POLITECNICO DI TORINO

Master’s Degree Course in Engineering and Management

Lean management in Additive manufacturing: a methodological proposal for quality control

Advisor:

Prof. Paolo Chiabert

Candidate:

Francesca Sini

Co-advisors:

Dott.ssa Giulia Bruno

Prof. Frédéric Ségonds

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Summary

Introduction

This thesis work was carried out throughout a collaboration between Politecnico di Torino and LCPI (Laboratoire Conception de Produits et Innovation), a research laboratory of the university Arts et Métiers ParisTech in Paris, which operates in the field of Industrial Engineering. The aim of the laboratory's work is to optimize the Design and Innovation Process by integrating education, research and industrial valorisations.

The thesis deals with additive manufacturing, a potentially disruptive technology, and it aims to highlight the opportunities it offers in two different directions: the former regards the effects of additive manufacturing on the manners enterprises may manufacture and deliver products to consumers; the latter concerns with the so-called *home fabrication*, which consists of 3D printer users who directly print products in their own home. Additive manufacturing leads to high levels of innovation for both consumers and companies, from geometrical flexibility to crucial reduction in wastes. However, the advantages may be threatened by the lack of a comprehensive and defined quality control methodology and by the fact the no high-quality levels are still guaranteed; therefore, there is the need to further study defects that affect 3D printed products and to propose new manners to control them.

The thesis is structured in five chapters and a conclusion section, in which the work is reviewed, results are summarized and future steps to complete the research are proposed. The first chapter provides an introduction for additive manufacturing and a brief explanation of enabling technological processes and materials. Furthermore, it is presented a first analysis regarding the advantages and disadvantages of additive manufacturing with respect to traditional manufacturing techniques: in particular, it is highlighted that despite being a relatively new technology, it is already possible to compare 3D printing performances with the one of traditional manufacturing, which counts more than two centuries of history. The second chapter presents lean manufacturing: it describes lean philosophy and principles and the most common tools that are used to reach the objective of maximizing the value perceived by customers by minimizing the activities that do not add any value, the so called *muda* (Japanese word for waste). Successively, it is enlightened how additive manufacturing allows to dramatically reduce or eliminate six out of sever sources of wastes (*muda*) identified in lean production. The waste that cannot still be reduced by additive manufacturing is the presence of defect in the final product: as it was stated in the previous lines, it is necessary to make further improvements in quality for additive manufacturing. Last paragraph in Chapter 2 proposes a cost analysis for additive manufacturing in order to make it clear when it may be more convenient than traditional manufacturing and which are the factors that may cause an high cost for additive manufacturing.

Since it is understood that quality is a crucial topic, defects that affect parts produced through additive manufacturing technology are studied in Chapter 3: they are classified into dimensional, surface and mechanical defects and each of them is described in detail. Chapter 4 provides a literature review of quality control proposals for additive manufacturing, after having presented the history of quality control and the most common approaches. In addition, 3D scanning techniques and instruments are described. Finally, Chapter 5 presents a methodology for quality control in 3D printing: it is explored the possibility to utilize the frontal camera of X generation iPhones as a low-cost scanner to rapidly acquire data of a 3D printed product and compare it with the original model. Finally, tests of the methodology and of the instrument made through a use case and successive results are presented, as well as further improvements that can be applied.

Chapter 1

Additive manufacturing

Additive manufacturing (AM) is the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". It is also known as additive layer manufacturing, 3D printing, digital manufacturing, rapid prototyping, rapid manufacturing. AM process starts with a creation of a 3D digital model: firstly, the file is translated into a "standard" 3D format (.STL is the most common one), then a slicing process is applied in order to enable the layer by layer manufacturing. Such file is sent to the AM machine and printed thorough different technologies. Once the part is manufactured, it may be necessary to carry out a post-processing phase, which may include excess material removal, surface finish processes, heat treatments, polishing and support removal through chemical or mechanical tools. The layer by layer production methodology has two main advantages: (i) geometry flexibility: any geometry can be produced in a single operation without any additional cost or time constraint; (ii) reduction in consumption of resources: only the precise amount of material necessary to the creation of the final product, avoiding the usual traditional manufacturing's wastes.

The history of AM starts in 1980s, when Hideo Kodama, from the Nagoya Municipal Industrial Research Institute, published information concerning the manufacturing of a solid printed model for rapid prototyping. In 1986, the first patent was granted to Charles Hull for his invention of a stereo lithography fabrication system, in which layers are added by curing photopolymers with ultraviolet light lasers. From that moment on, AM has grown from a new process used by a select few to a mainstream technology adopted by everyone: from hobbyists and engineers to manufacturers and researchers. Over the first years (1990-2000), AM was mainly used in the early stages of product design to produce visual appearance models, breadboard models, technological prototypes and the exploration of so call rapid tooling. During the early 2010s, processes were considered mature enough to allow the serial production of manufactured parts. Advanced AM techniques have been developed greatly in recent years, yielding broader industry applications, in particular product development and manufacture of final parts. Expectations are that future applications will involve final product production, mass production and democratized consumer 3D printers.

1.1. Additive Manufacturing Technologies

AM processes can be divided into seven main categories that use the identical machine architecture and for which the physical transformation processes of the materials are similar: VAT photo polymerisation, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, sheet lamination [1]. A brief description of the seven processes is provided in the following section.

1.1.1. VAT photo polymerisation

A liquid photopolymer contained in a vat (or tank) is selectively cured through the action of a light source. When a layer of resin is polymerised, the build plate is moved vertically (Z axis) by a distance which is set in the production parameters so that the cycle can be repeated until completion. There exist different variants depending on the nature of the light source (e.g. a laser or a UV light) and on the direction of the movement of the plate.

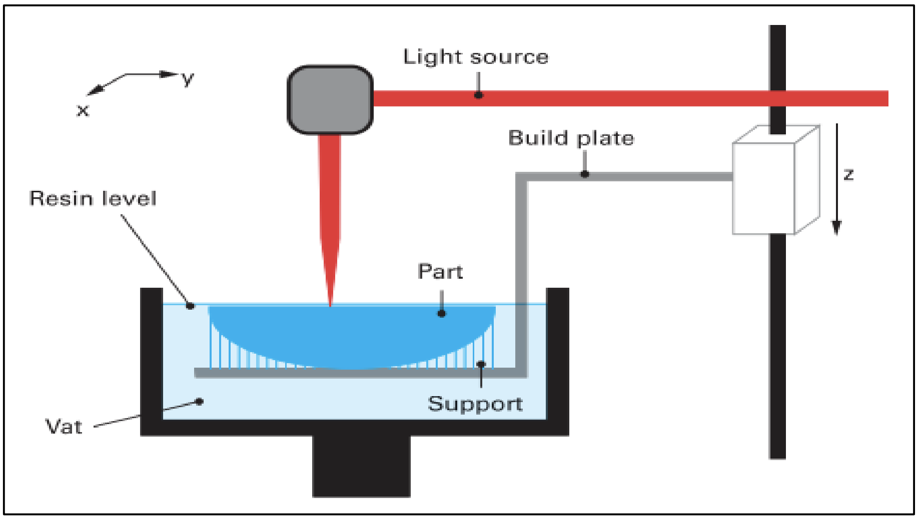

Figure 1.1: llustration of the VAT photopolymerisation process. Source: [1]

1.1.2. Material jetting

It uses print heads which deposit drops of material on the surface of the manufacturing area. Two types of material can be used: photosensitive resins and waxes deposited in liquid form.

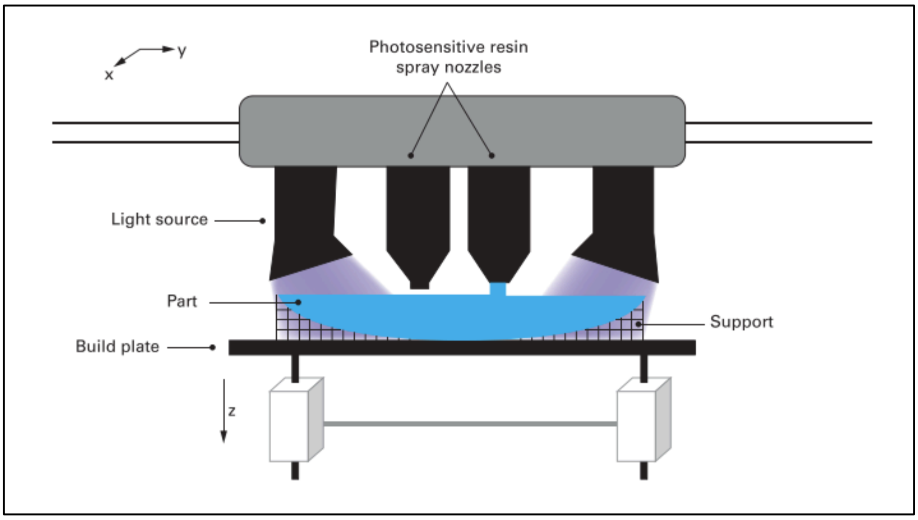

Figure 1.2: Illustration of the material jetting process (Polyjet technology) Source: [1]

1.1.3. Binder jetting

Similarly to material jetting, it is based on a deposition. In this case, liquid binding agent is selectively deposited in a powder bed, which acts like a support for the product. Several materials are compatible with binder jetting technology, from polymers to metals, including ceramics. Nonetheless, the parts are usually fragile thus they require a post processing phase.

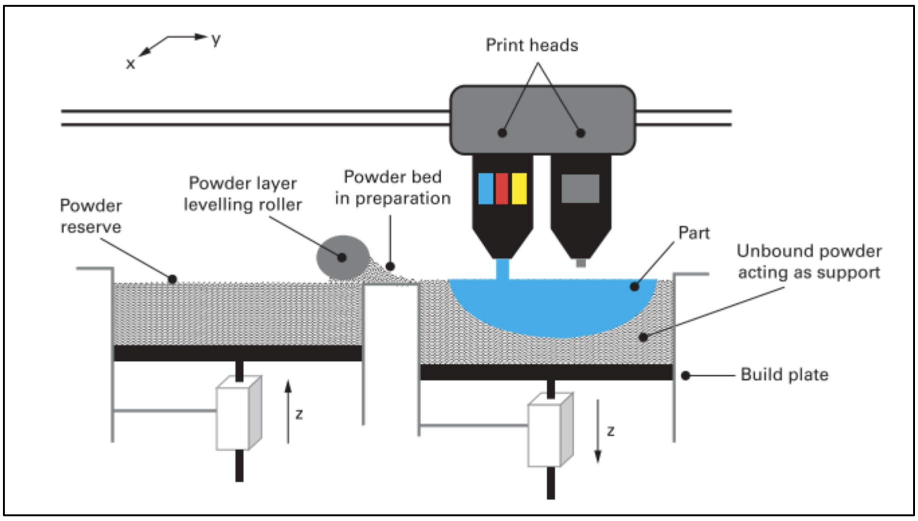

Figure 1.3: Illustration of the binder jetting process. Source: [1]

1.1.4. Powder bed fusion

Powder bed fusion methods use either a laser or electron beam to melt and fuse material powder together. The Powder bed fusion process uses any powder based materials. A post treatment of metal parts produced is essential in order to improve the mechanical behaviour

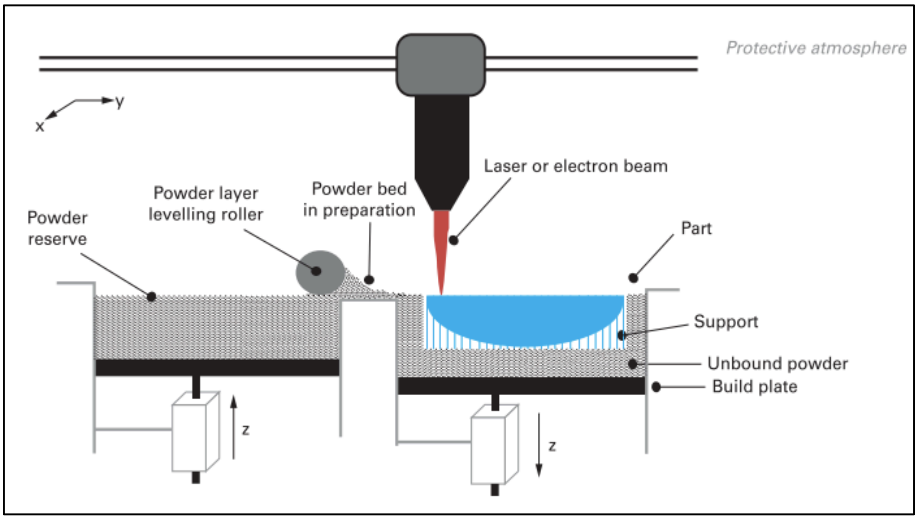

Figure 1.4: Illustration of the powder bed fusion process. Source: [1]

1.1.5. Material extrusion

The method consists on the heating of thermoplastic polymer material above its melting point and its extrusion through a nozzle which moves in X and Y directions on a printing platform that moves in the vertical Z-axis each time a layer has been deposited. Fused Deposition Modelling (FDM) machines can have an additional nozzle that allows the extrusion of the support material needed to generate complex shaped parts and/or the manufacturing of parts with different materials and no support.

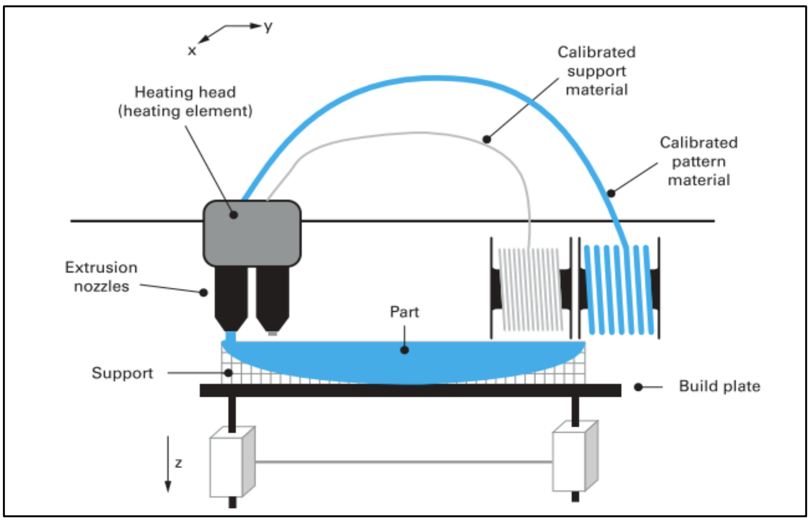

Figure 1.5: llustration of the material extrusion process. Source: [1]

1.1.6. Directed energy deposition

Its principle relies on the melting of a surface using an energy source with the simultaneous supply of a jet of power or a filament of material to the molten area, all in the presence of a protective gas.

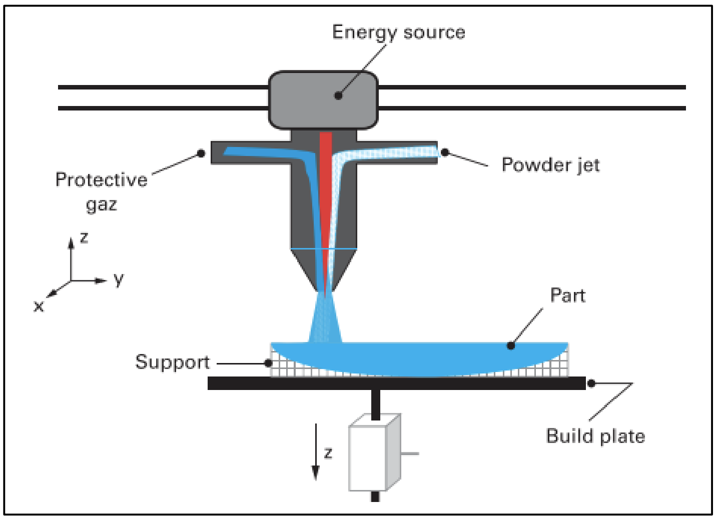

Figure 1.6: Illustration of the directed energy deposition process. Source: [1]

1.1.7. Sheet lamination

Sheet lamination is a combination between additive and subtractive manufacturing: sheets or plates of material are cut up using a cutting system (laser, cutting tool, ultra- sound, etc.), stacked and then bonded to one another (positioning, glueing, ultrasonic welding, or possibly the use of inserts, etc.) to form the product. All materials which exist in sheet form can be used.

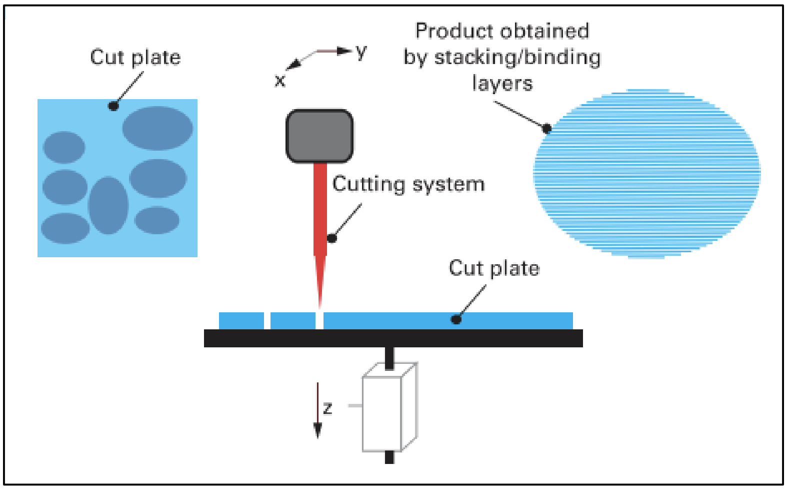

Figure 1.7: Illustration of the sheet lamination process. Source: [1]

Table 1.1 provides a synthesis of the material used and application for each of the seven main technologies.

Name	Basic Description	Usual Material	Applications
Fused Deposition Modelling	Layers are conformed by fusing and extruding a thermoplastic through a nozzle.	Thermo-plastics	Illustrative models and sketch-ups/functional models (technology and application dependant)
Powder Bed Fusion	A fine layer of particled material is deposited and sintered/melted by the action of a selective heating source.	Plastics; metals	Functional models/final parts
Direct Energy Deposition	Very similar to a welding process, a nozzle mounted on a multi-axis arm deposits material and provides a heating source to make up each layer.	Metals	Functional models/final parts
VAT Photopolymerization	Uses photopolymer resins that can be selectively cured by the action of a UV light.	Resins	Illustrative models and sketch-ups/functional models (technology and application dependant)
Material Jetting	With great similarities to a traditional printing process, inkjet printing heads are used to deposit the material that makes up each layer.	Resins; metals; wax	Illustrative models and sketch-ups/functional models (technology and application dependant)
Sheet Lamination	A material stored on a roll is applied and bound over a plain surface (first layer) or the previous layer, and then cut to the desired shape.	Paper; composites	Illustrative models and sketch-ups (paper). Functional models/final parts (composites)
Binder Jetting	A fine powder material layer is deposited, and selectively bound by the action of a print head.	Sandstone	Illustrative models and sketch-ups

Table 1.1: Main groups of additive manufacturing technologies

1.2. AM Materials

The choice of material is a very important factor because it has a significant impact on the quality and on the cost of the final product. There exist different typologies of materials that are suitable for AM processes that range from plastics, resins and metals; as well as ceramics and waxes. Moreover, new materials such as sand, graphene are tested and used. Depending on which processes is used, the feedstock is in a different form, e.g., wire, liquid, power, sheet.

The most common material for AM processes are plastics. ABS (Acrylonitrile Butadiene Styrene) and PLA (polylactic acid) are two thermoplastics particularly widespread for extrusion processes, such as FDM. ABS is a non-biodegradable very deformable (it can be flexed several times on itself without breaking) material which has a moulding temperatures of about 240°C. PLA, a biodegradable substance, is extruded at temperatures of about 200°C and it has the advantage of not requiring a heated work surface. The objects produced in PLA are more rigid than ABS ones, therefore they can be broken more easily.

Metals are particularly diffused for industrial applications, such as automotive and aerospace. Metals can be used in Powder bed fusion and directed energy deposition processes, but they are also available in the wire form for extrusion techniques. The set of common commercially available metals involves mostly aluminium alloys, titanium alloys, stainless steel, nickel superalloys, as well as Precious metals such as gold, silver or platinum for jewelleries.

1.3. Advantages and disadvantages of Additive Manufacturing

This paragraph provides a comparison between AM and SM, underlying the advantages and disadvantages of the first over the second (Table 1.2) in order to understand the possible future scenarios of deployment of AM, its opportunities and its limits. The comparison will also investigate the progress of both manufacturing processes in terms of time.

AM Advantages	AM Disadvantages
- Reduction in consumption of resources - Freedom of design - Low initial investment - Economies of scope - High customization - Weight reduction - Stock reduction	- Unsuitability for mass production - Raw material cost - Dimensions - Quality

Table 1.2: Advantages and disadvantages of AM with respect to traditional manufacturing

1.3.1. AM Advantages

- *Reduction in consumption of resources*: the primary difference between AM and SM consists in the fact that AM utilizes only the precise amount of material necessary to the creation of the final product, avoiding the wastes typical of traditional SM, which, on the other hand, operates by sequentially removing material away from a solid block of material. Therefore, AM avoids wastes by design.
- *Freedom of design*: the layer by layer production methodology allows to manufacture complex shapes and geometries without any constraint
- *Low initial investment*: traditional manufacturing processes require a relevant initial investment (for instance for the purchase of the plant, the machineries, the manufacturing tools), whereas initial cost for AM technology is almost limited to the 3D printer's purchase cost. It should be taken into consideration the idea to subcontract professional services of AM in order to lower at its minimum the initial cost. Nonetheless, the convenience in terms of cost per produced unit of AM with respect to subtractive manufacturing is crucially affected by the production volume: AM is currently more convenient for the

production of small batches, whereas it is still not appropriate for mass production, which exploit economies of scale and minimize the initial cost by producing high volumes, as it will be further explained in the section of the disadvantages.

- *Economies of scope*: AM is so flexible that it is possible to manufacture an infinite variety of product with no extra cost for tooling or set-up. In manufacturing, economy of scope is *"the reduction of costs that is the result of sharing resources, processes, and skills in producing a larger range of products"* (Definition from the Cambridge Business English Dictionary). In traditional manufacturing, economies of scope are complicated to achieve because each product needs a further substantial investment in order make it possible to share the process and the resources. On the other hand, economies of scope are easily reached in AM thanks to the lack of constraints in the manufacturing phase.
- *High customization*: personalization and customization are a direct consequence of the lack of additional tooling required and the geometry flexibility
- *Weight*: products manufactured through AM technologies are certainly lighter (up to 84%) than traditional products due to the nature of construction process.
- *Stock reduction*: AM makes it possible to significantly reduce the sources of stocks since it prevents the production in batches, promoting to produce final products only when demanded, avoiding the "make to stock model", with no unsold finished goods. The only source of stock is represented by the raw material.

1.3.2. Disadvantages

- *Not suitability for mass production*: on the one hand AM astonishingly decreases the per unit cost (PUC), but the difference progressively decreases as more units are produced. This happens because traditional manufacturing benefits of economies of scale and scope, a vital competitive advantage. Scale is defined as the *"reduction of production cost as a result of making and selling* *goods in large quantities, for example, the ability to buy large amounts of materials at reduced prices"* (Definition from the Cambridge Business English Dictionary). As a consequence, factories seek to reach the Minimum Efficient Scale, which is the minimum production volume that minimizes the initial fixed cost. Since AM eliminates fixed costs such as tooling, set ups and the extremely high initial cost, the per unit cost is almost independent from the production volume; therefore, it could be said that the economies of scale cost curve in AM is almost linear (it actually has a slightly negative slope), compared to traditional manufacturing's steep curve, as it is shown in Figure 1.8.

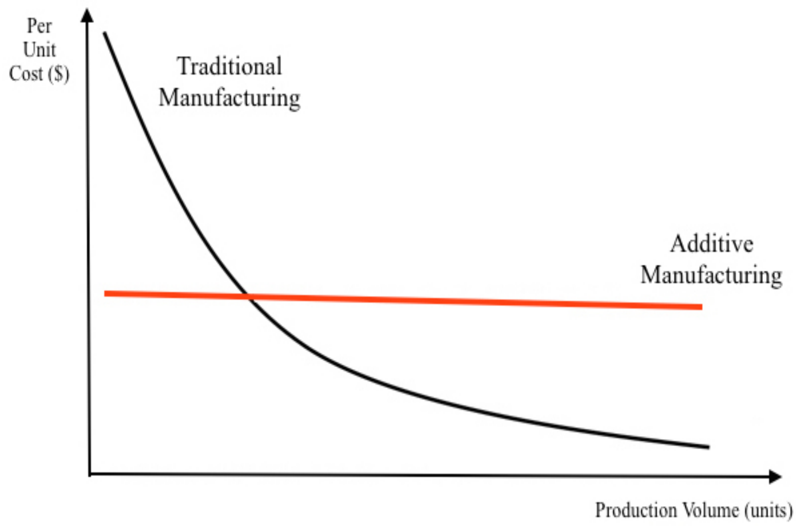

Figure 1.8: Relationship between production volume and per unit cost in AM and SM

- *Raw material cost*: the raw materials used in AM have a higher cost that raw material used for SM due to the peculiar characteristics needed. Nevertheless, it is reasonable to foresee a substantial decrease in the cost once AM technologies will be more diffused (Atzeni et Salmi, 2012).
- *Dimensions*: the maximum dimensions of the 3D printed part depend on the room available in the 3D printer.
- *Quality*: a wide application of AM is threatened by the lack of consistent quality with respect to traditional subtractive manufacturing. There is still need to improve the processes to produce products that meet the standards of SM.

Nevertheless, it should not be forgotten the fact that AM exists only since 1980s and that in few decades it has already revolutionized manufacturing.

1.3.3. Timeline comparison

It may be thought that AM will not overcome traditional manufacturing because of its current limits, but it is vital to consider that AM exists only for 40 years. Despite being a quite new technology with respect to traditional manufacturing, AM processes are already a standard for rapid prototyping and have relevant applications in the manufacturing of final products as well. Moreover, there is a huge margin of improvement, if it is considered the fact that history of traditional manufacturing is the result of centuries of studies and researches made by engineers and entrepreneurs, against the 40 years of existence of AM.

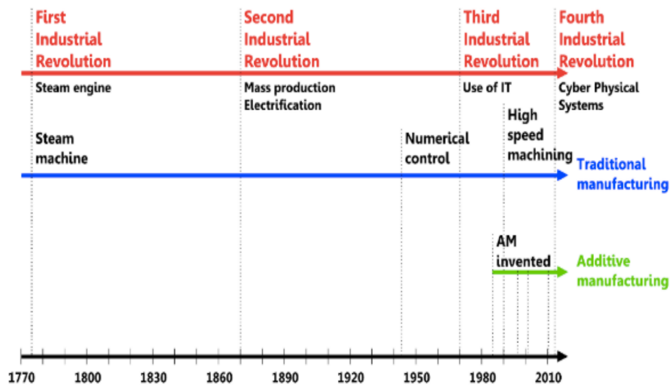

Figure 1.9: Comparison among the timelines for industrial revolutions, traditional manufacturing and AM technologies. Source: [2]

Figure 1.9 shows the time line of both traditional and additive manufacturing: the history of the former starts in 1770s with the first industrial revolution with the invention of steam engine. In 1793, Eli Whitney invented the cotton gin (cotton engine), a mechanical device that was used to remove seeds from cotton gathered by slaves in Colonial America.

The second industrial revolution started in 1870 and it is characterized by important scientific, technological and organizational revolutions in the fields of iron, steel, railways, electrification. During this period, mass production was born:

the industrial engineer Frederick Winslow Taylor introduced the *"scientific management",* which includes concepts that are still fundamental in the context of industrial engineering such as elimination of waste, standardization, rationality, empiricism. The main characteristics of mass production are:

- Economies of scale: costs are reduced by adopting the make to stock production model, increasing production volumes. Software such as MRP and MRP II are used to manage the manufacturing process, from the scheduling to the inventory control by considering the trade-off between quality, time and cost.
- Workforce is intended to perform repetitive tasks under managers' supervision.
- Product standardization: production systems are not flexible at all, thus no customization is conceived. Very high volumes of standard and basic products are produced, stocked and sold when demanded by customers.

Thanks to these factors, costs gradually decreased, making it possible for firms adopting such model to sell at a lower price. The most evident example was Ford, which made it possible to sell a car at the half of the price that a car had a that time. Significant innovations occurred between 1940-50, both from the technical and organizational point of view: numerical control allowed to automatically control and give instructions to machines through a code, permitting to achieve higher precision and quality. From the organizational point of view, in those years it started to arise in Japan the Toyota Production System (TPS), which lays the foundation for the lean manufacturing, which will be explained in detail in next chapter.

It is only in the period of the third industrial revolution, when traditional manufacturing had already more than two centuries of history and progress, that AM arose. From that moment on, it is rapidly changing: as new materials became available, new techniques have been invented, extending AM application to different industries and applications that go beyond the first usage in rapid prototyping. As years passed, AM patents started to expire and this enhances the technological diffusion and improvement. In 2005, the RepRap (which stands for Replicating Rapid prototype) project was started in the University of Bath with the aim to build a low-cost 3D printer that was able to print the major part of its own components. The project also promoted the open source characteristic of AM technology and all the designs were released in a free software license, the GNU General Public License.

In 2007, Shapeways, a Dutch start-up company based in New York, was founded with the aim to allow users to produce 3D printed products even though they do not own a AM machine: customers only have to upload their 3D printable file on the website and Shapeways can print it in more than 55 materials. Shapeways printed and sold more than ten million user-created objects in 2019. In 2008, the largest website where users can find and share 3D printing object files, was launched by MakerBot Industries, a 3D printer manufacturing company.

AM advancement has also been enhanced by the technologies that led to the rise of Industry 4.0, term coined in 2011 to express the new model of the fourth industrial revolution. At the same time, AM is a vital technology for Industry 4.0. Indeed, there exist nine main technologies defined by the Boston Consulting Group that enable Industry 4.0: Additive manufacturing; Augmented reality; Simulation; Horizontal e vertical integration; Industrial internet; Cloud; Cyber security; Big Data Analytics. The future of AM and its possible applications are still uncertain since continuous innovation occur very rapidly.

1.4. AM applications

From the industrial point of view, Rapid prototyping (RP) has been the main driver of AM development and, as a consequence, one of its first applications.

Once some AM techniques, such as powder bed fusion, were mature and precise enough to grant a quality comparable with the traditional manufacturing's, AM started to be used in all the phases of product development and for the direct production of final products. Nowadays, AM is mainly used for two generic purposes: product development and manufacturing of final products. Next sections will explain in further detail how AM is exploited in the two areas previously mentioned and the benefits that it gives.

1.4.1. AM for Product Development

Product development is the creation of products with new or different characteristics that offer new or additional benefits to the customer. Product development may involve modification of an existing product or its presentation or formulation of an entirely new product that satisfies a newly defined customer want or market niche (Ullman, 2010; Ulrich and Eppinger, 2003).

AM makes it possible to rapidly realize physical representations of ideas that can be tested before the final version of the product is made and launched into the market. Thanks to this revolution, the time to market and the development cost has significantly reduced, making AM a crucial technology for product development.

Even though the product development process differs from one firm to another depending on the industry, the product developed and several other variables, it is customary to distinguish four main stages. The following lines will describe such phases and the way AM is vital for the success of product development activities:

- *Product planning* is the initial phase of product development process, during which market needs and technological opportunities are researched. Based on the results of the research, it is defined the so-called *product brief* or *design brief*, a very high level of the product.
- *Conceptual design* is the first activity in the product development process that deals with the technological details of the new product. AM allows the development of non-functional prototypes (also known as concept models), which consist in a 3D representation of a product brief in order to assess the general aesthetic and proportions and collect the first appreciations and suggestions. Being non-functional, this kind of prototypes cannot test and verify the mechanical forces and the technical features of the product. It is easy to understand that at this stage AM has a pivotal role over subtractive manufacturing seeing that it is the only technology that is able to manufacture elementary but meanwhile realistic design concepts within a very short time and at a low cost.
- *Design and engineering*: once the concept model is tested and approved, the product architecture is defined and choices concerning *make, develop or buy*

decisions are taken. The engineering work is carried out: components and material are selected and computations are made to dimension them. The peculiar feature of AM at this stage of product development is that, given the design freedom it provides and the speed and ease with which the technology can be applied, it reduces the technical, time and cost restraints associated with traditional technologies. This allows an increase in the number of design and engineering iterations and a more rational distribution of the cost of demonstrator and prototype manufacture.

- *Prototyping and testing* phase is distinguished from the *design and engineering* stage for historical and conceptual reasons, even though nowadays firms tend to carry out them in parallel. In this phase, AM technologies are used for the creation of functional prototypes, which allow to test the technical features of the product (for instance the mechanical behaviour and the thermal properties) or a design objective (for instance, safety and maintenance properties). Depending on the application, functional prototypes are scaled or they have the actual size of the final product. The results of validation test of the prototypes are a decision-making tool that give indications about the quality of the product and possible improvements. Similarly to what already said for the previous stages of the product development process, the advantage that AM grants at this stage is to tremendously decrease the manufacturing time and the cost of design changes.

Once all the phases that have just been described are performed, it is necessary to design the process. Afterwards, the product is finally produced and launched into the market.

Even though the benefits of AM in the product development process are countless, there are some concerns as well: as more as AM facilitates product development, it contributes to the decrease in the degree of experience, expertize and training required to design a product, hence leading to an entry in the field by non-professionals [3].

1.4.2. AM for Parts Manufacturing

Even though the development of AM was born in the context of rapid prototyping in product development, it is currently well employed also for the production of final parts. The development of innovative, advanced AM techniques has progressed greatly in recent years, yielding broader and broader industry applications. Compared with subtractive manufacturing, AM is particularly suitable for producing low volumes of products, especially for parts with complex geometries. AM processes also offer great potential for customization, such as fabricating personalized implants for hip and knee replacements.

A distinction must be done for AM used for Rapid Tooling (RT) and for Direct Additive Manufacturing (DAM). Born in the 1990s, Rapid Tooling denotes the realization of moulds or functional tools with complicated shapes intended for mass production through the techniques used for rapid prototyping. RT is an indirect use of AM since the latter is involved in the production of the tool rather than in the production of the final product. Nevertheless, it would be a mistake to underestimate the importance of such application, as it enables to produce and modify tools at a low cost and a high speed, without the aid of the expensive traditional machining methods.

DAM stands for the production of products or components that are finished and functional. In general, it can be noticed that AM is mostly used in applications involving low production, small part sizes and having complex geometries (Berman, 2012). In particular, AM is mostly adopted in three major areas: made-to-order manufacture and customisation, short series or high added value items and made-to-measure manufacture. Additionally, a very frequent AM application regards the production of spare parts: instead of having high spare parts stock levels, manufacturing enterprises only save the 3D files and print them whenever a component needs to be substituted. Over the last years, DAM is accountable for a growing portion of use of AM. A part from the industrial applications, which will be explained in the following lines, a further usage that is becoming quite common is the *home fabrication:* users buy the appropriate equipment and directly print objects in their own place. In the past, only very passionate hobbyist owned 3D printing kits, but given the increasing adoption rate, there are some experts announcing that *''desktop manufacturing revolution [...] will change the world as much as the personal computer did''* (Anderson, 2012 [4]). Figure 1.10 shows the different AM adoptions, highlighting that even though on is successive to the other, every phase is an extension of the previous one and does not make it obsolete (Rayna et al, 2016 [5]).

Adoption stage	Started	Design	Tooling	Manufacturing	Distribution
Rapid prototyping	Early 1990s	✓			
Rapid tooling	Late 1990s	✓	✓		
Direct manufacturing	Late 2000s	✓	✓	✓	
Home fabrication	Early 2010s	✓	✓	✓	✓

Figure 1.10:AM adoption stages. Source: [5]

For what concerns industrial DAM, it is necessary to examine which industries make a higher usage of AM. It must be taken into account that also the firms that operate in sectors where AM is not broadly used, such as logistics and transportation or construction, are demonstrating an always higher interest and awareness of AM technology, even though its application would imply a different and unexperienced business model. For instance, according to the report *"3D printing: hype or game changer?"* [6], logistics and transportation companies are currently six times more interested and in AM than in 2016.

a) Aerospace industry

The aerospace industry is one of the first industries that has started to make an extensive use of AM, as well as being the industry that has the has the highest experience: 78% of companies operating in the aerospace industry interviewed by EY [6] claim that they have used AM. The high usage is due to the lightweight design, the complex geometries and the unconventional materials that characterize aerospace components, which are also very expensive, complicated and time consuming to manufacture with traditional techniques. What is more, AM technology is extremely fitting aerospace industry's needs because the production is restricted to a maximum thousands of parts.

General Electrics (GE) can be considered as an example of the importance of AM for aerospace firms. As stated by last years' GE annual reports, the company accredits its growth and increase in productivity to the substantial investments in AM technologies. GE makes continuous investments in firms specialized in AM technologies such as Morris Technologies in 2011 and Arcam AB, a leading Swedish metal 3D print manufacturer, as well as Concept Laser, a German 3D print firm, in 2016 for $ 1.4 Billions [7]. What is more, GE opened a Centre for Additive Technologies (CATA) at a cost of $ 40 Millions.

b) <u>Medical industry</u>

AM technologies find ample applications in the medical sector: medicine practices are being not just transformed but also revolutionized by AM. Examples of the crucial role of AM in medicine go form the possibility of making prototypes to the opportunity to create a very high quality bone transplant, passing through the scan and the reproduction of damaged bones that can be analysed. Thanks to AM technologies and the limitless forms and shapes that they can create, it is possible to accomplish transplants of bones that are practically identical to the original ones, achieving a better result while saving time and costs (James et. al, 1998). A very common application in the medical sector is given by the dental care: AM makes it feasible to build a plaster model of patients' teeth. Another new AM application in the biomedical industry is represented by the Biofabrication, defined as the *"production of complex living and non-living biological products from raw materials such as living cells, molecules, extracellular matrices, and biomaterials"* [8].

The most appropriate AM technologies in the medical fields are Laser Stereolithographic, laser sintering, FDM and layer laminate manufacturing; while the materials employed must obviously be not threatening for the human body and must not be rejected by it, such as biocompatible polymers.

c) Fashion and jewellery industry

Thanks to the extreme design freedom made possible by AM, it is extensively being applied in the development of products related to fashion, such as jewellery and apparels, where design combined with creativity is a vital element. What is more, fashion and jewellery is a sector that calls for customization and made to order high quality production and no technology is as able to meet these market needs as AM [9]. For what concerns the textile industry, AM perfectly responds to its seasonal needs: AM makes it possible a very short product development process and a fast production of new colours, design trends, new cuts. Even though 3D printed apparel is still mostly reserved to runway shows, some promising projects are making it always more close to local retail stores [10], especially items such as shoes, handbags and gloves. For what concerns footwear, it is possible to imagine that anyone will wear perfectly fitted shoes: big players like New Balance and Adidas are already developing 3D printed midsoles and Nike is experimenting the production of Flyprint uppers through solid deposit modelling.

The range of materials used for the addictive production of apparels is restricted to polymers, while there exists more freedom in the creation of jewels, for which materials vary from polymers to metals like gold, passing through metals such as bronze and stainless steel. The final polymer or metal product can be manufactured by using direct or indirect AM processes [11]: the former involves the direct fabrication of the final product by melting the metal powder through an energy source, the latter is used to produce the master pattern which will subsequently employed in the manufacture of the final product.

Figure 1.11: Example of AM applications in fashion. Source: “"2019 State of the Art in 3D Printed Fashion", by All3DP”

1.5. Diffusion of Additive Manufacturing

Figure 1.12 shows the Gartner Hype Cycle for Additive Manufacturing, which is a graphic representation of the technology’s state of maturity and adoption, with a forecast of the time of maturity. The Hype Cycle graphs describe five main phases:

- *Technology Trigger*: there are very high expectations, about the success of technology, even though no real application of the technology exists or it is commercially viable;
- *Peak of Inflated Expectations*: illusions, fed by advertisement, grow until they become unrealistic;
- *Trough of Disillusionment*: the market is extremely disappointed by the failure of expectations to materialize thus it ceases to pay attention to technology and considers it as a failure;
- *Slope of Enlightenment*: it starts to be understood the way the technology can give a beneficial contribution to some specific industries. As a consequence, realistic applications emerge;

- *Plateau of Productivity*: the last phase sees the affirmation of the technology in the market.

Gartner's 2018 Hype Cycle for Additive Manufacturing indicates that there are very high expectations in the fields of 3D printing for IP Protection, Oil & Gas and Organ Transplants. 3D Printing in Manufacturing Operations and some applications in the medical field (such as Bio printing for Life Science R&D, printing of medical devices and bio printed human tissue) are in the phase of *"Trough of Disillusionment"*.

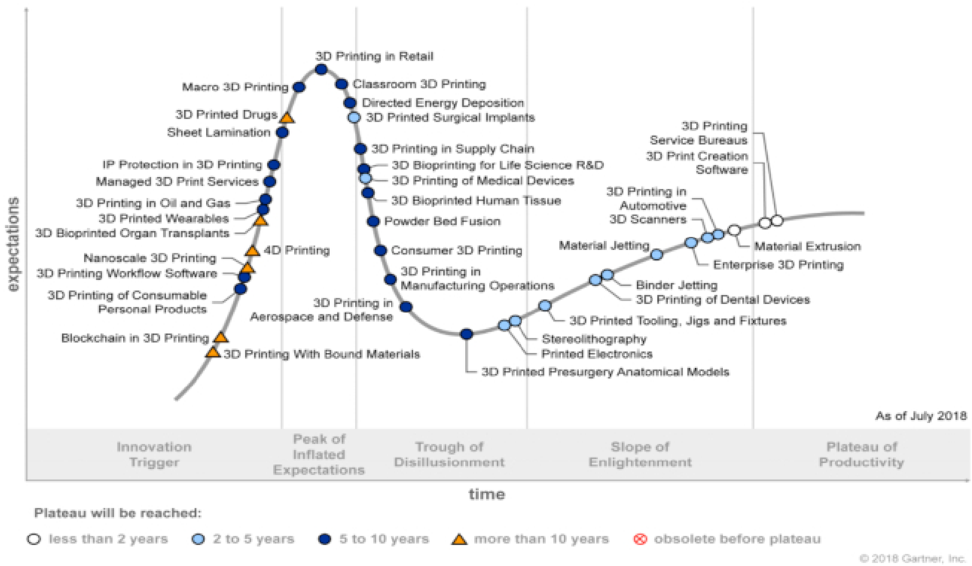

Figure 1.12: Hype effect for Additive Manufacturing

The Roger and Moore ([12], [13]) model helps to identify when AM will break through and be eventually used to its full potential. According to such model, there exist five typologies of consumers: Innovators (2,5% of adopters), Early adopters (13,5%), Early majority (34%), Late majority (34%), Laggards (16%). While innovators and early adopters are technology oriented customers that want to enjoy of the first mover advantage, the Early Majority has a more rational behaviour and switches to a new technology only when the technology has a certain degree of reliability. The *chasm* between the early adopters and the early majority is very significant because it implies that the technology is mature enough to satisfy not just the enthusiasts and the innovators, but also the rational adopters. a product that is highly successful with early adopters is likely to be unsuccessful when the early majority segment. This is not the case for AM: AM for finished products has crossed the chasm, reaching the 18% of companies in 2019 (compared to the 5% in 2016). What is more, 46% of consumers is expected to apply AM for the end-use parts by the end of 2022 [6].

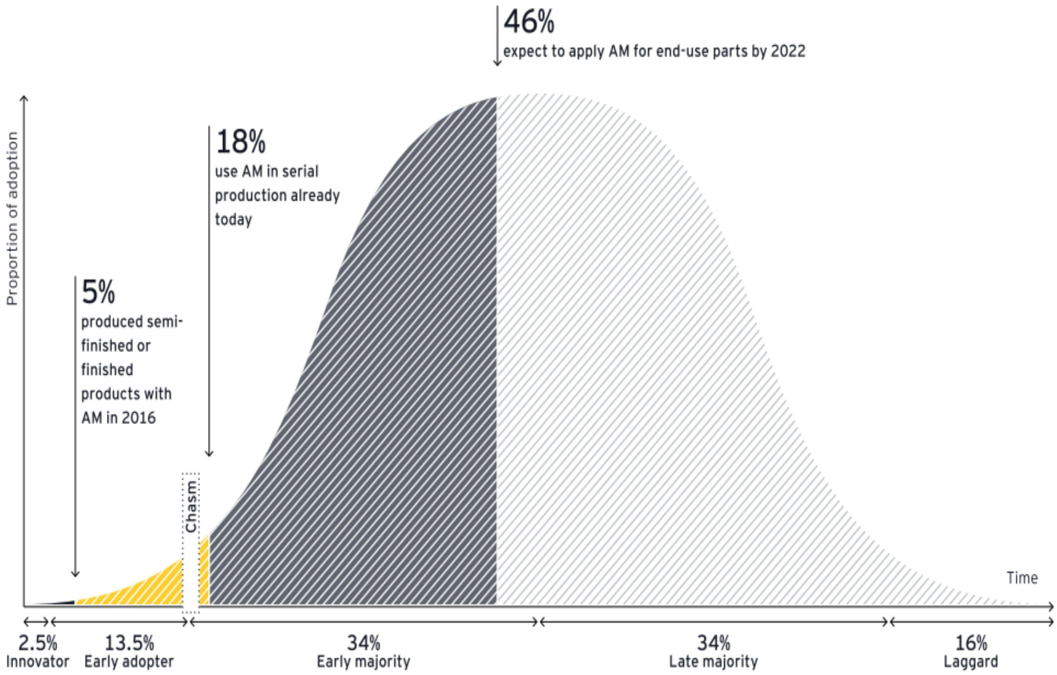

Figure 1.13: Adoption of AM to make end-use parts. Source: [6]

Rogers lists five attributes that have significant impacts on the rate of adoption of an innovation, explaining, in the statistical sense, between 49 and 87 percent of the variation in adoption rates: relative advantage, compatibility, complexity, triability, observability., explains the five factors for the AM technology:

- *Relative Advantage*: degree to which an innovation is perceived as being better than its precursor technology or idea (Rogers, 2010; Moore & Benbasat, 1991). As anticipated, literature in AM shows that there are several advantages with respect to subtractive manufacturing. Garza et al. [14] in the observational study "*Understanding the adoption of additive manufacturing"* mentions as the most appreciated advantages the geometric complexity for free and the fact that the 3D printer produces the component autonomously.
- *Compatibility*: degree to which an innovation is perceived as being consistent with the existing values, needs, and past experiences of potential adopters (Rogers, 2010; Moore & Benbasat, 1991). The less of behaviour change is required to adopt an innovation, the more rapidly it will diffuse.

- *Ease of use*: degree to which the innovation and technology is easy to learn and use (Moore & Benbasat, 1991). According to Garza et al, the usage of CAD (Computer Aided Manufacturing) and the choice of the AM technology is one of the greatest difficulty that users encounter when using 3D printing.
- *Triability*: degree to which an innovation may be experimented with before the adoption.
- *Obserivabili1y*: the degree to which the results of an innovation are observable to others. The higher the perceived Observability of 3D Printing, the higher the chances of its adoption.

The factors that affect the most the adoption of AM are Relative Advantage, Ease of Use and Trialability (Marak et al., 2019 [15]).

Another important factor that helps to understand the diffusion of a technology is the patent analysis: they are considered one of the most relevant output indicators of the technological innovation process (Hidalgo et al. 2009; Rodríguez and Tello, 2012). Since 2007, there has been a significant increase in the number of filled patents in AM: from less than 3K in 2009 tom more than 24K in 2018). In 2009 a key FDM patent expired and entered the public domain, driving the cost of FDM printers down, which could be the cause of the growth in the rate of increase of number of patents in the years 2010-2015. 3D printing has not yet reached the state of maturity therefore there is still great opportunity of growth: analyst firm IDC projects that worldwide spending on 3D Printing alone, a subset of our AM category, will reach about $22.7B by 2022 [16].

Figure 1.15 shows the companies that own the highest quantity of patents considering both the number of patents and the families of patents: General Electric, HP Inc and United Technologies Corporation are the three strongest 3D printing-related patent owners.

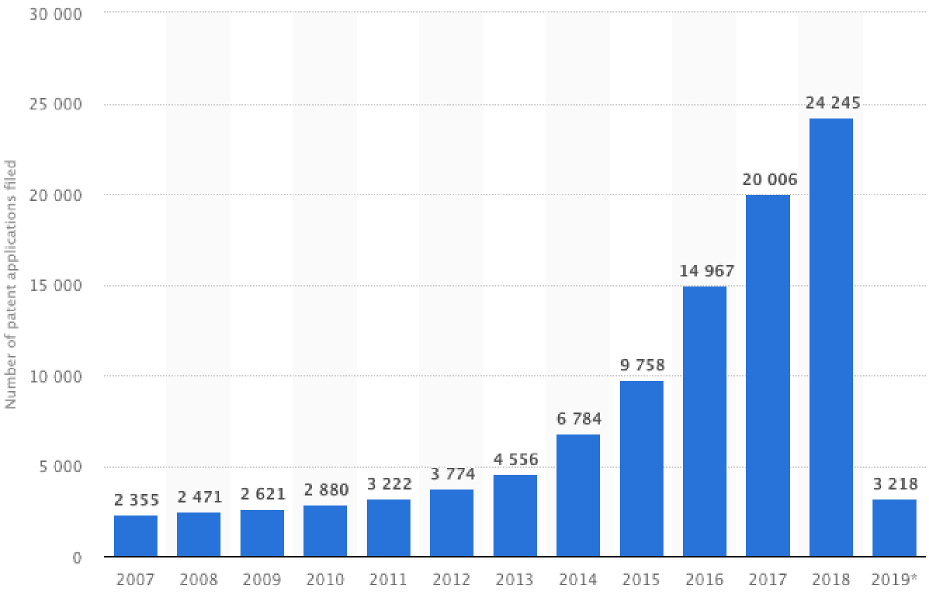

Figure 1.14: Number of 3D printing patent applications filed worldwide 2007-2019. Source: IPLYTICS

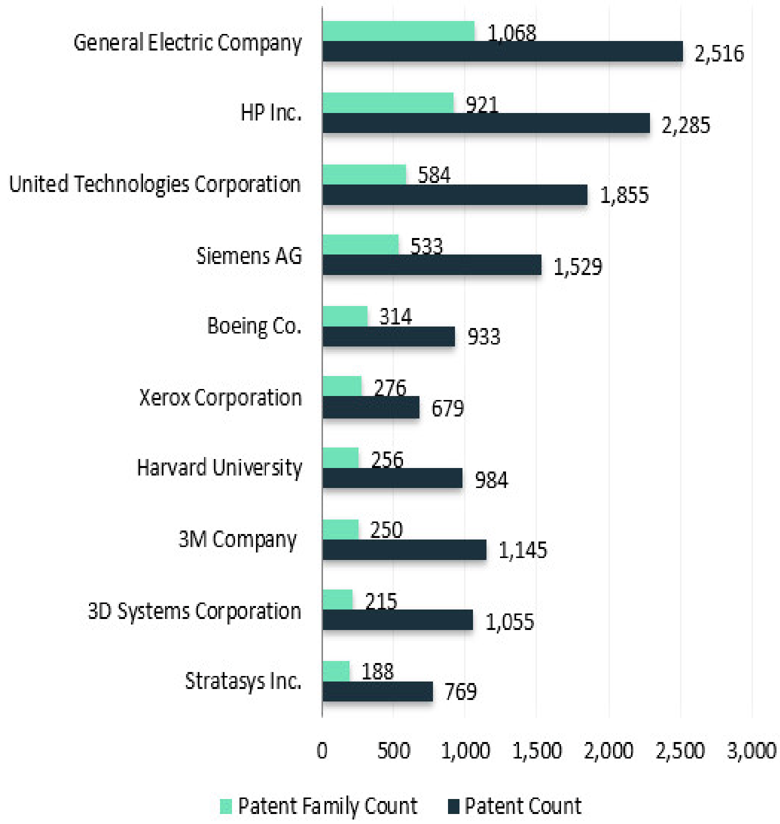

Figure 1.15:Top owners of 3D printing patent . Source: IPLYTICS

Chapter 2

Lean Management in Additive Manufacturing

2.1. Lean manufacturing

Lean manufacturing principles were born in the company Toyota after the Second World War; however the expression *"lean manufacturing"* was coined only in 1988 by John Krafcik in the article *"Triumph of the lean production system"* in the MIT Sloan Management Review [17]. It encompasses a broad array of industrial philosophies, concepts, and strategies thus it is arduous to give a precise definition; though, it can be affirmed with no doubt that its essential aim is to create added value for customers reducing as much as possible the wastes, "doing more with less" [18]. In their masterpiece *"Lean thinking - banish waste and create wealth in your corporation*" [19], Womack and Jones identified the five core principles on which lean production is founded (Figure 2.1).

1. *Value*: the critical starting point is the *Value*, defined as *"capability provided to customer at the right time at an appropriate price"*. Producers should make only activities that give the product an added value for which customers are willing to pay. Other operations that do not add any value for customers are considered as *"muda"* (Japanese term for waste) and should be eliminated.

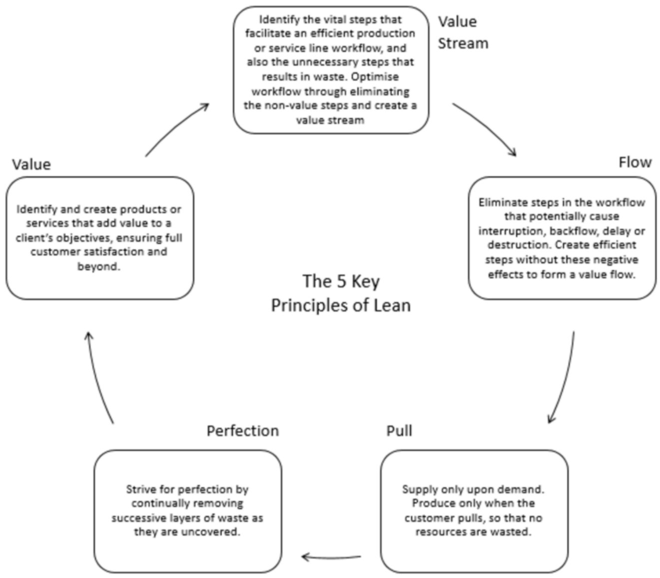

Figure 2.1: 5 key lean principles of lean. Source: [19]

2. Value stream: *"The specific activities required to design, order, and provide a specific product or service from the point of product (or service) concept, through launch, ordering raw materials, production and placing the product (or service) in the hands of the customers"* [20]. After careful analysis of the value stream, operations are divided into: (i) Value Adding (VA), activities that clearly create value for customers [21]; (ii) Necessary but non-value adding (NNVA, Type one muda), activities that create no value but that are unavoidable with the current technology and assets; (iii) Non-value adding operations (NVA, Type two muda), activities that do not add value to the product and that are not necessary for the realization of it. The latter activities, which will be analysed in depth in the next section, should be reduced, if not eliminated.
3. *Flow*: once wasteful activities are eliminated, VA activities are reengineered in order to obtain a smooth and uninterrupted process.
4. *Pull*: in order to reduce resources and inventory wastes, production depends on the actual demand and not on demand forecast, as foreseen by the push production system, which follows the make to stoke model. The advantages of pull system are: Reduced WIP and Cycle Time, smoother Production Flow, Improved Quality, Reduced Cost [22]. (Figure 2.2)

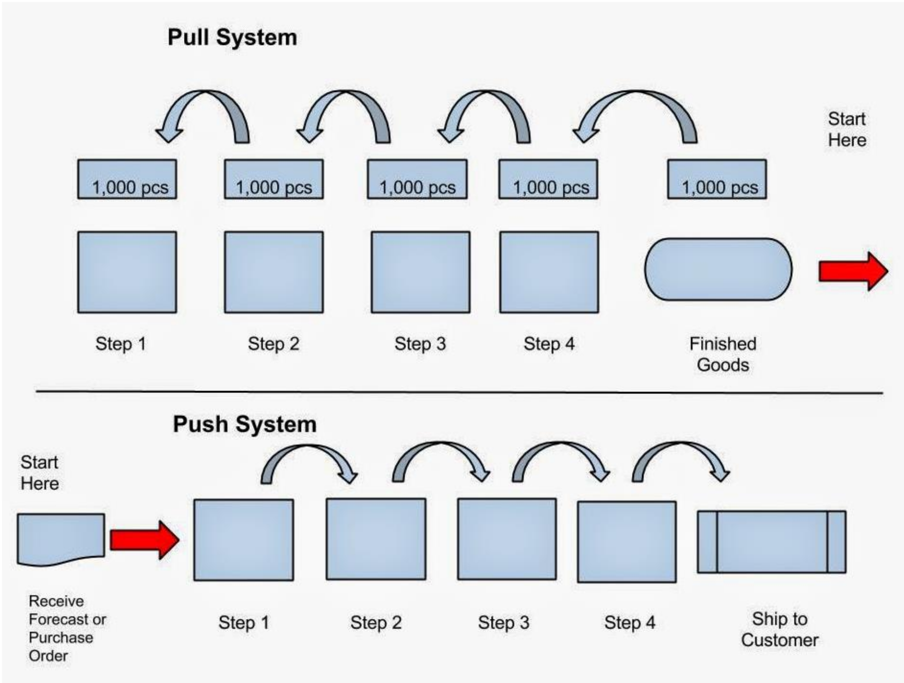

Figure 2.2: Pull and push production systems

5. *Perfection: "complete elimination of muda so that all activities along a value stream create value."* This fifth principle makes the pursuit of lean a never-ending process, as there will always be activities that are considered muda in the value stream and the complete elimination of muda is more of a desired end-state that a truly achievable goal.

Finally, lean philosophy can be synthetized as *"Creating more value with less."* Today it is arguably the paradigm for operations and its influence can be found in a wide range of manufacturing and service strategies (Katayama and Bennett, 1996).

2.1.1. Muda

The following section provides the list of the seven main Non-value adding operations (NVA, Type two muda):

1. *Overproduction*: production (or purchase) of items before they are ordered by a customer. Producing more than necessary leads to high level of storage of inventory, increasing the inventory cost and the risk of obsolescence, besides

excessive lead time in the production line. The TPS (Toyota Production System) attempts to "Just in Time" (JIT) because every item is made only when it is needed or required by the customers.

2. *Waiting*: idle time in which the item is not processed or moved.
3. *Transporting:* the product does not gain any value for which the customer is willing to pay when it is moved from a place to another. On the contrary, when the product is touched or moved unnecessarily there is a risk that it could be damaged thus it is convenient to move it as little as possible.
4. *Over processing:* make operations that give the product a higher quality than the one required by customers. This also includes using components and tools that are more precise, complex, expensive or higher quality than absolutely required.
5. *Unnecessary Inventory:* components necessary to manufacture an item present in the process, in the form of raw material, work in progress (WIP), or finished product. It is a direct effect of overproduction and waiting. The higher is the unnecessary inventory, the higher are the lead times, the delays in the identification of problems in the production line and the waste of production space.
6. *Unnecessary/ Excess Motion:* movement of resources through the shop-floor that does not add any value to the final product. Motion includes also personnel's movements, which may lead to safety and health issues.
7. *Defects:* Having to discard or rework a product due to earlier defective work or components results in additional cost and delays.

In addition to the 7 *muda* described above, two other categories of waste are identified: *muri* and *mura*. The former indicates the overburden, which is the waste from overloading resources and people. Indeed, the work overload can have critical consequences: overloading personnel may lead to their frustration, absenteeism, injuries or accidents, whilst machinery overloading may cause early impairments or components' breaks. The expression "*mura*" refers to irregularities in work load, which generate an alternation between periods of *muri* and periods of underutilization of workforce and machineries. Hence, it is necessary to stabilize and balance the workload as much as possible.

2.1.2. Lean tools

Given the 5 principles, Lean philosophy foresees plenty of actions and tools to be implemented in order to continuously improve performances and efficiency. The most common ones are described in the following lines:

- Five-S (Osada, 1991 [23]) represent five Japanese words starting per S that aim to describe five steps to maintain clean, properly organized and effective the work station. Namely, the five steps are: *"Seiri"* (Sort: separate useful tools from unnecessary things); *"Seiton"* (Set in order: tidy such tool in a definite and precise position so that everyone knows where to look for a tool it); *"Seiso"* (Shine: clean up in the workplace in order to make problematics clear); *"Seiketsu"* (Standardize: define operating standards to maintain order and cleanliness in the workplace); *"Shitsuke"* (Sustain: promote the order and cleanliness standards and verify compliance by staff).
- Poka-yoke systems are used to minimize personnel's mistakes within the process or to immediately highlight them so that they can be corrected without serious consequences on production line.
- Single Minute Exchange of Dies (SMED) (Dillon and Shingo 1985 [24]) consists in a series of techniques to minimize setup times, which do not add any value for customers. The goal is to bring the set-up time to a single digit, in minutes, which allows to produce smaller size batches, reducing inventory and waiting times.
- Heijunka is a tool used to level production and reduce the lots' size, with the aim of producing at a constant rate and making the process more flexible to sudden changes in demand.
- Six Sigma (Motorola 1985) is an approach that aims to pursue excellence, in line with continuous improvement: the objective, in fact, is to produce only 3.4 defective parts per million. It is applied following the DMAIC cycle, which consists in the following steps: Define, Measure, Analyse, Improve and Control.
- Value Stream Mapping (VSM) is a tool used to designate the entire production path, from suppliers to final customers aimed to the research of any problematics and solutions for continuous improvement. It is particularly effective to discover transport and motion sources of waste.

- Kanban (Sugimori et al., 1977 [25]) is a common technique for Just in time and to endorse the reduction of inventory and overproduction. It is the Japanese term for "tag" or "cartel"; indeed, production is based on the presence of two typologies of cartels: When a component is used, a conveyance kanban is removed from the container, and is then attached to another container, upstream, containing other components. Likewise, parts to be processed are associated to a production Kanban. If no Kanban is accessible, any part can be processed.

2.2. AM opportunities for Lean Manufacturing

Lean manufacturing allows to standardize production processes, to balance workflow, and to produce smaller size lots with respect to mass manufacturing. On the one hand, these factors lead to crucial improvements on factory's efficiency, on the other hand, there are some concerns about the fact that an excessive degree of standardization may have a negative impact on the company's innovation capability (Chen et al, 2009 [26]). Indeed, companies should not just improve existing processes, but also pursue other forms of innovation. Within the Management of Technology (MOT), Abernathy and Clark (1985, [27]) categorized innovations into four group depending on the degree of changes they bring in the technology and in the market: architectural, niche, regular and revolutionary; whilst Henderson and Clark (1990, [28]) distinguished innovation into incremental, modular, architectural and radical. In the context of taxonomies, lean manufacturing is a source of regular and incremental innovation. The former implies crucial positive effects on efficiency, production cost and performances, but it does not involve a significant change in market and technology; the latter indicates that there is not a relevant variation neither in the underlying technology not in the product architecture, which is reflected in the company organization. On the other hand, AM technology may represent a radical innovation that overcomes some of the limits the prevent the complete realization of LM objectives. Lean principles aim and succeed to crucially reduce the sources of waste described above, but they will never bring to the complete elimination of such wastes and sometimes they only transfer them to the previous ring in the supply chain; conversely, AM technologies may potentially eliminate every muda.

The first waste that lean principles cannot avoid in any manner is the loss in material due to the production by removal; on the contrary, AM production process consists in the overlapping of different layers and only the exact amount of necessary material is used. The entire production, from the blank to the final product, totally occurs in the 3D printer: this means that there is no components' storage and that the only source of inventory is the raw material. Moreover, wastes due to movements in the production line are completely abolished. Being the supply chain much shorter, transportation wastes are abated. Waiting times are radically reduced as well: set up times to adapt machineries to production of different parts do not exist in AM, which is also able to reduce time to market thanks to all the advantages it provides in the product development phase. Another important advantage of AM is the possibility to produce by batches of one single product. Lean production is distinguished by mass production for being demand driven and for fosters smaller sized batches in order to minimize final product inventory, however the latter can be eliminated only by producing a part only when demanded by customers. This makes it possible to customize every product without any consequence on the production line thanks to AM design freedom. From a broader perspective, AM can radically reduce supply chain management costs as it is able to shorten the supply chain and be more proximal to customers. The *muda* that AM is not able to solve yet is the one about defects. In fact, AM technology is not mature enough yet to grant a consistent quality. For this reason, in next chapters defects affecting 3D printed products will be studied and a methodology to control their quality will be proposed.

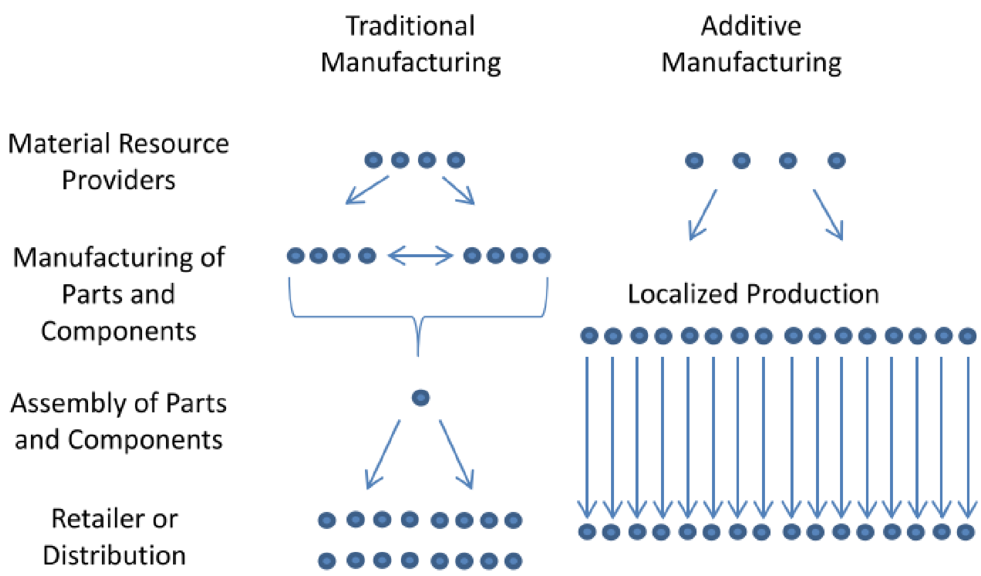

Figure 2.3: Traditional supply chain versus Additive manufacturing supply chain. Source: [29]

Because of all these advantages, it can be stated that the total production cost, including material and energy, is reduced. Next paragraph aims to show a comparison between costs, material and energy used in traditional and additive manufacturing.

2.3. AM cost analysis

In the previous chapter, advantages of AM over traditional techniques were explained, however the crucial point of decision making are costs and economical breakeven points for different technologies. Moreover, it must be clarified that AM costs and benefits strongly depend on the industry considered thus an industry-specific investigation of AM-costs over the whole lifecycle would be necessary. However, at this stage and for the copes of this thesis, a general cost analysis will be provided.

There exist two main methodologies to perform a cost analysis (Young 1991, [30]): the well-structured cost and the ill-structured cost. In the previous paragraph, it was presented an ill structured cost analysis, which considers costs that are hidden in the supply chain such as inventory, production failures and set up costs. It is now necessary to make a well-structured cost analysis where materials, labour and machine costs for AM are investigated. In literature, two methodologies to analyse AM costs are proposed: the first one implies a comparison between costs in AM with traditional technologies (subtractive manufacturing and injection moulding) aimed to understand under which conditions AM is convenient; the second one consists in the identification of the resources used in order to assess in which steps there can be some reductions. Two principal models are particularly interesting: Hopkinson and Dickens (2003, [31]) and Ruffo et al. (2006, [32]). Hopkinson and Dickens compute the average cost per part considering materials, labour and machine costs for three AM technologies (stereolithography, fused deposition modelling and laser sintering) and compared them with injection moulding, under three important assumptions, typical of traditional manufacturing: (i) the same depreciation of 8 years is set for both AM machine and the injection moulding furniture); (ii) the machine has high utilization rates (~90%) like injection moulding apparatus, which is mostly used for high volumes; (iii) only a single type of product is manufactured for one year, even though the huge AM advantage is the great variability in samples that can be produced. In this analysis, energy consumption and space rental are not considered since they are accountable only for less than one percent of the total cost. The results of the study show that the AM's uppermost cost is the machine cost, regardless of the technology (even though fused deposition modelling machines costs are considerably lower than others'). Material costs are a meaningful component of the final cost, whereas labour cost are not particularly relevant. For what concerns the comparison with injection moulding, it emerged that AM techniques can be economically convenient with respect to injection moulding only in case of volumes not exceeding a certain quantity.

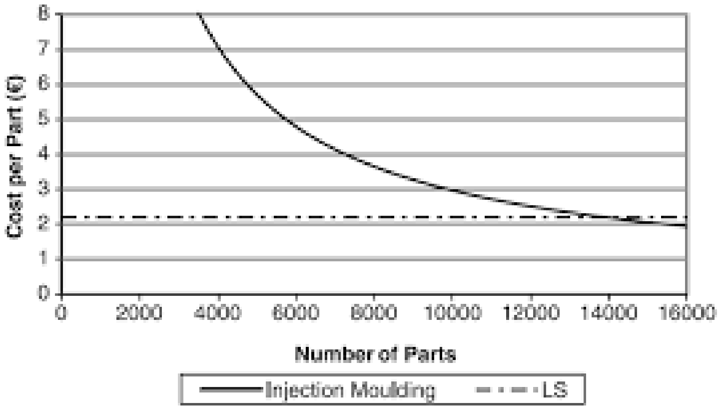

Figure 2.4: Comparisons between cost per part in Injection Molding and laser sintering. Source: [31]

Ruffo et al. tried to overcome Hopkinson and Dickens' restrictive assumptions. They tried to adapt the model to low/ medium volumes, which are realistically more suitable for AM. In order to achieve this goal, they proposed a cost model for laser sintering technology that considers (i) direct costs, namely material costs computed as the product of material's price $P_{material}$ in €/kg and the mass M in kg; (ii) indirect costs, calculated as the product of the total building time (T = time to scan the section + time to depose the powder layer + heating times) and a cost rate ($P_{indirect}$). Total cost is the sum of these two costs and cost per part can be obtained by dividing the total cost per the number of parts produced.

$$C = P_{Material} * M + P_{Indirect} * T$$

The results of their research slightly differ from Hopkinson and Dickens study (Figure 2.4): the curve is not flat, but it has a negative slope for low production volumes and it presents a sawtooth shape due to the filling of the machine bed space and set up times. Moreover, it resulted that per part costs are actually higher than the ones resulted from Hopkinson and Dickens' research.

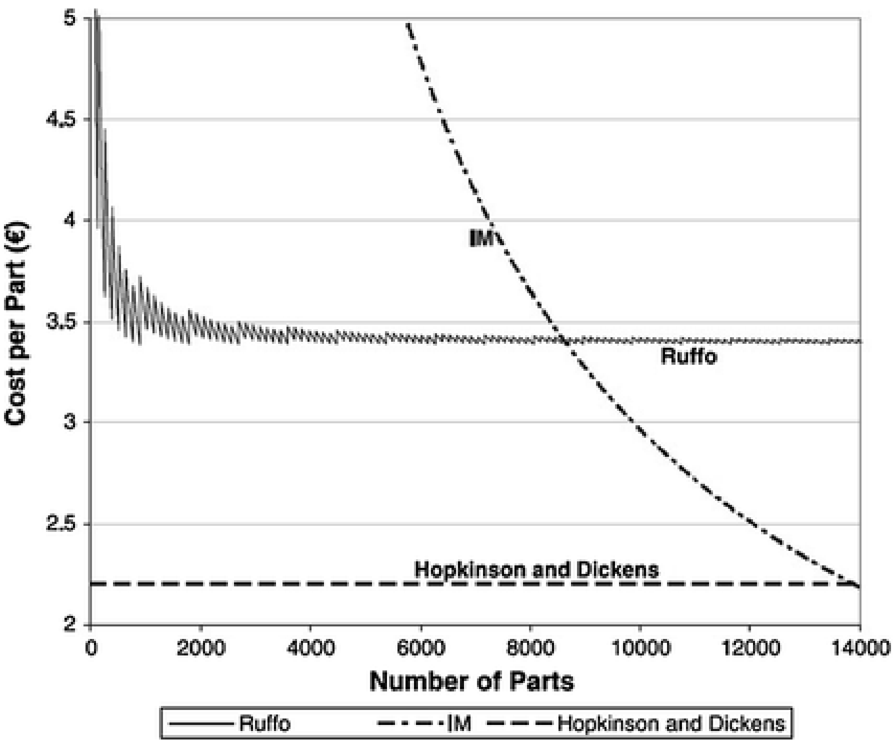

Figure 2.5: Cost model comparison of LS and IM. Source: [32]

In a well-structured costs perspective, it is necessary to analyse in further detail the three main factors: material, machinery and labour.

For what concerns material, on the one hand the quantity of material used in AM is lower than the one used in traditional manufacturing, on the other hand, since AM is a relatively new technology, material costs may exceed traditional manufacturing ones. Indeed, material costs constitutes more than 30 percent of total AM cost, against an approximately 0.2 – 0.7 percent for traditional manufacturing. Atzeni et al (2012, [33]) made a comparison between a traditional high-pressure die-casting and direct metal laser sintering for the production of end-usable metal parts and it emerged that in the first case material cost amounted to 2.59 € per part (16 € per kg), against a 25.81 € per part, almost ten time more expensive, (145.00 € per kg) in the second case. For what concerns plastic material cost, Atzeni et al (2010, [34]) compared the cost for the production of a plastic part through the traditional injection moulding and AM with two SLS machines P390 and P730. In that case, it resulted that the material cost per part was 0.00105 €, against 950 € for the machine P390 and 2,000 € for the 3D printer P730. There is no doubt on the fact that AM raw material costs are currently less convenient than traditional manufacturing ones, however it is believed that the increasing AM technologies' usage can create an economy of scale effect and lead to a reduction in raw material costs. Such decrease can, in turn, foster AM technology further adoption. (Stoneman 2002, [35]).

With reference to labour costs, AM processes radically break them down: labour activities related to AM include the data preparation, the refilling of raw material in the machine and post processing activities such as support removal; whilst the production process itself is nearly labour free. According to the aforementioned researches, labour costs are accountable only for the 2 or 3 percent of total cost.

Machineries represent the main driver of total cost, causing on average 60–70 percent of total direct costs. However, there are important distinctions depending on the typology. In general, it can be stated that metal machineries are much more expensive than plastic ones and that prices range from $ 0.1 million for industrial polymer systems and $ 1.0 million for industrial metal systems. Nowadays, there is an ever-increasing availability of low-cost desktop 3D printers on the market whose price can range from \$ 300 to \$ 1000.

Chapter 4

Typologies of defects in Additive Manufacturing

Quality of 3D printed products can be affected by defects that involve three main categories: (i) geometry and dimension, (ii) surface quality, (iii) mechanical properties.

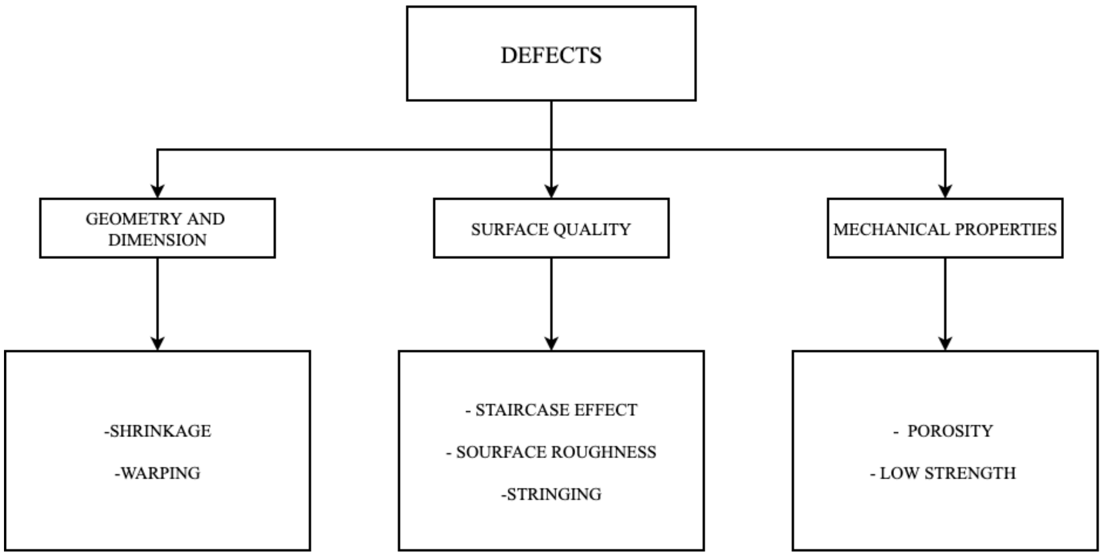

Figure 0.1: Defects in AM

Figure 0.1 offers a synthesis of the main defects, that will be described in further detail the following sections. Figure 0.2 represents an Ishikawa diagram as an attempt to explain the causes of defects in AM. Defects can be due to incorrect printing settings (e.g. temperature, pressure), inconveniences in the machine such as lack of maintenance, mistakes in the design model or its conversion into printable files, the feedstock and finally mistakes due to inexperience of users, who often proceed by trial and error.

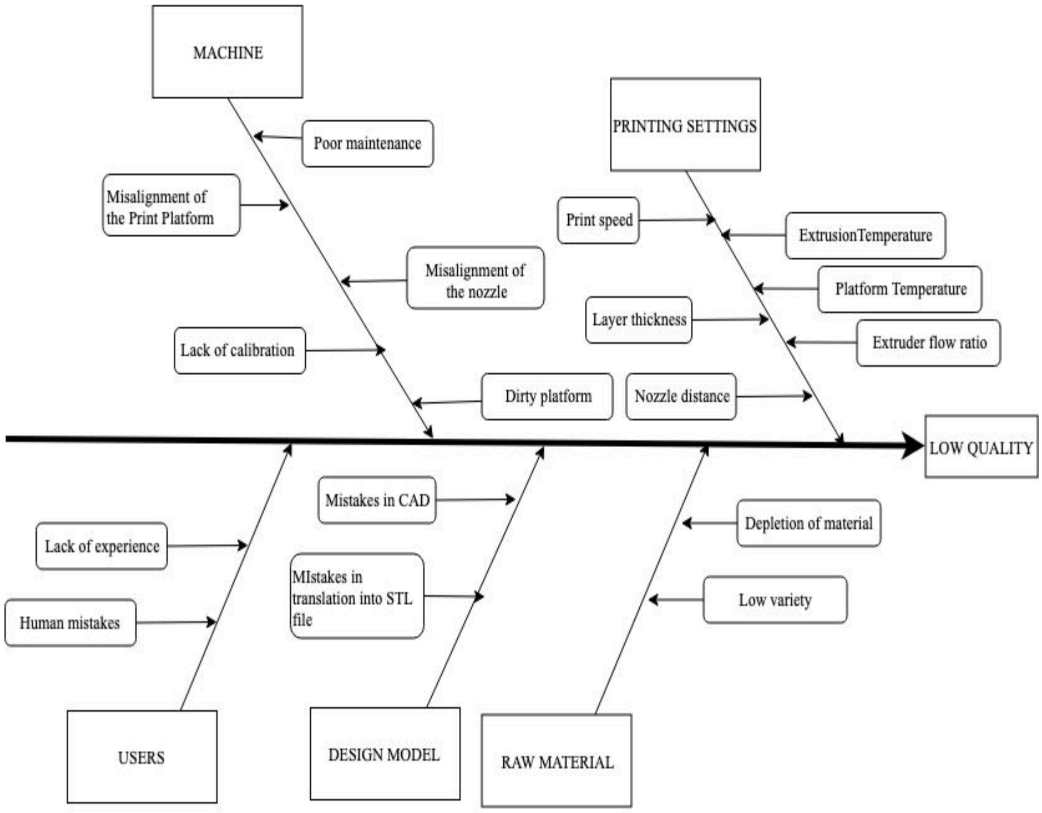

Figure 0.2: Ishikawa diagram

2.4. Defects affecting geometry and dimensions

Geometry accuracy is the deviation of the printed object with respect to the form of the CAD model; dimension accuracy is the degree of compatibility between the dimensions of the obtained product and the nominal dimensions foreseen by the CAD model (Górski et al, 2013 [36]). Geometrical and dimensional accuracy are considered crucial control issues in direct AM as they remain a *"major bottleneck for application of 3Dprinting in direct manufacturing"* (Huang et al., 2015 [37]). Nowadays, AM technologies are able to accomplish accuracies of maximum values of 100 microns and it is generally necessary to add further processing to additive manufacturing processes in case more precision is needed [38].

The most widespread defects affecting geometry and dimensions are shrinkage and warping. The former is a geometric reduction in the size of the product whilst the latter is a change in the nominal shape caused by a non-uniform shrinkage.

2.4.1. Shrinkage

Shrinkage is a *homogeneous* decrease in length, area or volume of a component with respect to the model without any external force due to the cooling phase in thermal processes when there is a phase change from liquid to solid. Huang et al [37] proposed a description of the model of shrinkage: let's assume that a product has a nominal shape Ψ_0 and actual shape Ψ. It is appropriate do define the shrinkage effect as:

$$\Delta\Psi = \Psi - \Psi_0$$

Shrinkage can be distinguished into:

- *in-plane shrinkage:* shrinkage occurs in the XY plane;
- *building direction shrinkage:* shrinkage occurs in the Z plane. It is the most frequent typology because of the so called "z-growth" phenomena;
- *isotropic*: shrinkage occurs identically in all directions

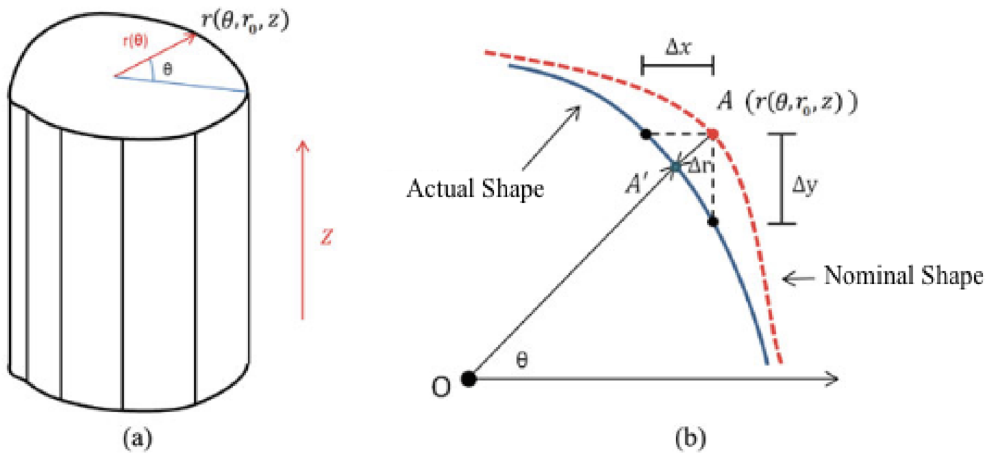

Figure 0.3 (a) Polar coordinate representation and (b) shrinkage under the polar coordinates. (Source: 37)

Chen et al. [39] consider shrinkage rate as the most significant indicator of dimensional accuracy and they define it as the ratio between actual dimensions of the manufactured part and the nominal dimensions designed by CAD.

In case of isotropic shrinkage, the linear shrinkage (S) and the volumetric shrinkage (S_v) are related by the following equation [40]:

$$S = 1 - (1 - S_v)^{1/3}$$

Assuming that $S_v << 1$,

$$(1 - S_v)^{1/3} \approx 1 - S_v/3$$

Therefore,

$$S \approx S_v/3$$

In such case, it is very straightforward to prevent and correct the defect by applying to all dimensions a "shrinkage compensating factor" and building the sample with a bigger size in order to compensate the restriction and obtain a product that respects the features proposed by design. Unfortunately, isotropic shrinkage is extremely uncommon because cooling is associated with a phase change, which occurs at the surface; therefore, it is particularly complex to compensate. Many studies have been carried out until now ([41], [42], [43], [44]), and it has emerged that machine settings importantly affect the possibility that the shrinkage effect arises.

2.4.2. Warpage

Warpage occurs when the produced parts have a shape different from the original CAD shape due to an inhomogeneous shrinkage across the part during the building process. Inhomogeneous shrinkage occurs very often because when samples are printed, they firstly expand slightly but contract as soon as they get cold. If material contracts too much, this causes the print to bend up from the build plate, leading to the so-called "curling effect". On the other hand, the strength transmission between different layers can cause the trapezoid deformation: "*applied layers additionally compress previously printed ones due to their higher shrinkage rates, while previously printed layers inhibit the free shrinkage of subsequently printed layers"* (Schmutzler et al, 2019 [45]).

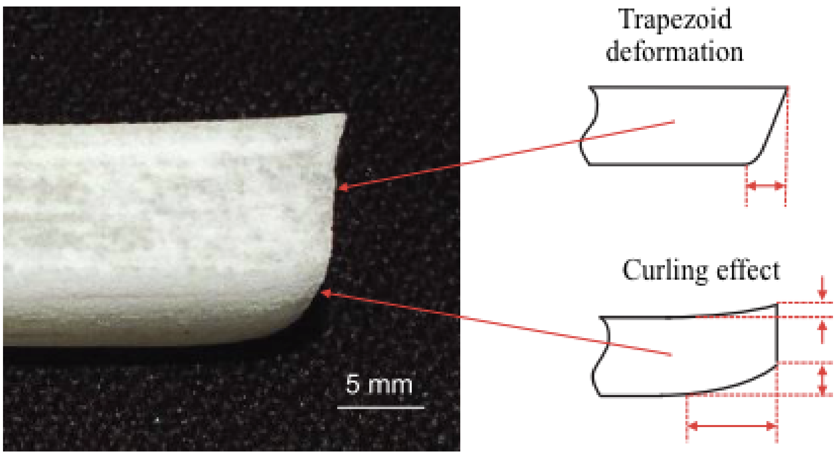

Figure 0.4: Deformations caused by inhomogeneous shrinkage. (Source: [45])

2.5. Defects affecting surface quality

Surface quality of products is a crucial characteristic since it may have a strong impact on the dimensional accuracy, as well as on the cost that incurs for the post processing activities required to obtained the expected surface finish. It can be affected by the following defects.

2.5.1. Staircase effect

The staircase effect is a common defect that occurs in the process of slicing when the layer marks become distinctly visible on the surface of the parts. One of the parameters that influence the most the presence of the staircase effect in a curved surface is the “layer thickness” (Malekipour et al., 2018 [46]): in order to manufacture an object through AM technologies, the CAD file is firstly divided into various rectangular sections and the final part is the result of the printed sections with the height of layers’ thickness. In case of a curved shape, the rectangular shape of the layers prevents the total conformation to the original shape (Figure 0.5).

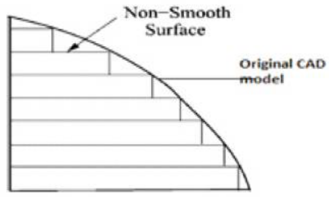

Figure 0.5Staircase effect. Source:[47]

Certainly, the thinner are the layers, the higher the number of layers deposed, therefore, the lees heightened is the staircase effect (Figure 0.6)

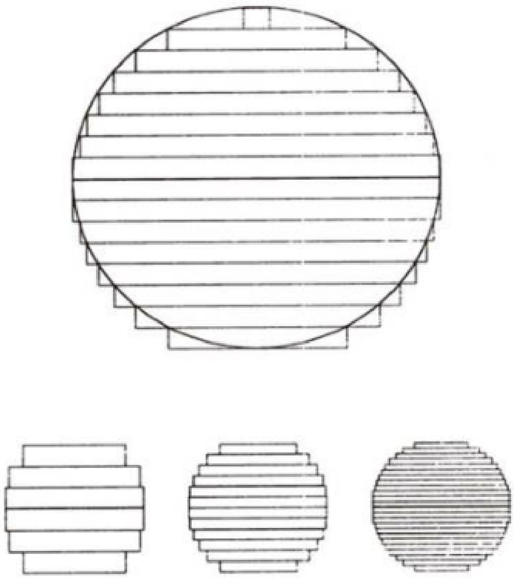

Figure 0.6: Dependency of layer thickness on the staircase effect. Source:[39]

The presence of the staircase effect is directly related to the intrinsic nature of AM technology, namely the layer by layer production, therefore post processing phases are needed in order to minimize such effect. Nevertheless, there are currently several studies that search for new technologies to prevent the defect. For instance, SCP® (Smooth Curvature Printing) is a technology realized by Solidscape that reduces the staircase effect in curved section of the products by dynamically varying the speed and the layer thickness during the production process (Yap et al., 2014 [48]).

2.5.2. Surface roughness:

Surface roughness can be defined as (i) a measure of the variance in a part's surface topology, which can vary from smooth to coarse, and as (ii) the variations in the height of a surface with respect to a reference plane. From an arithmetical point of view, it is used the average roughness (R_a), which is computed in the following manner:

$$R_a = \frac{1}{n}\sum_{i=1}^{n} |y_j|$$

where y_j is the vertical distance from the mean line to the j^{th} data point and i is the facet of interest (Leary, 2017 [49]).

The presence of surface roughness defect is mainly due to the transformation of the CAD model into STL files (facetisation or tessellation): the model geometry is approximated through a series of triangles (also known as facets) and their normal, leading to a non-smooth surface (Figure 0.7). Afterwards, the STL file is sliced into the appropriate number of layers that will have a certain thickness.

Figure 0.7: From CAD model to STL file

Adaptive slicing is a technique that is used in order to minimize the effect: the STL file is not sliced into equivalent layers, as it usually occurs, but the slicing part changes according to the profile where the minimum surface roughness can be obtained.

Another cause of the surface roughness may also be caused by shrinkage (Wenbin et al., 2015 [50]): if shrinkage occurs in one layer, it may cause the successive layers to shrink as well. The cumulative effect can result into a stepped surface.

Moreover, printing parameters can be controlled in order to minimize as much as possible the defect. According to the literature studies in surface roughness in AM made by Hartcher et al. (2019, [51]), it is agreed that the parameters that affect the most the surface roughness are the print speed and the building orientation of the sample. On the other hand, there exist different ideas regarding the influence of the parameter "layer thickness": Vasudevarao et al. (2000, [52]) and Pérez et al (2002, [53]) agree on the fact that since the staircase effect has a negative impact on the surface roughness thus layers' height is a crucial parameter that influences it, whereas Campbell et al. (2002, [54]) claim that it is found that staircase effect is not a relevant cause of surface roughness.

2.5.3. Stringing or Oozing

Stringing occurs when small strands of material are printed where there should be void spaces. It is a defect that is present primarily in material extrusion technologies when the temperature settings are too high. When this happens, the material becomes less viscous and it flows out of the nozzle, causing a leaking out of the filament. (Figure 0.8)

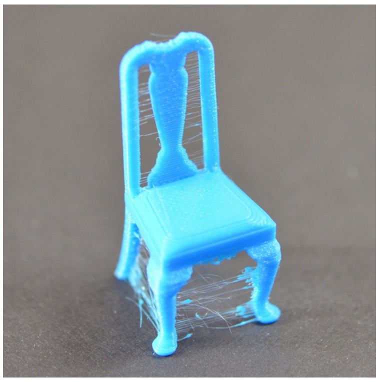

Figure 0.8: Stringing effect

2.5.4. Fractures and cracks

When a layer is printed over the previous one, it is necessary that it adheres properly, otherwise there is the risk that a crack or a fracture occurs between the layers, that may also result in the break of the final product (Figure 0.9). Cracks can also be caused by the rapid shrinkage effect, in fact materials that do not properly resist to thermal shocks such as ceramics and fragile metals, are more likely to present this kind of defect.

Figure 0.9: Fractures and cracks

2.6. Defects affecting mechanical properties

The following defect could threaten the effectiveness of mechanical features of 3D printed products. They will be explained in the following sections:

2.6.1. Porosity

Porosity is the fraction of void volume over the total volume. The presence of voids (even very small ones) may in some cases lead to poor mechanical properties.

Such defect occurs in particular in the products manufactured through processes that involve the usage of laser (e.g.: powder bed fusion, sheet lamination). A low degree of porosity is a vital feature for those products that are supposed to endure high stress applications in order to reduce the probability the part gets broken when it is used; on the other hand, a low degree of porosity may be necessary for the production of particular samples, such us biomedical implants, in view of the fact that pores facilitate the integration with biological tissue (Heinl et al., 2008 [55]). According to Slotwinski, et al. (2014, [56]), porosity can be measured in different manners: Bulk Mass Measurements, Localized Mass Measurements, Archimedes Measurements, X-Ray Computed Tomography (X-Ray CT).

2.6.2. Low strength and Stress behaviour

There may not be high cohesion between layers deposited, causing a low resistance to the stress traction.

Another point to take into account is the repeatability, which is the degree of dimensional compatibility of two products of the same nominal geometry, manufactured in the same conditions, with identical values of the process parameters.

2.7. Effects of poor quality

Is the first chapter, it was stated that one of the big opportunities and potentials of AM over traditional manufacturing is that it could be more sustainable, firstly because it overcomes the traditional process of creating by removing material; secondly because it eliminates other sources of wastes such as movements, stock levels; moreover, it minimizes energy consumption, in particular for small production volumes (Telenko et al., 2012 [57]). Ideally, the only waste could be the support material. However, all these advantages and opportunities should not be wasted by producing defective parts: quality control should be performed in order to avoid as much as possible any defects. Indeed, failures increase both the material and energy consumption, undermining the benefits of AM.

Ease of production encourages greater consumption: users and designers are not careful enough on quality and in case a product does not meet the desired specifications and quality, they are encouraged to produce a new copy due to the very low cost of production, without being aware of the environmental impact of their trial and error approach [58] [59]. There are worries about the disposal of such defective products. It is very hard to find any consensus about the degree of recyclability: on the other hand, such printer filaments cannot be recycled by most municipal recycling programs: they are classified as type 7, or ("Other") in the ASTM International Resin Identifier Codes, which means that they cannot be processed by normal plastic recycling plants. Wastes should be sent to special independent plastic recycling and processing companies, but the process is not so immediate and many centres do not accept plastic waste from a non-verified source, which disincentives both private users and enterprises' commitment to recycle. Undoubtedly, sustainable feedstock must be used for AM technologies to be really sustainable: there are several proposals to produce filaments of the most common 3D printer materials (ABS and PLA) from recycled plastics. B-pet (https://bpetfilament.com/) produces recyclable filaments with 100% recycled materials; Refil (https://www.re-filament.com), a company whose aim is to produce fully recyclable filaments with a quality that is comparable or higher than the standard filaments' one, claims it has produced ABS filaments from car dashboards and PET filament from old PET bottles; ReDeTec (https://redetec.com), whose aim is to make 3D printing as accessible as possible, ideated a revolutionary product that allows users to recycle waste plastic into valuable 3D printer filament [60].

In order to reduce the production of failed parts and the wastes that they cause, it is necessary to implement a quality control that should involve not just enterprises that have adopted AM into their business models, but also 3D printer users that print objects on their own.

Chapter 3

Quality control in Additive Manufacturing

As it has been anticipated in the first chapter, there exist important concerns on the quality of final parts produced through AM technologies and the consequences that they can have. The lack of consistent quality is mostly due to the fact that there is still not an extensive study of the processes and the control systems (Mokhtarian et al., 2018 [61]). As stated by the National Institute for Standards and Technology (NIST), *"the variability in part quality due to inadequate dimensional tolerances, surface roughness, and defects, limits the metal AM broader acceptance for high-value or mission-critical applications"* (Colosimo et al., 2018 [62]).

3.1. Quality control history

Before explaining in detail the common practices in quality control for AM, it is necessary to give an overview of quality and the literature in quality control. The most widely accepted definition of quality is *"quality of a product is a measure of the degree of conformance to applicable design specification and workmanship standards"* (Misra, 2008 [63]). Crosby [64] defined quality as *"conformance to requirements or specifications"*; Feigenbaum [65] as *"the total composite product and service characteristics of marketing, engineering, manufacture, and maintenance through which the product and service in use will meet the expectations of the customers"*; Taguchi [66] as *"loss imparted to the society from the time a product is shipped"*; Juran [67] simply defines quality as *"the fitness for use"*. Whatever definition it is used, it is vital to underline that (i) quality concept is fundamentally based on customers and their requirements' satisfaction; (ii) quality is inversely proportional to variability, thus it is necessary to decrease variability to improve product and process performances.

In order to grant a quality level within the expected standards, it is crucial to perform quality control (QC), a set of techniques and means that are used to manage, monitor, and control the production. The approach toward quality has radically changed in the last century. According to Feigenbaum, it is possible to distinguish different phases in the history of QC:

- *Inspection Quality Control* (1920-1940): during the period of the second industrial revolution, Taylor introduced in his book *"The principles of scientific management"* [68] the principles of inspections as a crucial step in industrial engineering. From that moment on, new departments solely dedicated to quality control started to arise in enterprises. Inspections foresaw that every item was tested after being produced in order to ensure that no faulty product left the factory. It is to be noticed that product control was *a posteriori*: only after that the production process was over, products were controlled and rejected if they were discrepancies with the standard. In the same period, Shewhart, who is considered quality management's grandfather, laid the foundations for Statistical Quality control by introducing the usage of control charts. Inspection of the 100% of production was replaced by acceptance sampling plans thanks to the development of new statistical approaches.
- *Statistical Quality Control* (1940-60): Shewhart opened the door to the crucial revolutions that occurred in the field of quality management in the years between 1940 and 1960 Deming ideated the 14 points for Total Quality management listed in [69] and he introduced the principles of Statistical Quality Control in Japan, where lean manufacturing philosophy was being conceived. Juran, whose 10 steps to improve quality are shown in Table 3.1 , bestowed a more human imprint to quality management and further strengthened Japanese quality beliefs with his trip in Japan in 1954.
- *Total Quality Control* (1960-80): next era in QC is characterized by *"zero defect"*, a concept introduced by Philip Crosby that does not literally refers to perfection, but it rather expresses the aim to eliminate as much as possible wastes and defects by standardizing the processes. In his revolutionary book *"Quality is free"* [64], Crosby claimed that quality was an investment that

produced profit and that it must not just controlled but also managed. Ishikawa introduced the so-called "quality circles", which consist in small group of workers (between 4 and 12) who discuss about quality issues with managers and propose improvement actions. Indeed, Total Quality Control reckons on an effort from every level of the company, from the top management level to workers, with the aim of continuously improving performances (*kaizen*) and ultimately augmenting customers' satisfaction.

- *Total Quality System*: (1980-1990) the bottom up approach to quality laid foundation for Total Quality System. Taguchi claimed that lack of quality constitutes a real loss: the bigger the deviation from specifications, the greater the loss for the enterprise. He announced the ideas of parameter and tolerance design and he proposed the experimental design in order to avoid *ex ante* any defect by reducing variability and granting higher reliability to production processes. From that moment on, new methodologies to improve quality management have been proposed such as Six Sigma, Total Quality Management.
- *Product Lifecycle Management*: finally, in 2000s an integrated and holistic approach came into being in order to manage all the aspects of the product, including quality for all its life phases, from the conception until its disposal.

1. “Create constancy of purpose for improving products and services.”	8. “Drive out fear.”
2. “Adopt the new philosophy.”	9. “Break down barriers between staff areas.”
3. “Cease dependence on inspection to achieve quality.”	10. “Eliminate slogans, exhortations and targets for the workforce.”
4. “End the practice of awarding business on price alone; instead, minimize total cost by working with a single supplier.”	11. “Eliminate numerical quotas for the workforce and numerical goals for management.”
5. “Improve constantly and forever every process for planning, production and service.”	12. “Remove barriers that rob people of pride of workmanship, and eliminate the annual rating or merit system.”
6. “Institute training on the job.”	13. “Institute a vigorous program of education and self-improvement for everyone.”
7. “Adopt and institute leadership.”	14. “Put everybody in the company to work accomplishing the transformation.”

Deming’s 14 Points

1. “Establish awareness for the need to improve and the opportunities for improvement.”	6. “Report progress.”
2. “Set goals for improvement.”	7. “Give recognition.”
3. “Organize to meet the goals that have been set.”	8. “Communicate results.”
4. “Provide training.”	9. “Keep score.”
5. “Implement projects aimed at solving problems.”	10. “Maintain momentum by building improvement into the company's regular systems.”

Table 3.1: Juran’s 10 steps to quality improvement

3.1.1. Quality control approaches

It is necessary to make further distinctions in the field of quality control. The first distinction is the one between process control and product control. The former involves the control of the stages and sequences that bring to the manufacturing of a desired quality product; the latter is the control of the product itself and it is aimed to reject all those products that do not meet the specifications. Secondly, there is the distinction between online and offline quality control. Offline process control is a crucial step for failures' prevention: process parameters are set in such way to minimize the deviation of product's specifications with respect to the standard. In such field, Taguchi experimental design is a necessary approach to come up with off-line process control: n parameters are kept under control in order to minimize variability. Offline product control consists of controlling a sample from the production line and verify whether it respects specifications. Offline quality control is limited by the fact that when a faulty product is found, it is rejected and lost; however, it may be necessary to perform a corrective action in real time and this is what on line quality control does thanks to statistical methods and control charts.

3.2. Quality control in AM

Mass manufacturing makes extensive use of series of statistical tools to monitor in real time the production process in order to detect any variations that may result into the production of an article that does not meet specifications. However, such methods rely on a vast sample data, thus they cannot properly be adapted to AM, for which it is more complicated to collect a big quantity of data as it used to produce a low number of pieces of the same type. Being AM a relatively recent technology, there is not a consolidated unique methodology for the quality control. In literature, there are several proposals for both process and product control.

For what concerns the former, AM process parameters are monitored and statistical and analytical methods are used to predict the effect they may have on the product quality. Boschetto and Bottini (2014, [70]) developed a model to predict dimensional deviations of fabricated parts as a function of the process parameters;

Rao et al (2015, [71]) used statistical analysis and nonparametric sensor-based Bayesian modelling approaches to optimize process conditions for obtaining the best surface roughness and to detect process drifts in real-time; Shirke et al (2018, [72]) used Taguchi method to study the effect of process parameters on tensile strength; Chen et al (2016, [39]) et al. used the same method to optimize process parameters to obtain the best surface roughness quality; Mokhtarian (2019, [73]) proposed a systematic methodology to extract cause-effect relationships among variables to predict the effect of specific design and manufacturing parameters on part defects and to estimate the needed input parameters backwards.

The later directly monitors the piece. Slotwinski et al. (2014, [74]) used ultrasonic sensors in order to monitor products' porosity level; Lin (2019, [75]) simulated an online quality control to detect and identify defects by comparing the surface point cloud obtained by laser scanning with the ideal surface extracted from the CAD model (Figure 3.1); D'Antonio et al (2017, [**2**]) proposed an integration between Manufacturing Execution System (MES) with Design For Additive Manufacturing (DFAM) to collect information with MES and use it to improve DFAM performance.

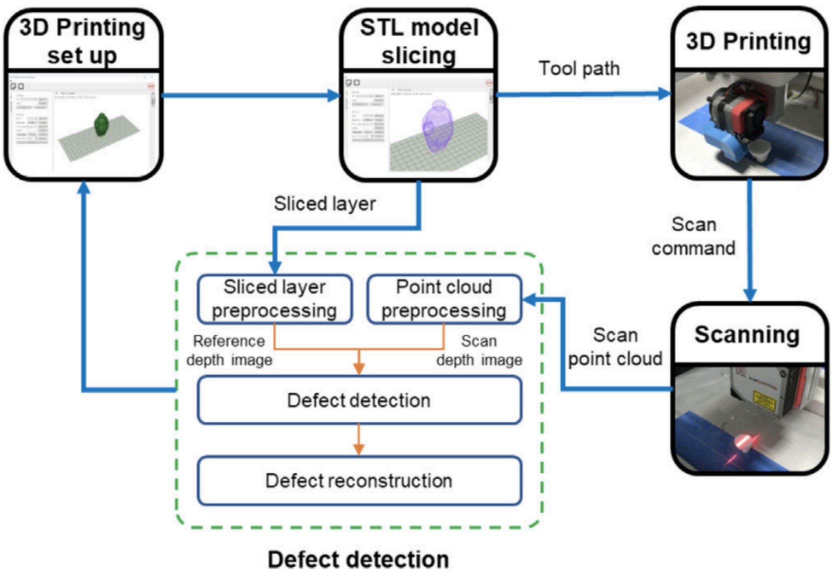

Figure 3.1: Quality control methodology. Source: [75]

The methodologies proposed in literature involve the usage of very expensive equipment such as with respect to the result and that cannot be generally used by standard consumers, who use 3D printing more like a trial and error process [14] and produce parts with a very low quality, which results in high wastes in material and energy.

3.3. 3D scanning

3D scanning is the process of transforming a 3D object into a point cloud. The 3D scanner collects information about the object, its shape, colour, texture and the environment around it and uses it to create a digital copy. This process can be performed through different technologies. The most relevant ones are:

- *Photogrammetry*: numerous photos of the object to be scanned are taken with a phone or a camera from different angles, subsequently they are stitch together by a software which is able to identify the pixels that match to the same physical point and reconstruct the point cloud accordingly. Photogrammetry requires a long time to take the big quantity of pictures (at least 40) and specially to process all the data with the software. On the other hand, it grants a high degree of accuracy, which, however, depends on the quality of the pictures.
- *Light-based scanning*: lights are projected onto the object of interest, then transformed into a digital point cloud. Two types of light scanning technologies exist: the first projects patterns that measure spatial deformations; the second (the most commonly used) projects laser lights that detect the object's shape by getting deflected by its varying angles.
- *Contact scanning*: the digital file representing the object is created after a direct physical contract of the scanner onto its surface.: the probe is moved all over the object and is able to collect detailed information, granting high levels of accuracy and precision; on the other hand, the process necessitates a long time.
- *Laser pulse scanning*: a laser beam is projected by a light scanner onto the surface of the object of interest, it is reflected and it returns to a sensor. The time that passes from the projection to the reflection provides information about the geometry of the product. This technology ensures high precision, but, again, it requires long processing times.

3.4. Theory of statistical errors

Whenever a measurement is performed, it is subject to an error: the only action of measure causes changes in the system, thus the result cannot be perfectly consistent with the real value of the measured variable.

Measurement error (ME) is defined as the difference between the measured quantity value (MQV) and a reference quantity value (RQV) [76].

$$ME = MQV - RQV$$

where MQV is the result of the measurement and RQV is the real value of the measured quantity, which cannot be known with certainty but only estimated.

Based on the sources that cause the errors, these are classified into three main groups:

- *Gross errors*: they are caused by human oversight and a lack focus while reading and recording the MQV (for instance, a person may forget a digit when reading or recording, or he may misread a value). Gross errors can easily be revealed and solved by repeating the same operations several times or by measuring other quantities that have a simple and immediate relationship with the measured one.
- *Systematic errors*: portion of measurement error that remains constant or varies in a predictable way in replicate measurements because they are triggered by defective equipment or an inappropriate experiment design. Since this typology of error occurs consistently in every observation, they don't affect the variability of the distribution, but only a shift in the central tendency, as shown in Figure 3.2.

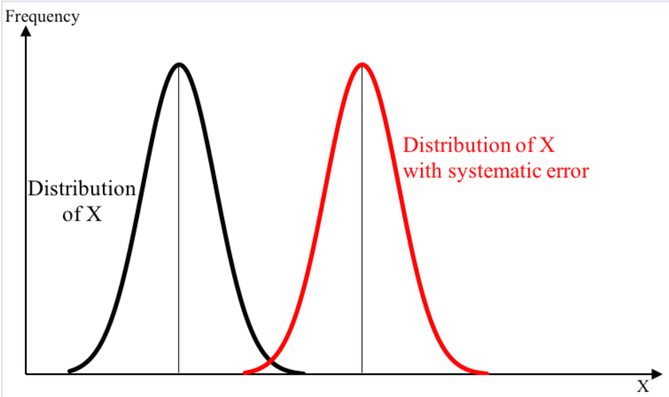

Figure 3.2: Effect of systematic error on the distribution

It is appropriate to distinguish systematic errors into three major categories: (i) instrumental: defects of the instrument itself and its technical features, dating back to construction or consequent to its deterioration; (ii) environmental: use of the instrument under inappropriate conditions or under conditions that are different from those foreseen for its correct use; (iii) theoretical: excessive simplification of the experiment or measurement process.

The source of the bias can be known or not: it is possible to reveal the presence of unsuspected systematic errors by measuring the same quantity through different instruments and methods, which may provide different results. Nevertheless, even if there is no difference in the results, it cannot never be stated with certainty that the measurement is free from systematic errors, which are generally identified only by a careful and meticulous critical analysis of both the instrument and the procedures. Once discovered, a systematic error can be eliminated by modifying either the instrument or the procedure, or by making an appropriate correction to the result of the measurement (although this generally entails an increase in the random error).

- *Random errors*: portion of measurement error that varies in an unpredictable manner in replicate measurements thus it can affect either positively or negatively the distribution of the observation. They affect the variability of the distribution around the average, without having an impact on the average itself (the opposite situation with respect to systematic errors), as it is shown in Figure 3.3.

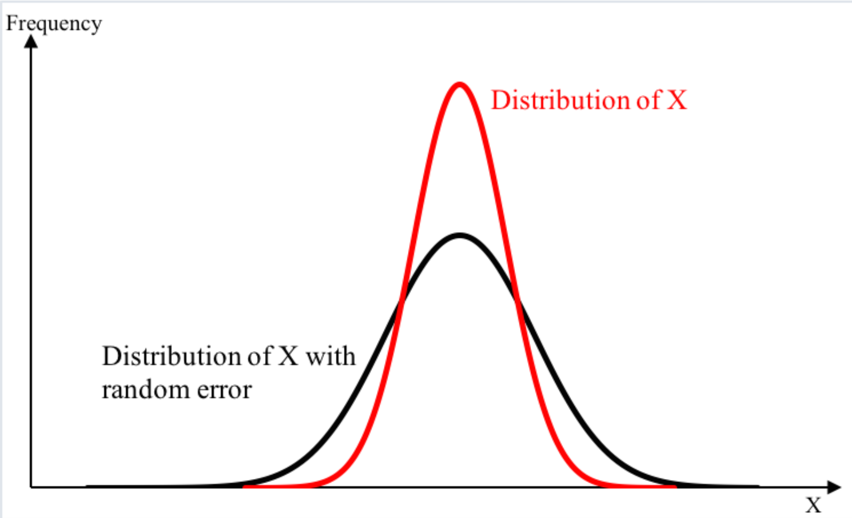

Figure 3.3:Effect of random error on the distribution

They may be the result of a copious number of causes that are complex to identify therefore they can difficultly be eliminated; nevertheless, their effects can be mitigated by correcting the measures with compensation methods. Even though they cannot be eliminated, their influence can be foreseen through statistic methods.

Chapter 4

Methodological proposal for low cost quality control

A new methodology that involves low cost equipment is proposed. Similarly to Lin's (2019) procedure, a product is printed and then scanned. The point cloud resulting from the scan is successively compared with the CAD model in order to detect any defect. In particular, the methodology aims to control geometry and dimensional accuracy, which is considered the most important source of defect [37].

Since it is wanted that all 3D printer users perform and are educated to quality control, the methodology does not use a professional and expensive 3D scanner, but an instrument that is easily accessible to a high number of users. The same instrument can be used by those enterprises which start to approach AM or which cannot afford an investment in 3D scanners.

4.1. The methodology

The methodology is described in detail in Figure 4.1. As it was previously described AM process starts with a 3D file, which must be converted into a "standard" 3D format, such as .STL format. Successively, slicing process is applied to the 3D file so that it can be manufactured layer by layer. The methodology proposes to pause the process every time that k layers (e.g., k = 15 - 20) are deposed and verify whether the intermediate product is compatible with the STL model. If it results that the product is not compatible with the model, the production is stopped. In this manner, it is soon understood whether the product will present important defects and wastes in material and energy are prevented.

In order to perform a quasi-real time monitoring, it is necessary that the acquisition process occurs rapidly, otherwise it would be impossible to stop the production so often. However, professional scanners, even though they ensure high accuracy and precision levels, require such long times and complex procedures. Next paragraph will present a new low cost, light weight, portable, device that can be used as a scanner for rapid data acquisitions.

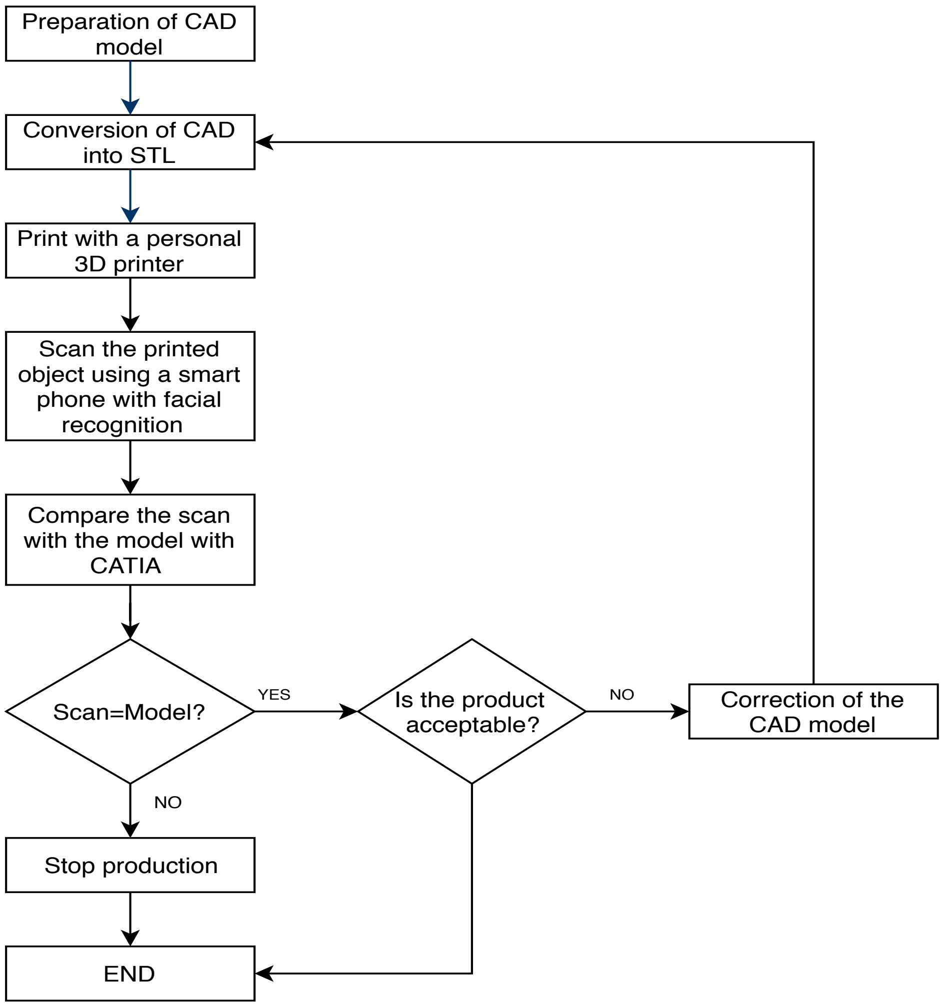

Figure 4.1: Methodology for AM quality control

For the purpose of this thesis, which is to educate users to quality control and reduce wastes due to the production of faulty products, a low cost and fast acquisition scanner. It is proposed to utilize a last generation iPhone (X models) as a scanner for 3D printed products. Indeed, they are equipped with the TrueDepth

Camera, which is the system used as internal frontal camera. Its main function is to support facial recognition: it accurately captures face data by projecting and analysing more than 30,000 invisible points to create a face depth map; what is more, it captures infrared image. The depth map and the infrared image are successively transformed into a mathematical representation and compared to the recorded facial data.

Figure 4.2 shows the so-called notch of iPhone X with the components of the TrueDepth Camera: a part of a traditional 7MP camera, there are other crucial components. Flood illuminator beams infrared light in order to verify the presence of a face; afterwards the 30,000 points are flashed onto the object surface in front of the device by the dot projector; the light points are received and read by the infrared camera, which is able to create a model of the surface. An infrared radiator ensures accuracy in the detection even when there are poor lighting conditions and a proximity sensor makes the system know when a user is close enough to activate.

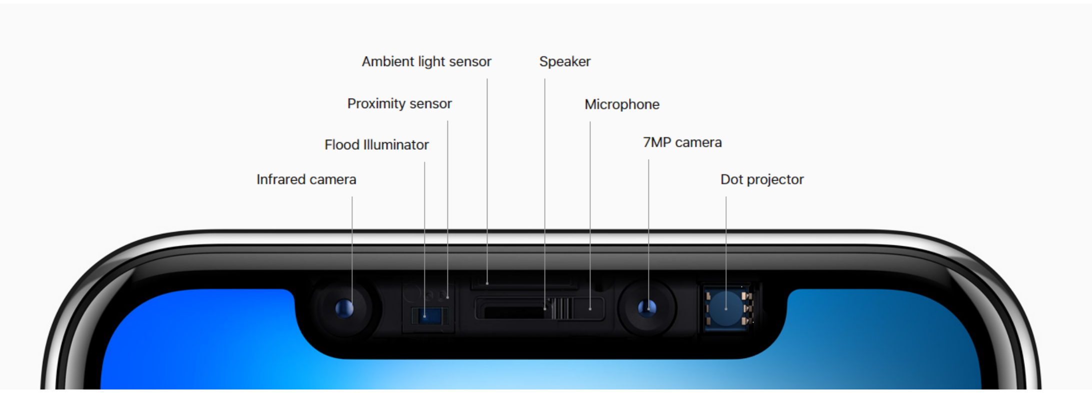

Figure 4.2: TrueDepth Camera System. Source: [77]

Thanks to this innovative technology, users can unlock the phone, authorize payments and purchases through the facial recognition, but it also opens new doors for several industries. In the interest of this thesis, it is crucial to explore TrueDepth Camera performance characteristics as a scanner and explore whether it can be used as a portable, light, cheap scanner with rapid acquisition time and low energy consumption. The efficacy of such instrument is tested through a use case, which will be described in the following paragraph.

4.2. Use case

The methodology and the idea to use employ the TrueDepth Camera as a scanner are tested through a use case, a gnome (Figure 4.3). Gnomes are considered the perfect 3D printing tests as they have some standard characteristics that are suitable to assess printer and scanner features: triangular slouched cap, rounded face and nose, detailed beard, heavy clothes and boots. Among several gnomes that can be found online, Makerbot gnome is undoubtedly the most common and the easiest to find on Thingiverse. Even though it is a simple object, Makerbot gnome presents curves, several surface details, and different types of geometries; at the same time, it does not have any deep depressions or overlapping features that would be difficult to capture even with a professional scanner.

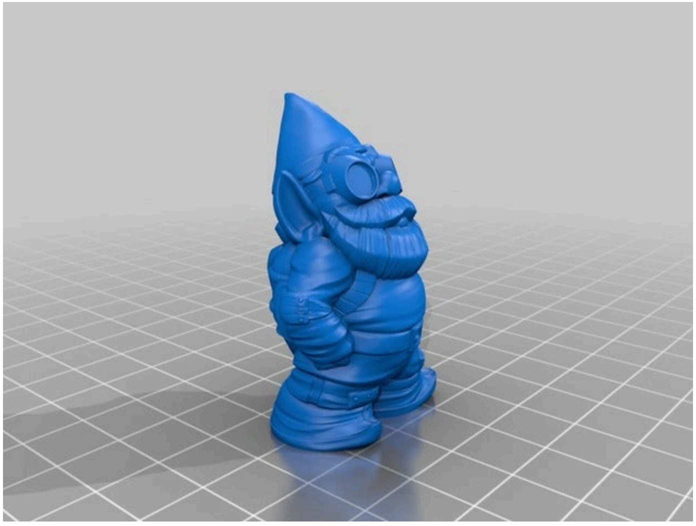

Figure 4.3: Use case. Source: https://www.thingiverse.com/thing:138642

The makerbot gnome has been printed through a FDM technique and it has been scanned with the TrueDepth Camera. The scanning process is extremely fast and easy: it is enough that a person turns the telephone around the object and it takes only a few minutes (6 minutes). The acquisition process may be further simplified and automatized. It is possible to imagine a tool that make the phone turn around the object so that it is not necessary that a person performs this task. It is important to note that the opposite process acquisition (the phone turns around and the phone does not move) cannot be taken into account because the TrueDepth Camera detects also the background and needs it to recognize the object.

The point cloud obtained by the scan is transformed into a .stl file and uploaded on CATIA (acronym that stands for Computer-Aided Three-Dimensional Interactive Application), a software developed by the French company Dassault Systèmes that supports CAD, computer-aided manufacturing (CAM), computer-aided engineering (CAE), product lifecycle management (PLM).

As it can be appreciated in Figure 4.4, the scan allows to perfectly recognize the shape of the gnome, although not all details are accurately detected. However, it is necessary to clean and refine the point cloud because it presents some isolated points and because the TrueDepth Camera detects not just the object of interest but also the surface on which it lays. It is necessary to pay a very high level of attention when performing the task of cutting the surface and be precise to meet the exact level at which there is the starting layer of the object otherwise this can have a negative impact on the result of the deviation analysis.

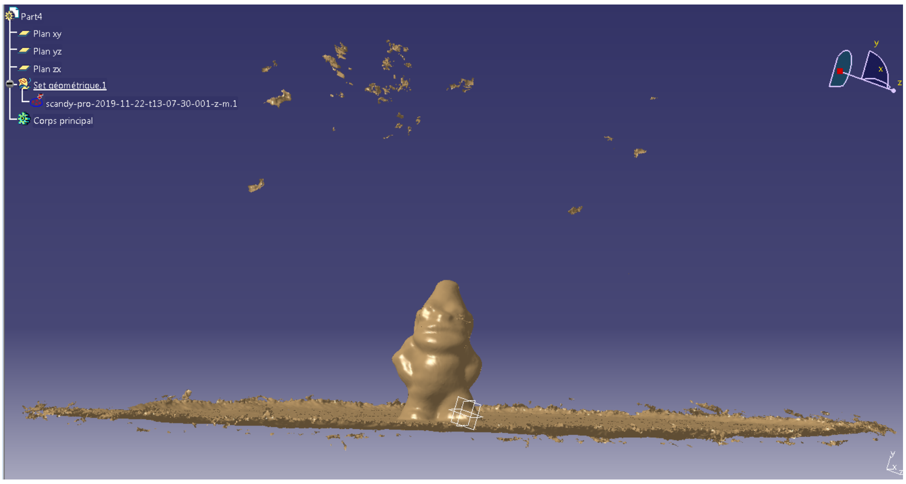

Figure 4.4: Scan by TrueDepth Camera

Once the scan is clean, it is possible to compare it with the original .STL model. The two point clouds are overlapped and a dimensional deviation analysis is performed. Figure 4.5 shows the result of such comparison: from the dimensional deviation analysis, it results that there are some areas highlighted with a red colour, which indicates a 2 mm deviations and some area are highlighted for a -1.6 mm difference. Thus, the difference between the scanned object and the original model ranges between -1.6 and 2 mm.

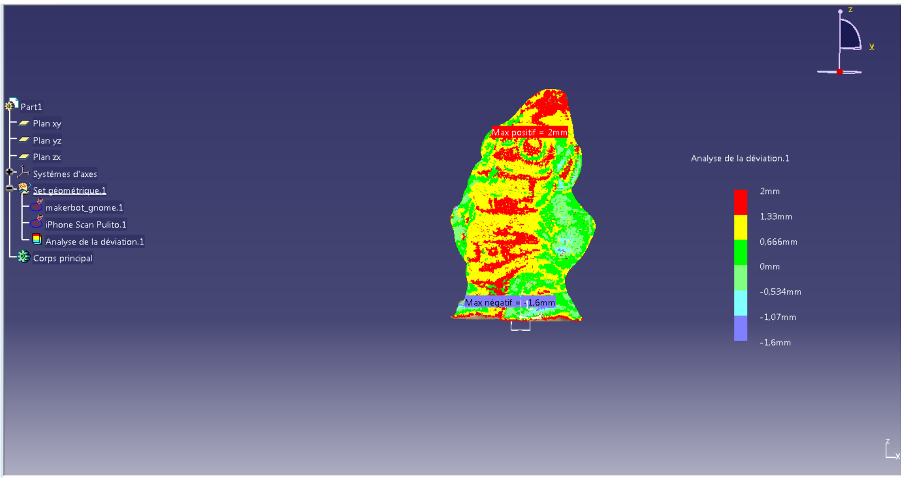

Figure 4.5: Comparison between the model and the scan done with the TrueDepth Camera

At this point, it is vital to understand whether such difference is due to a defective production of the gnome or it is caused by a systematic instrumental error. In order to investigate on this question, the same printed object has been scanned with the Solutionix D500, a professional scanner which is specialized for small and detailed objects such as jewelleries, the most complex products to scan. It grants the capture even of small details thanks to its accuracy of 0.01 mm and a resolution (point spacing) of 0.056 mm. (Figure 4.6).

Technical Data

Section	Solutionix D500
Resolution	2 x 2 Mpx
Measuring area (mm)	120
Point spacing (mm)	0.056
Dimensions (mm)	290 x 290 x 340
Weight	Approx. 12 kg
Interface	USB 3.0 B type

Figure 4.6: Solutionix D500 technical features.
Source: https://digitizedesigns.com/3d-scanners/solutionix-d500/

The result of the comparison between the original model and the point cloud generated by the Solutionix D500 are shown in Figure 4.7: it can be appreciated that in this case the deviation ranges from -0.709 to 0.794 mm, against the range -1.6 / 2 mm. If on the one hand the Solutionix D500 ensures high accuracy, on the other hand the time required to obtain such a good result is way longer that the time required to scan the object through the TrueDepth Camera. Indeed, the scan and the transformation of the point cloud into an .STL file took 1 hour and 20 minutes. Such a long time makes it impossible to consider the idea to use the scanner for a quasi-real time quality control and control the product each 15/20 layers are deposited.

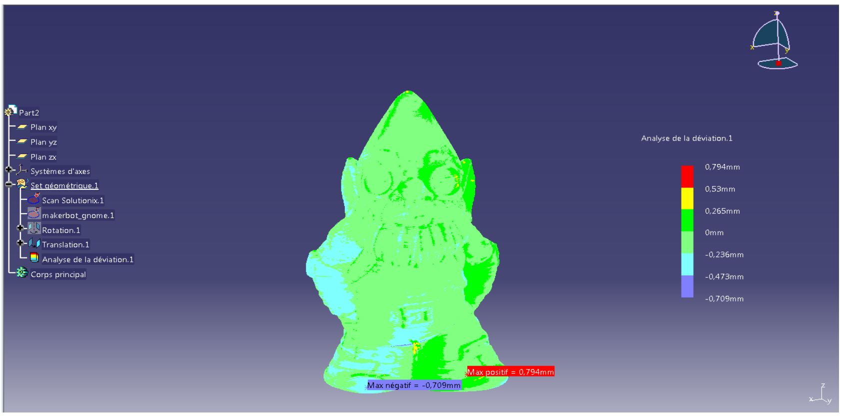

Figure 4.7 : Comparison between the model and the scan done with the Solutionix D500 scanner.

Figure 4.8 offers a synthesis of the process that has been carried out:

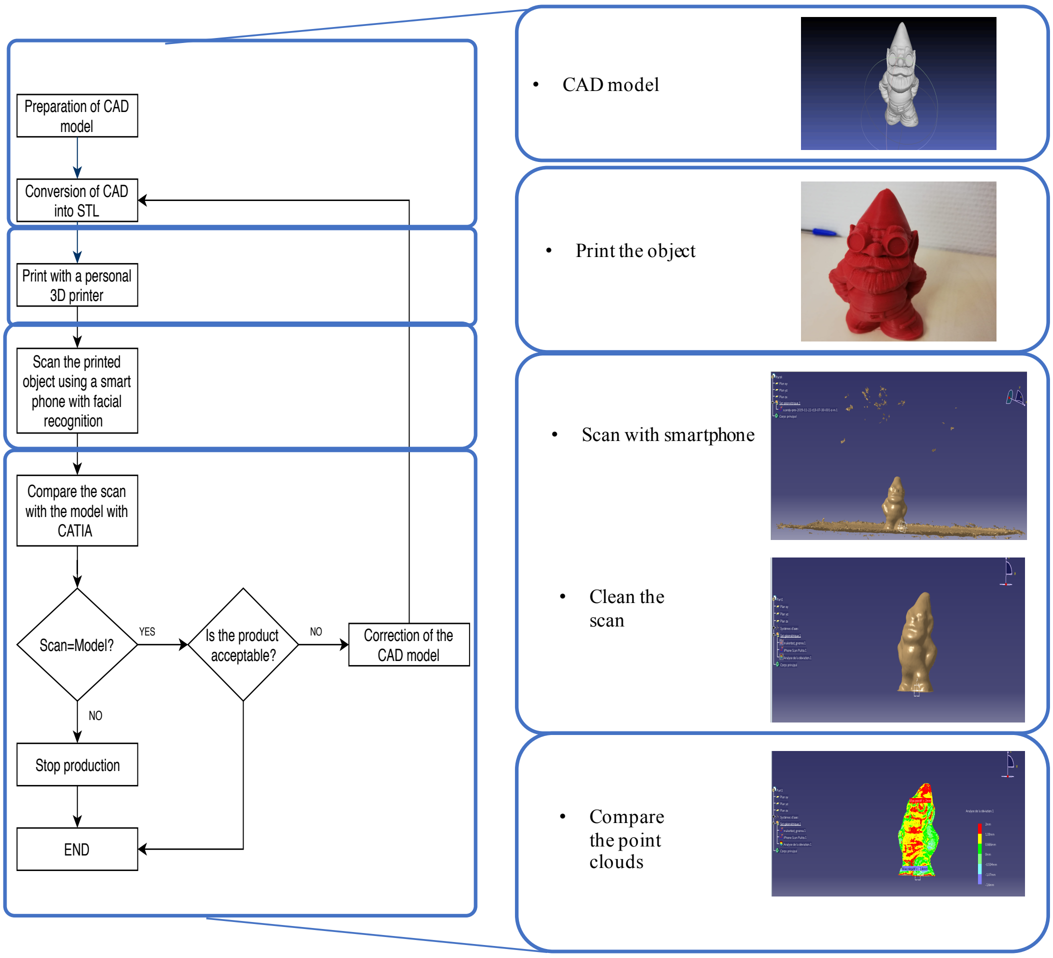

Figure 4.8 Methodology applied to the makerbot gnome

4.3. Discussion of results

Considering the difference between the results obtained using the TrueDepth Camera and the professional scanner, it can be said that TrueDepth Camera has an accuracy that is suitable for the quality control in 3D printing in case no submillimetre precision is required. Considered that the accuracy of the TrueDepth Camera is way lower than the one of professional scanners, it is necessary to make further analysis on its accuracy, precision and stability as an instrument. If a more detailed analysis is made on the results obtained with the two instruments, it can be noticed that the areas in which TrueDepth Camera had more difficulties in precisely detecting the details, resulting in a less accurate scanning, is the central part in which there are the recesses. Apparently, the Camera is not able to recognize the differences in depth and measures in such kinds of area. However, there is ground to believe that TrueDepth Camera is able to give more reliable results in case of surfaces without this kind of recessions and irregularities. Further experiments should be performed in order to confirm this hypothesis.

Further studies about the TrueDepth Camera were made in and it is discovered that it is the result of the acquisition by Apple of an Israeli 3D company pioneer in 3D sensor technology, PrimeSense, which developed the system used by Microsoft's Kinect to detect movements and enable users to play Xbox videogames without any controller. The company was acquired by Apple for $ 360 Million in 2013; therefore, it can be supposed that the technical features are at least as good as Microsoft's Kinect used as a scanner. Geoffrey et al. (2017, [78]) studied the accuracy and precision of a Kinect as a scanner for biological science and from their research it emerged that accuracy ranged between 2.5 mm and 5.8 mm. Even though a higher experimental sample would be necessary, it is possible to state that TrueDepth Camera has resulted into a better scanning instrument that Microsoft's Kinect.

Conclusions

In this thesis work, additive manufacturing technology was reviewed and analysed. An investigation on additive manufacturing's opportunities over traditional manufacturing's technologies and organizational models was carried out and it resulted that there exist extraordinary possibilities, although it is a so much younger technology than subtractive production. Indeed, it was born only less that forty years ago, but it has not just already completely revolutionized product development practices thanks to rapid prototyping techniques, but also allowed the direct production of final products that can present even better characteristics than the ones manufactured through traditional processes. The most critical advantage guaranteed by additional manufacturing is that the final part has not any geometrical constraint since layers are added one over the other, thus products are designed thinking only about the performance and not about the manufacturability; furthermore, there is not waste due to material removal typical of subtractive manufacturing. A part from these indisputable advantages, in the thesis it is highlighted the way additive manufacturing can enhance lean and agile manufacturing and the opportunities for supply chain and product lifecycle. It may help to solve a crucial objective for lean manufacturing, which is the reduction in *muda*, namely wastes: motions in production lines are abolished as the entire production, from the blank to the final product, totally occurs in the 3D printer; the need for stock is drastically reduced since it is possible to produce by batches of one single product and the only source of inventory may be the raw material one; set up times are abated since a change in tools to produce different products is not necessary. Furthermore, the advantages of additive manufacturing for product development drastically diminish time to market and the fact that every part is produced singularly makes it possible to customize every product without any consequence on costs or delays in production. Additive manufacturing makes production more proximal to customers, thus it enables to shorten supply chains and the related costs by reducing packaging and transportation costs.

Nonetheless, there are still vital improvements and technological challenges for additive manufacturing in order to improve materials performance and costs and to optimize processes and post processing activities. A crucial factor that absolutely need to be enhanced is quality: the presence of defects in 3D printed products is the only *muda* that additive manufacturing technologies are not able to reduce yet; therefore, in this thesis a methodology is proposed for making a quasi-real time quality control for dimensional accuracy, which is considered the *"major bottleneck for application of 3D printing in direct manufacturing"* and the major threaten for a wide application of additive manufacturing.

Because from 2010, after the expiration of a vital patent for fused deposition modelling, there is an always higher adoption rate of desktop 3D printers and of the so-called *home fabrication*, it is proposed to utilize a low-cost instrument to perform the quality control: the TrueDepth Camera, namely new generation X iPhones' internal camera. It is used as a scanner to control in a quasi-real time the produced sample and verify whether it meets the specifications foreseen by design by making a dimensional deviation analysis. Thanks to the experiments conducted at LCPI (Laboratoire Conception de Produits et Innovation) at the University Arts et Métiers ParisTech in Paris, it resulted that TrueDepth Camera, despite being more than fifty times cheaper than a professional scanner, is able to perfectly recognize the shape of the use case and has the great advantage of guaranteeing a very rapid process acquisition (in the order of minutes) compared to professional scanners (one hour and twenty minutes for the scanner Solutionix D500, whose performance was compared with TrueDepth Camera one). As it can be expected, accuracy level is lower than the one of a professional scanner: indeed, some errors were detected even though there was not any relevant difference between the model and the sample dimensions. However, it is safe to state that TrueDepth Camera can be used as an instrument to perform quality control for 3D printing when no submillimetre precision is needed. Moreover, it is believed that it can represent a tool to educate 3D printer users to take into account how relevant is performing quality control and the wastes in terms of material, energy consumption and costs it can help to minimize. The usage can also be suggested to small and medium enterprises that start their approach toward additive manufacturing technologies and do not want or cannot afford a significant investment in an instrument for quality control.

Certainly, more investigations should be made regarding the accuracy of the TrueDepth Camera as an instrument for scanning 3D printed products in order to better define the cases in which it is opportune to use it without any concern: in future, it could be studied whether there exist some shapes that are detected in a better manner or whether there are some parameters that influence positively or negatively the acquisition process.

List of Abbreviations

Acronym	Description
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
DAM	Direct Additive Manufacturing
FDM	Fused Deposition Modelling
JIT	Just in Time
LCPI	Laboratoire Conception de Produits et Innovation
ME	Measurement error
MQV	Measured Quantity Value
NNVA	Necessary but Non-Value Adding
NVA	Non Value Adding
PLA	Polylactic Acid
PUC	Per Unit Cost
QC	Quality control
RP	Rapid prototyping
RQV	Reference Quantity Value
RT	Rapid Tooling
SMED	Single Minute Exchange of Dies
TPS	Toyota Production System
VA	Value Adding
VSM	Value Stream Mapping
WIP	Work in Progress

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