wide range of industries with its different technologies, it is important to understand the way each process performs in practical use cases. The comparison presented in (Table III-4) allows the decision makers to determine which technology is the most suitable to adopt based on what they are manufacturing whether it is for rapid prototyping or functional used parts or mass customization.

Rapid Prototyping refers to the quick fabrication of models and parts, usually for testing design and form before mass production. It does not always need to be strong or long lasting, it is more about speed, accuracy and surface finish.

Functional end-use Parts are final products and components used directly in real applications. They require mechanical strength, resistance and reliability.

Mass Customization, unique parts are fabricated in large numbers for specific applications such as in dental implants.

The suitability is expressed in a value ranging from poor, moderate, good to excellent. This comparison bridges the technical aspect with the application context.

Table III-4: Suitability for practical use cases

AM process	Rapid Prototyping	End-use Parts	Mass Customization
Material Extrusion	Excellent	Poor	Good
Vat Photopolymerization	Excellent	Poor	Good
Powder Bed Fusion	Good	Excellent	Moderate
Material Jetting	Excellent	Poor	Excellent
Binder Jetting	Good	Moderate	Excellent
Sheet Lamination	Good	Poor	Poor
Direct Energy Deposition	Poor	Excellent	Poor

III.4 Cost and investments

The investment aspect plays a crucial role in the decision making of which AM technology is the most suitable to select. Based on major factors such as the cost to purchase the machine which varies drastically from desktop printer to million-dollar industrial systems, the operational cost and material cost; (Table III-5) bellow compares these factors as well as the investment aspect focusing on the Return on Investments (ROI) estimated time.

The different costs vary depending on the complexity of the process, material type and production scale [9]. The cost is expressed in a value ranging from low to high.

The ROI measures how long it takes for the investment in the AM technology to pay off, it reflects the economic feasibility of a process over time. ROI is expressed in a value ranging from short (fast recovery) to long (slow recovery).

Table III-5: Cost and Investments comparison

AM process	**Initial Machine Cost**	**Material Cost**	**Operating Cost**	**Estimated ROI Time**
Material Extrusion	Low	Low	Low	Short
Vat Photopolymerization	Low to medium	Medium	Medium	Short
Powder Bed Fusion	High	High	High	Long
Material Jetting	Medium to high	High	High	Medium to long
Binder Jetting	Medium	Medium	Medium	Medium
Sheet Lamination	Medium	Low	Medium	Medium
Direct Energy Deposition	High	High	High	Long

III.5 Suitability for SMEs

Unlike large industries, SMEs (Small and Medium Enterprises), usually have restrictions often related to budget, space availability and work experience. In this context (Table III-6) highlights the factors that are relevant to the suitability of various AM processes for SMEs. The factors proposed in our study are: Initial Investments, Training Requirements, Space Requirements, and overall SME Suitability.

Initial Investment is the upfront capital required to adopt the AM technology, including the cost of the machine and setup. It is expressed in a value ranging from low to very high.

Training Requirements represents the level of technical knowledge and skill needed for operators and staff to effectively use and maintain the AM process. It is expressed in a value ranging from minimal, intermediate, advanced to specialized.

Space Requirements describes the physical space needed to install, operate and maintain the equipment, including storage for materials and post processing. It is expressed in value ranging from small to large.

Scalability indicates how easily the technology can be scaled up or down based on production or business growth.it is expressed in a value ranging from poor to excellent.

Overall SME Suitability summarizes how appropriate the AM process is for small and medium sized enterprises, based on affordability, ease of use, space needs and growth potential. It is expressed in value ranging from limited to excellent.

Table III-6: Suitability for SMEs comparison

AM process	Initial Investments	Training Requirements	Spaces Requirements	Scalability	Overall SME Suitability
Material Extrusion	Low	Minimal	Small	Good	Excellent
Vat Photopolymerization	Moderate	Minimal	Small	Poor	Very good
Powder Bed Fusion	High	Advanced	Large	Good	Limited
Material Jetting	High	Intermediate	Medium	Moderate	Limited
Binder Jetting	Moderate	Intermediate	Medium	Excellent	Very good
Sheet Lamination	Moderate	Specialized	Medium	Poor	Moderate
Direct Energy Deposition	Very high	Advanced	Large	Good	Very limited

III.6 Discussion and exploitation of the study results

This section presents a discussion of the study results and how they can be exploited in the development of AM technology/process selection tool. It consists of two parts. The first part gives an exhaustive discussion on the techno-economic parameters influencing the choice of AM processes. The second part lays the basis for the development of a programmable AM process selection support tool.

III.6.1 Discussion of the study results

The techno-economic study table (TableIII-7) included in this chapter presents a comparative overview of key techno-economic factors that influence the practical application of different additive manufacturing processes. The following four variables (Process Complexity, Maintenance Cost, Estimated ROI time and Suitability for SMEs) were selected based on their relevance to real world implementation and long-term sustainability. Together, these four variables offer a balanced evaluation framework that combines technical complexity with economic impact.

The table evaluates seven major additive manufacturing processes using four practical and economically relevant criteria. The variables previously mentioned, represent both the operational demands and the strategic consideration involved in the technology adoption. In the following section, each process is examined in relation to these variables to better understand their strength, limitation and suitability for different use cases.

Material Extrusion process stands out for its simplicity and low operational demands. With low maintenance cost, a short ROI time and excellent suitability for SMEs, it is clearly the most accessible and cost-effective AM process. Its wide adoption is supported by its user-friendly setup, low machine and material costs and minimal training requirements. This makes it ideal for educational institutions, small manufacturers and prototyping centers.

Vat Photopolymerization process balances moderate complexity with medium maintenance cost and a short ROI time, offering very good SME suitability. It provides higher precision and surface quality but requires more care in resin handling and post processing. Its suitability lies in applications like dental, jewelry and prototyping design, where detail and finish are prioritized.

Powder Bed Fusion process ranks among the most complex processes, with high maintenance requirements and a long ROI time. Its limited suitability for SMEs is due to high cost of equipment, materials and strict environmental controls. Despite this it is unmatched in producing high strength, functional parts for aerospace, medical and automative industries.

Material Jetting process offers excellent surface resolution but lack when it comes to maintenance demands and ROI time, placing it in the limited SME suitability category. While it supports multi-material and full color printing, the need for regular maintenance makes it more suitable for specialized prototyping firms.

Binder Jetting process is a balanced option, with medium complexity and maintenance costs, a medium ROI and very good SME suitability. It is scalable and compatible with a range of materials. Although post processing can be intensive, its dry process and lower energy requirements make it attractive for low to mid volume production.

Sheet Lamination process is rated medium in complexity with low maintenance cost and moderate SME suitability. While its use cases are often limited to paper, plastic, or metal sheets it has advantages in low-cost prototyping or large format part production. The medium ROI time reflects the balance between simplicity and limited functional part capability.

Direct Energy Deposition process is the most complex and least SME friendly process. It has high maintenance costs, a long ROI and very limited suitability for smaller operations. However, it excels in production of large metal parts and in repair applications, especially in heavy industries.

Table III-7: Techno-Economic study summary table

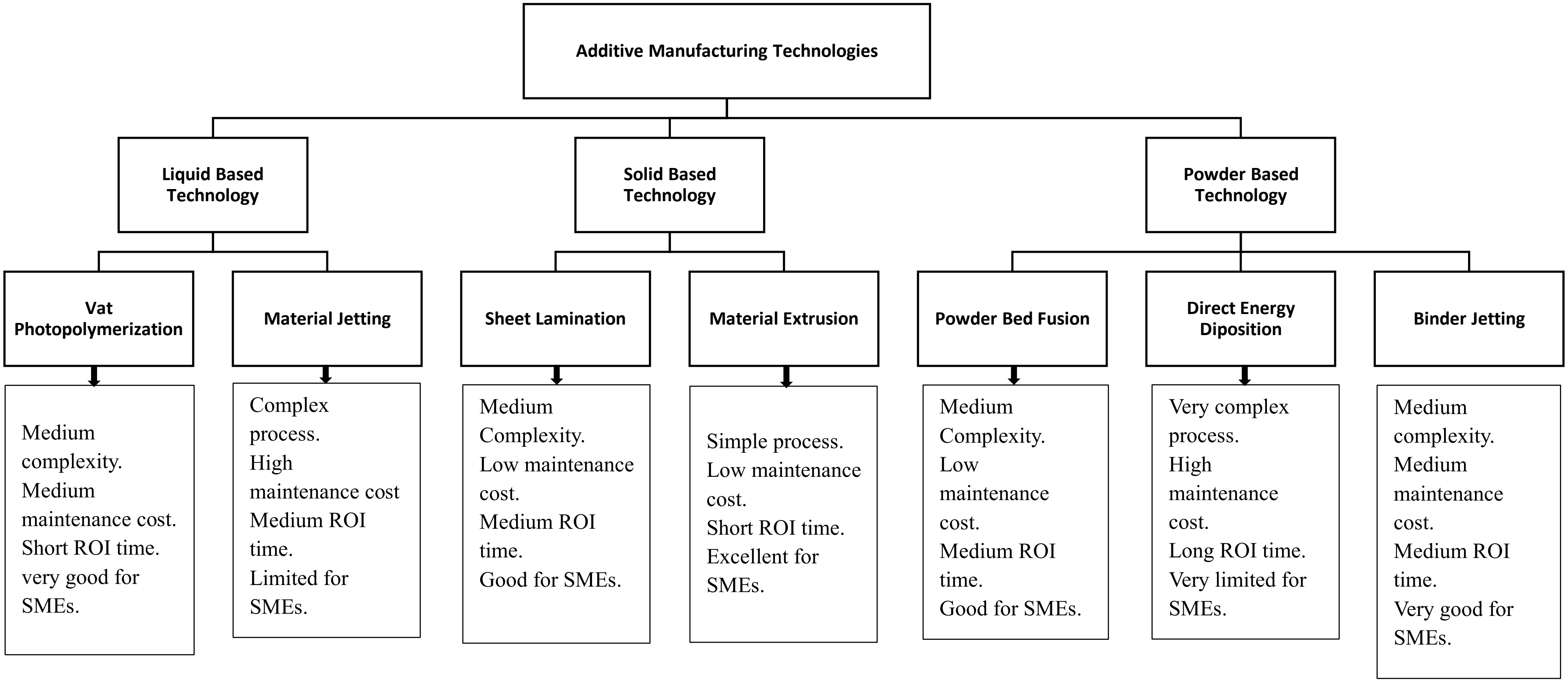
AM process	Process Complexity Level	Maintenance Requirements Cost	Estimated ROI time	SMEs Suitability
Material Extrusion	Simple	Low	Short	Excellent
Vat Photopolymerization	Medium	Medium	Short	Very good
Powder Bed Fusion	Very complex	High	Long	Limited
Material Jetting	Complex	High	Medium to long	Limited
Binder Jetting	Medium	Medium	Medium	Very good
Sheet Lamination	Medium	Low	Medium	Moderate
Direct Energy Deposition	Very complex	High	Long	Very limited

In addition, we present the organizational chart in Figure III.1 that visually summarizes the comparative results discussed in the previous section. It groups the seven main additive manufacturing processes according to their complexity, maintenance demands, ROI expectations, and SME suitability. The chart also categorizes each process based on the physical form of the material used whether it is powder based, liquid based or solid based, to further clarify material handling and process characteristics. The differences are explained as follows:

- ***Powder based technologies use fine metal or polymer powders that are selectively fused or bound.***
- ***Liquid based technologies rely on resins are cured or solidified layer by layer.***
- ***Solid based technologies involve filaments, sheets or wire that are cut, melted or bonded to build parts.***

It is important to note that some processes can operate with more than one material form depending on the system configuration, for example, DED can use either metal powder or metal wire as its feedstock.

Figure III.1: The Techno-Economic study summary



The comparative study of the different AM processes reveals the variation in complexity, material processing, maintainability, and economic limitations as presented. Processes such as PBF and DED, although they allow high part accuracy and material flexibility, are linked to high setup demands, post processing requirements, and high investments. In contrast, material extrusion techniques show simplicity in operating and maintenance making them more suitable for SMEs.

Material form and availability also play a crucial role in the selection of the suitable AM process. Technologies like BJ need materials in specific forms, restricting the process for certain applications. Maintenance frequency also differs significantly impacting operational efficiency and cost control in the long run.

From the Techno-Economic viewpoint, it is revealed that there is no single process that addresses all needs across the industries. Instead, AM processes selection depends on a compromise between requirements of part functionality, material availability, complexity tolerance and investment capability. As AM continues to develop at a significantly fast pace, future advancements will likely shift the Techno-Economic features granting continuous evaluation.

III.6.2 AM process selection support tool

This section offers simple examples of algorithms that can be the base for programming a selection tool. This tool can be expressed as three modules as follows:

- Investment/Cost based module.
- Product Function based module.
- Material Type based module.

- **Algorithm example for Investment/Cost based module:**

```
If    the organization is SME    then    select material extrusion
                                         or photopolymerization

        Else if    the budget is flexible              then
                   select PBF or DED

            Else if    the budget is limited           then
                       select photopolymerization
                       or material extrusion
            End if
        End if
End if
```

- **Algorithm example for Product Function based module:**

```
If      the purpose is end-use parts    then    select PBF or DED or BJ
        Else if     the purpose is rapid prototyping    then
                    select material extrusion
                    or photopolymerization
                    or material jetting

                Else if    the purpose is mass customization  then
                           select material extrusion
                End if
        End if
End if
```

- **Algorithm example for Material Type based module:**

```
If      polymer is required           then    select material extrusion
                                              or photopolymerization

        Else if     metal is required                  then
                    select DED or PBF or BJ
        End if
End if
```

III.7 Conclusion

This chapter presents a techno-economic comparative study of the AM processes from both technological and economic perspectives. This study has permitted the development of various comparative tables based on Process Complexity, Maintenance Cost, Estimated ROI time and Suitability for SMEs. The comparative results have been summarized in an organizational chart. In addition, examples of algorithms that can be used for programming a selection tool are presented for three modules: investment/cost, product function and material used.

General Conclusion

This dissertation has started by exploring additive manufacturing from both a technological and economic perspective, offering a structured overview of its evolution, current practices and emerging innovation. Through this first part, we collected information about the key processes, materials used and cost that define the field today. These data form a foundation for the second part: the comparative study of the practicality and economic feasibility of various AM technologies for various industrial scenarios.

By evaluating each process based on complexity, material requirements, setup, maintenance needs and suitability across different sectors, including SMEs, we arrived at a clearer picture of where each method fits within today's manufacturing landscape. Furthermore, the cost and investment analysis presented helps highlight the tradeoffs that come with adopting these technologies in real world applications from both technological and economic perspectives.

The conducted techno-economic comparative study has permitted the development of:

- various comparative tables based on Process Complexity, Maintenance Cost, Estimated ROI time and Suitability for SMEs.
- a summary organizational chart
- algorithms as a basis for programming a selection tool based on investment/cost, product function and material used

This dissertation provides a starting point for further inquiry and exploration in the dynamic and fast-moving field of additive manufacturing on one hand. On the other hand, the developed tables, summary chart and algorithms can be enriched and used for the development of a computer-based AM technology selection tool.

References

[1] Ghisays, J. (2024, July 7). The evolution of 3D printing technology: What's next?

[2] May, V. (2024, July 26). The history of additive manufacturing: from the 80s to today. PrototalUK.

[3] https://prototaluk.com/blog/history-of-additive-manufacturing/

[4] https://www.historyofinformation.com/detail.php?id=3864

[5] https://www.hp.com/us-en/printers/3d-printers/learning-center/metal-additive-manufacturing.html#section=the-birth-of-metal-3d-printing

[6] https://all3dp.com/1/3d-printing-jewelry-the-ultimate-guide/

[7] Gibson, I., Rosen, D., & Stucker, B. (2015). Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer.

[8] https://www.hp.com/us-en/printers/3d-printers/learning-center/3d-printing-process.html

[9] Wohlers Report 2023 - Wohlers Associates. (2023, May 31). Wohlers Associates.