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Benchmarking of Extrusion Based Additive Manufacturing Processes

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Contents

Abstract

In the second half of the 18th century started in Britain the first industrial revolution. Tasks previously handmade done in hundreds of small weavers' lab were gathered under the same roof: the cotton mill. The factory was born. The second industrial revolution took place in the US during the first decades of the 20th century when Henry Ford developed his groundbreaking automobile manufacturing company introducing the new era of mass production. Now a third revolution is under way. Manufacturing is going digital. A number of remarkable technologies are converging: clever software, novel materials, more dexterous robots, Additive Manufacturing and a whole range of web-based services. The factory of future will focus on mass customization [1] [2]. In the next years manufacturers will be governed by two sets of rules: economies of scale production for interchangeable part produced at high volumes, and economies of one for highly customizable products that can be built layer by layer [3]. One of the key pillars should be Additive Manufacturing – AM. This process will push the production of goods closer to the consumers, democratizing manufacturing on a global scale and allowing to be cost-effectively customized to customers' needs. Indeed, after a first phase in which just few and very expensive machines were available, patents began to expire, and the market of open source desktop printers have spread, passing from 66 systems sold to 528'952 desktop printers sold in 2017 [4]. The decrease in prices of traditional printers and the improvement in performance has given rise to a new category of professional printers which will contribute substantially to the diffusion of Additive Manufacturing in professional studios, craft companies and SMEs.

After the initial phase, in which AM was used almost exclusively for rapid prototyping, 3D printing began to systematically support the other production methods and several industries are analyzing the competitive advantage that AM can give to their activities. For instance, GE Aviations has switched to printing fuel nozzles of certain jet engines. It expected to churn out more then 45'000 of the same design a year with printing technology that allows a nozzle that used to be assembled from 20 separately cast part to be fabricated in one piece. GE says this will cut the cost of manufacturing by 75% [5] and it will generate fuel savings of up to USD 1.6 million per aircraft per year [6].

In 2018, the Additive Manufacturing market offers seven main sub technologies and a range of emerging technologies too capable of processing polymers, metals, ceramic, composite and biological materials. Mordor Intelligence has valued $8.3 billion in the value of the global 3D printing market in 2017 and estimates it will reach 35.36 billion in 2023 [7].

Choosing the most relevant technology and system will depend on a company circumstance. There has been limited progress in the standard and measurement science in AM [8]. According to EY report lack of information about the technology is the main reason of why the majority of the companies have already not considered AM process as a truly viable option [9]. Many manufacturers and users do not have utmost confidence and certainty that AM parts would exhibit consistent quality and reliability within and across different 3D printers.

The main purpose of this thesis is to contribute filling this knowledge gap to help user making a more informed decision on process selection and gain more confidence on using AM technologies. The work is especially going to focus on extrusion-based systems due to its common use and availability. First, after a general introduction on AM process with particular attention to the extrusion one, a new benchmark part will be designed in order to develop a qualitative and quantitative comparison between desktop and medium/high-end extrusion-based additive manufacturing systems. The aim is to develop benchmark parts and benchmarking procedures aimed at performance evaluation of extrusion-based Additive Manufacturing process and materials in terms of achievable geometric features, thin features and warpage. The test will be conducted with two material: PLA and ABS, two among the most common material for this process. Finally, at the end of this research, using the data collected in the previous phase, AM Ashby Charts will be developed in order to give to a potential user/customer a visual and intuitive decision-making tool which can facilitate purchasing decision among different machines.

CHAPTER 1
Additive Manufacturing

1.What is Additive Manufacturing?

In the early years of AM the most commonly used term to describe this technologies was Rapid Prototyping, reflecting the main application of the process: the creation of models and prototype parts rapidly before final product release or commercialization. As the technologies progress, this term resulted increasingly inadequate to effectively describe the more recent applications. Improvements in quality, accuracy and available materials translate into a much closer link to the end product. Many parts are now directly manufactured layer upon layer upon layer, so it is not more possible to label them as prototypes.

In 2015 a formed Technical Committee within ASTM international agreed that new terminology should be adopted [10]. They define Additive manufacturing - AM as the process of joining material to make objects from 3D model data, usually layer upon layer as opposed to subtractive manufacturing methodologies, such as a traditional machine. This definition of Additive Manufacturing basically highlights four main components:

- A digital 3D model of the component or product
- Material that are consolidated from the smallest possible form
- A tool for laying materials
- A digital control system to lay down material layer by layer in order to build the shape of the object

Additive manufacturing is thus completely different from the more traditional subtractive or compressive manufacturing. In a subtractive process a block of material is carved out to produce the required shape. A compressive process pushes a semisolid or liquid material into a desired shape, in which then it will be harden or solidify. Instead, as said before, an additive process builds a component by joining particles or layers of raw materials. The most conventional fabrication process, such as milling, turning, grinding, casting or molding belong to the subtractive or compressive category. These machines are difficult to use on parts with very small features or complex geometry and on top of that all these processes require planning, tooling and fixture design and manufacturing. They often take weeks or even months to complete. On the other hand, AM technology employs an additive process that replicates physical parts layer by layer from their model generated using a three-dimensional Computer Aided Design system, without the need for process planning. Each layer is a thin cross-section of the part derived from the original CAD data and each layer must have a finite thickness to it and so the result part will be an approximation of the original data. The closer each layer is the closer the final part will be with the original (Fig.1.1). All commercialized AM machines so far use a layer-based approach, they essentially differ in the materials that can be used, how the layers are created, and how the layers are bonded to each other. Such differences will determine factors like the accuracy of the final part plus its material properties and mechanical properties. They will also determine factors like how quickly the part can be made, how much post-processing is required, the size of the AM machine used, and the overall cost of the machine and process. [11]

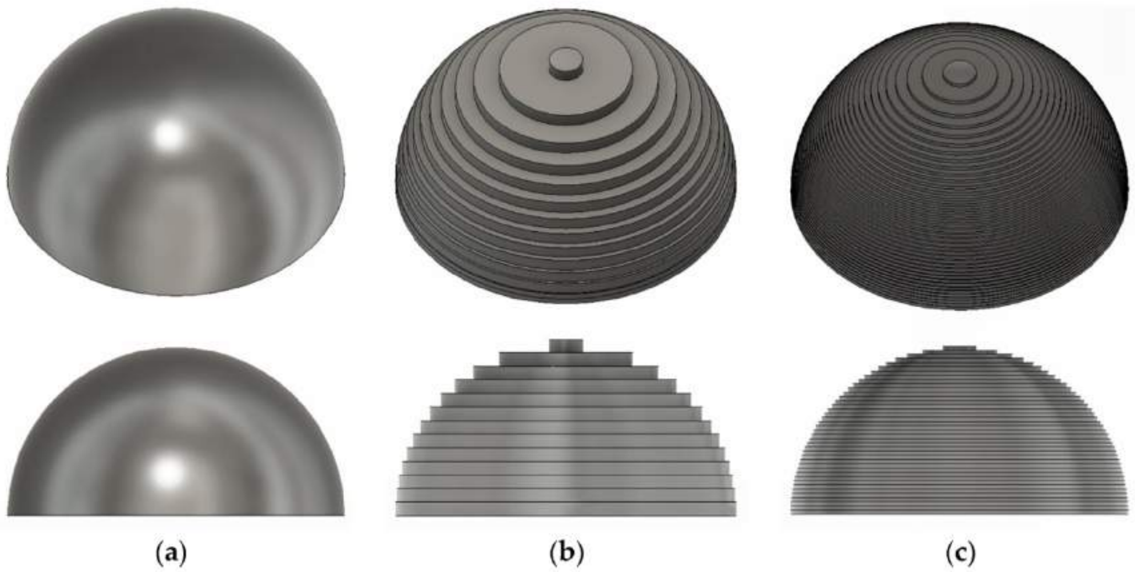


Fig. 1.1 – The effects of different layer thickness (a) ideal sphere, (b) sphere sliced at 0,8mm layer high, (c) sphere sliced at 0,25mm layer high [12]

2.History of Additive Manufacturing

In 1981 Hideo Kodama experiments about a functional rapid-prototyping system using photopolymers. A printed model was built up in layers, each of which to a cross-sectional line in the model. Later in 1984 Charles Hull made AM history by inventing Stereolithography, a method to create solid object by fixing and hardening, on top of each other, thin layer of photopolymer resin, a material that changes their properties when subjected to ultraviolet light. In 1986 the first SLA working machine was produced and the 3D System, the first 3D printer company, was born. This new technology was a big news to inventors, who could now theoretically prototype and test their design without having to make a huge upfront investment. In 1992 another AM technology, whose patent has been filed in 1989 by Scott Crump, was commercialized by Stratasys: the fused deposition modeling. FDM extrudes thermoplastic materials in filament form to produce part layer by layer. In 1992 the Selective Laser Sintering, which has been patent in 1986, became commercially available. Using heat from laser, SLS fuses powder materials, instead of liquid or filament. In 1999 the medical 3D Bioprinting was born. The first lab-grown organ, an urinary bladder, was successfully transplanted to a patient. In 2000 came on the market the first inkjet printer and the first multicolor 3D printer. In its first years of life 3D printing were in his infancy and has not been widely disseminated due to the very high costs of use. In 2004 Adrian Bowyer, professor of mechanical engineering at the University of Bath founded the Rep Rap open-source project with the aim of building a machine which can both produce plastic objects and build itself, or at least print most of its own parts, using FDM technology. In order to cut down the costs, the professor shared all the information about the machine and adopted an open-source materials philosophy, pushing the users trying new material and sharing the result. Suddenly people everywhere had the power to create whatever stuff they could dream up on their own. From now on, the democratization of manufacturing had captured the public's imagination, as had the idea of mass customization. The first SLS machine became commercially viable in 2006, which opened the door to on-demand manufacturing of industrial parts. In the same year 3D-printing startup Objet built a machine that could print in multiple materials, which allowed a single part to be fabricated in different versions, with different material properties. The creative innovations of the decade were topped off in 2008 with the launch of collaborative co-creation services such as Shapways, a AM marketplace where designers can get feedback from consumers and other designers and then affordably fabricate their products. In the same year the first usable 3D printed prosthetic legs is created and used. It was printed as is without requiring additional later assembly. In 2009 Makerbot hit the scene, providing open-source DIY kits for makers to build their own 3D printers and products. In 2015 Swedish company Cellink put the first standardized commercial bio-ink on sale. Made from a seaweed-derived material called nanocellulose alginate, the bio-ink can be used for printing tissue cartilage [13]. In 2018 AM in construction gains momentum as houses are being printed to solve the housing crisis globally [14]. The fashion industry adopts AM technology for complex design creations [15]. The sport industry is using 3D printer to enhance performance [16]. The medical industry continues to advance with printed cells and prosthetics. Entrepreneurs are succeeding in bringing their product to the market and can compete with larger companies.

At this point, the barriers to entry for designers and inventors were falling every day. The price of 3D printer, due to economies of scale and expiration of the patent, is falling rapidly, new material are being explored every day and the technical specifications in general are becoming always better (Fig.1.2).

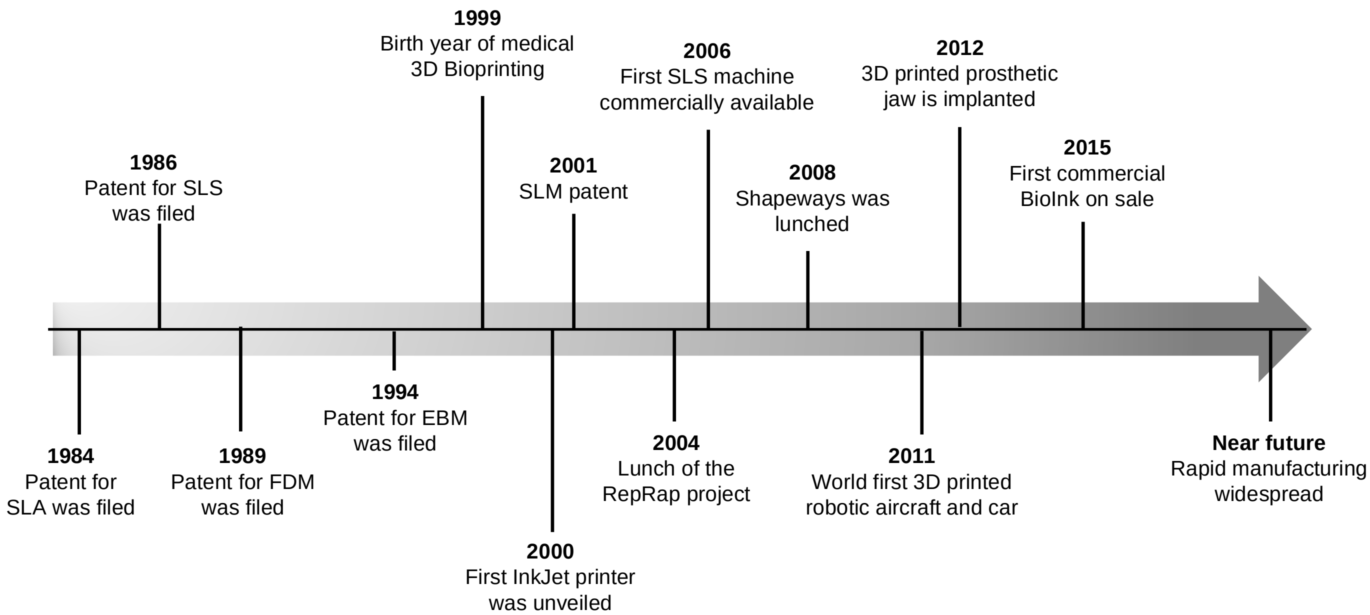


Fig. 1.2 – AM history time line

3. Additive Manufacturing general process

AM technologies allow to produce physical objects from a digital model develop through CAD programs or scanned with laser techniques. The file with the project to be printed contains the instructions that the printer must follow. The realized models are produced thanks to the perfect position of layers of condensed materials of various nature that aggregate and form a real solid matter. The result is an object that incorporates all the features and measures previously designed by. In general, eight steps are involved in the AM process, as shown in Fig. 1.3 [11]. This sequence of steps is generally appropriate to all commercial AM technologies, though different technologies may require more or less attention for a number of this stage. For instance, talking about the Post-process step, the parts manufactured by a stereolithography AM process general required a high Post-processing time when compared to those equal to zero of the printed parts extruded by EAM equipment.

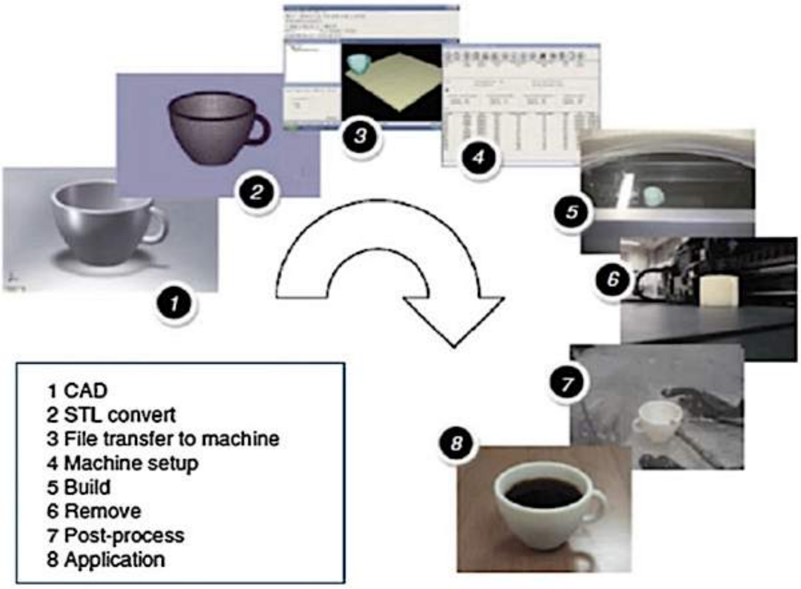


Fig. 1.3 – Generic AM process chain [11]

3.1. CAD model

The first tool to be used is a software that allows to obtain a drawing of the external geometry of the object to be printed. For this representation, it can use any professional CAD software or reversal engineering equipment, such as laser and optical scanning. It may be that AM technology will be used to prototype and not to build the final product, but in either case, there are many stages in a product development process where digital models are required [11]. All AM parts must start from a software model and the output must be a 3D solid or surface representation.

3.2.Conversion to STL

The second step is to convert the CAD file into Standard Tessellation Language - STL format. The term STL was derived from STereoLitography, which was the first AM technologies from 3D Systems in 1990s. STL is a simple way to describe a CAD models in term of its geometry alone. Nearly every AM machine accepts the STL file format and nowadays nearly every CAD system can output such a file format. During this process the surface of the CAD model is discretized, generating a number of triangles more or less high. The higher the number of planar elements, the better the approximation of our object will be but at the cost of bigger file size, that obviously require more time to be process. The approximation is never perfect, and the facet introduce coarseness to the model. There have therefore been a number of software tools developed to detect such errors and rectify them if possible, anyway it is very important to find the right balance between file size and print quality.

3.3.Slicing

The STL file describing the part is brought into the slicing program that is usually proprietary and comes with the AM machine in order to be transferred to the AM machine. The software generates a series of closely spaced 2D cross-sections of the 3D object and each one is converted to a sequence of machine instructions. In the physical world, each slice has a finite thickness, so the resulting part will be an approximation of the original data. During this step the user can adjust the size, location and orientation of the model. The latter specification is a real important one for several reason. First, the physical part fabricated using AM is anisotropic, so the proprieties, such as tensile strength of the component change from one coordinate direction to another [17]. Second part orientation partially determines the amount of time required to build the model. The programs, depends on the AM technology, also may generate an auxiliary structure to support the model during the build.

3.4.Machine setup

The AM machine must be properly set up prior to the build process. All AM machine will at least some setup parameters that are specific to that machine or process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, interior fill pattern, building speed, etc. (Fig. 1.4). It is common to have default settings or save files from previously defined setups to help speed up the machine setup process and to prevent mistakes being made. In addition to prepare the machine software parameters, most machine must be physically set up for the build.

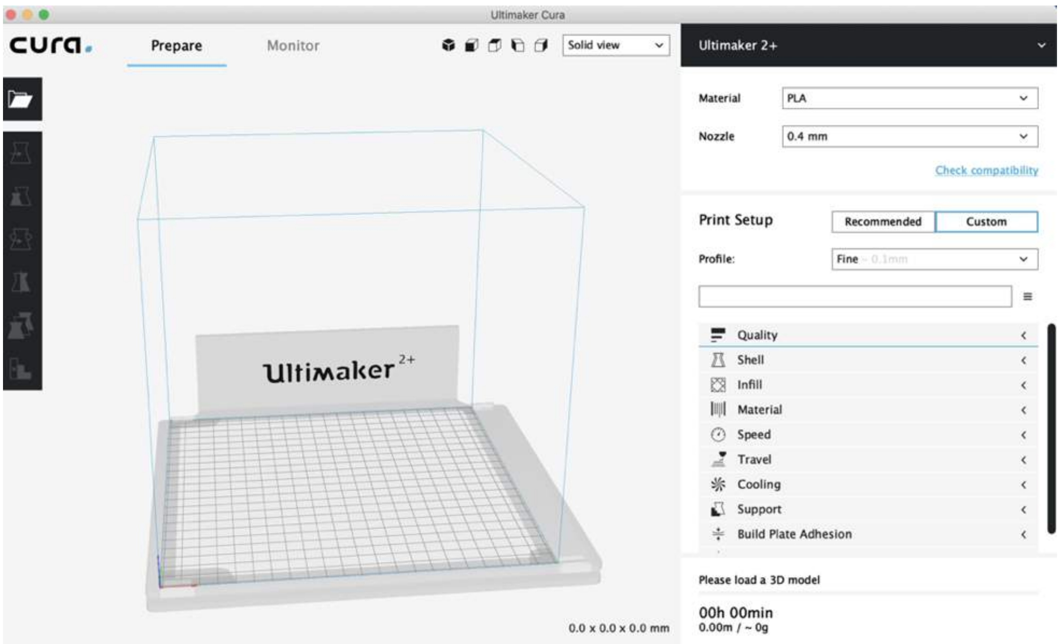


Fig. 1.4 – 3D FDM printer' setup software view [18]

3.5.Build

The physical model will be fabricated using one of the several building techniques. Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.. As long as no errors are detected during the build, AM machine will repeat the layering process until the build is completed

3.6.Remove

Once the AM machine has completed the build, the parts must be removed. In all cases, the part must be either separated from a build platform on which the part was produced or removed from excess build material surrounding the part. While some processes have been developed to produce easy to remove supports, there is often a significant amount of manual work required at this stage. This require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts. There is a certain degree of operator skill required in part removal, since mishandling of parts and poor technique can damage the part. The cleanup stage may also consider as the initial part of step seven, the post-processing.

3.7.Post-processing

Once removed the part from the machine, it may require an amount of additional cleaning up, polishing or sandpapering before they are ready for use. Parts may be weak at this stage, like photosensitive materials which need to be fully cured before use, or they may have supporting features that must be removed. This stage in the process is very application specific. Therefore, it often requires time, experienced and intensive manual manipulation.

3.8.Application

Following post-processing parts may now be ready to be used. However, they may also need additional treatment before they are acceptable for use. For example, they may require priming and painting or some minor cleaning or surface finish processes to improve the appearance and the durability of the part. Treatments may be laborious and lengthy if the finishing requirements are very demanding. They may also be required to be assembled together with other mechanical or electronic components to form a final model or product.

4.Additive manufacturing benefits and limitations

Compared with traditional production methods AM offer enormous benefits, especially in market environment characterized by demand for customization, flexibility, design complexity, and high transportation costs for the delivery of end products [19]. In the long-term run AM can completely change the way products are designed and build, as well as distributed, sold and serviced (fig. 1.5). Holmstrom *at al*. [20] suggest the unique characteristics of AM production lead the following benefits:

- No tooling is needed significantly reducing production ramp-up time and expense. The par is obtained directly from its CAD model, with almost absolute absence of human errors in production.
- Small production batches are feasible and economical. Not costly setup is required.
- Possibility to quickly change design and drastically lower the cost of engineering changes and reduce time-to-market. For instance, the rapid prototyping helps reduce average prototyping time and cost by 63% and 75%, respectively [9].
- Allows product to be optimized for function (for example optimized cooling channels).
- Allows economical custom products (batch of one).
- Possibility to reduce waste. For some applications especially in the metal sector, case studies show that the waste of raw material is reduced by up to 40% when using additive technologies instead of subtractive technologies [21]
- Supply chains optimization. Production can be easily synchronized with customer demand. Shorter lead times, lower inventories.
- Design customization and lightweight component manufacturing.

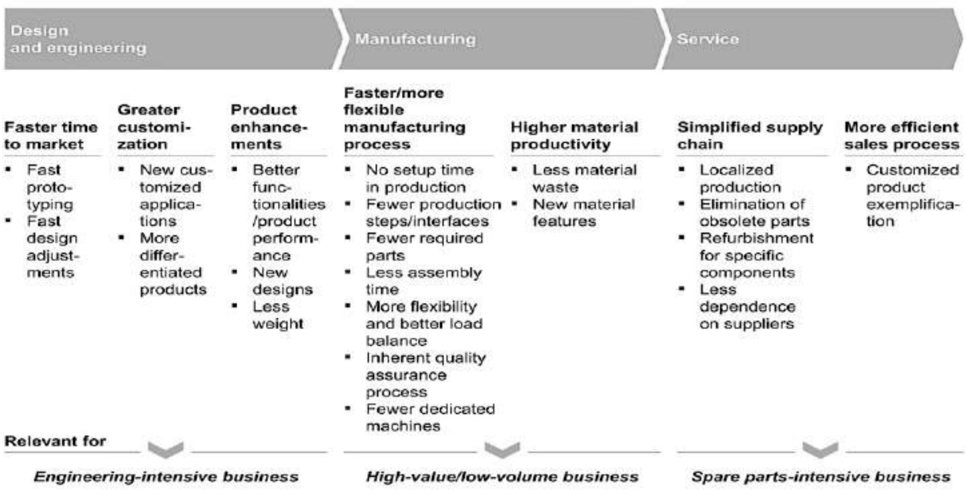


Fig. 1.5 – AM potential benefit [22]

Another benefit, not mention before, but increasingly relevant, is the lower environmental impact of AM technologies compared to traditional ones [23]. For example, Serres *et al.* [24] proposed a study comparing an AM process and machining on a mechanical part manufactured out of titanium alloy, pointing out how 3D printing reduces about 80% of the environmental impact.

All these benefits have been captured in a lot of applications spanning different businesses. Although the advantages, we must also consider the critical issues that, de facto have prevented a massive diffusion of AM technologies. For instance, available materials and the surface finishes are still constrained [19]. Furthermore, also the build space of AM machines could be a problem, setting a physical limit to product dimensions. With current AM technology, quality issues are also a concern. Creating object layer by layer may affect negatively surface quality and roughness. Parts may lack resistance to environmental influences and fail with exposure to high stresses [25]. In addition, the precision of the produced parts still needs improvement. Therefore, reproducibility of parts cannot be assured, and global quality as well as testing standards are still to be defined [25]. Moreover, design tools have yet to fully exploit the possibilities AM technology offers. Missing guidelines currently make it difficult for non-experts to optimize product designs and attain the necessary know-how [26]. In the end, speaking about rapid manufacturing, there is another issue to take into account: the machine costs. AM process is worthwhile only if the production volumes are low. There is a break-even cost point between conventional and additive manufacturing when comparing cost part and production volume (Fig. 1.6). Clearly, if AM technologies were to be more adopted then the economies of scale should allow reduced machine cost.

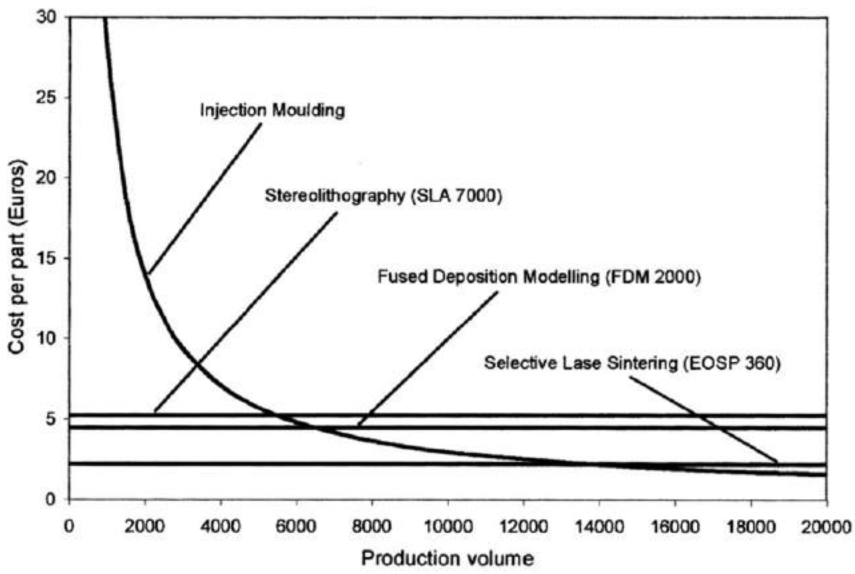


Fig. 1.6 – Break-even analysis between AM and Injection Molding [27]

5.Additive Manufacturing technology overview

Since the birth of Additive Manufacturing various techniques have been developed almost simultaneously. There are various similarities as well as distinct differences between each one. The mechanisms and materials introduced along with the technological advancements have resulted in a number of different methods of categorizing AM process.

There are several systems to classify AM process. Two possible classification were proposed by Kruth [28] in 1991. The first one is related to the way material is created or solidified. The second to way the shape is build. However, in this section we are going to use the more recent classification proposed by the American Society for Testing and Materials in 2010, which classifies AM process in seven categories: Binder Jetting, Direct Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination and Vat Photopolymerization [10] (Fig.1.7).

Additive manufacturing process	Maximum build envelope (mm^3)	Minimum feature size (mm)	Typical tollerance (+/- mm)	Minimum layer thickness (mm)
Binder Jetting	4000x2000x1000	0.1	0.13	0.09
Directly Energy Deposition	1000x800x650	0.04-0.2	0.1	0.03
Material Extrusion	5000x37800x3600	0.178	0.178	0.178
Material Jetting	1000x800x500	0.1	0.025	0.013
Powder Bed Fusion	600x400x500	0.04-0.2	0.05-0.2	0.03
Sheet Lamination	7200x1800x900	0.2	0.1	0.05
Vat Photopolimerization	2100x700x800	0.1	0.15	0.016

Tab.1.1 – AM classification and general characteristics/restriction

5.1.Binder Jetting

In the late 1980s, Sachs *at al.* invented the 3D printing technology, commercial name for Binder Jetting, that was later patented to print plastic, ceramic and metal parts. This AM process is similar to the Selective Laser Sintering process, but instead of using a CO_2 laser to sinter the powdered material, an ink-jet printing head deposits a liquid adhesive that binds the material. In the 3D Printing machine there are two pistons: one for feeding the powder and the other for lowering/raising the building chamber. The 3D Printing process begins with the powder supply being raised by a piston and a leveling roller distributing a thin layer of powder to the top of the build chamber. The multi-channel ink-jet printing head then deposits binder solution onto the loose powder, forming the first cross-section. These regions of powder are glued together wherever the binder is printed. The remaining powder remains loose and supports the part during the process. When the cross-section is completed, the build piston is lowered, the powder feed piston is raised, and a new layer of powder is added on the previous layer by the leveling roller. The process is repeated, and the part grows layer by layer until the part is finished. After its completion, the loose supporting powder can be brushed away and the part removed. The main advantages of this process are that no chemical post-processing is required, no resins have to be cure, usually the machines and the materials are less expensive resulting in a more cost-effective process [29]. The disadvantages are that the resolution on the *z* axis is low compared to other additive manufacturing process (0.25 mm). If a smooth surface is needed a finishing process is required but this is a very slow process, sometimes taking days to build large complex parts [29]. In Figure 1.7 is shown the basics Binder Jetting process.

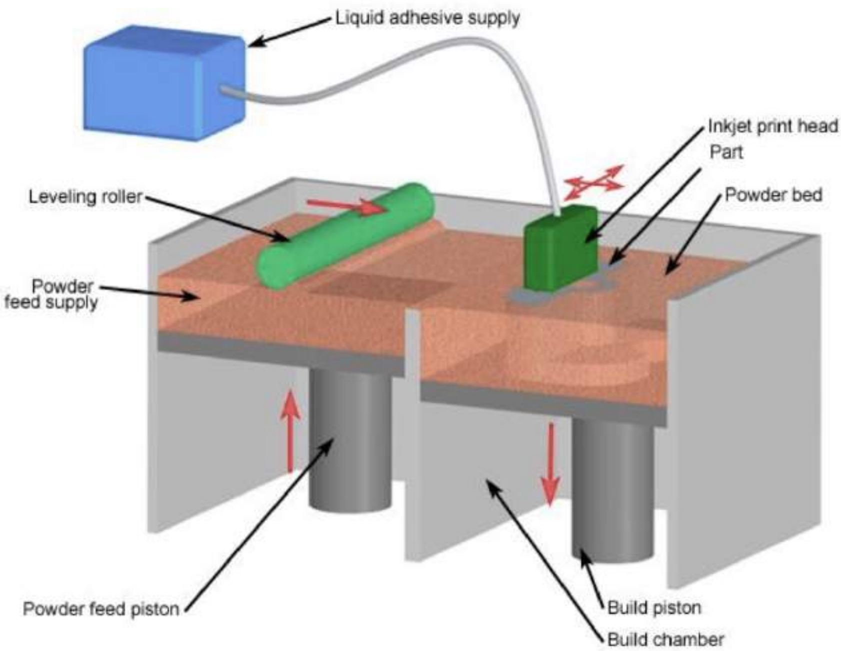


Fig. 1.7 – Schematic view of Binder Jetting process [30]

5.2.Direct Energy Deposition

Direct energy deposition (DED), also known as laser engineered net shaping, laser solid forming, direct light fabrication, direct metal deposition, electron beam AM and wire +Arc Am has been used for manufacturing high-performance super-alloys. A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies (Fig. 1.8). This process uses a source of energy (laser or electron beam) which is focused on a small region of the substrate in order to melt the material upon deposition. Unlike powder bed fusion techniques DED processes are used to melt materials as they are being deposited. In order to prevent material degradation during high temperatures, the process is usually made in a vacuum chamber. This method allows for both multiple-axis deposition and multiple materials at the same time [31]. Moreover, DED can be combined easily with conventional subtractive processes to complete machining. This technique is commonly used with titanium, Inconel, stainless steel, aluminum and the related alloys for aerospace applications. In general, DED is characterized by high speeds [32] and very large work envelopes. However, it has a lower accuracy (0.25 mm), lower surface quality and can manufacture fewer complex parts compared to SLS or SLM [11]. Therefore, DED is commonly used for large components with low complexity and also for repairing larger components. DED can reduce the manufacturing time and cost, and provides excellent mechanical properties, controlled microstructure and accurate composition control [33].

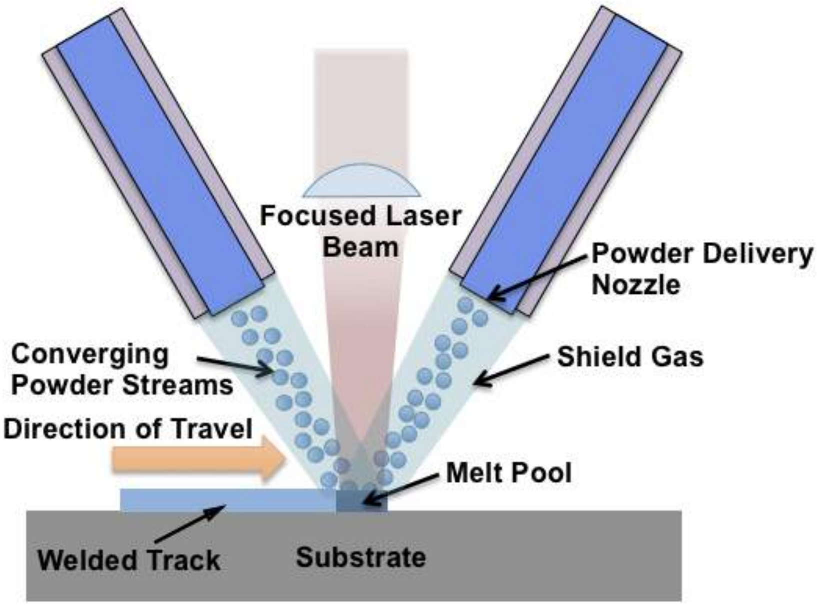


Fig. 1.8 – Schematic view of Direct Energy Deposition system [34]

5.3.Material Extrusion

Extrusion based 3D printers, also known as Fused Filament Fabrication or Fused Deposition Modeling, are probably the best-known AM technology among people. This is due to the fact that FDM machines are of all AM machines the cheapest and most affordable ones. During the process the semisolid feedstock contained in a reservoir, in form of pellet or filament, is forced out through a movable nozzle when pressure is applied (fig. 1.9). Under the properly temperature and pressure condition extruded material will flow on the platform or on top of previously printed layers and bond with adjacent material before solidifying. The resolution and accuracy of models are limited by nozzle diameter [35], instead the build speed by the need for the nozzle to physically cross the build area There are two primary approach when using an extrusion process [11]. The most common approach uses temperature as a way to control the material state. The alternative approach consists of exploiting chemical change to cause solidification. In such cases, a curing agent, residual solvent, reaction with air, or simply drying of a "wet" material permits bonding to occur [11]. This process is mainly use in biochemical application where material has to be biocompatible with living cells. The main advantages of this process are that no chemical post-processing is required, no resins cure, less expensive machines, materials resulting in a more cost-effective process [36] and in general the simplicity [33]. There are, however, some disadvantages such as weak and anisotropy of mechanical property, layer-by-layer appearance, poor surface quality, slow build speed [11].

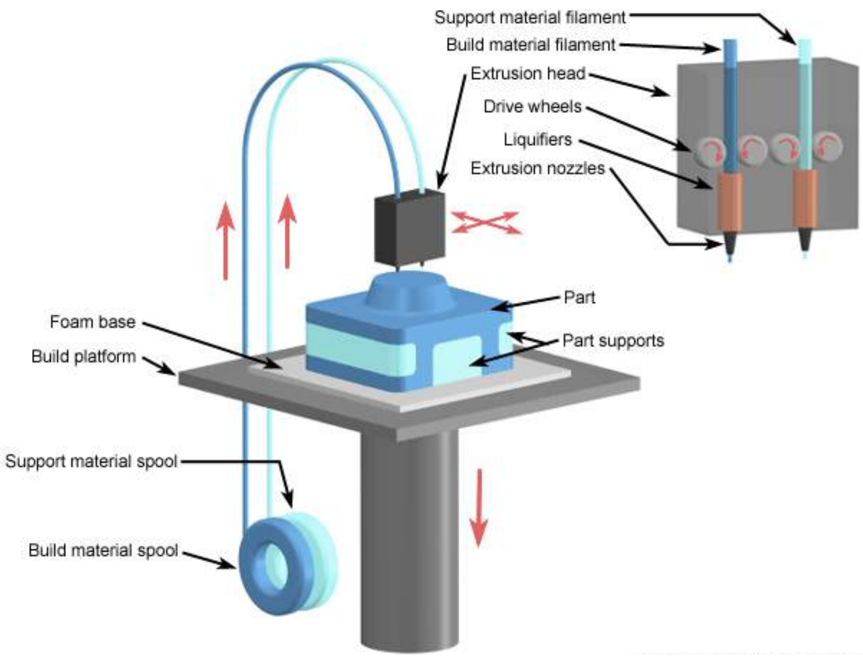


Fig. 1.9 – Schematic view of one of the most common extrusion-based solution [37].

5.4.Material Jetting

Inkjet printing is one of the main methods for additive manufacturing of ceramics [33] and photocurable resins, usually acrylic based [31]. In this method the low viscosity material is dispensed in drops through many individual nozzles from the printed head (Fig. 1.10), resulting in rapid, line-wise deposition efficiency [11]. While jetting material is in a liquid state and it is hardened shortly after using UV lamp producing fully cured models without post-curing. After that, the build platform is lowered by a layer thickness and next layer is deposit and cured. Continuing with the process in this way finished part is obtained. This method is fast and efficient, which adds flexibility for designing and printing complex structure [36]. On the other hand, the accuracy of the dimensional resolution and quality of inkjet-printed parts is closely related to the ink parameters, such as particle size and viscosity, and to extrusion parameters, such as extrusion rate and nozzle travel speed [38].

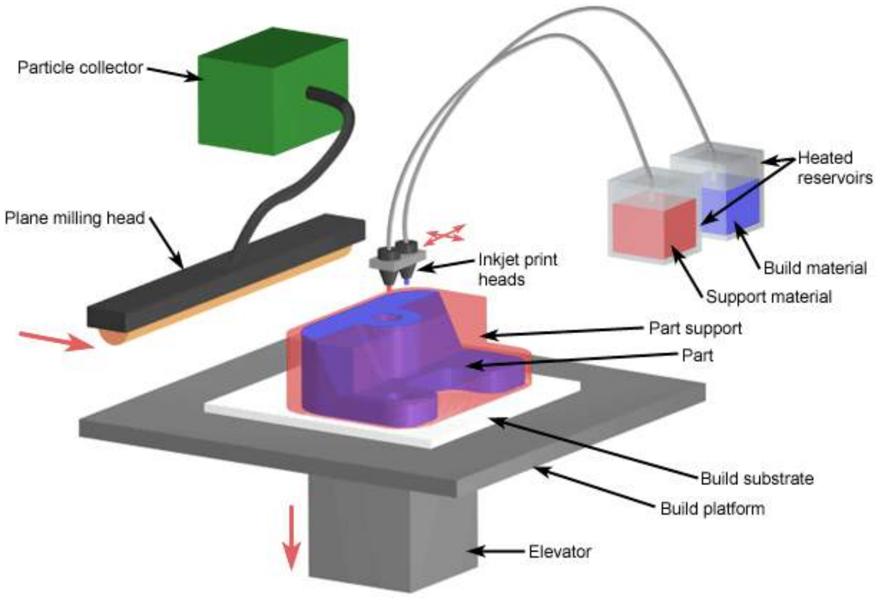


Fig. 1.10 – The Inkjet Printing System [37]

5.5.Powder Bed Fusion

Powder bed fusion is counted among the oldest technologies commercially introduced. It can utilize variety of materials and final products can be fully dense functional parts. Theoretically, all materials that can be melted or re-solidified can be use in Powder Bed Fusion process. As suggested by the name in this process it is used material in form of powder. In an inert or partial vacuum atmosphere, thin layers of powder material are spread and closely packed on the build platform or upon another layer. Then the powder is selectively cured together, melted (Selective Laser Melting - SLM) or sintered (Selective Laser Sintering - SLS) by a heat source (fig. 1.11). The deposition and fusion process continue until the part is finished. After cooling, the excess powder is removed, further processing and detailing such as coating, sintering or infiltration are carried out. Powder size distribution and packing, which determine the density of the printed part, are the most crucial factors to the efficacy of this method [39]. There are many types of Powder Bed Fusion machines. Different machine might utilize different heat sources, such as laser or electron beam, or different handling powder systems, but the general process does not differ much from the one describes above. The two main advantages of Powder Bed Fusion are fine resolution and high quality of the printing [36]. However, the main drawbacks of Powder Bed Fusion are the slowness of the process, the high costs and the complexity of the machinery

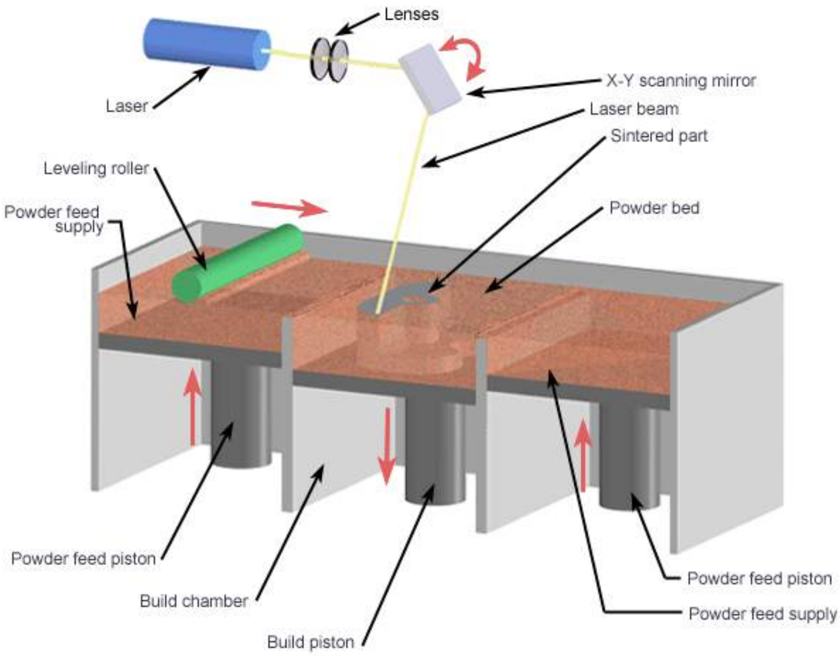


Fig. 1.11 – One of the most common Powder Bed Fusion machine: the SLS [37].

5.6.Sheet Lamination

Sheet lamination is one of the first additive manufacturing available methods. The process uses raw sheets or ribbons of metal which are cut using a mechanical cutter or CO_2 laser to desired shape and bounded with different techniques to previous layer (fig. 1.12). Each sheet represents one cross-sectional layer of the CAD model of the part. The excess portion of paper sheets which is not contained within the final part are left for the support and after completion of the process, can be removed and recycled [11]. Almost any sheet material, that can be bonded together, can be used in some way. Post-processing such as high-temperature treatment may be required depending on the type of materials and desired properties [36]. There are two main binding approach in Sheet Lamination process. The first one uses ultrasonic welding to bound material sheet together. The second uses paper as material and adhesive instead of welding. Both processes are low temperature and allows for internal geometry to be created [40]. However, it is possible to find other solution to achieve bond between layers, such as thermal bonding and clamping. LOM can result in a reduction of tooling cost and manufacturing time and is one of the best additive manufacturing methods for larger structures [36]. The main disadvantages of this technique concern poor surface quality, without post-processing, and limited dimensional accuracy. In addition, the detail reproduction and durability of small parts features is comparably low [41].

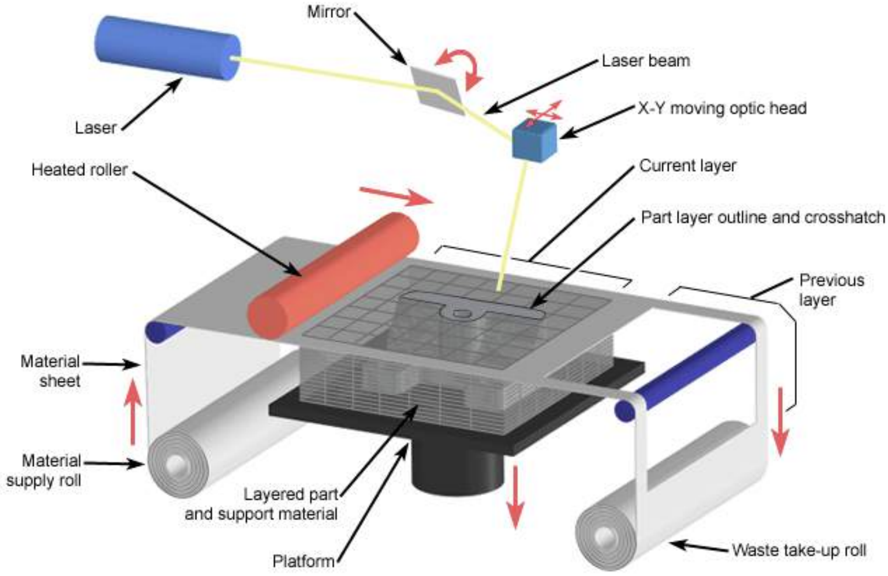


Fig. 1.12 – Laminated Object Manufacturing process[37].

5.7.Vat Photopolymerization

Vat Photopolymerization is the earliest methods of Additive Manufacturing, which was developed in 1986 [42]. Vat Photopolymerization process uses vat of liquid, radiation-curable resins, or photopolymer, out of which the model is constructed layer by layer (fig. 1.13). An ultraviolet light, or another source of radiations, such as electron beam, gamma ray, visible light or X-rays, is used to cure and hardened the resin where indicated by the CAD model. The unreacted resin is removed after the completion of printing. A post-process treatment such as heating or photo-curing may be used in order to achieve the desired mechanical performance. Two primary configurations were developed for photopolymerization processes in a vat, plus one additional configuration that has seen some research interest [11]. The configurations are:

- Spot scanning approaches, where layer is cured by a laser which is projected onto a very small resin surface by mirror. By changing the angle mirror the location of the laser spot can be modified.
- Mask projection approaches use Digital Micromirror Devices that can irradiate a single layer simultaneously to cure an entire layer at once.

- Two photon approaches use two separate lasers. One laser is not enough powerful to cause the chemical reaction and solidification. This occurs only in the small region where the beams of lasers intersect.

Vat Photopolymerization prints high quality parts at a fine resolution as low as 10 μm [43]. On the other hand, it is relatively slow and expensive process, the range of printing materials is very limited [36] and long-term stability of the components tends to be an issue [31]. Also, possible cytotoxicity of residual photoinitiator and uncured resin is another concern [43].

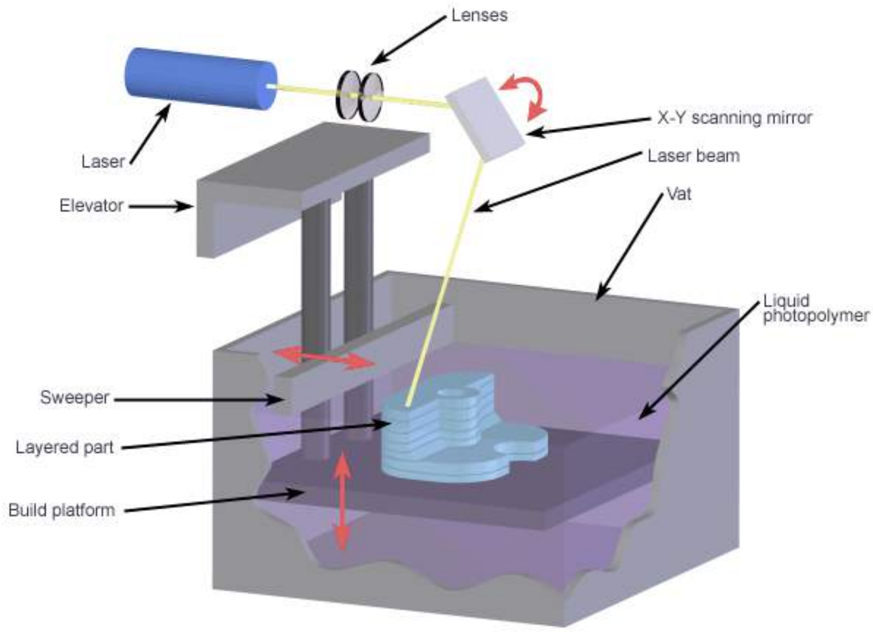


Fig. 1.13 –Vat Photopolymerization process with spot scanning approach [37].

CHAPTER 2

Extrusion based AM process and market overview

1.Extrusion based machine types

Extrusion based additive manufacturing – EAM, also known as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM), is the most versatile AM process [44] and currently the most popular on the market [11] thanks to the continued improvement in the performance and cost reduction of manufacturing systems, as well as the development of new feedstock material. The term Fused Deposition Modelling are trademarked by Stratasys Inc. the company which first patent the technology in 1992 (fig 2.1). In consequence of this trademark competitive manufacturers has referred to this process as Fused Filament Fabrication. As written in the previous chapter extrusion-based 3D printer builds parts layer by layer by heating, melting and extruding feedstock, typically thermoplastic, through a small nozzle. Molten polymer roads are laid in the horizontal plane to complete the cross-section of a part, and the stacking of consecutive cross-sections creates the final freestanding 3D object [44]. In the market it is possible to find four different type of extrusion-based 3D printers: Cartesian, Delta, Polar and SCARA.

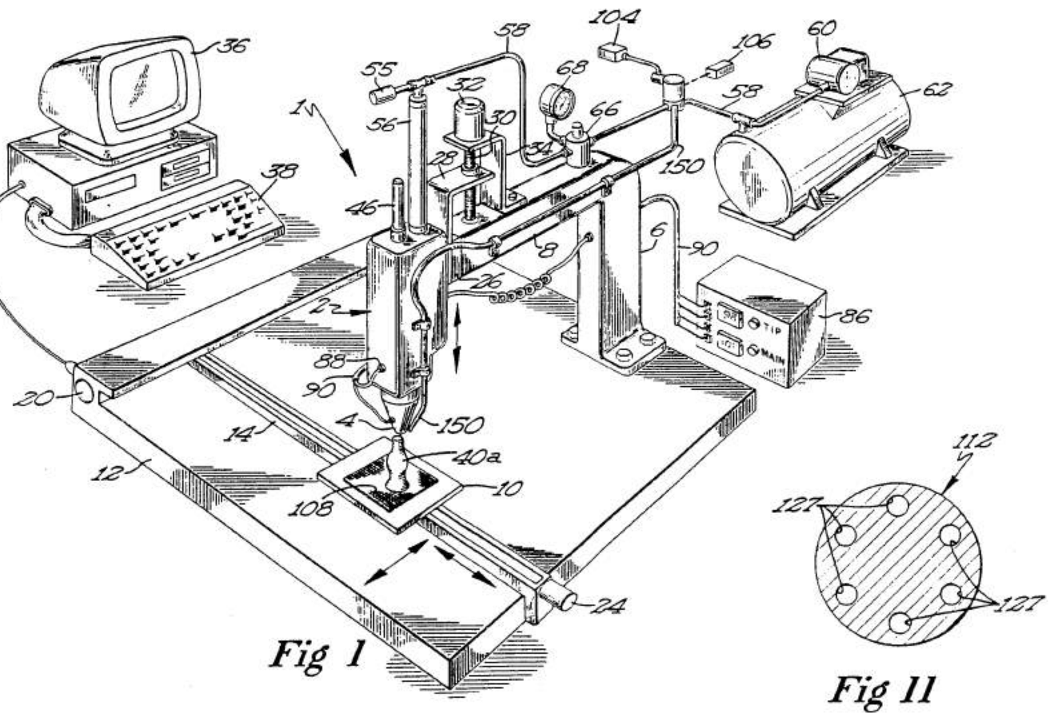


Fig. 2.1 – One of the images from the FDM patent that summarized the extrusion-based process [45]

1.1.Cartesian 3D printer

Cartesian printers are the most common system found on the market. Based on the Cartesian coordinate system in mathematics, this technology uses three-axis: X, Y, and Z to determine where and how to move the print head in three dimensions. In this type of printer, the printing bed usually moves only on the Z axis, with the print head sites on the X-Y plane working on two dimensions (fig. 2.2). However, there are two main types of Cartesian printers [47]:

- MakerBot style, based on a fixed plane X, a movable Z print bed and a movable Y printhead.
- RepRap style based also on a fixed plane X, while the Y axis is controlled by moving the print bed itself and the Z axis is accomplished by moving the whole printhead system.

Two popular brands in the Fused Deposition Modeling market that use Cartesian technology for their printers are Ultimaker and MakerBot.

1.2.Delta 3D printer

These printers are being seen more and more on the extrusion-based AM market. These machines operate with Cartesian coordinates and involves a round printing plate that is combined with an extruder that is connected through three arms to three vertically rails that are standing upright in a triangular configuration. The position and direction of the print head is achieved moving the arms up and down along the rails. Due to this, it is more mathematically complex to find the head position of a Delta printer. Delta printers are becoming more popular because this particular configuration enables faster printing and more a more compact size than the Cartesian printers [48]. One of the most popular brands for this type of machine is Wasp.

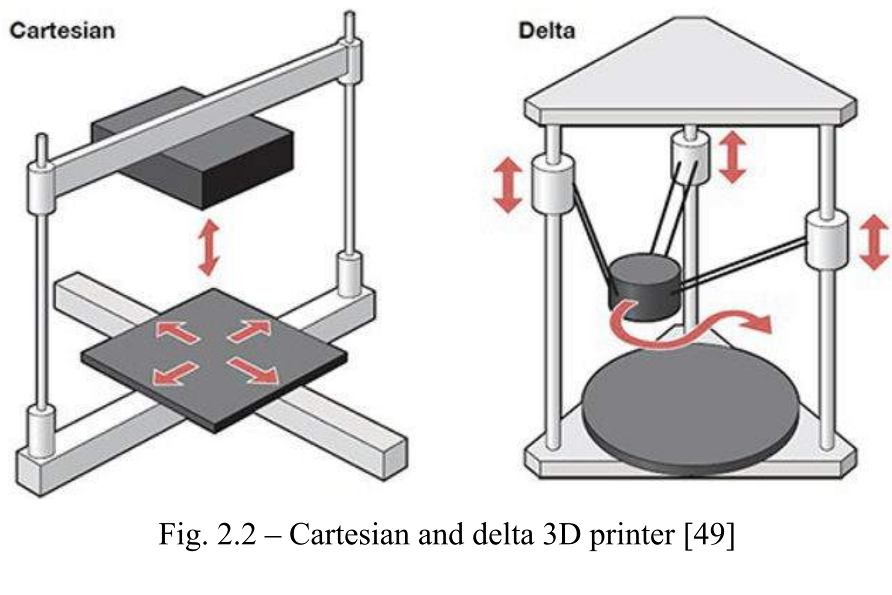


Fig. 2.2 – Cartesian and delta 3D printer [49]

1.3.Polar 3D printer

Polar 3D printers' positioning is not determined by cartesian coordinates, but by polar coordinates system. It's similar to the Cartesian, except that the coordinate sets describe points on a circular grid rather than a square. This means that the bed rotates and moves at the same time, with the extruder moving up and down. The main advantage of Polar 3D printers is they only two engines, whereas Cartesian printers need at least three, one motor for each axis. Moreover, polar 3D printers can have a greater build volume within a smaller space, lacking the requirement of a XYZ framework to move around [46].

1.4.SCARA 3D printer

The Selective Compliance Assembly Robotic Arm – SCARA is a very precise system. The machine that moves and looks like an industrial robot. In this type of printer, the printing bed is not fixed to the machine, while the printhead is connected to a robotic arm and free to move. Although not a commonly used printing process, this FDM printing method is beginning to see an increase in use, especially thanks to the flexibility when positioning the printer head that allow to easy create complex structures [49].

2.Extrusion based process

In general extrusion process can be seen as a complex trade-off dependent of different parameters such as input pressure, temperature, nozzle diameter and material characteristics, in order to achieve the best quality in the shortest time.

According to Gibson *et al.* [11] there are seven key features that characterize a generic extrusion-based process, which can be summarized in four point:

- Loading material
- Liquefier and print head
- Solidification, bonding and support generation
- Plotting and path control

2.1. Material feed mechanism

Typically, feedstock material is supplied as a solid and the most suitable methods of supply are in pellet form or as a continuous filament. In both cases the process required specific diameter or pellet dimension, strength and certain other properties.

In a pellet feed mechanism, the material is generally pushed into the liquefier chamber with the aid of a conveying screw or similar propelling process. In a filament-based system, instead, materials are fed through the system using a pinch roller mechanism like that illustrated in figure 2.3. A stepper motor is connected to one of the rollers providing energy to move the filament through the system. One or both of the rollers may have a grooved or toothed surface like a gear to create sufficient friction for the roller to grab the filament and feed it to the liquefier without slippage. The pressure on the filament between the rollers is typically sufficient to slightly deform the filament, usually leaving small tooth marks, but these should be designed so as to avoid crushing the filament [50]. Typical feedstocks are amorphous thermoplastic polymer filaments with a diameter of about 1.75 mm

Directly using plastic pellets to print has many advantages such as low cost, fast processing speed and widely available materials [51] [52]. On the other hand, there are some disadvantages, such as heavier system extruder than filament one because of the need to convert pellet into usable material, or the impossibility to retract the flow of extruded material and then less control over the print [52]. However, this technology is relatively new and requires a lot of research to become as robust as the traditional filament-based system.

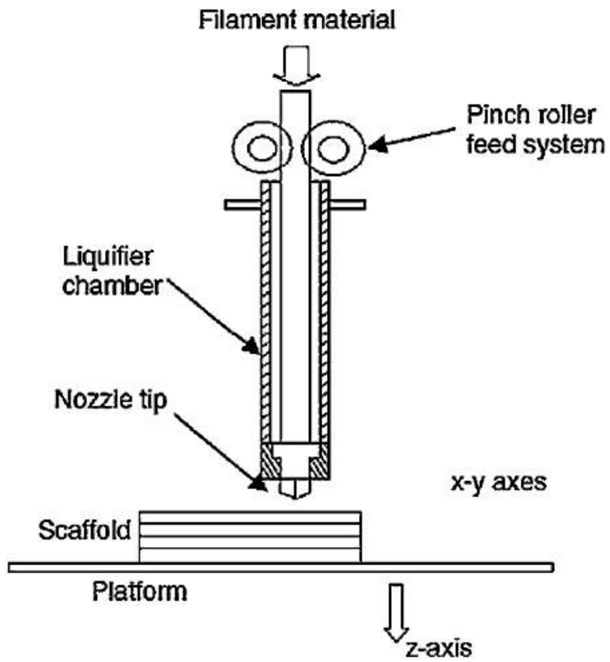


Fig. 2.3 – Schematic filament extrusion-based system [11]

2.2.Liqufier and print head

The core of extrusion-based AM process is the liquefier chamber in which the polymer is melted and push through the nozzle, typically conical. The heat is applied by heater coils wrapped around the chamber and ideally, they should maintain a constant temperature in the melt, but the larger is the chamber, the more difficult it becomes. The amount of melt in the liquefier will depend on the heat flux and the material feed rate. Feedstocks are generally amorphous polymers which do not have a distinct melting point. As the temperature increases, the viscosity of the melt decreases, allowing it to flow through the print nozzle more readily with a smaller pressure drop. Higher melt temperature also leads to better adhesion between successive beads and therefore greater mechanical strength in the finished part, but higher temperature can also lead to polymer degradation, breaking down polymer chains, weakening the finished part and leaving residue on the inside of the melt channel. A higher temperature required also additional cooling following extrusion.

The print head is closely integrated with the liquefier chamber and it could be fixed or removable. The size of nozzle opening obviously puts a limit on the resolution that may be achieved and the maximum layer height. The larger the diameter of the nozzle, the faster the material will flow, but with less resolution obtainable. Typically, nozzle diameter is between 0,3 mm and 0,4 mm.

The print head-liquefier chamber assembly is connected to a gantry that enables motion in the X and Y directions. Since the plotting head has not negligible mass, it contains an inertial element when moving in a specific direction and any change in direction must result in a deceleration followed by acceleration. The corresponding material flow rate must match this change in speed or else too much or too little material will be deposited in a particular region [11]. Power to enable the motion is usually supplied by an electric stepper motor and transduced through a gear and timing belt, screws or helical gear racks. The velocity at which the extrusion system can move is primarily limited by the stiffness of the construction of the gantry.

2.3.Solidification, bonding and support generation

Material is extruded onto a horizontal build platform, that could be movable or fixed. The melt must adhere to this surface, but not so well that the part cannot be removed when the print process is complete. A lot of machines utilize a disposable build sheet or adhesive glue suitable for the build material which is placed on the build plate.

Ideally the extruded material should maintain the same shape and size. However, gravity, surface tension and cooling may cause the material change shape, shrink and warp [11] [53]. In order to mitigate these effects, it is important that the differential temperature between the liquefier chamber and the build area is kept to a minimum. This could be done thanks to a heated build platform or a closed temperature-controlled building chamber. The first solution is usually adopted by the cheapest extrusion base AM machine; the second, it could be found in the industrial system that treat high melting polymers, such as Ultem or Peek. It also important to ensure a gradual cooling process with smooth profile.

The melted material must also have residual heat energy to activate the surfaces of the adjacent regions, causing bonding. If the energy is not enough, the regions may not adhere or adhere, but with a distinct boundary between new and previously deposited material. This can represent a fracture surface where the materials can be easily separated. On the other hand, too much energy may cause the previously deposited material to flow, which in turn may result in a poorly defined part [54].

The extrusion-based technique has particular toolpaths to fill one-part layer. The most used toolpath is the raster fill. First the outline of the layer is formed by the contour toolpaths, then the interior is filled with a back and forth pattern and an angle of 45° to the x-axis, helping to distribute the strength in each part more evenly. Alternating layers are filled with a raster direction at 90° to one another [55].

Finally, it is important to underline that not all the features can be printed free-standing. In some case it needs additional fabrication of supports for keeping all the part in place during the process. The support material could be the same of the final component or a different one. In the first case the part must be carefully designed so that the support material can be remove later. Working on the temperature it can be purposely create a fracture surface between the part and the support material which allows an easy separation of parts. In the second case another extrusion chamber must be provided. The different material propriety can be exploited in order to separate mechanically or chemically the supports from the part.

2.4.Part finishing

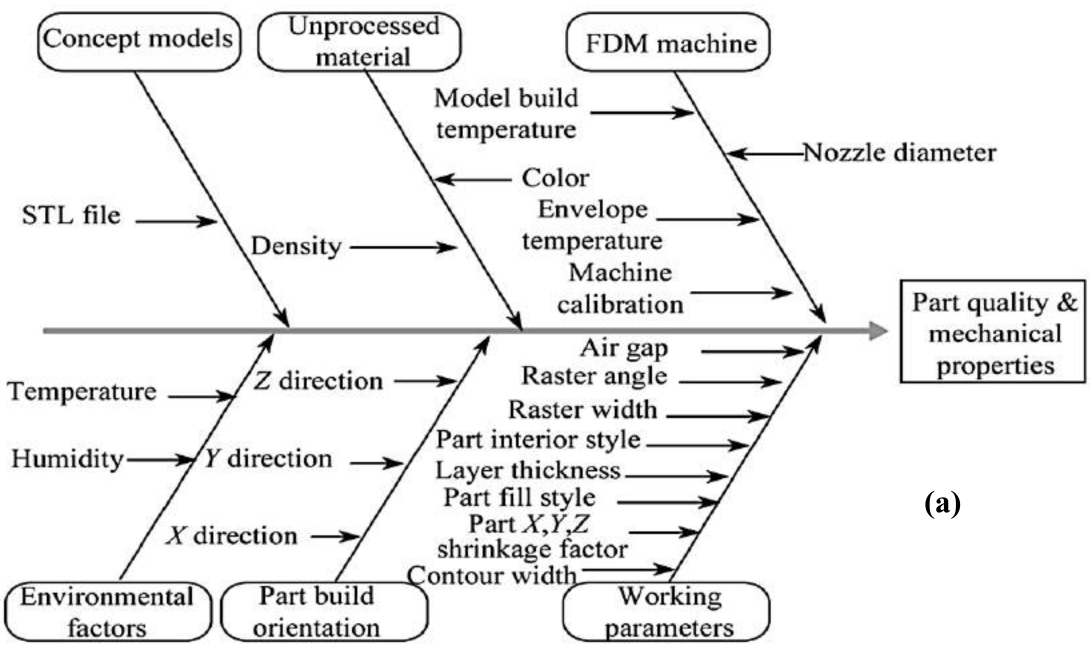
As far as the nozzle diameter is small and the layers thickness thin, ridged surface is an unavoidable characteristic of the final parts. This phenomenon, also called staircase effect, is one of the heaviest drawbacks of extrusion-based systems. In order to achieve a smooth surface two main approaches can be adopted: chemical [56] and mechanical smoothing [57]. As an alternative the application of a surface coating could be another viable solution to obtain the required surface finish, adding also more strength to the final part [58]

3.Build process parameter

There are many important parameters that affect AM part performance [59-61], quality [62-63], mechanical properties [57-63] or build time [64] of parts fabricated by extrusion-based process (fig. 2.4).

The main working parameters can be summarized as follow [66] (fig. 2.5):

- Part orientation. It refers to the inclination of the build part in a build platform. A very important parameter given the anisotropy properties of the printed parts that also influences production time and support generation.
- Layer thickness. It is recognized as the height of the deposit slice from FDM nozzle and depend upon the type of nozzle used.
- Raster or bead width. It is the width of the filament that machine's nozzle deposits used to fill interior region of the part curves.
- Raster angle. It refers to the inclination of the deposited beads of filament. As mention above a typical configuration is an angle of 45° to the x-axis. Component printed at 45° orientation angle and 100% infill density has higher tensile strength.
- Air gap. This is the space between two adjacent filaments on same layer and it is influencing the infill density. It could be positive or negative. A zero-value meaning that beads touch each other. This results in a dense structure which requires a longer build time. Strength is maximum at 80% infill density.
- Contour width refers to the width of contours tool path that surrounds the part.
- The number of contours to build around the part shape.



(a)

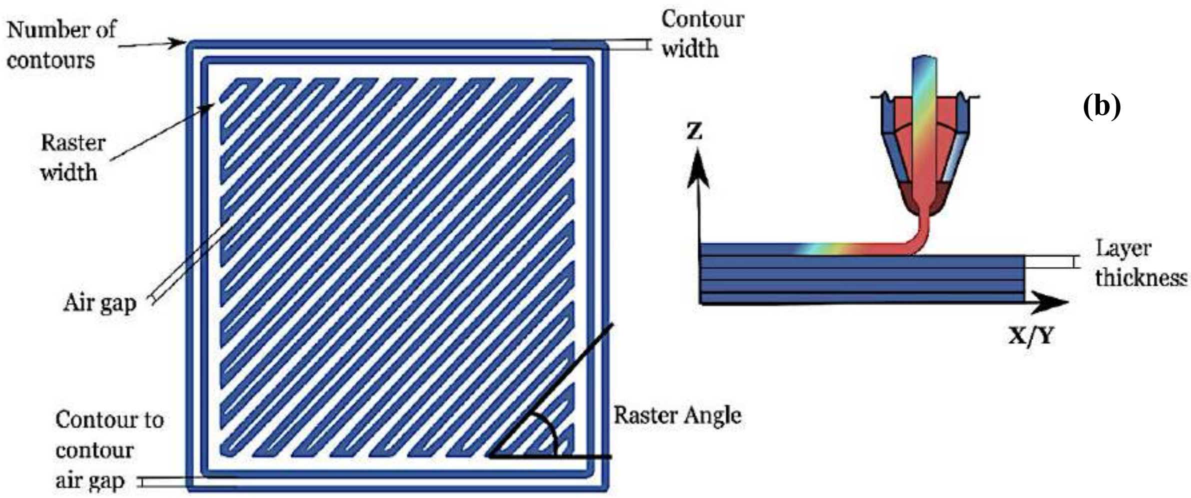


Fig. 2.5 – **(a)** Ishikawa diagram of extrusion-based process parameters [66] **(b)** Parameters of Extrusion-Based process [67]

4.Material overview

In principle any material which can be melted and then harden can be used in extrusion-based systems. This includes a wide range of materials from thermoplastic polymers to cold slurry [68], metal [69], wood [70], composite [71] and various bioinks [72-73]. Despite this is a rapidly changing field, current FFF printers is almost entirely focused on extrusion of thermoplastics that are amorphous in nature characterized by:

- Sufficient viscosity to maintain shape after extrusion and enabling them to solidify quickly and easily
- When material is added in an adjacent road or as a new layer, the previously extruded material can easily bond with it
- Low shrinkage/warpage

Among the large variety of engineering thermoplastics applied in FDM, acrylonitrile-butadiene-styrene copolymers (ABS) and polylactide (PLA), which will be used for the benchmark, polycarbonate (PC), and polyamides (PA) represent the most prominent ones [74]. Each of these materials can be found on the market in different pellet's or filament's diameter size and color. The latter is a particular important aspect that should be not underestimated because often the additives insert in the material to color it, can compromise the proprieties of the material itself.

These 3D printer's feed material can be provided by the machine's maker, third-party producers or created by the user himself with filament extruder machine, such as Lyman Filament

Extruder or filabot. However, the last option is not always feasible, indeed some 3D printer manufacturers design their printers to only work properly with the materials produced by themselves.

Below it will be discussed the two most common used material in extrusion-based process: PLA and ABS, which will be also used in the following chapter to benchmark different 3D printers (tab. 2.1). These materials are easy to find and have similar average price between $25 and $35/kg. However, filament costs can go from $18.96 to $175.20/kg for special filaments which is 20 to 200 times above the cost of raw plastic [75].

4.2.PLA

PLA is biodegradable and biocompatible thermoplastic aliphatic polyester obtain from fossil fuels or derived from renewable resources such as agricultural by-products rich in carbohydrates [76] (fig. 2.6). PLA can exist in three stereochemical forms: poly-L-lactide (PLLA), poly-D-lactide (PDLA) and poly-DL-lactide (PDLLA) [77]. PLA with a content of 50-93% L-lactic acid is completely amorphous [78]. The greatest advantages of PLA after its biodegradability is the fact that it creates no toxic gases while melting and because of that can be printed with no ventilation system. It also has a low glass transition temperature of 57°C.

Most PLA is extruded around 200°C and its formulations soften at the glass transition temperature, where the material suddenly loses its stiffness but does not yet change phases. This means that extruded PLA has more time to relax any internal stresses as it cools and can be printed in unheated atmosphere with no build plate heat and no special adhesives without warping. PLA is heavier and less deformable than ABS but has a retraction index of 2-3%. However, PLA is generally not considered to be a good structural material due to its low impact strength and temperature stability compared to other FDM plastics [79]. The polar bonds in PLA can also make it susceptible to water absorption which can cause issues because water can partially breakdown PLA causing it to become even more brittle.

4.1.ABS

Acrylonitrile Butadiene Styrene is a common non-biodegradable 3D-printing filament material. ABS is particularly variable due to the fact that the three monomers used in its production can be added in different ratios and at different stages (fig 2.6). Specifically, the styrene improves the stiffness, the transparency and the workability, the acrylonitrile improves the chemical resistance, the resistance to the heat and the tensile strength, and finally the polybutadiene increases the tenacity and the properties at low temperatures. The portion can vary from 15%

to 35% acrylonitrile, 5% to 30% butadiene and 40% to 60% styrene [80]. There are two phases of the ABS terpolymer: a continuous phase of styrene–acrylonitrile (SAN) and a dispersed phase of polybutadiene.

ABS is usually picked over PLA when higher temperature resistance and higher toughness is required. For instance, for the majority of applications, ABS can be used between -20°C and 80°C, even if its mechanical properties vary with temperature and composition. Contrary to PLA, ABS produce toxic gases while melting, producing a notable scent and causing headaches quickly [81]. It is always recommended to make sure any ABS extrusion process is done in a well-ventilated space. Moreover, ABS compared to PLA does not have great resistance to UV rays and is not suitable for contact with food.

ABS is favored for its rheological properties which make relatively smooth surfaces but is not resistance to many solvents. However, this can be used as an advantage when smoothing the surface of printed parts. ABS's major drawback for common FDM is its high glass transition temperature of 105°C, which causes it to retain internal thermal stresses early in a print and often warp and peel away from the build plate. Remedies for this issue include generation of rafts or brim, maintaining an elevated build plate and/or atmospheric temperature, using a ducted fan to equalize the temperature of the plastic at the point of deposition or use of chemical adhesives on the build plate. Most ABS is extruded around 235°C – 255°C.

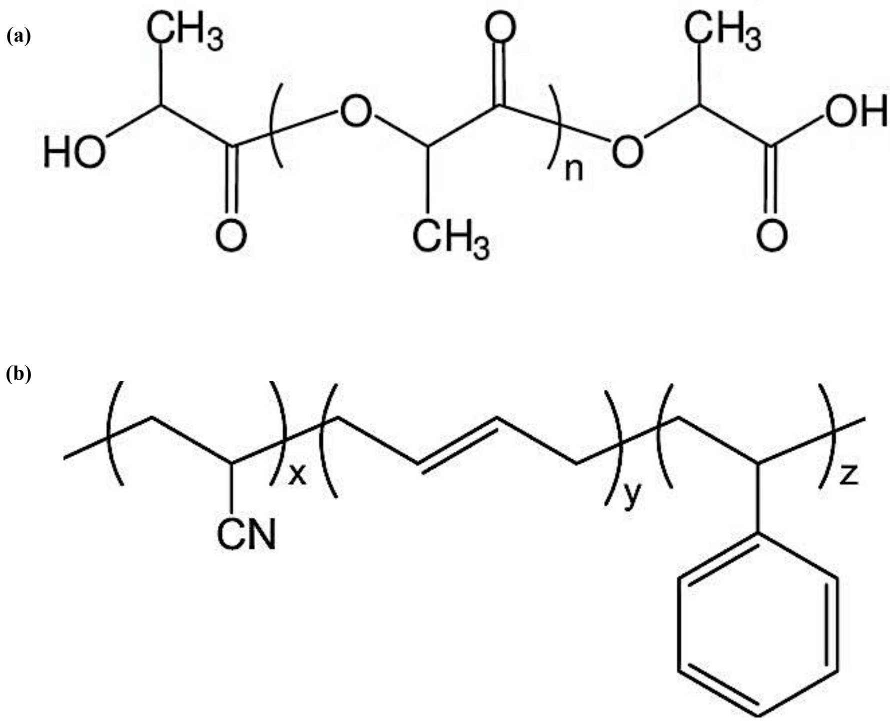
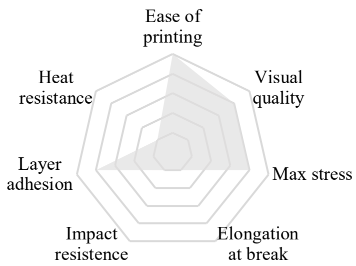
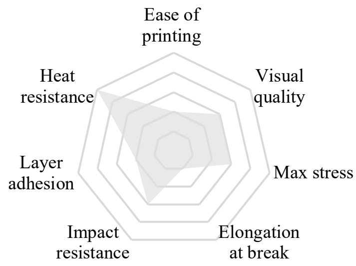


Fig. 2.6 – **(a)** Chemical structure of PLA. **(b)** Generic chemical structure of ABS [82-83]

	PLA	ABS
Spider Graph		
Physical Properties		
Melt flow rate (g/10 min)	6.09	41
Density (g/cm^3)	1.24	1.1
Mechanical properties		
Tensile stress at break(MPa)	45.6	33.9
Elongation at break (%)	5.2	4.8
Izod impact strength (kJ/m2)	5.1	10.5
Thermal properties		
GTT (°C)	60	97
Melting point range (°C)	45-160	225-245
Printing specifications		
Print temperature (°C)	210	250
Print bed temperature (°C)	60	80
Shrinkage/Warping	Minimal	Considerable

Tab. 2.1 – Physical, mechanical, thermal and printing properties of Ultimaker's filament [18]

5.Market Overview

Since the mid-1980s AM equipments have changed drastically. By combining different analysis conducted by multiple market researchers, Deloitte estimated that the entire AM industry was worth around $4.8 Billion in 2015. Then, using the same accumulation of various market forecasts, they were able to average out both the pessimistic and optimistic predictions and estimate that the market will be worth around $20.5 billion by 2020 [84]. Currently, the total AM industry, consisting of all AM products and service worldwide grew to $7.336 billion, excluding internal investments from the likes of Airbus, Adidas, Ford, Toyota and hundreds of companies [85].

According to Sculpteo [86] during 2018, 70% of the survey's respondents among 1000 interviewees between CEO and engineers, increased their expenses in AM, against 49% last year. In 93% of the cases also the respondents are seeing AM systems as competitive advantage, and the 46% of respondents saw a greater return of investment this year.

According to the Wohlers Association [85] today's 3D printers are concentrated at two ends of a spectrum: high cost–high capability and low cost–low capability. At one end, there are high-end printers, with a price over $5000, they generally use closed source software and target at enterprises. These devices generally have better accuracy, bigger build envelope and a broader pool of usable material than less expensive machine. Stratasys, with an expected revenue between $670 and $700 million for 2018 [87], is the best-known representative of this category and one of the biggest AM company in the world. On the other end low-end printers, which are targeted at consumers and hobbyists. These less-expensive devices have some crucial limitations. They can be extremely difficult to calibrate, maintain and use. For instance, if the heated bed on which the plastic material is being extruded is even one or two degrees too cold, the object won't form properly; while a degree too hot can cause it to stick to the plate. This deters many consumers from buying a device, and those that do often abandon their machine after producing only a few objects: according to one forecast, only ten percent of home machines under $1,000 are 'plug-and-print' in 2016 [88]. But this trend will accelerate as the market consisting primarily of early birds are evolving into a market in which average consumers dominate. Some of the most important companies in this segment are: Prusa and XYZprinting.

After FDM patent expirations, dragged from open source RepRap printers [89], based on open-source software and thanks to its safety and its user friendly the extrusion-based systems became the most used technology worldwide [90] with the cheapest machines among the other main AM devices [91]. In this regard, the two ends of the spectrum are converging in the middle matching the voice of the customers and the Wholer's classification price range described above could be not suitable anymore (fig. 2.6). Therefore, in this work we will refer to low-end and high-end printers like those machines which have a price lower than $3000 and higher than $15000 respectively, introducing a new class in the middle. These printers from new entrants and established vendors have high performance levels but a lower price point. For instance, this is reflected in printers from MarkForged which offer the ability to print using carbon fiber composites in a desktop form factor for less than €4500 [92]. Or printer like Spiderbot HT 4.0, which allows customer to print high-temperature and advanced plastics, such as PEEK and PEI, by limiting deformation, warping and post processing in a desktop configuration for a tag price below €10000 [93].

Though low and medium cost 3D printer's history much shorter compared to industrial 3D printers, this market segment has been booming in recent years. The amount of low and medium end 3D printers has surpassed industrial printers by several scales in terms of growth rate and quantity [84] open the door for widespread use amongst small business, entrepreneurial applications and educational institutions.

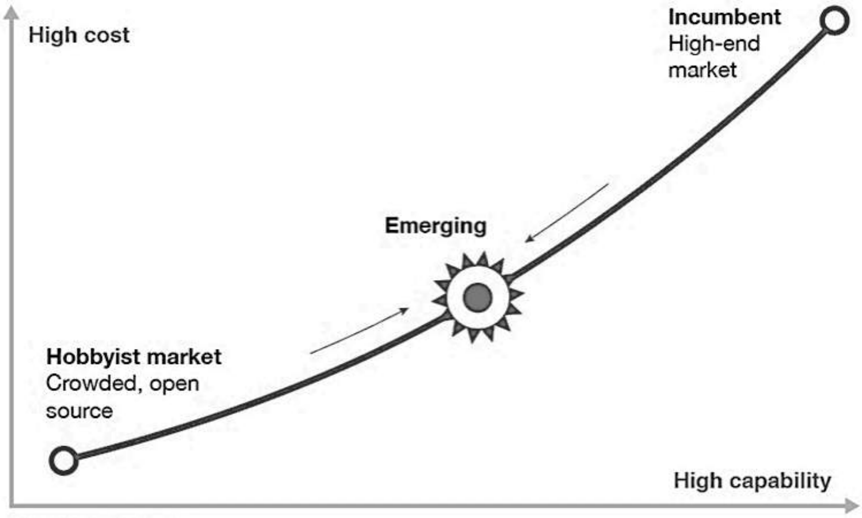


Fig. 2.6 – Market spectrum for 3D printers [88]

CHAPTER 3

The Benchmark

1.Background

Since 1990s the number of AM process and technologies increased and with them it increased the need for tools and procedures allowing to assess the capabilities and limitations of a specific system or to compare different process. Therefore, many authors developed benchmarks artifacts, that is a standard mainly used for:

- Specify requirements
- Communicating guidance
- Documenting best practices
- Defining test methods and protocols
- Documenting technical data
- Accelerating the adoption of new technology

In this context a benchmark part consisting of three-dimensional part features build in a variety of size, locations and orientations in order to compare and evaluate AM performance system. Standards can be particularly important for emerging, highly technical industries, such as AM, because they provide the foundational element on which the industry might be built.
A classification of benchmarks for AM process was first prosed by Mahesh [94]. He suggested to classify test artifacts in three different groups according to their main purpose: geometric benchmark, mechanical benchmark and process benchmark. In some online STL sharing open-platforms, private individuals and companies are sharing new kind of benchmark, that it could be called: torture benchmark such as the one proposed by Kickstarter in collaboration with Autodesk [95]. This new type of artifacts, that are very similar to the geometric ones, such as the one propose by *Vincente et all.* [96], focuses in general only on special features, such as freeform, negative tolerance and bridging for which there are no measurement standards, and they are specially designed to evaluate the performances of the printers under stress. These test parts push the printers to its limits generally until the fabrication of the artifacts visibly failure, where with the term failure is meant the lack of manufacturing visible to the naked eye at least once of one feature.
This work focuses on geometric benchmarks, which are used, to check and compare the geometrical and dimensional performance. The purpose is to develop or individuate, if already exists, an available artifact by which consumers can evaluate the quality of an AM machine to

meet consumer specified metrics. However, there are many examples in literature of the utilization of geometrical standard test part, some of which are briefly discussed in this chapter.

2. Rules for geometrical benchmark design

All of the AM test artifacts are different, but they have many commonalities. Common aspects are to be expected because much of the research builds upon the findings of previous work, and many researchers were influenced by the rules put forth by Richter and Jacobs in 1992 [97]:

- be large enough to test the performance of the machine near the edges of the platform as well as near the center
- have a substantial number of small, medium, and large features
- have both holes and bosses to aid in verifying beam width compensation
- not consume a large quantity of material
- be easy to measure
- have many features of a "real" part (*e.g.*, thin walls, flat surfaces, holes, *etc.*).
- not take too long to build

Nevertheless, it should be noted that the last aspect concerning the building time depends on the layer thickness and on the machine speed, so it is not exclusively affected by part geometry. Following their study, eleven years later, Byun and Lee [98] referenced these rules, but added that the test part should include features along all axes and should include features used to assess the minimum feature size obtainable. They also stated to avoid redundancy features and that freeform features are difficult to be measured and evaluated. While many of these qualities are important considerations in designing a test artifact, an ideal part should not just highlight most errors and limitations of a machine or process, but it should also correlate those errors and limitations with specific aspects of the machine or process themselves. In order to do this, the test artifact should [99]:

- have simple geometrical shapes,
- require no post-treatment or manual intervention (*e.g.*, there should be no support structures)
- allow the assessment of spatial repeatability

In addition, several researchers state or imply the need for a test artifact to include multiples of the same feature to allow repeatability measurements. However, including multiples of the same feature tests the machine or process capability to produce that same feature at different places within the work volume; it does not test the repeatability of the machine or process.

Since various conditions may result in different systematic errors at different locations in the build volume, this leads to differences in the shapes of features produced in these positions. Therefore, if multiple artifacts were produced by a system with perfect repeatability, features produced in the same position in the build volume would be exactly the same, but they still may be misshapen.

Lastly, in 2017 Rebaioli and Fassi [100] taking into account all the previous work and in contrast with some them presented a non-process specific guideline for designing a benchmark artifact:

- The artifact base plate should have the same size as the system's build platform or, if it is smaller, it should be replicated at the platform corners and center
- The total part volume should not be excessive
- Both convex and concave, flat and non-flat, simple geometrical features that do not require support structures should be included in the test part
- More complex features, such as overhangs, inclined surfaces, bridges, and freeform surfaces, are used to test the process limitations with regard to specific AM geometries, but they can be difficult to measure.
- The test part should have features in a wide range of dimensions
- The features should be aligned along all the machine cartesian axes
- The features should be positioned as to allow and facilitate the measurement process, considering the selected measuring system
- Before designing the test part, it is fundamental to define the measurement system

3.Review of notable geometric benchmark parts

In the following subsections some notable benchmark artifacts reported in literature are briefly presented and discussed.

3.1.Kruth (1991)

Kruth was the first to propose a geometrical benchmark artifact in order to compare three different AM technologies: stereolithography, selective laser sintering and laminated object [28]. This inverted U-shape part possess several different features, such as vertical and inclined cylinders, surface both straight and inclined, pegs and overhangs as shown in figure. The benchmark part is also relatively small if compared with current print surfaces.

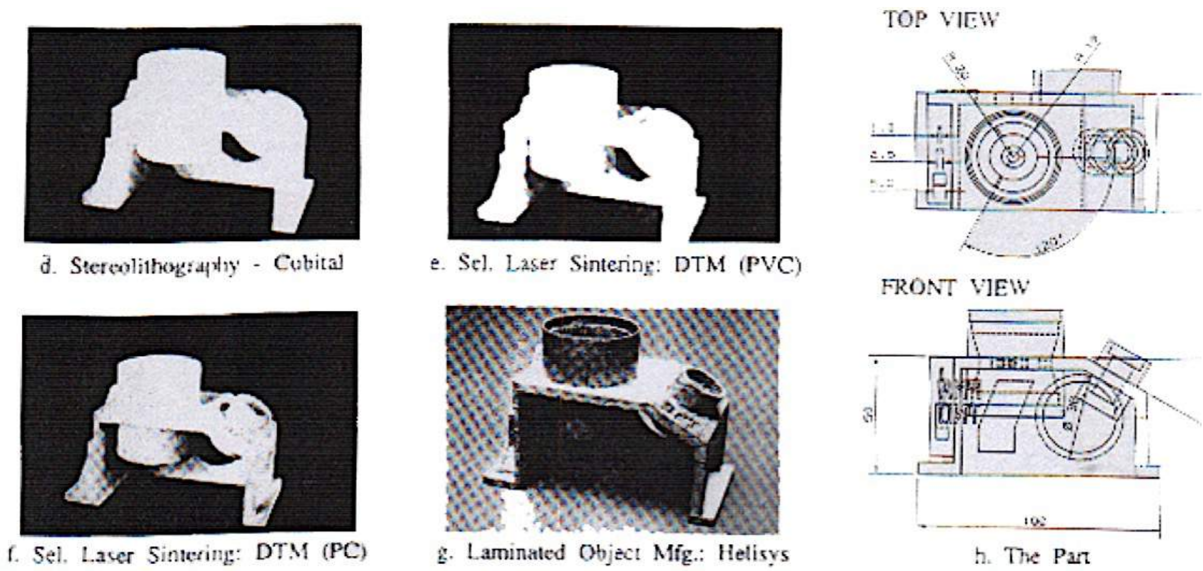


Fig. 3.1 – Benchmark artifacts proposed by Kruth [28]

3.2.Childs and Juster (1994)

Childs and Juster's used a square shape benchmark artifact to evaluate linear accuracy and repeatability of different AM technologies: stereolithography, selective laser sintering, fused deposition modelling and laminated object manufacturing [101]. The size of the piece is very considerable, 240x240x40 mm, thus warping is likely to occur. Anyway, the part includes repeated and different dimensions features including: two freeform surfaces, one bridging, thin walls, two dimples of large radius, some draft angles and overhangs (fig 3.4).

3.3.Ippolito *et al.(*1995)

Ippolito, Iuliano and Gatto [102] also used a square shape to valuate accuracy, surface roughness and tolerance of different AM process and with different material according to ANSI-ISO standards. They used a benchmark proposed by 3D System company, currently one of the biggest AM companies along with Stratasys, a simple part but with many missing features as can be seen from the figure 3.3. The results of their study showed that the user part was unsuitable for assessing the performances in the creation of the non-flat surfaces. Therefore, a shell of uniform feature, comprising of a cylinder merged with a sphere was proposed.

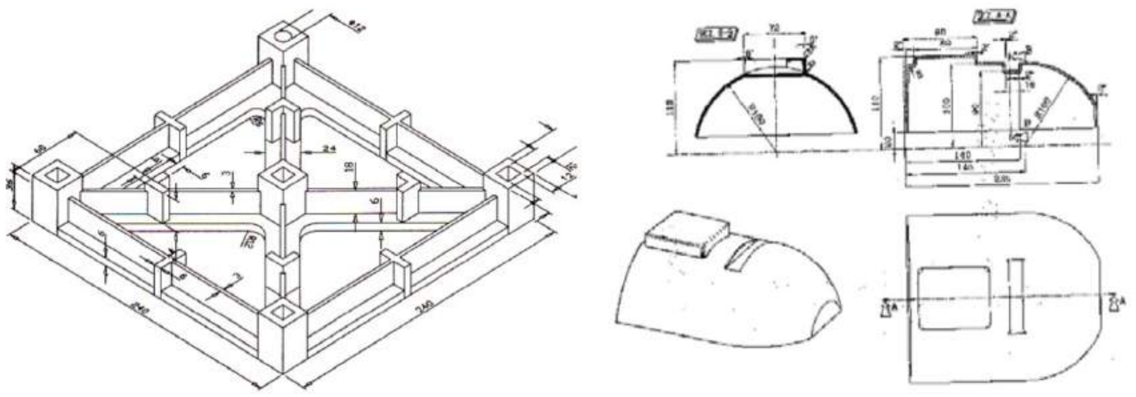


Fig. 3.2 – Benchmark artifacts proposed by Ippolito *et al.* On the right side the part use to evaluate non-flat surface [100].

3.4.Xu *et al.*(2000)

This rectangular shape benchmark part was developed for studying four different AM process as the artifacts before [103]. The test part is used to investigate not only dimensional accuracy, with different geometric features of different size, but also the capability of the process in terms of constructing special features such as fine solid feature, overhangs, large flat surface and small notches (fig.3.4). The goal of the artifacts was to provide data for decision support and enable comparative performance analysis of different technology.

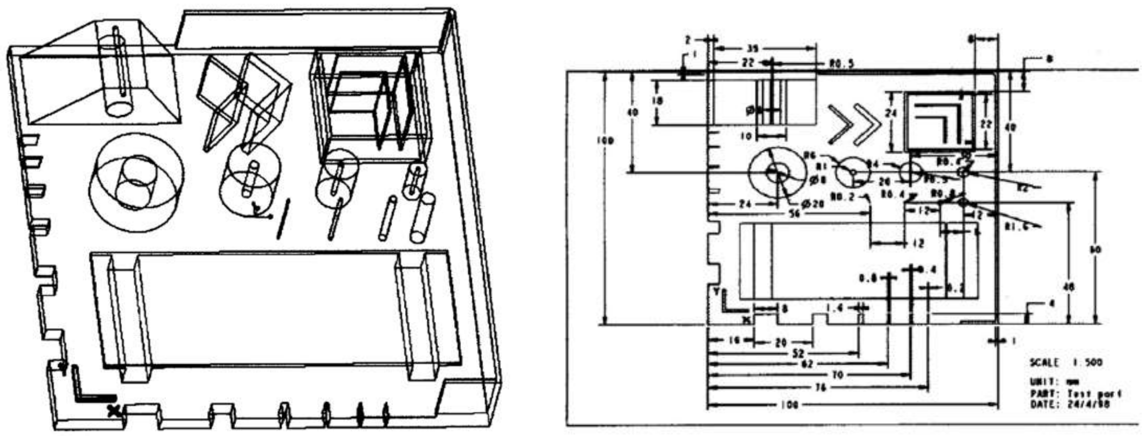


Fig. 3.3 – Benchmark artifacts proposed by Xu *at* . [103].

3.5.Mahesh et al. (2004)

Mahesh et al. [104] designed a square based benchmark test taking into accounts advantages and disadvantages of the previous artifacts found in the literature before 2002. The part incorporates different key shape and features, ranging from solid and hollow cylinders to square, freeform surfaces, overhangs and bridging as it's possible to see in figure 3.4. The artifact was particularly designed in order to be consistent to standardized measuring techniques, referring to the existing ISO standards for the use of CMM in measurement. The benchmark part was utilized to compare, in terms of capability to manufacture particular and fine features, accuracy and repeatability on different AM technologies: stereolithography, selective laser sintering, fused deposition modelling and laminated object manufacturing.

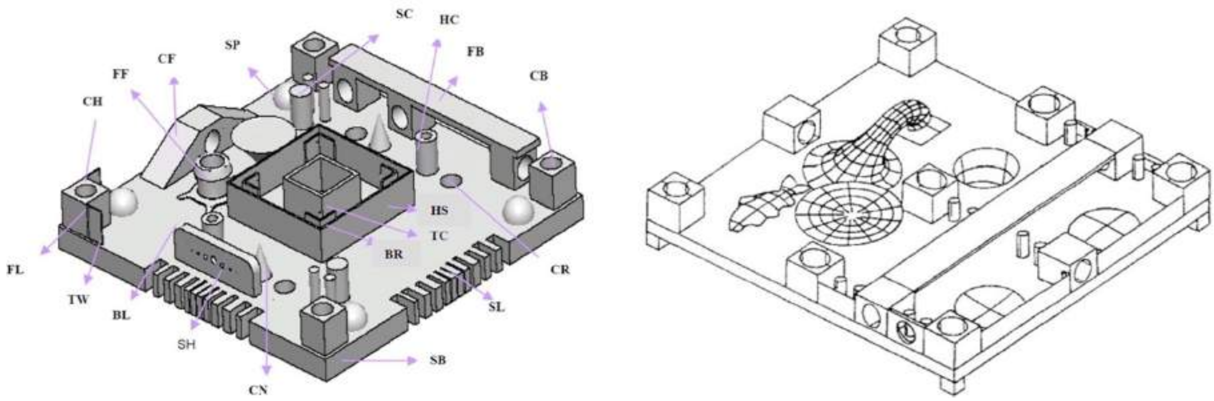


Fig. 3.4 –Starting from the right, the artifacts proposed by Mahesh *et al.* [104] and Childs and Juster [101].

3.6. Kruth *et al.*(2005)

In 2005 Kruth [105] proposed another limited dimension benchmark in order to compare five different selective laser sintering and selective laser melting commercial systems from the point of view of dimensional accuracy, surface roughness, speed, repeatability and mechanical properties, such as hardness, strength and stiffness. In particular the benchmark was developed not only to analyze the process limitations, but also to optimize each process iteratively.
The artifacts contain different features such as sharp corner, small holes and cylinder, thin walls and overhangs.

3.7.Johnson *et al.*(2011)

Johnson et al [106] developed a new benchmarking model notably for quantitative evaluation of the performance of an open-source AM system based on fused deposition modeling. As shown in figure 3.7, the proposed part includes different geometric features that allows the assessment of the dimensional accuracy, thermal warpage, staircase effect and geometric tolerances.

3.8.Moylan *et al*. (2012)

This square based standardized part was proposed in 2012 by Moylan *et al*. [107] on behalf of US National Institute of Standards and Technology in order to investigate the performance and

capabilities of an AM system, with a primary focus on metal-based additive process, and for linking the measured errors to specific sources. The measured values and non-measured observed features provide an indication of the AM device's performance, especially when compared to results provided by other test artifacts manufactured on another AM machine.
As shown in figure 3.7, the benchmark, results a bit thick and redundant or poor in features. However, it is one of the few available in STL format online [108].

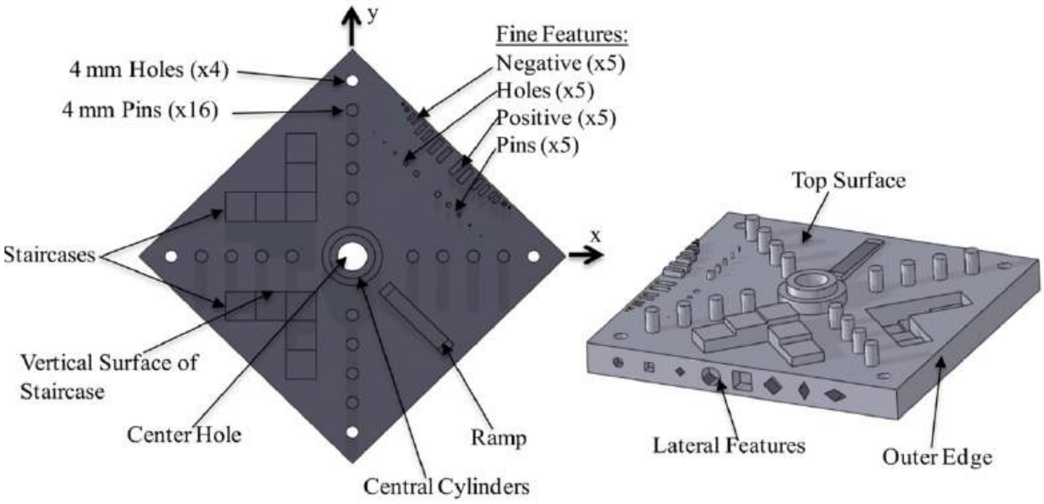


Fig. 3.5 – Solid model of the benchmark artifacts proposed by Moylan *et al*. [107].

3.9.Sanchez *et al*. (2014)

This geometric model is a modified version of the benchmark artifacts proposed by the National institute of Standard and Technology developed to evaluate geometrical accuracy performance of an open source FFF additive manufacturing equipments [109]. As shown in figure 3.8, the author modified the original test part including different types and less redundant features, but some of them are still missing and the base are too chunky.

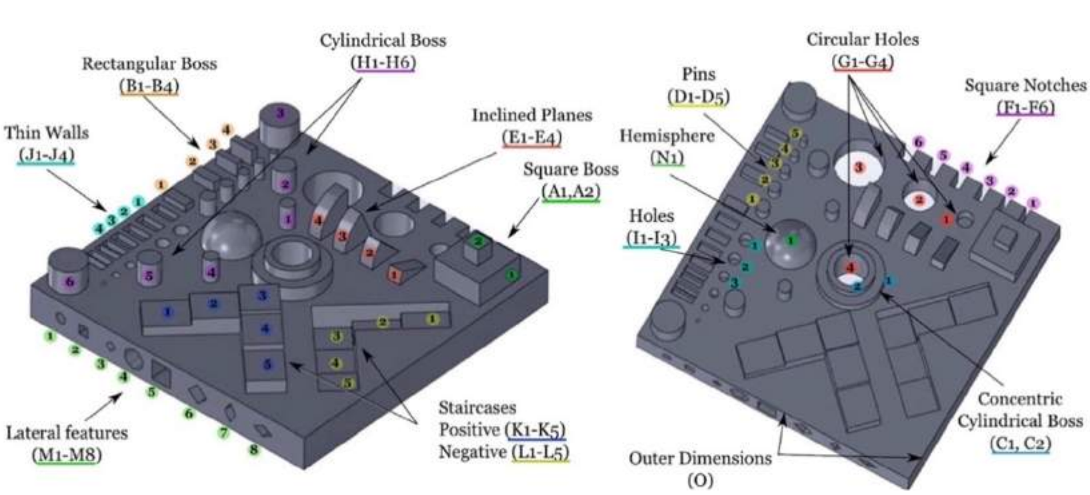


Fig. 3.6 – Solid model of the benchmark artifacts proposed by Sanchez *et al*. [108]

3.10.Minetola *et al.*(2016)

This benchmark artifact was proposed in order to compare expensive industrial FFF system and low-cost machine referring to the ISO Standard IT grades to facilitate the comparison between different machine [110]. This square based test part includes several classic geometries of different sizes, in both concave and convex shapes, as defined by the ISO 286 standard and the part does not require support structures for its production.

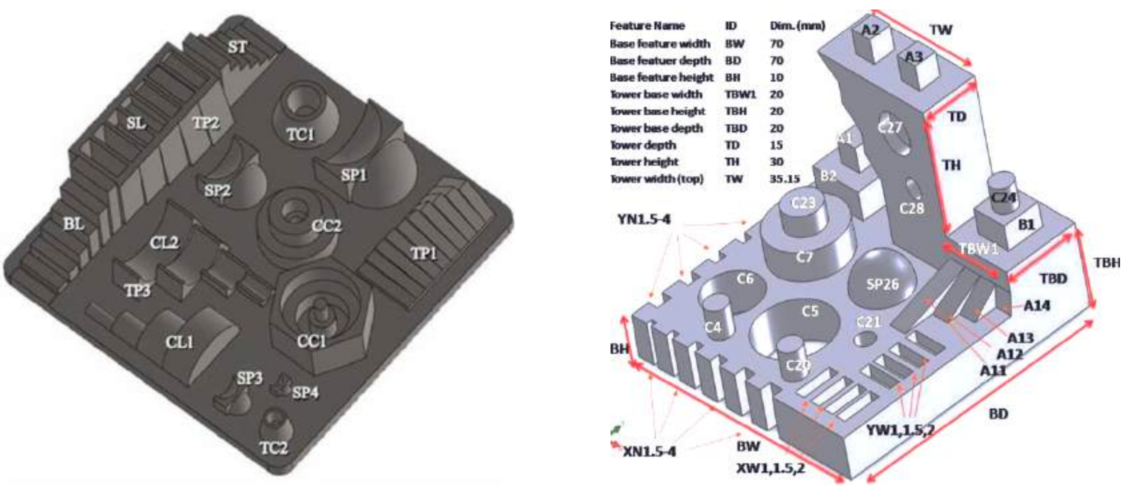


Fig. 3.7 – In order, the CAD model of the part proposed by Minetola *et al.* [109] and Johnson *et al.* [105].

4.Proposed geometric benchmark part

Among all the about 60 benchmarks in the world of additive manufacturing none of them looks complete. Some of them such as the one proposed by Mahesh *et al.* or Minetola *et al.* have a good number of features in a different range of dimensions, but the size and consequently the time to build are really important, approximately in the range of 4-6 hours for a standard quality print, depending on the machine and printer settings that are going to be used. On the opposite side, it possible to find benchmark part, for instance the one proposed by Brajlih *et al*. [111] with a really short build time, but not enough features to do a proper dimensional and geometric analysis. Moreover, not many benchmark parts, among those discussed in literature, are available online and only a few amount papers provide all the measures to allow the exact reproduction of the artifact. Consequently, it was decided to develop a new benchmark part continuing the path marks out by Moylan *et al*. [105] and Sanchez *et al*. [109].

The new geometric benchmark part, which can be observed in figure 3.8, was designed using SolidWorks and exported as STL. The purpose of this test part is to evaluate geometric and dimensional accuracy, printing time, vertical and horizontal surface finish, minimum feature size and overhangs.

The modify artifact consists of a square base measuring 100(L)x100(W)x5(H) mm with different geometric features in a wide range of dimensions. Compared to the part proposed by *Sanchez et all.* [109]:

- the shape of the base' corners have been rounded off, reducing the local stress concentrations and consequently limiting warping that has an adverse effect on geometry accuracy of the fabricated part
- several features in different dimensions were added, such as cones, horizontal holes, cubes, convex and concave quarter of spheres, more inclined slopes and overhangs
- the thick of the base was reduced to 5 millimeters instead of 10, maintaining it thin enough to limit warping, but saving more than 25-35% in term of manufacturing time of the starting part. On equal material and print settings, the percentage gap depends on which software and machine are used to slice the part, originating the g-code and manufacturing the part
- has different extra features: cones, fillet, negative spheres, incremental overhangs with a different degree angle, 10° and 15°, horizontal holes, cubes and more inclined planes. Even if some of these special features are difficult to measure, with the optical microscope it should not be a problem evaluating, at least qualitatively, some of them, in order to define device's limitations.

As consequence, the lateral features are dropped, but anyway they would not be useful for testing printers that come with unique extruder or without soluble support material, such as many of the low-cost FFF printers. However, even if all the printers in consideration had the possibility to use some support materials, its use would require benchmark part post-processing which would risk compromising the measurements. Finally, since for the measurement it will use an optical microscope and a 3D scanner, there are not particular limitations in the arrangements of the feature.

The benchmark part, illustrated in figure 3.10, could be divided into 17 different types of class: square notches, pins, circular holes, cones, fillet, brackets, concave and convex spheres, cylindrical boss, cube, inclined planes (from 0° to 45°, increasing 5° each plane), rectangular boss, thin walls, positive and negative staircases, outer dimensions, concentric cylindrical boss and overhangs. Each group is formed by various related features that form majority of static and kinematic couples in a conventional mechanical system.

Every feature is associated with at least one type of dimensional accuracy. This approach will make it possible to characterize the performance of a 3D printer, and consequently it will make it possible to differentiate the machine from the other machines. Table 3.1 summarizes the function of the main geometric features in the proposed benchmark part design, whereas table 3.2 provides a full comparison between the proposed benchmark part and some other notable artifacts. In this comparison it will be taken into account not just the geometric features but also the dimension of the part's base, that should be large enough to include all the geometric features, but not too much to require an excessive build time. As can be seen from the table, the developed benchmark is the one that has the best tradeoff between number of features and dimension.

In terms of size only the model proposed by Johnson *et al*. [106] is better, but even if the base platform is compact some features are too much height, until almost 60 mm, thus losing all the benefits in terms of build time arising from a small base design. As for the features, just the benchmark artifact proposed by Mahesh *et al*. has almost the same number of features compared to the proposed model, but it is also really oversized, almost the double. Moreover, some of these features like the overhangs or the inclined planed are not properly design. For instance, the inclined planes are just two, providing only two different inclination angles, that are not enough to determine and complete analyze the surface profile.

Apart from its purpose for comparative evaluation, the benchmark part can also be used to optimize the machine as we will see later. This may involve simple trial-and-error experiments to proper designed experiments to fabricate the benchmark part and fine-tune the parameters till the best attainable features can be built. Other influencing factors include different types of materials, and to a certain extent, rely on the experience of the operator.

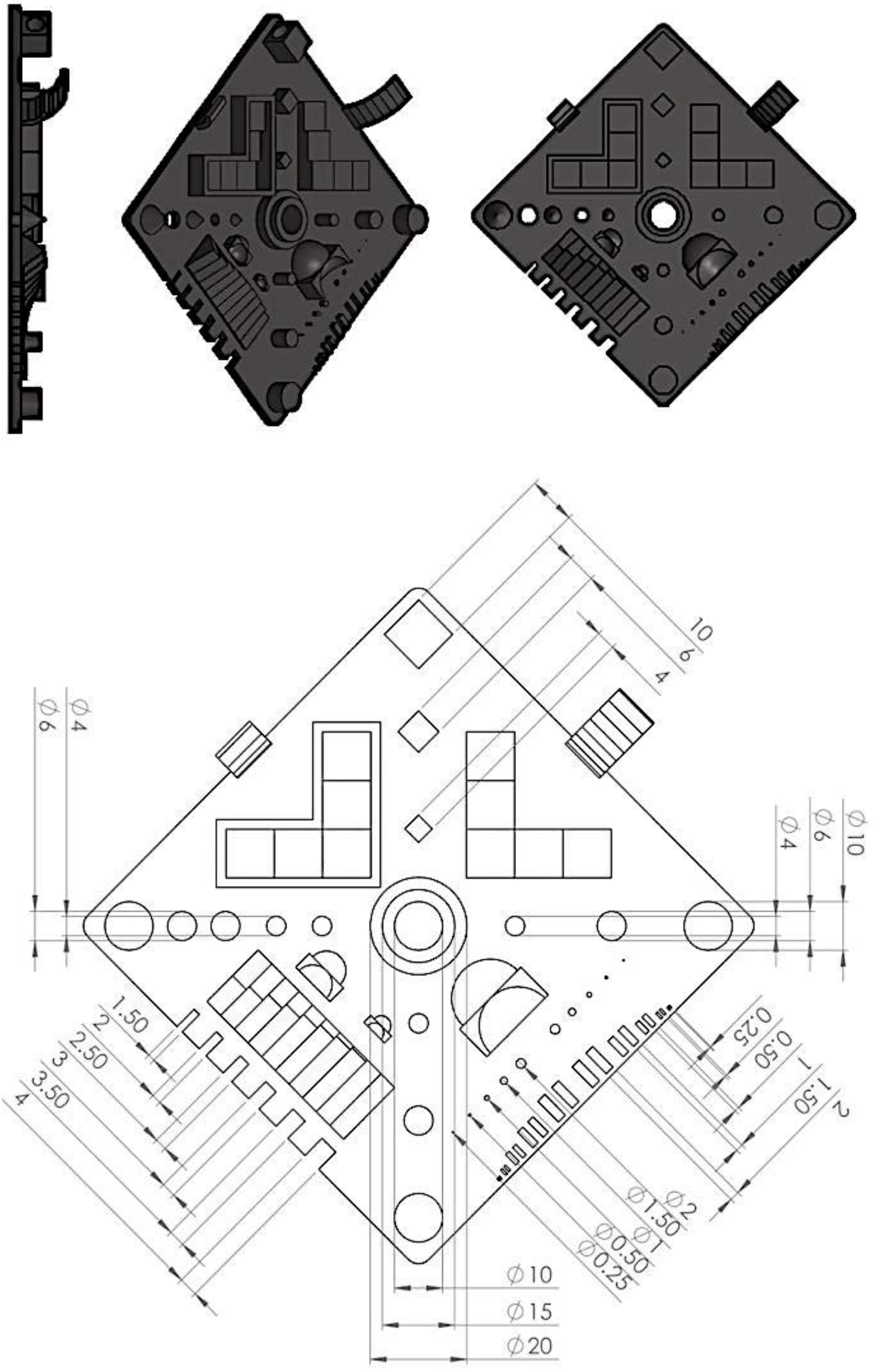


Fig. 3.8 – Proposed benchmark data sheet (dimensions are in millimeters)

and part from different point of view.

Features	Purpose
Square base	Flatness, straightness and XY accuracy
Rectangular boss and holes	XY and Z accuracy, straightness, minimum required separation of feature, thin walls accuracy
Circular holes	Diameter accuracy, roundness and centricity
Cubes	Flatness, straightness, linear XY accuracy and parallelism
Cylindrical holes	Diameters accuracy and relative position, symmetry, roundness and centricity
Concentric cylindrical boss	Diameters accuracy, roundness, centricity, perpedicularity and concentricity
Quarters of sphere or hemisphere	Accuracy and surface finish of a continuously changing sloping surface
Brackets	XY and Z accuracy, straightness and to measure the angle build
Fillets	Study the capability of do such features
Solids cylinder	Diameters accuracy, relative positions, repeatability, symmetry, roundness cylindricity
Cones	Sloping profile, taper, relative position and symmetry
Square notches	Thin walls accuracy, straightness, flatness and consistency
Inclined surface	Different sloping profile, angularity and Z accuracy
Positive and negative staircases	Z and XY accuracy, flatness, straightness, parallelism and perpediculartiy
Square base and outer edges	Straightness and flatness
Pins boss and holes	Diameters accuracy, minimum size feature achievable
Overhangs	Angular accuracy and sloping limit

Tab. 3.1– A summary of proposed geometric features and purpose

Feature	Proposed artifacts	Kruth's artifacts	Mahesh *et al.* artifacts	Sanchez *et al.* artifact	Moylan *et al.* artifacts	Minetola *et al.* artifacts	Johnson *et al.* artifacts	Xu et al. artifacts	Childs and Juster artifacts
Dimensions of the base (mm)	100 x 100 x 5	100 x 50 x 50	170 x 170 x 5	90 x 90 x 10	100 x 100 x 10	110 x 110 x 6	70 x 70 x 10	100 x 100 x 5	250 x 250 x 20
Vertical cylinder holes	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cylinder	✓	✓	✓	✓	✓	✓	✓	✓	✓
Positive and negative sphere part	✓	-	-	-	-	✓	-	-	✓
Positive and negative staircase	✓	-	-	✓	✓	✓	-	-	-
Thin walls	✓	-	✓	✓	✓	-	✓	✓	✓
Fillet	✓	-	✓	-	-	✓	-	-	-
Overhangs	✓	✓	-	-	-	-	✓	-	-
Fine Features	✓	-	✓	✓	✓	-	-	✓	-
Horizontal cylinder holes	✓	-	✓	-	-	✓	✓	✓	✓
Cones	✓	-	✓	-	-	-	-	-	-
Cubes	✓	-	✓	✓	-	-	✓	-	✓
Notches	✓	-	✓	✓	-	✓	-	✓	-
Inclined plane	✓	✓	✓	✓	✓	✓	✓	-	✓
Brackets	✓	✓	✓	-	-	-	✓	✓	✓
Freeform	-	-	✓	-	-	-	-	-	✓
Chamfered ends	-	-	✓	-	-	-	-	-	-

Tab. 3.2 –Comparison of geometric features and dimensions in reported benchmark part.

CHAPTER 4

Comparison between different EAM equipment

1.Experiment design

The benchmark parts will be printed with three different FFF printers: one low-end, the Prusa MK3, one medium-end, the Spiderbot HC 4.0 and one high-end, the Stratasys uPrint se Plus. The test artifacts will be printed with each machine two times, one with standard quality print settings and one at super-high quality. The parts will be print in ABS with all the machine available. Moreover, with the Prusa MK3 also the PLA will be used. The same material will not be used for all the prints, indeed the Stratasys is compatible with generic material. Some printers can just work with one material or a specific brand of materials. Cause of that, during the experiment will be use ICE's filaments of PLA and ABS in different color (white, black) for all the printers except with the Stratasys with which the proprietary ABSplus and SR30 filaments will be used instead. Except with the pieces printed by the Stratasys no post-processing steps were made.

Since the pieces have to be printed with different materials and different printers, each system has been set-up in a targeted way to get the best piece under each condition. Indeed, reasoning in terms of Additive Manufacturing, although the physical principles are always the same, each printer adopts different technology solutions. Moreover, low-end desktop printers often come as kit which must be assembled and parametrized by the customer, ergo with a high component of human error always to be taken into account. Therefore, choosing fixed parameters, rather than custom ones could favor one printer rather than another, compromising the results of the experiment. Each printer, thus, will be set individually, always referring to and using the slicing software recommended by the manufacturer for each individual machine. This allows to evaluate the general performance of the printer-software system from a real customer point of view.

After the printing, the benchmark parts will be removed from the build platform and will be compared between them and to the CAD model in term of geometric accuracy, warpage and thin features using a 3D scanner and a SEM. Visual inspection by microscope could provide an adequate indication of whether or not the feature was successfully built, a particular important aspect when it comes to fine features that could inhibit access of a typical CMM probe. Furthermore, during the process, it will also keep track of the build time, to compare the printing time forecast by the slicing software with that actual time taken by the machine. At the end of this chapter the result will be compared and discussed, in order to be implemented in the decision-making process.

Finally, it is important to point out that the measurement procedure just presented is a post-process metrology. The removal of the part from the plate could slightly modify the shape of part [112]. However, there are not many studies related to this topic and not corrective factor has been yet presented, thus making impossible to take into account this aspect. However, since this is a common aspect among all the parts it can be assumed that this does not compromise the comparison between the different printed parts, but only the one with CAD model.

2.The compared extrusion-based 3D printers

In the following chapter subsections, the different extrusion-based 3D printer that will be use for the benchmarking are briefly illustrated.

2.1. The Prusa i3 MK3

The Prusa i3 MK3 was lunched in 2017 and it is actually one of the best desktop printers available on the market [113] and the most used 3D printer in the world [114]. It can be purchased fully assembled or as assembly kit, with a tag price of €999 for the first option and €769 for the second. Anyway, due to the printer being open source there have been many variants produced by companies and individuals worldwide, and like many other RepRap printers the Prusa i3 is capable of printing some of its own parts (fig. 4.1).

This cartesian 3D printer has a magnetic removable and heated bed with a usable build area of approximately 250 mm x 210 mm and a maximum build height of 210 mm. The machine architecture is very simple: the building platform translates along Y axis, whereas the extrusion head, which can be heated up to 300°C, is moved by stepper motor in the XZ plane. The chassis and electronics allow a fast printer speed, around 200 m/s, with an indicated layer height between 0.05 – 0.35 mm [115]. Any thermoplastic is printable with this device included Nylon and PC. The main characteristics are summarized in table 4.1.

The MK3 is compatible with most printing software, including Cura and Simplify3D. However, there are also printing software that specifically caters to the Prusa i3: the PrusaControl and the Slic3r Prusa Edition. The former is meant for casuals and beginners while the latter includes more advanced options for intermediate users.

Technical specifications	
Build volume (mm^3)	250 x 210 x 210
Supported Materials	PLA, ABS, PET, HIPS, Nylon, Flex PP, Laywood, ASA, Bamboofill, Laybrick, T-Glase, Ninjaflex, Brozefill, PC, Carbon-fiber enhanced filament
Number of extruders	1
Extruder head max temperature (°C)	300
Building platform max temperature (°C)	120
Minimum layer thickness (mm)	0.05
Filament diameter (mm)	1.75
Nozzle diameter (mm)	0.4 (easly changable)

Tab. 4.1– Technical specification of Prusa i3 MK3 [115]

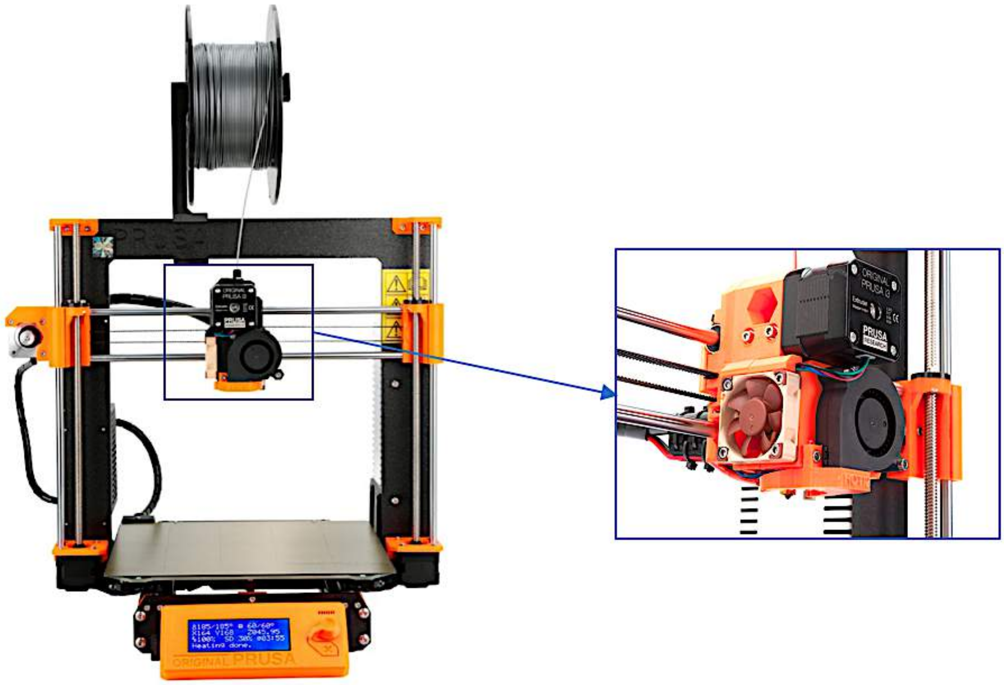


Fig. 4.1 –The Prusa i3 MK3 and a zoom on the extruder head and cooling system

2.2. The Spiderbot HT 4.0

Spiderbot HT 4.0 is a delta 3D printer released in September 2018 by the French manufacturer Spiderbot. The system leverages a new technology developed by the company's founder, Philip Boichut, to support affordable 3D printing with advanced and high-temperature plastics such as PEEK, PEKK and PEI. In order to do so, the delta system features an exclusive system for pre-heating the part using infrared radiation, maintaining just the part at a very high temperature and not all the whole print chamber. Thanks to this solution the outside of the enclosure at the radiant level does not exceed 65°C, while the part is heated at more than 200°C. This makes it possible to achieve better results on technical materials by limiting deformations, warping, shrinkage, and even by reducing post-processing requirements [116].

The upper part of the extrusion head is liquid cooled, with the water temperature never exceeding 45°C, even when printing at the maximum temperature of 420°C, which means goes to 45°C to 420°C over a few millimetres guaranteeing excellent control of the deposited material and a reduction in the risk of clogging the cold zone. The cylindrical build volume measures 200 mm x 180 mm with a PolyEthermilde build platform that can reach temperature up to 240°C.

This printer is delivered with two slicer software, adapted versions of KISSlicer Pro and Cura, each software with its specificities and advantages. The first one with more finely tuned path settings, expecially in the support and post post-processing areas, the second more easy to us. The price is between 7495€ and 8600€ ex-VAT depending on the configurations and options.

Technical specifications	
Build volume (mm^3)	200 x 180
Supported Materials	PLA, ABS, PEEK, PEKK, PEI, Exotics
Number of extruders	1
Extruder head max temperature (°C)	420
Building platform max temperature (°C)	260
Minimum layer thickness (mm)	0.01
Filament diameter (mm)	1.75
Nozzle diameter (mm)	0.3 (easily changeable up to 0.8)

Tab. 4.2 – Technical specification of Spiderbot 4.0 HT [93]

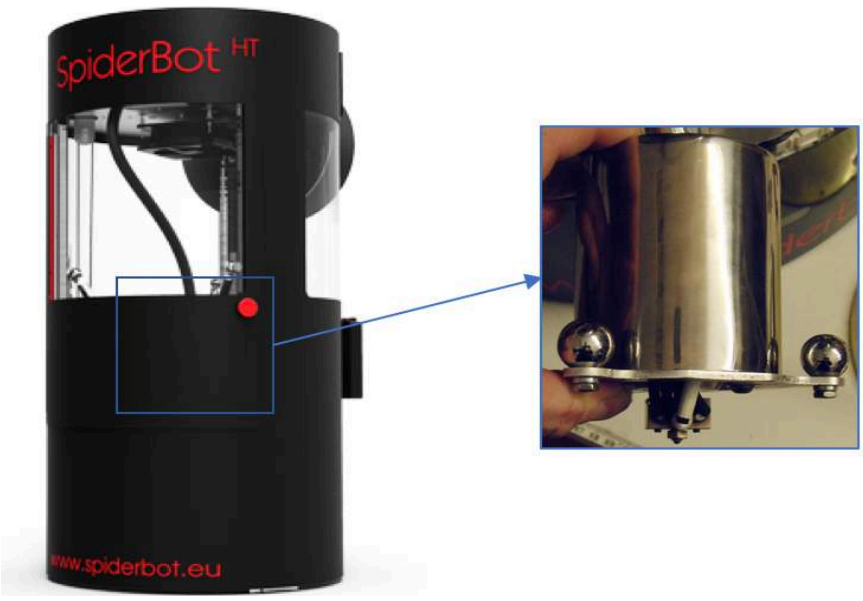


Fig. 4.2 –The Spiderbot 4.0 HT and a zoom on the extruder head

2.3.Stratasys uPrint SE Plus

The uPrint SE Plus was released in 2010 and it still is the Stratasys' most advanced and largest desktop 3D printer, known for its high reliability and its ease of use. The price was around €19000 at the moment of the launch, the highest among the printers that will be tested during this work and the only one representatives of the high-end category. On the official Stratasys website of the printer is no longer sold and has been recently replaced by a new model. Anyway, it is still possible to buy one uPrint SE plus online with a tag price around 14000€.

The uPrint SE Plus comes with a fully enclosed print chamber and has the ability to print multiple colors (though only one color can be printed in a single job) and a soluble support material. It is compatible only with two Stratasys' proprietary materials, the ABSplus and the SR-30, a soluble support material. Both feedstocks are very expensive and have a price around 100-200 €/Kg. An optional second material bay can be added in order to provides twice the uninterrupted print capacity. As an option it is also possible to buy with the printer all the products necessary for removing the support material from the printed part.

The uPrint SE Plus has a single extruder head that moves over the X and Y axis, whereas the bed platform, which measures 203 x 203 x 153 mm, over the Z. Other technical specifications are summarized below in the table 4.3.

This printer, such as all other Stratasys are delivered with their dedicated operating software: GrabCAD and CatalystEX, a workstation software for the uPrint and Dimensions printer lines. GrabCAD simplifies the traditional 3D print preparation workflow and provides intelligence around printer usage so it can get quality prints, faster.

Technical specifications	
Build volume (mm^3)	203 x 203 x 153
Supported Materials	ABS, solvable material
Number of extruders	1
Extruder head max temperature (°C)	300
Building platform max temperature (°C)	N/A
Minimum layer thickness (mm)	0.254
Filament diameter (mm)	1.75
Nozzle diameter (mm)	0.4

Tab. 4.3– Technical specification of Stratasys uPrint SE Plus

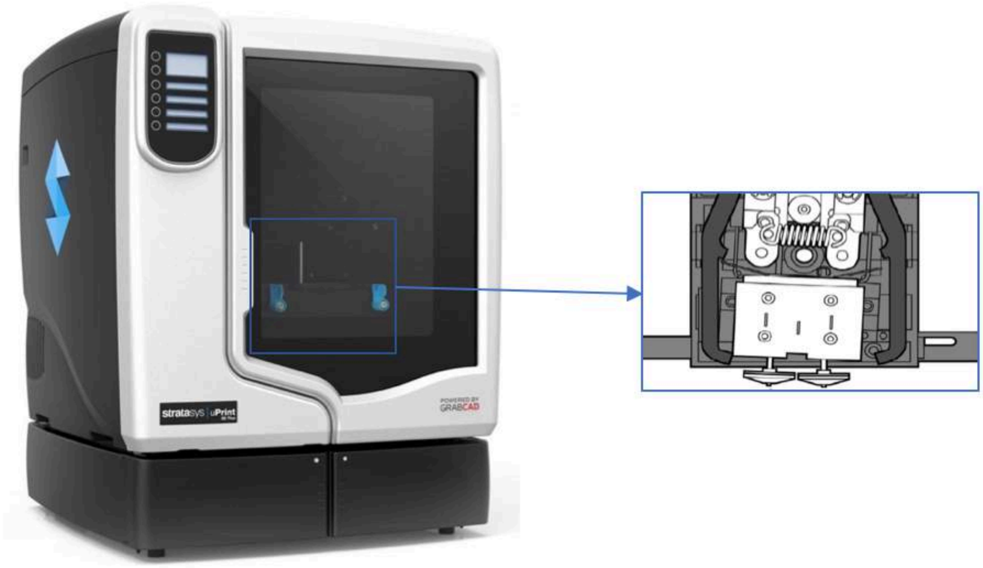


Fig. 4.3 –The Stratasys uPrint SE Plus

3.Benchmark fabrication

The fabrication of the benchmark part is performed according to the instructions of the experiment design. The distinct printer settings will be discussed below in details together with the problems encountered.

3.1.Printing the benchmark part with the uPrint SE Plus

The goal with this printer was to achieve two benchmarks, one with standard settings and another one in very high quality. The hardware-software system has proved to be less flexible but extremely reliable compared to the other machine.

The open source software GrabCAD was used for the slicing and the G-code generation. The printer set-up panel is easy to use, but not flexible, just three options are editable: Support Style, Part fill style and Slice Height. The software determines where and how place support material according to the option chosen by the operator between Smart, Basic or Surround. Moreover, to prevent warping, for each part printed a raft made of support material is provided as a default setting that cannot be removed.

Once being switched on, the machine calibrated itself autonomously and after 30 minutes it is possible to proceed with the prints. The two benchmark parts was almost printed with the same printer settings, the only difference was the Slice Height, as can been seen in the table 4.4 at the end of this subchapter, where all the print settings used to create the benchmark parts are collected. The lower the value, the more detailed the print and vice versa. Only two options

were available: 0.254 mm or 0.3302 mm. Obviously, the former was chosen for the high-quality part that takes almost 3 hours and 13 minutes to be manufacture, and the latter for the standard quality one, that takes 1 hours and 1 minutes less than the previous part. As can be observed in the figure 4.4, thanks to the temperature-controlled printing chamber and the raft there are no warping problems in either piece, despite the ABS is a material that tends to warp very easily.
At a first glance the differences between the two printed parts can hardly be seen. However, from a more careful analysis it is possible to notice how, due to the less accuracy, the standard quality part has worst surface quality, less precision in the manufacturing of small features and also a sight gap between the infill and the outer perimeter walls. The difference in accuracy can also be seen in the higher finish of the raft in the high-quality part. It is also interesting to note that under the same conditions, with the exception of the layer height, the software has decided to intervene on the fourth inclined plane of the benchmark model with support material only in the high-quality printed part.
Since there is no possibility to not use the support material during the printing process the part was printed in ivory ABSplus, which is up to 40% stronger than standard ABS material [117], and SR-30. Before proceeding with the measurement, the support materials have to been removed, so a post-processing is required. This procedure consists in submerging the printed pieces into a 70°C pre-heated solution made of water and sodium hydroxide for at least 2 hours. Various factors determine how long it takes to remove support material in the tank, such as:

- The volume of support material on the part to be remove
- The amount of dissolved solids in the solution tank
- The pH level in the solution tank
- Solution agitation around the parts

The printed parts were left immersed, in the solution made of four liters of water and 90 gr of WaterWorks Soluble Concentrate P400SC mainly based on sodium hydroxide for 3 hours and 56 minutes (figure 4.4). The tank use for this procedure was EMAG Emmi-D60, an ultrasonic heater. Ultrasonic cleaning is based on the principle of cavitation which consists in the formation of air bubbles which, if put in contact with a liquid substance in an ultrasonic field, generate high pressure and pressure waves. Specifically, the sound waves generated by a transducer come into contact with a specific detergent, which form air bubbles. The latter, thanks to their high mobility, go to clean and sanitize every small cavity ensuring an optimal result as can be seen in figure 4.5 part (c). No manual post processing was necessary after the chemical removal of the support.

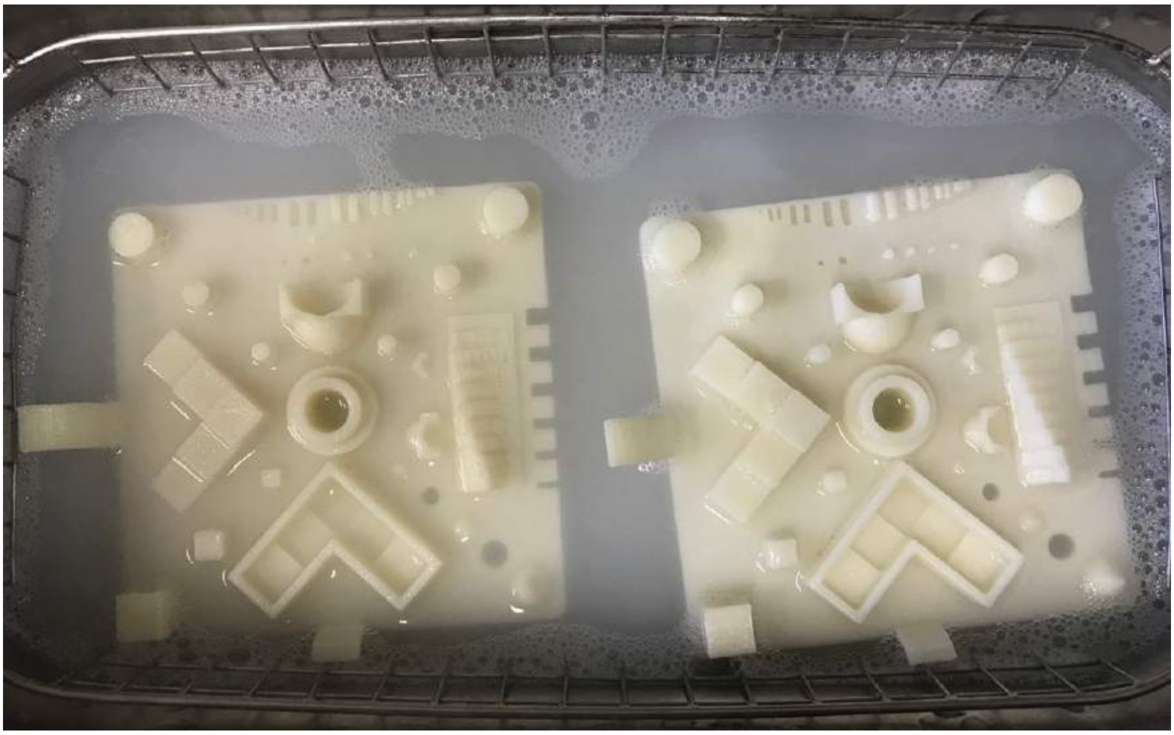


Fig. 4.4 – Removal of support material from benchmark parts through the EMAG Emmi-D60

	Standard quality part (a)	High quality part (b)
Quality	Standard	High
Layer Height (mm)	0,254	0,3302
Material	ivory ABSplus, SR-30	ivory ABSplus, SR-30
Fill Pattern	Low Density	Low Density
Print Speed (mm/s)	n/a	n/a
Heated Chamber temperature (C°)	75°C	75°C
Radiant Temperature (°C)	n/p	n/p
Bed Temperature (°C)	n/a	n/a
Nozzle temperature (°C	n/a	n/a
Fill density (%)	n/a	n/a
Software	GrabCAD	GrabCAD
Print time suggested (h)	02:26	03:24
Real print time (h)	02:13	03:12

Index: n/a Not available n/p not present in the machine

Tab. 4.4 –Printing settings use for Stratasys uPrint SE Plus

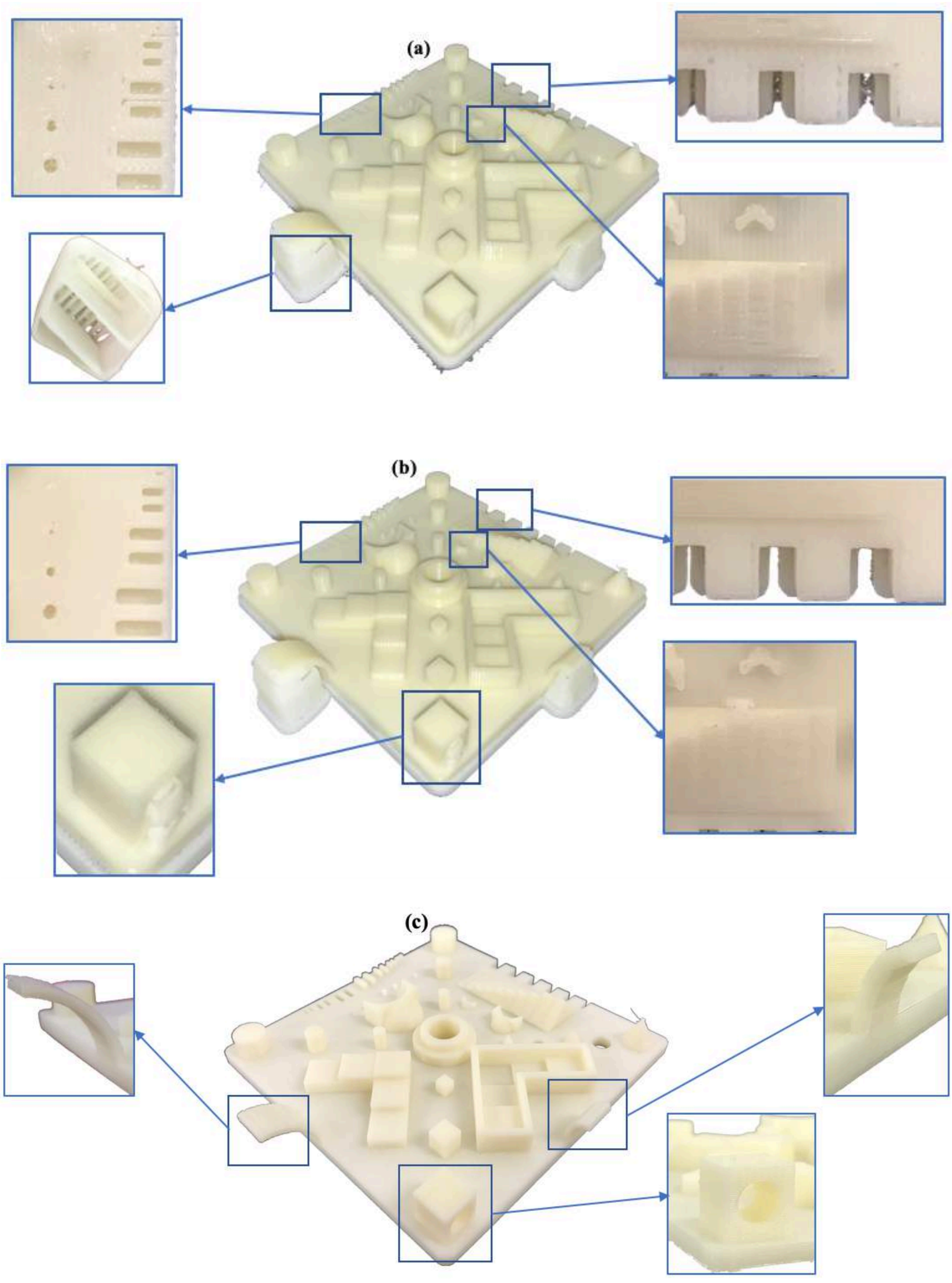


Fig. 4.5 – ABSplus benchmark part view printed with the uPrint SE Plus. **(a)** Standard quality printed part. **(b)** High quality printed part. **(c)** Standard quality printed part after support material removal.

3.2.Printing the benchmark part with the Prusa i3 MK3

With the Prusa i3 MK3 four benchmark parts have been printed, two of them in generic silver PLA, one in standard quality and the other with high quality settings, and two others then done with a black generic ABS.

To convert the 3D model into printing instructions was used Slic3r. The Slic3r project was born in 2011 within the RepRap community as an effort to provide the growing printing technology with an open and flexible toolchain. The code and algorithms are not based on any other previous work [118]. This open-source software allows the user to modify almost all the print parameters and it is certainly the most flexible and complete of those tested, although in order to fully exploit all these possibilities, a high level of know-how is required. For less-trained customers, the software also offers some generic printer and filament pre-settings. However, despite being a good starting point, these presets setting have not proved to be effective above all from the material point of view. Every machine indeed is different because hand build and moreover, there are several filament manufacturers and each of these materials has its own characteristics such as elasticity, average filament diameter, ideal extrusion temperature, presence of additives etc., all parameters that could affect the printing quality and could give rise to various problems if not correctly set. For instance, during the manufacturing of the benchmark different issues have been encountered, such as: buckled filament, extrusion stopped mid-print, warpage, nozzle clocked, missing layer and stripped filaments.

To limit all the problems related to the machine, the device has been recalibrated from scratch and several print tests were made. Despite this, printing with PLA continued to present two problems with the high-quality part: the bulking of the filament and the clog of the nozzle after the printing of the square base infill. Three possible causes were then identified:

- Additives contained in the filament that make the flow of irregular material going to clog the nozzle and obstruct the feeding system.
- Extruder head print and travel speeds. Indeed, in some cases when printing with high accuracy and the sequence of retractions is repeated with particular frequency (i.e. printing the various geometric features distant from each other above the square base of the benchmark part), more or less the same portion of the filament is find in a convulsive path forward-backward and the teeth of the cog do not always find the same position, ending up literally consuming the filament. The grip is lost ("click" sound) and any subsequent rotation of the pinion rather than dragging the filament ends up consuming it further. The current print at this point failed.

- The compression on the liquefier side of feed rollers reaches a critical limit. An approximation of the critical pressure P_{cr} that can be place on the filament can be obtained from an Euler bulking analysis:

$$P_{cr} = \frac{\pi^2 E d_f^2}{16 L_f^2}$$

Where E is the elastic modulus of the filament, d_f is the filament diameter and L_f is the filament length from the roller to the entrance of the liquefier [119]. Moreover, being the compression module trend directly proportional to the displacement rate [120] and assumed that the critical pressure level is not very high in absolute value, this could explain why as the printing speed decreases with high quality part the problems become more insistent.

Before proceeding with a time-consuming chemical analysis of the material to verify solution 1 or 3, it proceeded by reducing the printing speeds to certify that the problem was not caused by this. Reducing the extrusion head print and travel speed, initially set at 200 mm/s, no bucking of the filament or clog of the nozzle occurs.

The standard quality benchmark was printed with a layer height of 0.2 millimeters, for the high quality one it was decided to set the layer height to 0.1 millimeters. As to the print speed, this is not fixed. Depending on the part to be printed, it increases and decreases within a range from 15 mm/s for the first layer, up to a maximum of 200 mm/s for the infill. In all the prints a skirt has also been insert around the model. A skirt is an outline that surrounds the part without touch it. It is extruded before starting to print the model in order to prime the extruder and establish a smooth filament flow. All the other print settings are summarized in tables 4.5 and 4.6 below.

Unlike the Stratasys uPrint SE Plus which is a network printer and accessible from any computer with internet access known the IP address of the machine, the Prusa is a SD printer. Therefore, before proceeding with the printing the g-code must be loaded on an external memory card which then must be inserted in the specific compartment located near the printer LCD screen. After choosing the G-Code to be fed to the machine, depending on the set temperature, the printer takes about 3 to 6 minutes to reach the set temperature and another 1 minutes to calibrating the Z-axis. Then the printing begins. Finally, it is also interesting to note that with this printer it is always possible to adjust some printing parameters such as bed or nozzle temperature, fan speed or flow rate during the printing.

3.2.1.PLA benchmark part

Calibrating the printer for the PLA was quite long and took several days to reach satisfactory results, such as a good adhesion of the first layer to preventing an excessive warping that has an adverse effect on the geometric accuracy. The problem was partly solved by raising the bed temperature, slowing down the print speed of the first layer, and slightly raising the nozzle head temperature during the extrusion of the first layer. Doing this thought, the lower layers of the base, that are warmer, tend to shrink more compared to the higher ones, generating a slight deformation in the shape of an inverted bowl.

At first glance, the benchmark made with standard print settings is almost identical to that made in high quality, although the staircase effect is more evident on the lower quality piece as can been seen in the figure 4.6. Furthermore, the highest quality benchmark presents a stringing effect more widespread probably due to the slowest movement speed of the nozzle.

	Standard quality part (a)	**High quality part (b)**
Quality	Standard	High
Layer Height (mm)	0,2	0,1
Material	Generic orange PLA	Generica orange PLA
Fill Pattern	Grid	Grid
Print Speed (mm/s)	25 (first layer) – 200 (travel)	15 (first layer) – 140 (travel)
Heated Chamber temperature (C°)	n/p	n/p
Radiant Temperature (°C)	n/p	n/p
Bed Temperature (°C)	65 (70 first layer)	65 (70 first layer)
Nozzle temperature (°C	200 (210 first layer)	200 (210 first layer)
Fill density (%)	20	20
Software	Slic3r	Slic3r
Print time suggested (h)	02:44	04:59
Real print time (h)	02:41	04:55

Index: n/a Not available n/p not present in the machine

Tab. 4.5 –Printing settings use for PLA benchmark part printed with the Prusa i3 MK3

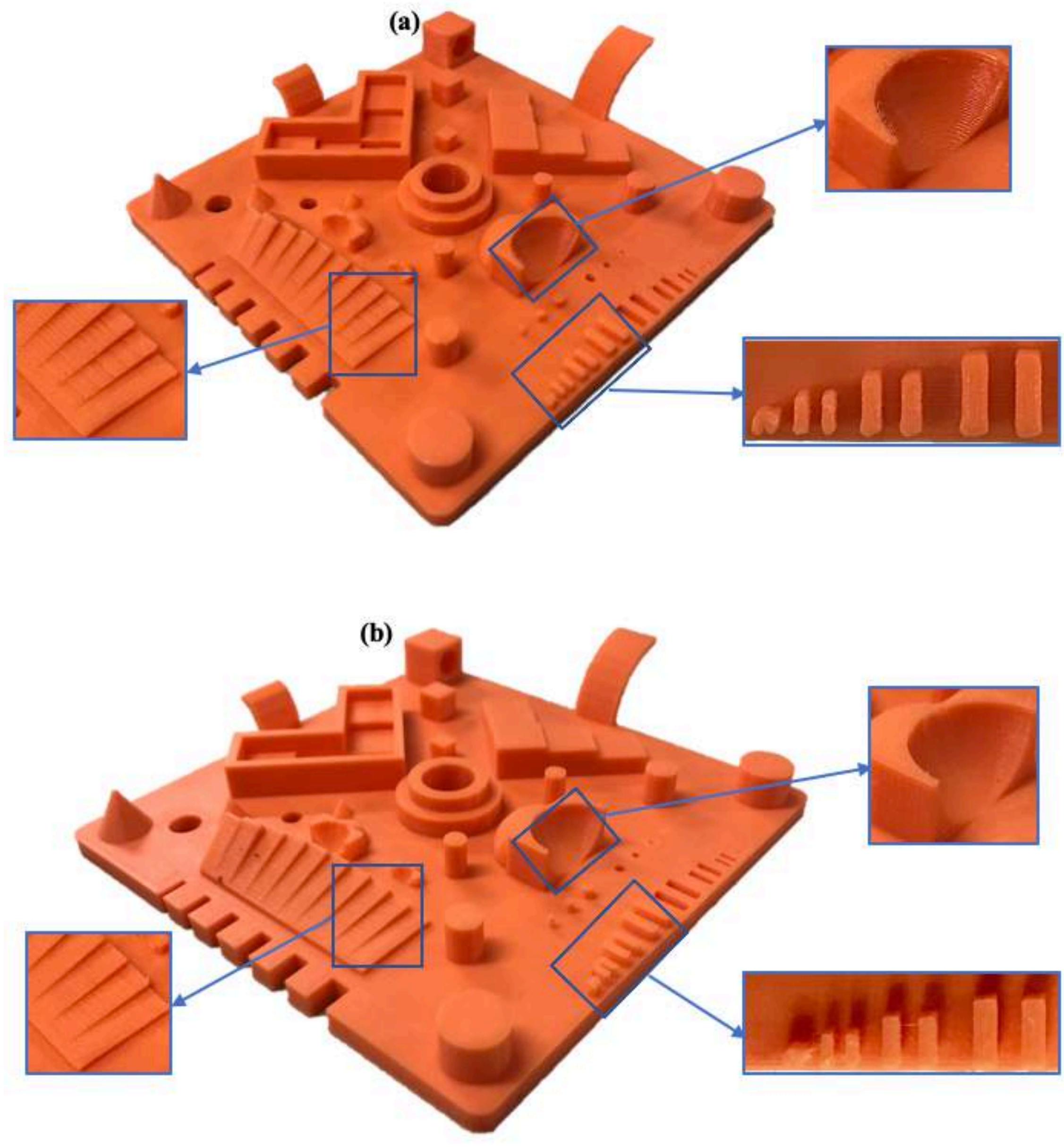


Fig. 4.6 –PLA benchmark part printed with the Prusa i3 MK3. **(a)** Standard quality printed part. **(b)** High quality printed part.

3.2.2.ABS benchmark part

During the printing of the benchmark parts in ABS with the Prusa i3 MK3 the main problem was the warpage. Both the parts, whether printed at normal quality and printed at high quality, were produced distorted from the center towards the corners causing also features and layer misalignments that makes the prints seem very messy. The warpage is caused by differential shrinkage of material in the printed part, or rather, the differential contraction of the part as it cools after extrusion, that occurs when the density of the polymer varies from the processing temperature to the ambient temperature, creating internal stresses. These so-called residual stresses, act on a part with effects similar to externally applied stresses. If the residual stresses are high enough to overcome the structural integrity of the part and not uniform, the part will warp, as can be seen in figure 4.7.

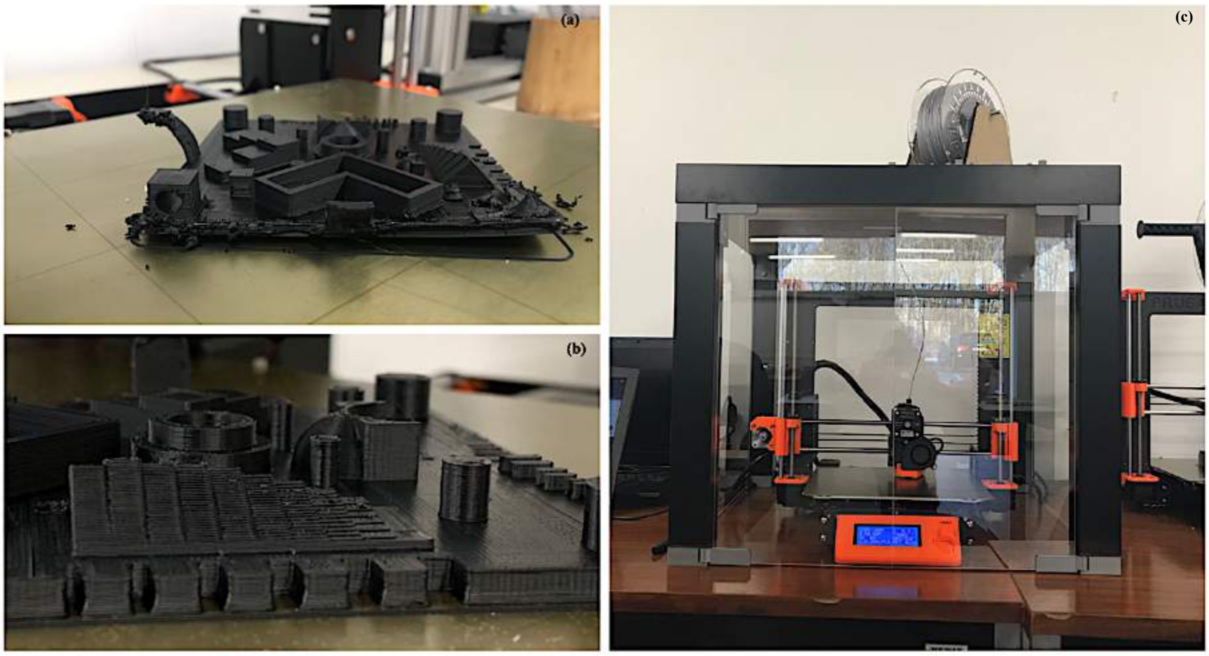


Fig. 4.7 – Standard quality benchmark part printed without the handmade chamber **(a)**. Standard quality part printed inside the handmade chamber **(b)**. Handmade chamber **(c)**

To reduce the warpage, the forums frequented by the various lead users were consulted and it was decided to create an external covering trying to homogenize the cooling and create, among other things, a sort of printing shelter able to protect the build plate from any external air current flows (figure 4.5). Anyway, properly heated build chamber cannot be sold or used for the production of commercial parts, because in many countries the usage of such solution is still under patent by Stratasys [121]. However, given the same printer settings, which are specified in the table 4.7, the benefits on the part quality are evident (figure 4.7).
As it can be seen from the picture above the chamber made of plywood, Plexiglas and 3D printed PLA (the parts in gray), is not perfectly sealed but enough to reduce the difference between the processing temperature and the ambient one, and so limiting the warpage without been able to eliminate it in any case. During the benchmark parts manufacturing, thanks to a mercury thermometer positioned inside the printing chamber, temperatures were registered, ranging from 21°C, at the beginning of printing, up to 30°C at the end of the process.

In this case also, the printed part with the better resolution has smoother surface finish and better accuracy, as can be seen in the figure 4.8., but arising a greater warpage compared to the printed part with a lower quality, in particular on the corner where is the cone. This was probably due to the slowest printing speed or some alteration in the external environment temperature that the handmade printed chamber could not prevent. However, in both components the overhang positioned on the opposite side of the base respect to the notches were not printed well or not printed at all, suggesting the need for support or different targeted print settings for the realization of such feature especially at slowing down of the printing speed. For example, a better quality could be obtain increasing the layer cooling fan power, indeed in conditions of minimum contact the longer the materials take to cool, the grater the chances are that sagging, delamination or collapse will occur as in this case [122].However, this particular procedure cannot be done through the Slicer software, but it must be done manually during the printing process when needed.

	Standard quality part (a)	**High quality part (b)**
Quality	Standard	High
Layer Height (mm)	0,2	0,1
Material	Generic black ABS	Generica black ABS
Fill Pattern and density	Grid	Grid
Print Speed (mm/s)	25 (first layer) – 200 (travel)	10 (first layer) – 200 (travel)
Heated Chamber temperature (C°)	n/p	n/p
Radiant Temperature (°C)	n/p	n/p
Bed Temperature (°C)	115 (120 first layer)	115 (120 first layer)
Nozzle temperature (°C	230 (250 first layer)	230 (250 first layer)
Fill density (%)	20	20
Software	Slic3r Prusa Edition	Slic3r Prusa Edition
Print time suggested (h)	02:52	04:54
Real print time (h)	02:48	04:50

Index: n/a Not available n/p not present in the machine

Tab. 4.7 –Printing settings use for ABS benchmark part printed with the Prusa i3 MK3

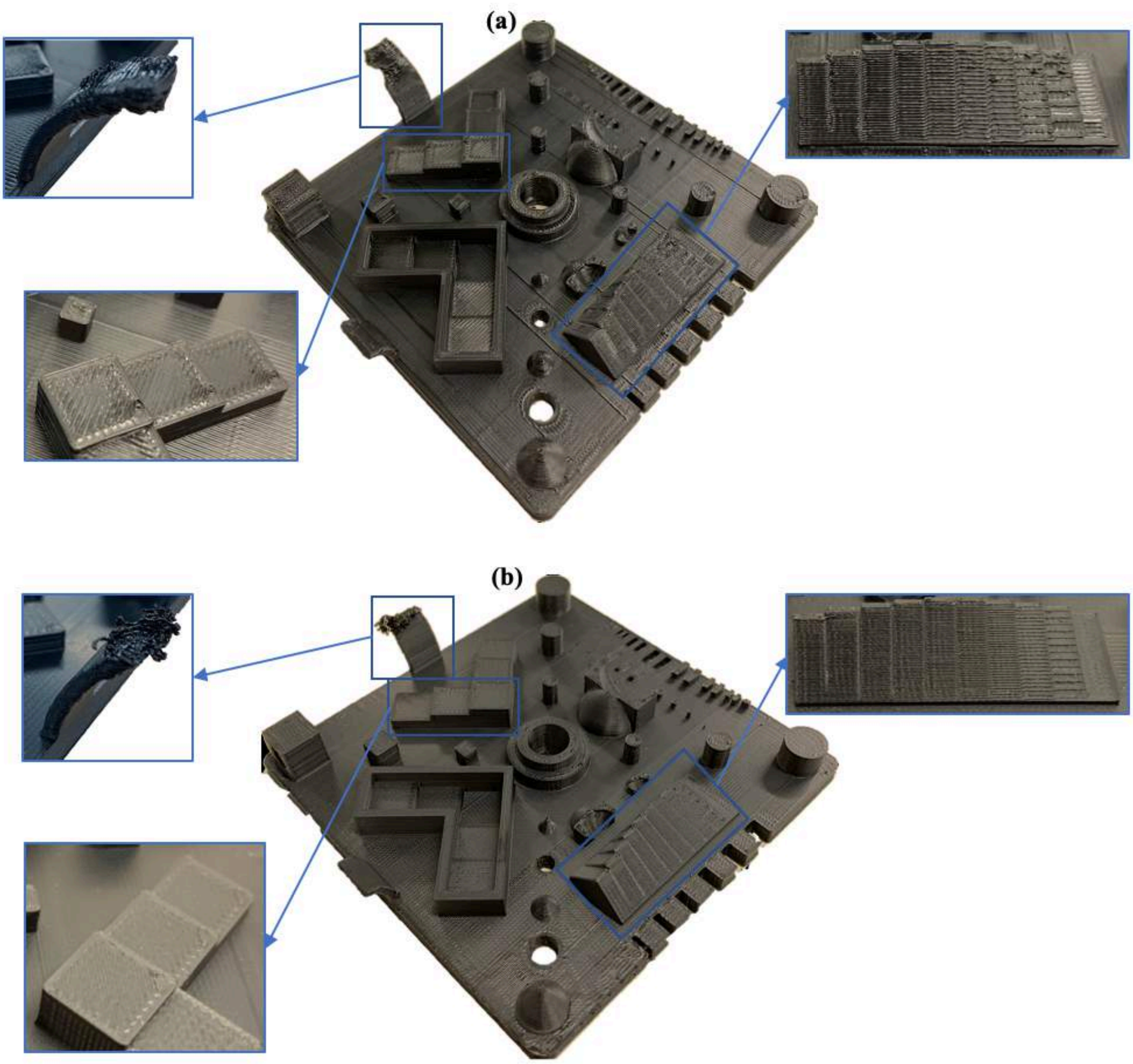


Fig. 4.8 –ABS benchmark part printed with the Prusa i3 MK3. **(a)** Standard quality printed part. **(b)** High quality printed part.

<u>3.3.Printing the benchmark part with Spiderbot HT 4.0</u>

As to the Spiderbot HT 4.0, four different benchmark parts in virgin ABS were printed. Three of them were printed with standard quality printer settings, but at different printed chamber temperature, respectively:

- 20 °C, the normal ambient temperature. This ideal condition was not achieved during the print experiment due to the heat given off by irradiation from the build plate and the extruder head that overheat the internal environment up to up to 24-28°C.

- 75°C, the same printer chamber temperature measured inside the Stratasys uPrint SE Plus during the benchmark parts printing. This environment temperature was achieved bringing manually through the Repetier-Server the radiant heaters up to 344°C.
- 25-30°C, the same printer temperature measured inside the handmade Prusa i3 MK3 printer chamber during the benchmark parts printing recorded with a mercury thermometer put inside the case during the benchmark parts printing. However, since these temperatures are almost similar to the first one, it was decided to omit the printing of the benchmark part in these temperature conditions.

The last benchmark part to print instead will be printed at high quality print settings with the same printed chamber temperature shown above that give the best result among those tested.
The slicing software is a custom version of Cura and it contains only preregister printer setting for PEEK, PEKK and PEI. The suitable print settings for ABS were then identify looking at the printer settings of the Prusa slicing software, working directly on the G-Code and through several printing tests. During the settings' trial the printer did not always behaved well such as the Stratasys, manifesting in particular some server connecting problems, which made the printer unusable for several days.
The printer has a controlled temperature printer chamber. Room heating is provided by an innovative system of radiant heaters that are disposed all around the chamber pointing towards the printing area, instead, room cooling is provided by a fan system. With this new heating system, it is possible to focus the heat on the part to print leaving the printing chamber at a significantly lower temperature. The temperature of the radiants can goes up to 590°C but find the optimal temperature for ABS was not easy because a lot of factors should be taken into account, such as the type of material, the ambient temperature, the radiated heat from the radiant heaters, the radiated heat from the extrusion head, the heat transmitted by conduction and irradiation in the printing chamber from the plate, not to mention the lack of uniformity of the perceived heat from the printed part. Moreover, the radiant heaters temperature could just be set working directly on the G-Code or the Repetier-Server user interface but no through the slicing software, that allows only to turn off or switch on the radiant heaters. However, in line with what is written in the Spiderbot User Manual, know that the temperature perceived by the printed part can be estimated as the half of the temperature at which the radians are set it was decided for the benchmark part to be printed at 75°C to make two attempts: the former, as described at the beginning of this chapter, with the printing chamber temperature set up to 75°C regardless of the heat perceived by the part, and the latter with a temperature perceived by the

part around 75°C, so with the radiant set around 140-150°C, regardless the printer chamber temperature.
The first printing attempt, that can be seen in the figure 4.9, did not go so well. The printing temperature of the first layer set a 230°C was too low, not allowing the first layer to perfectly adhere to the build platform and the other layers to correctly bind each other. As consequence the part has warped hindering the extruder head path, which ended up slamming on the printed piece and detaching itself from the magnetic supports which keep the head in place as can be seen in figure 4.8. In some cases, however, the extruder head does not remain suspended as in the figure and ends up falling onto the printing build plate damaging it and itself, thus making the presence of an operator always necessary during the printing process in order to stop it manually if necessary. Another problem encountered concerning the adjustment of material flow and filament retraction during the extrusion head direction changes. Each printer is different from the others and therefore even if the general printing parameters related to the flow are known, these must be adjusted for every single printer and every different brand material. Among other things, being the printer just released on the market the information and other users experience in this regard practically not exist. The lack of optimum settings of these parameters has obviously compromised the quality of the printed parts, as can be seen in figure 4.10, especially for the manufacturing of the smaller features where even the slightest errors in this sense are evident. These considerations should be taken into account when reading the quality and quantitative evaluation and comparison between the different benchmark parts.
It is finally important to point out that the first test parts have been printed with a raft. A solution adopted not so much to prevent warping but because of the damaged build plate that can be seen in the figure 4.8. A big problem for measurements, indeed since this printer only has one extruder the raft must be made of the same material as the benchmark part and therefore cannot be removed without compromising the print geometry and so the measurements. However, for the official benchmark parts, a new build plate has been placed and the raft manufacturing was not necessary.
As well as in the uPrint SE plus the ABS filament is stored in a special compartment at controlled temperature and moisture level to not compromise physical, morphological and thermal stability of the feedstock [123]. The material chamber is physically separated from the printer but sold together with it.
The printer settings adopt for the benchmark parts manufacturing are almost the same for all the benchmark parts, used can be find in the table 4.9 below.

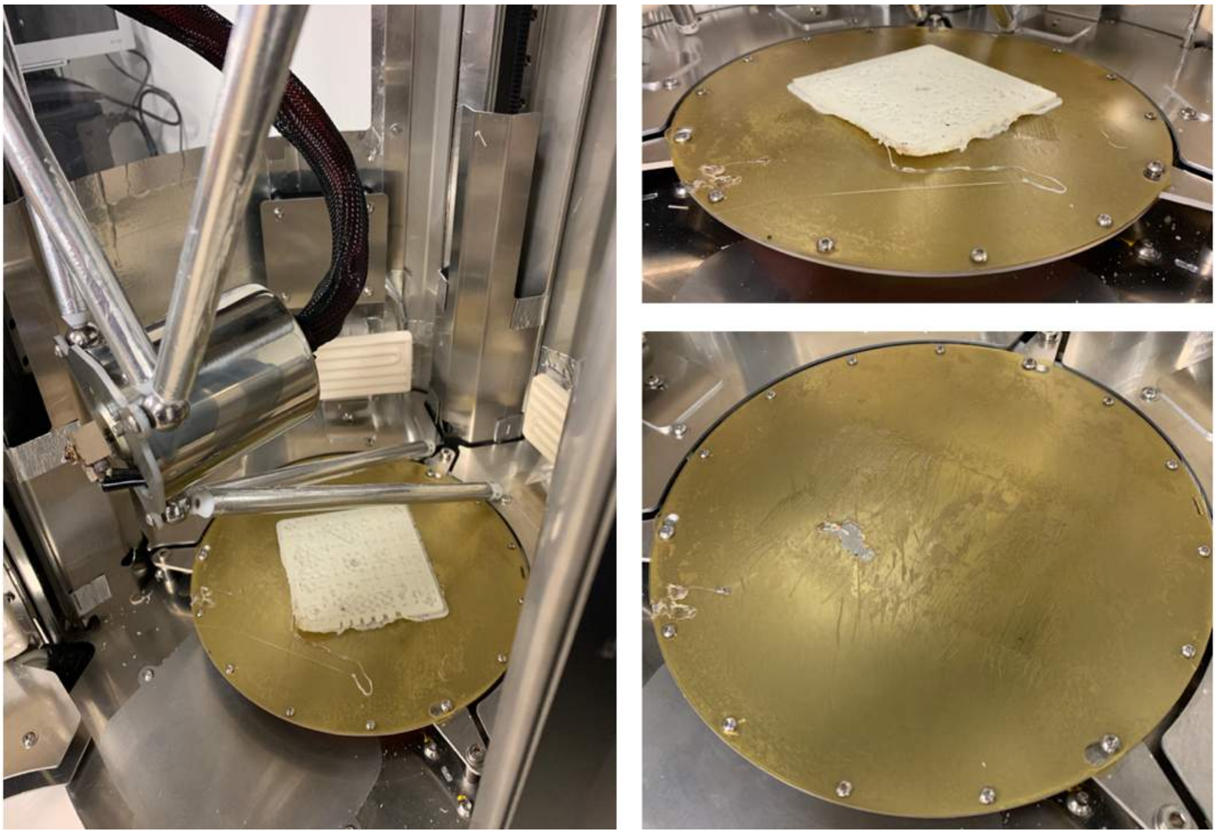


Fig. 4.9 – Spiderbot HT 4.0 problems encountered during the print tests.

As can be seen in figure 4.10 on the next page, the printed benchmark parts with the Spiderbot are different from each other. The best quality was achieved in the high-quality printed part **(a)** and in the standard quality part printed at 24-28 degrees **(d).** The former looks better in term of surface roughness and thin features or details, but the latter does not have gaps between infill and outer wall and looking better when comparing special features such us overhangs. The worst printed part, instead, is the one printed with a chamber temperature of 75°C **(b)**. Indeed, as previously explained, a chamber temperature of 75 ° C translates into 344°C of the radiant heaters and then a temperature inside the part close to 170-180°C, definitely too hot to allow a proper bonding when it comes to ABS above all if it considers the absence of a fan system on the extrusion head which facilitates the solidification of the material as soon as it is extruded. However, in general, the quality of the parts is poor. In all the printed parts it is possible to find extrusion residues on the surface or it is possible to check how the layers have not been perfectly deposited on top of each other. Moreover, the parts printed at higher temperatures or remained longer inside the chamber, are slightly more yellowish, as if the material had deteriorated.

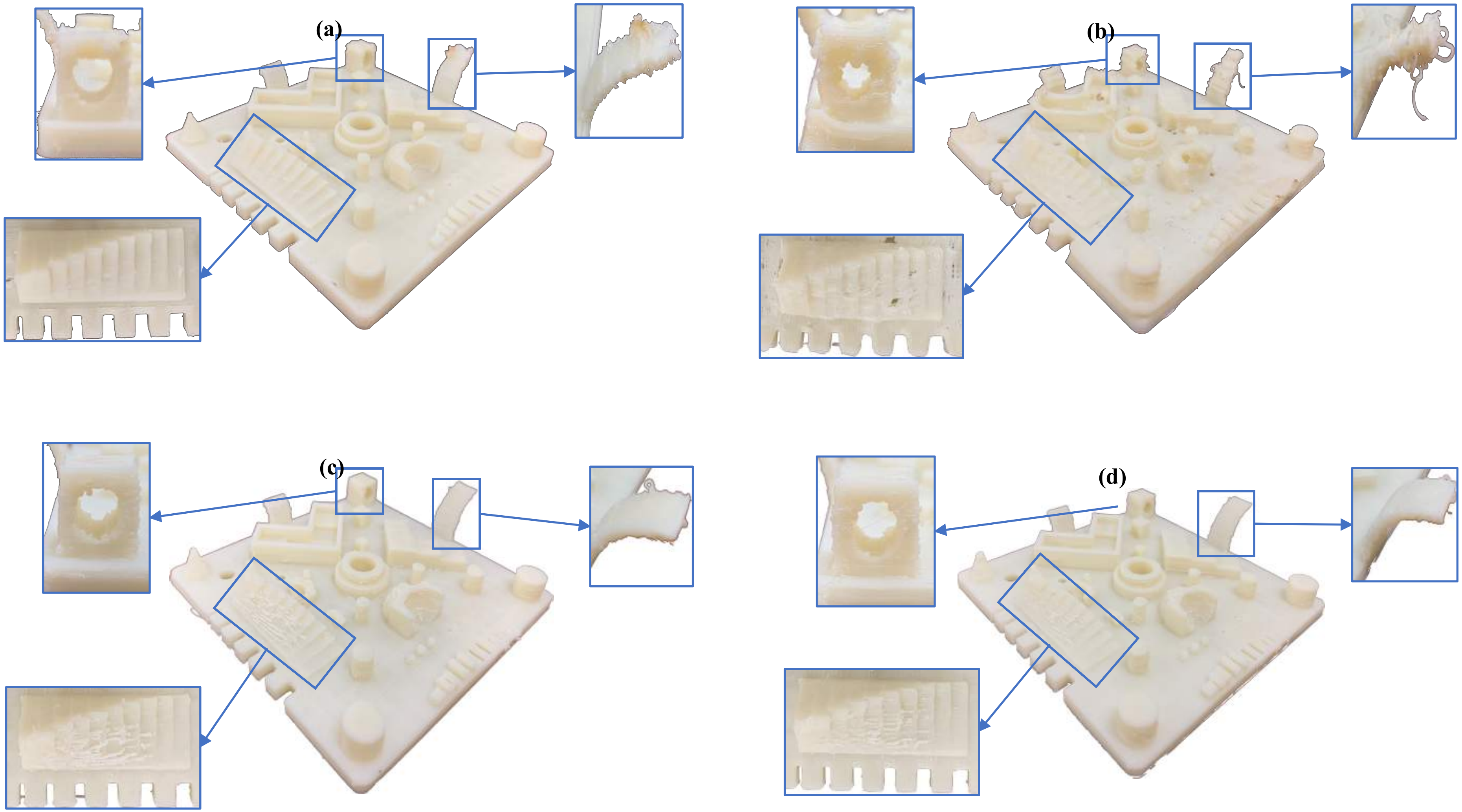


Fig. 4.10 – ABS benchmark part printed with the Spiderbor 4.0 HT. **(a)** High quality part 25 – 30°C. **(b)** Standard quality part 75°C**. (c)** Standard quality part 45°C. **(d)** Standard quality part 25 – 30°C

	High quality part 25-30°C (a)	Standard quality part 75°C (b)	Standard quality part 45°C (c)	Standard quality part 25-30°C(d)
Quality	High	Standard	Standard	Standard
Layer Height (mm)	0,1	0,2	0,2	0,2
Material	Generic virgin ABS	Generic virgin ABS	Generic virgin ABS	Generic virgin ABS
Fill Pattern	Grid	Grid	Grid	Grid –
Print Speed (mm/s)	15 (first layer) – 80 (travel)	20 (first layer) – 150 (travel)	20 (first layer) – 150 (travel)	20 (first layer) – 150 (travel)
Heated Chamber temperature (C°)	24 – 28°C	75°C	41-46°C	24 - 28°C
Radiant Temperature (°C)	0°C	344°C	150°C	0°C
Bed Temperature (°C)	115 (120 first layer)	115 (120 first layer)	115 (120 first layer)	115 (120 first layer)
Nozzle temperature (°C	235 (240first layer)	235 (240first layer)	235 (240first layer)	235 (2450first layer)
Fill density (%)	20	20	20	20
Software	Cura (costumed version)	Cura (costumed version)	Cura (costumed version)	Cura (costumed version)
Print time suggested (h)	8:49	03:17	03:17	03:17
Real print time (h)	8:51	03:12	03:13	03:13

Index: n/a Not available n/p not present in the machine

Tab. 4.9 –Printing settings use for ABS benchmark part printed with the Spiderbot

4. Measurements

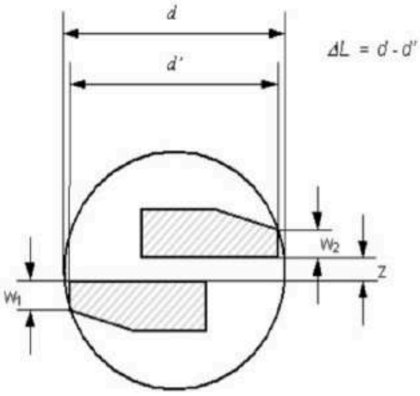
The measurements were taken with a Nikon profile projector V-16E (fig 4.12), and a Hogetex digital caliber. The former, with a measurement error equal to +/- 0,001 mm, was used to measure holes diameter and notches, the latter, with a measurement error of +/- 0,02 mm, to measure other group of features. According to the 10:1 metrology rule, both instruments can be used, since the total tolerance of a generic EAM is +/- 0,2 mm for the industrial and +/- 0,5mm for the desktop one [123].

Tab. 4.11 – Nikon profile projector V-16-E and Nikon optical comparator SC-102

The caliper was also used to measure hole diameters and notches as well, in order to compare, at the end of the analysis, the two different measurement systems results. Particularly interesting comparison, not so much for the different accuracy of the measurements systems, as for the different measurement mode. A profile projector indeed is a device that applies the principles of optics to the inspection of manufactured parts. In such device the magnified silhouette of the part is projected upon the screen, and the dimensions geometry are measured. Therefore, measuring holes or notches only the most protruding layer is considered (if not perfectly aligned). With the caliper, instead, the measurements depend on the layer where the jaws lean, which may not always correspond with the outermost protuberance or layer. Finally it's important to underline that when measuring internal diameters of less than 10 mm, an error is made due to the fact that the thickness of the measuring surfaces of the internal jaws, however small, does not allow to measure the diameter of the hole but, even with the best positioning , the caliper detects the measurement of a rope as shown in the following figure 4.12 where a cross-section of the hole is shown. The measurement error (ΔL) due to the curvature of the internal surface of the hole is a function of the thickness of the internal spouts (W1 and W2) and of the gap between them (Z) according to the following relation which refers to the figure shown:

$$\Delta L = d - d' = d - \sqrt{d^2 - (w_1 + z + w_2)}$$

Given the absence of a second caliber to estimate the error and the small value of the errors was however decided to neglect this aspect during the analysis of the data and the comparison between Caliper and Profile Projector.



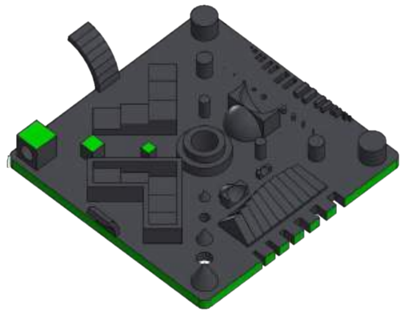
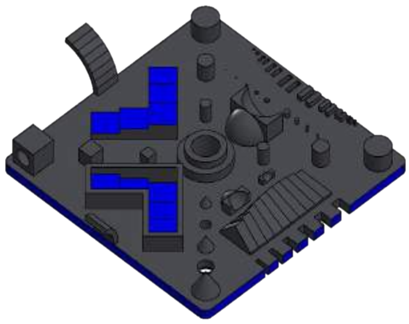
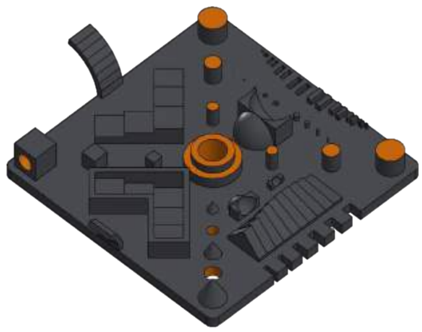
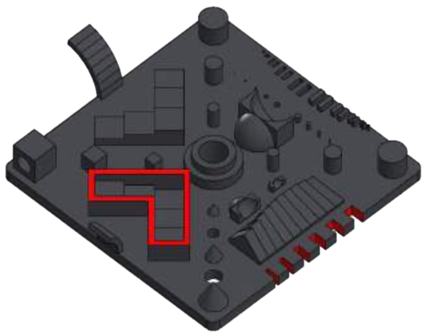
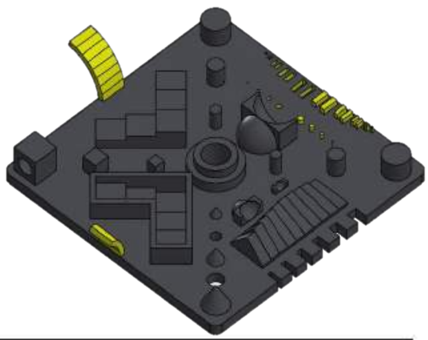
Nominal diameter dimension (mm)	(W1+Z+W2)				
	0,3 mm	0,4 mm	0,5 mm	0,6 mm	0,7 mm
1,5	0,03	0,05	0,09	0,12	0,17
2	0,023	0,041	0,06	0,09	0,13
2,5	0,018	0,032	0,05	0,07	0,1
3	0,015	0,027	0,042	0,06	0,08
3,5	0,013	0,023	0,036	0,05	0,07
4	0,011	0,02	0,031	0,045	0,06
4,5	0,01	0,017	0,042	0,038	0,05
5	0,009	0,014	0,026	0,033	0,047
6	0,008	0,013	0,021	0,029	0,041

Fig. 4.12 – Measurement errors occur during the estimation of small diameter holes with Caliper.

For each of the 10 benchmark parts 43 features were measured with Digital Caliper and other 22 features have been inspected with a SEM and evaluated qualitatively (tab. 4.10, tab. 4.11). Moreover, as mentioned above, for 9 out of 44 features the measurements were also taken with the profile projector, in addition to those taken with the digital caliper. For each feature 10 measurements were taken in order to minimize the incertitude. All the measures, which can be find in the Appendix 1, were taken in the metrology laboratory at the FapLap of the University of Ghent, a controlled environment, at an ambient temperature of 21°C and following the instructions established by the ISO reference legislation.

ID	Family of features	Nominal dimensions (mm)	Measurement tools
C1 - C6	Cylindrical Boss	⌀C1=⌀C3= 4; ⌀C2=⌀C4= 6;	Digital Caliper
		⌀C3=⌀C6= 10	
CC1 – CC2	Concentric Cylindrical Boss	⌀CC1= 20; ⌀CC2= 15	Digital Caliper
PS1 - PS5	Positive staircase	Height PS1= 3; Height PS2= 5	Digital Caliper
		Height PS3= 7; Height PS4= 6	
		Height PS5= 4	
NS1 - NS5	Negative staircase	Height NS1= 7; Height NS2= 6	Digital Caliper
		Height NS3= 4; Height NS4= 5	
		Height NS5= 3	
W1	Wall	Width W1= 2	Digital Caliper
SB1 - SB3	Square boss	SB10= 4x4; SB2= 6x6	
		SB3= 10x10	
RN1 - RN6	Rectangular Notches	RN1= 1,5; RN2= 2; RN3= 2,5	Digital Caliper, Profile Projector
		RN4= 3; RN5= 3,5; RN6= 4	
OD1 - OD4	Outer dimensions	OD1=OD2=OD3=OD4= 100x4	Digital Caliper
H1 - H4	Holes	⌀H1= 10; ⌀H2= 4; ⌀H3= 6	Digital Caliper, Profile projector
		⌀H4= 6	
O1-O2	Overhangs	O1(10à,20°,30°,40°,50°,60°,70°)	SEM
		O2(15°, 30°,45°)	
RB	Rectangular Boss	distance between RB1= 2	SEM
		distance between RB2= 1,5	
		distance between RB3= 1	
		distance between RB4= 0,5	
		distance between RB5= 0,25	
TW	Thin walls	TW1= 2; TW2= 1,5; TW3= 1	SEM
		TW4= 0,5; TW5= 0,25	
P	Pins	⌀P1= 2; ⌀P2= 1,5; ⌀P3= 1	
		⌀P4= 0,5; ⌀P5= 0,25	
SH	Small holes	⌀SH1= 2; ⌀SH2= 1,5; ⌀SH3= 1	SEM
		⌀SH4= 0,5; ⌀SH5= 0,25	

Tab. 4.10 – Benchmarking measured features description and measurement tools adopt for each feature.

Dimensional Accuracy	Features	
XY Plane	SB1-SB3 OD1 - OD4 length	
Z-Direction	PS1 - PS5 NS1 - NS5 OD1 - OD4 height	
Diameters	C1 - C6 CC1 - CC2 H1 - H4	
Thin walls	W1 RN1 - RN6	
Thin feature and overhangs	O1 - O2 TW1 - TW5 P1 - P5 SH1 - SH5 RB1 - RB5	

Tab. 4.11 – Corresponding geometric features for each type of dimensional accuracy.

5.Experimental results and discussion

In this part, it will be first presented a statistical analysis of all the previous measurements. Then it will be carried on a comparison analysis among all the benchmark parts manufactured, both quantitative and qualitative. Finally, the measures collected through the Profile Projector and the Digital Caliber will be compared and discussed.

5.1.Statistical Analysis

Upon completion of the benchmark parts manufacturing, the measurements were performed using a digital Hogetex caliper with a measurement degree of 0.01mm. Each feature of each benchmark samples was measured 10 times, reducing the incertitude of the measurement. Therefore, a total of 4400 measurements were taken from the 10 benchmark parts fabricated, 440 each one. Using the nominal value of each feature represented in tab. 4.10 it is possible to establish the probability of the machine for making features that fall within a particular range of dimensional percentage change. For each of these measurements, the percentage deviation from the nominal value was then measured and a frequency histogram was created (fig. 4.13)

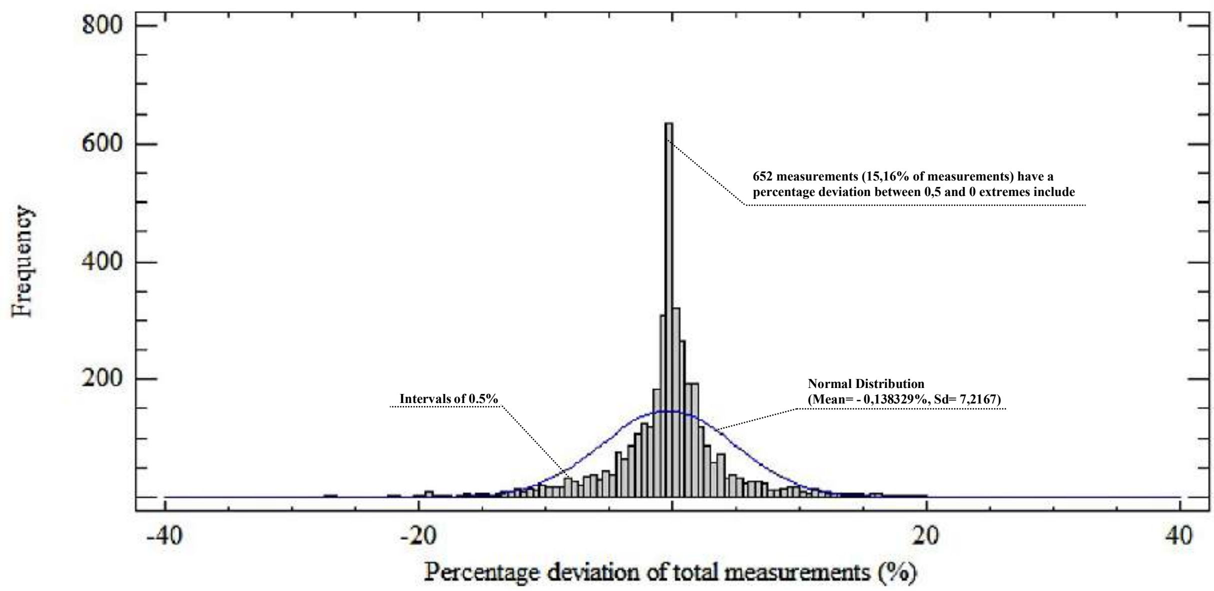


Fig. 4.13 – Distribution of the total Caliper measurements of percentage deviation

The normal distribution well fits the collected data, except for the high peak. It also possible to note a general tendency of the EAM equipment to undersize the printed parts.

Considering the ideal machine as the one whose probability for manufacturing the geometric benchmark models is 100% within an infinitesimal range close to zero, it was possible to establish the probability of EAM equipment to print a part within a specific range. Chosen a range that goes from -1% and 1% with the respect to a target measurement, the overall probability of the system is 37,58%, but expanding the range up to 5% and down to -5% the probability skyrockets to 76,1%. It should be emphasis that in the analysis above the benchmark printed with the Spiderbot with the radiant heater at 344°C. These are clearly unsuitable printer settings for the ABS and they gave a poor and inaccurate result. If this part measurements are excluded from the analysis the overall probability of the machines for manufacturing the benchmark part is almost 81% within a -5%, 5% range.

The statistical analysis of the percentage deviation of the measurements will be then carried on analyzing the different data collected divided by each printed part. The 10 frequency histograms are illustrated in the figure 4.14 on the following page. As notice before, there is a general uniform shrinkage affected all the parts, with an average value of -0,864% and of -0,43% for the printed part in PLA and ABS made with the Prusa and the uPrint respectively. Instead, the ABS parts manufactured with the Spiderbot, in particular the ones printed at 25°C and 75°C register a slightly oversizing. Looking at the graphs the best results were achieved by the uPrint. In this case the normal distribution perfectly fit the data trend, in particular for the part printed in high quality. Even in the case of the Prusa MK3 i3, in particular as regards the PLA, the data are fairly well distributed along the normal distribution, with averages generally more distant from zero but deviations almost similar to those recorded with the parts printed by the Stratasys. For the left-over parts, those printed in ABS with Prusa and Spiderbot, the question is slightly different. The normal distribution, especially in the former, fits good data trend. The means stay within the range that goes from -2,09 to 1,82, going however to touch the lowest average of -0,19 with the part printed by the Spiderbot at 45° - 50°C. The standard deviation of these part instead skyrockets, reaching up value of 16,4329. The increasing standard deviation values could suggest that the oscillations of real parts surface profile at the macroscopic level influence the measures rather significant with respect to the average line. As already noted above, indeed, seems to be a close correlation between surface roughness and standard deviation. Since all the measures were taken with the same instrument, under the same environmental conditions and following the same procedure a high standard deviation can only be an indication of how much the surface of the part is irregular. Indeed, the less uniform the surface, the more odds there are that the caliper’s jaws be placed in one of the peaks or valleys of the real surface profiling of the piece causing significant fluctuation in the measurements as illustrated in figure 4.15. However, even problems with flow management or layer misalignment could cause high standard deviation values. At this point, only an analysis of the surface roughness and a characterization of the material used could confirm or not one or the other hypothesis.

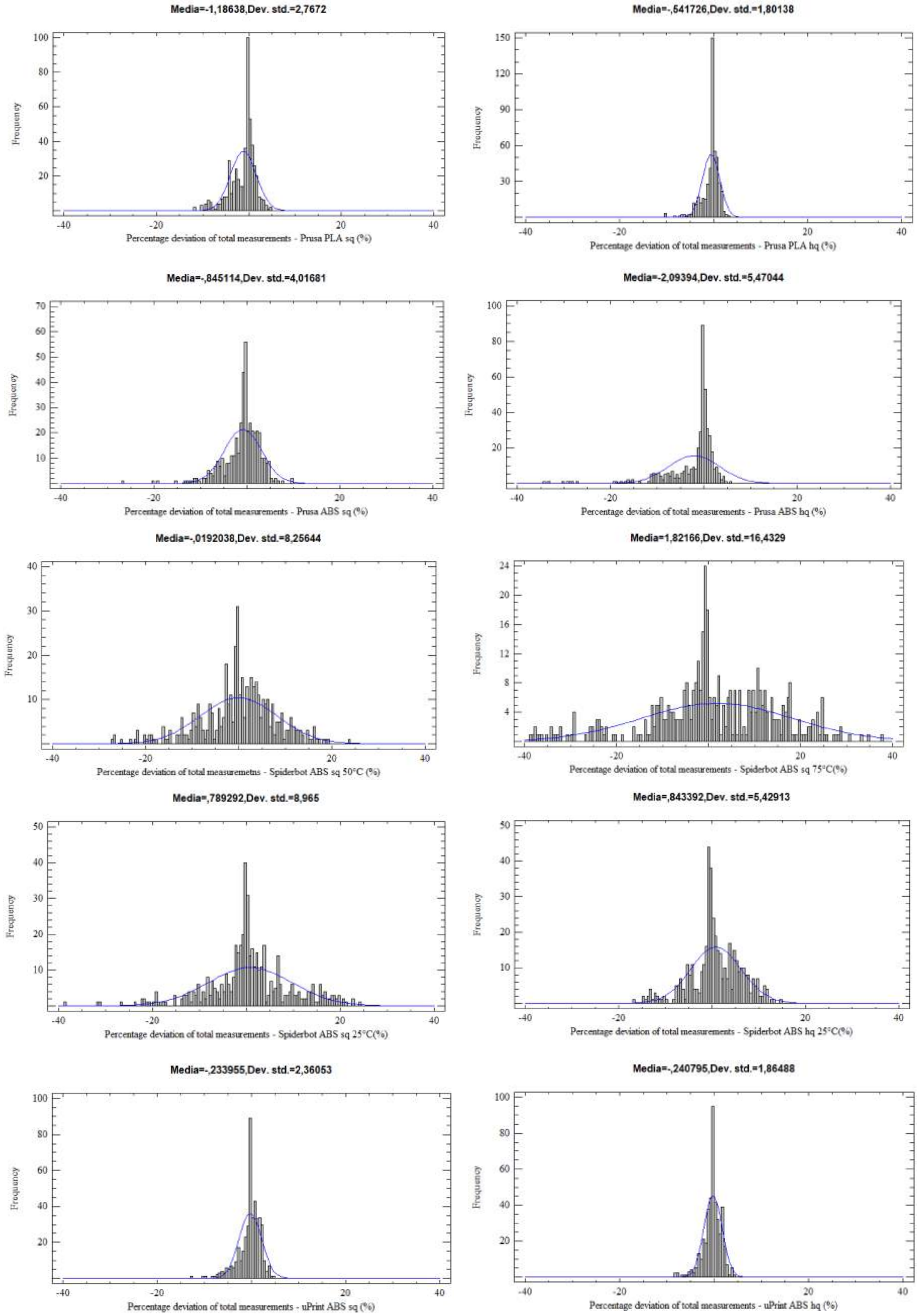


Fig. 4.14 – Distribution of the total Caliper measurements of percentage deviation for each printed benchmark parts (intervals = 0,5%).

In general, the most accurate parts also have the lowest standard deviation value, except for parts printed in ABS with the Prusa and with the Spiderbot. In this case, although the pieces are printed on average with a discrete accuracy (except for the part printed at 75°C), the standard deviation takes very high values ranging from 4,01681 up to 16,4329. Unfortunately, it has not been possible to find a direct relationship between surface roughness and standard deviation of the measures, so this aspect will not be considered for the purposes of the analysis.

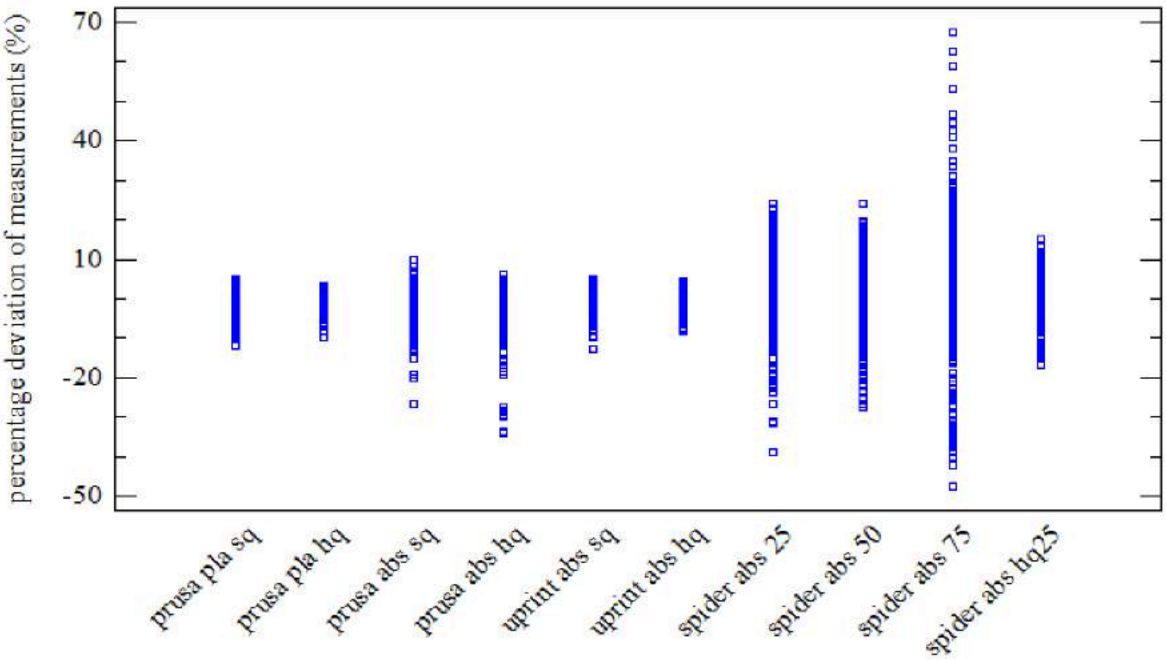


Fig. 4.15 – Scatter chart of total caliper measurements percentage deviation divided according to the printer used to manufacture the benchmark part and the printer settings.

5.2.International Tolerance

Introducing the International Tolerance (IT) grade established by ISO-ANSI standards UNI EN 20286- I (1995) based on the total set of measurements taken and the corresponding deviations, the maximum tolerance grade obtained for the samples is calculated. This value places the dimensional performance of the Prusa i3 MK3, the Stratasys uPrint SE Plus and the Spiderbot HT 4.0 with respect to the performance of other AM techniques. The standard tolerance value considers a tolerance factor i µm indicated by equation:

$$i = 0{,}45\sqrt[3]{D} + 0{,}001D$$

where D is the geometric mean of the range of nominal size in mm. In this case, the standard tolerance value is calculated for a range of nominal size. For a generic nominal dimension D_{CAD}, the number of tolerance unit n is evaluated as follows [124]:

$$n * i = 1000(D_{CAD} - D_{mea})$$

where D_{mea} is the measured dimension. Using the latter equation, the maximum value ni among the set of measures obtained from the fabrication of the 10 parts is yielded (fig. 4.16). On a global scale, this value makes it possible to compare the performance of the open source machine 3D printer with the other AM technologies positions [102] which commonly assume a Tolerance Grade between IT14 = 400i µm and IT16 = 1000i µm included.

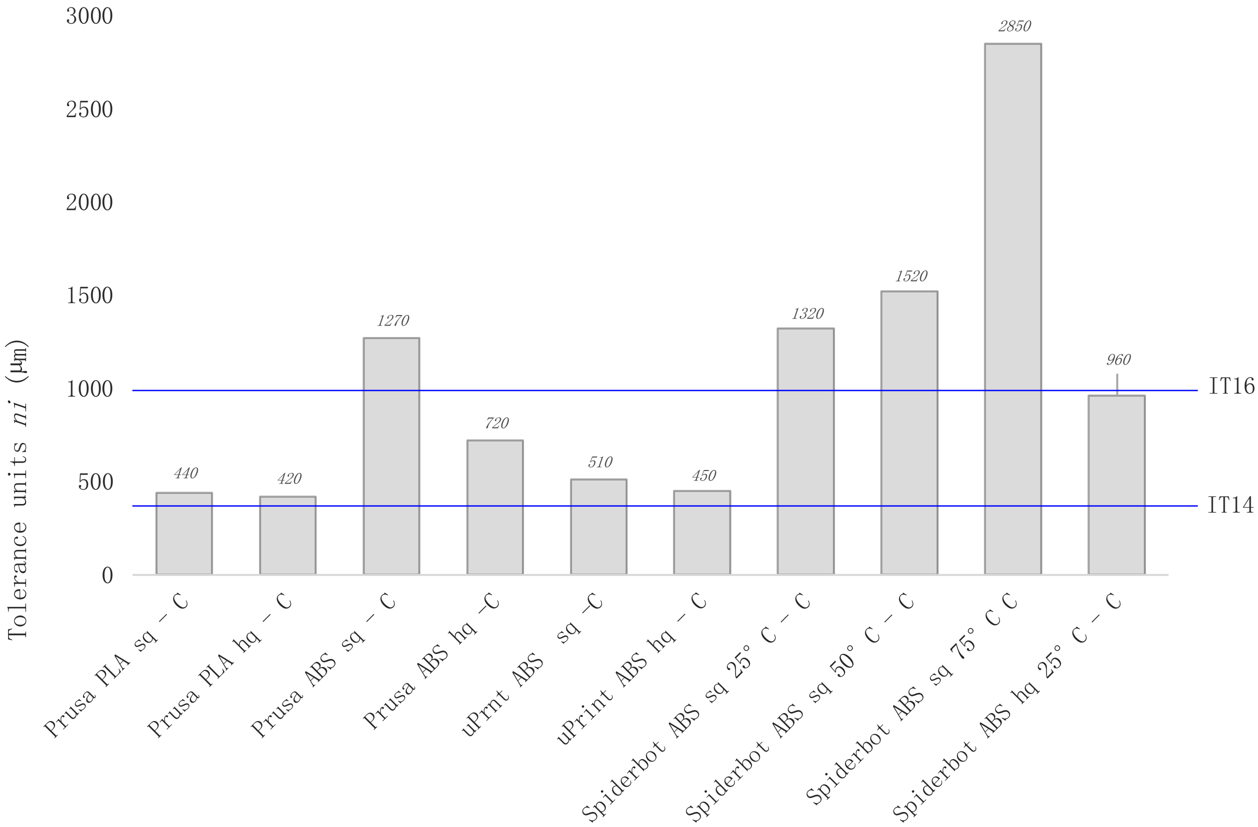


Fig. 4.16 – Comparison of the maximum tolerance grades among different EAM equipment and printer settings.

As it possible to see through the figure 4.16 the performance of the uPrint with ABSplus and Prusa with PLA are very similar and include within the range of standard tolerance grade, IT14 – IT16. The performance of the Prusa and the Spiderbot with ABS in high quality settings also falls into this range. The other parts manufactured instead do not fall into this range, in some cases even moving away significantly, as in the case of the Spiderbot. No surprise, however, if it takes into consideration that the Spiderbot is a printed just born and developed essentially for printing PEEK and PEI.

Finally, it is interesting to point out (figure 4.17) the comparison of IT grades between conventional manufacturing processes, including the AM techniques.

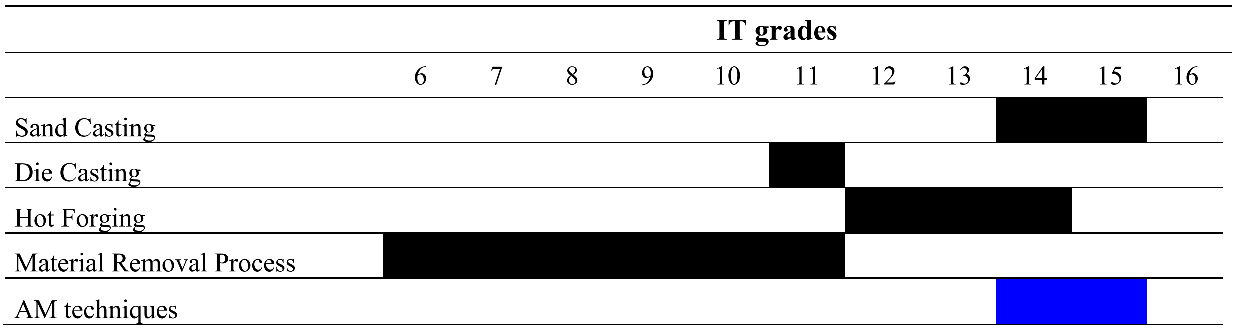


Fig. 4.17 – Tolerance grades for various manufacturing processes

6.Qualitative and quantitative evaluation

In this section, each benchmark parts will be evaluated in terms of accuracy, warping, thin feature and overhangs. Each parameter will first be evaluated individually, then the results will be collected, synthesized and compared.

6.1.Accuracy evaluation

To properly quantify accuracy level and in order to compare it with other parameters of different nature or not quantitative, an evaluation method has been proposed. For the ten measures of each feature for each different benchmark parts the mean and the standard normal deviation was calculated (Appendix 1). Then, starting from the statistical analysis, the best benchmark part has been identified, to be taken as a reference to determine an appropriate evaluation system. The best results, statistically speaking, were obtained with the Prusa - PLA and uPrint - ABSplus under high quality printer settings conditions. In light of the mean closest to zero and almost identical standard deviation, it was decided to take the high-quality benchmark manufactured by the Stratasys as a reference to establish the different ranges of the rating scale. In particular, given the percentage difference D_i of the measurements mean of each feature m_i from the corresponding nominal dimensions n_d as:

$$D_i = \left| \left({}^{m_i}/_{n_d} * 100 \right) - 100 \right|$$

it has been decided to give a rating of 5 to all those features for which the value of D_i is smaller or equal to the one calculated for the same part characteristic manufactured by Stratasys uPrint SE Plus with high quality printer settings. Then applying the same reasoning, called D_{iShq} the percentage difference of the mean value of the uPrint HQ benchmark part feature's measures from the respective nominal value of the same feature and D_{ixxx} the percentage difference of the mean value of the generic benchmark part feature's measures from the respective nominal value, the evaluation scale is shown in table 4.12.

Range	Qualitative Evaluation	Quantitative score
$D_{ixxx} \leq D_{iShq}$	Very good	5
$2D_{iShq} \leq D_{ixxx} \leq 2D_{iShq}$	Good	4
$3D_{iShq} \leq D_{ixxx} \leq 3D_{iShq}$	Satisfactory	3
$4D_{iShq} \leq D_{ixxx} \leq 4D_{iShq}$	Poor	2
$5D_{iShq} \leq D_{ixxx} \leq 5D_{iShq}$	Worse	1
$D_{ixxx} > 5D_{iShq}$	Fail	0

Tab. 4.12 – Evaluation ranking of feature accuracy

As can been seen from the results illustrated in table 4.13, they reflect the expectations. In general, high quality parts are more accurate than those printed in standard quality with the same machine, although the gap between the different part varies from one printer to another.
The best benchmark parts produced are those manufactured by the Stratasys whether with standard quality or high-quality printer settings. It is also significant to note how, in terms of accuracy, Prusa working with the PLA can obtain results very similar to those obtained by the standard quality part printed by uPrint, as proof of what it could already be deduced from the comparison in terms of IT grades. However, what that chart could not show, contrary to this table, is how much the accuracy of the part made with the high-quality industrial printer is much better compared to the other parts, as can be seen from the total of the various scores. The less accurate parts instead are those manufactured by the Spiderbot, with a generally decreasing accuracy as the increasing chamber temperature.
Finally, from this data it is also possible to obtain some general information on the XY plane, Z-directions, diameters and thin walls accuracy of EAM process. Gathering then the same features of each benchmark parts in 4 different cluster, one for each type of dimensional accuracy, and calculating the average of the total average scores assigned to each feature, it is possible to identify where the general EAM equipment shows the highest level of criticality. With an average score of 1,743 the thin walls accuracy is the worst, while with an average score of 3,928 the z-direction accuracy results the best. The diameters and XY plane accuracy instead, has recorded average scores of 2,02 and 2,325 respectively.

	Prusa i3 MK3 PLA		Prusa i3 MK3 ABS		Stratasys uPrint SE		Spiderbot HT 4.0			
Features	SQ	HQ	SQ	HQ	SQ	HQ	SQ 25°C	SQ 50°C	SQ 75°C	HQ 25°C
C1	3	3	2	4	4	5	4	5	0	5
C2	0	0	4	0	0	5	0	0	0	0
C3	2	3	0	3	4	5	0	0	0	0
C4	4	4	2	4	5	5	0	0	0	0
C5	0	0	0	0	0	5	0	0	0	0
C6	5	2	0	5	5	5	0	0	0	0
CC1	0	0	2	5	2	5	0	0	0	0
CC2	4	5	5	5	5	5	0	0	0	4
H1	4	5	3	3	4	5	2	1	0	3
H2	4	5	4	3	4	5	2	1	0	3
H3	5	5	4	4	4	5	1	1	0	3
H4	4	4	4	3	4	5	1	1	0	1
RN1	3	1	0	0	2	5	0	0	0	4
RN2	3	3	2	0	2	5	0	0	4	4
RN3	3	3	2	0	3	5	0	0	1	3
RN4	3	4	0	0	4	5	1	0	0	1
RN5	2	3	0	0	4	5	1	0	0	4
RN6	0	0	0	0	0	5	0	0	0	0
SQ1a	4	4	3	2	3	5	0	0	0	0
SQ2a	5	5	5	5	5	5	0	0	5	2
SQ3a	5	5	1	4	4	5	0	2	3	3
SQ1b	4	5	1	2	5	5	0	0	0	0
SQ2b	3	5	0	3	5	5	0	0	0	0
SQ3b	0	0	0	0	0	5	0	0	0	0
NS1	5	2	4	4	0	5	0	0	0	4
NS2	5	5	5	4	4	5	4	3	4	5
NS3	4	5	4	4	3	5	4	3	1	4
NS4	5	4	5	5	3	5	4	0	4	5
NS5	5	5	5	5	4	5	5	4	1	5
PS1	5	5	5	5	5	5	4	5	1	5
PS2	5	5	4	5	5	5	4	4	2	5
PS3	5	5	5	5	5	5	5	5	3	5
PS4	5	5	5	5	5	5	4	5	4	5
PS5	4	5	4	5	5	5	3	3	0	5
W1	5	5	0	2	5	5	0	0	0	0
OD1 height	5	5	5	4	4	5	5	3	0	2
OD2 height	4	4	3	3	4	5	2	3	0	1
OD3 height	4	4	5	4	4	5	5	1	0	0
OD4 height	5	5	4	5	4	5	5	3	0	2
OD1 width	2	3	0	3	4	5	0	0	0	0
OD2 width	1	2	2	4	5	5	4	3	1	0
OD3 width	0	0	0	0	5	5	5	0	0	0
OD4 width	0	0	0	0	0	5	0	0	0	0
Total	**144**	**148**	**109**	**127**	**152**	**215**	**75**	**56**	**34**	**93**

Index: SQ = standard quality HQ = high quality

Tab. 4.13 – Comparison of the various EAM equipment based on the fabrication of the geometric benchmark part under different printer settings (5=very good, 4=Good, 3=Satisfactory, 2=Poor, 1=Worst, 0=Fail).

6.2. Thin features evaluation

As concerned the thin feature there were inspected with a SEM the only possible alternative to measure very small characteristic. The initial intent was to take the measurements of these features using the microscope, but we realized that this was not well calibrated as illustrated in figure 4.18. In particular, the measurement of the features varies as the distance of the objective lens varies from the sample making practically impossible to compare the measured values.

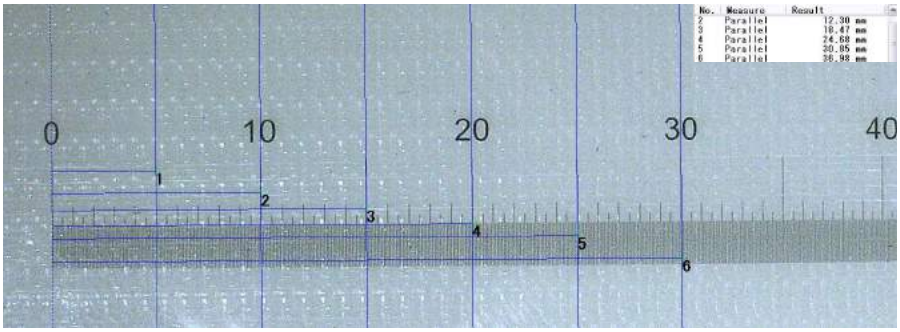


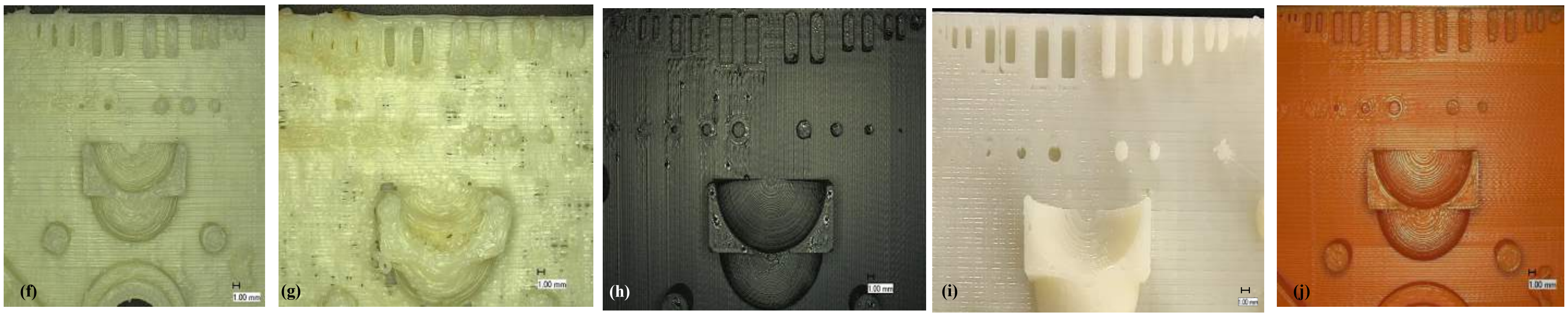
Fig. 4.18 – Evaluation of microscope calibration with grade slide.

Therefore, it was decided to continue with qualitative assessment of these attributes. In particular, thin features can be divided into 4 groups: rectangular boss, thin walls, pins and small holes, each of which is composed of 5 features respectively. Considering each of these group separately, each of them will be assigned a score from 0 to 5 depending on the number of thin features manufactured with accuracy and precision, i.e. in the part there just 3 pins out of 5, the score will be 3. For the reference, a thin feature will be considered manufactured when it is sharply distinguishable, and the printed characteristic is not messy.

The photos taken with the microscope for the thin features of each benchmark are shown in figure 4.19. However, it is important to note that in some cases these thin features are not realized not by machine limits, but rather for the non-conversion of the feature from the STL file to the g-code. Unfortunately, this is not determinable with certainty, but must surely be taken into account when reading the results.

The evaluation of each benchmark part is shown in table 4.14. Specifically, a score of 1 to 5 was assigned to each group of thin features as outlined above. After that the total score among each benchmark part was obtained. The results are quite homogeneous at least for the parts printed with the Prusa and the uPrint. Detached instead, even if only slightly, is the Spiderbot that behaves in general discretely except for the parts printed in standard quality at 75 ° C environment temperature.

(a) Spiderbot ABS HQ 25°C **(a)** Spiderbot ABS SQ 25°C **(c)** Prusa ABS SQ **(d)** uPrint ABS HQ **(e)** Prusa ABS HQ



(a) Spiderbot ABS SQ 50°C **(a)** Spiderbot ABS SQ 75°C **(c)** Prusa ABS HQ **(d)** uPrint ABS SQ **(e)** Prusa ABS SQ

Fig. 4.19 – Details of thin feature of each benchmark (HQ = high quality, SQ = standard quality)

Another aspect to be highlighted after analyzing the data is certainly that the gap between industrial printer and desktop printer is lost when we speak in terms of the thin features, rather than accuracy. The precision in the manufacture of these parts, demonstrated by Prusa, that can also be seen in the pictures above, is really surprising, going to equal or even exceed in quality terms the same parts made by uPrint, particularly evident for instance, comparing the pictures **(j)** and **(i)** in figure 4.19

	Prusa i3 MK3 PLA		**Prusa i3 MK3 ABS**		**Stratasys uPrint SE**		**Spiderbot HT 4.0**			
Group of thin features	SQ	HQ	SQ	HQ	SQ	HQ	SQ 25°C	SQ 50°C	SQ 75°C	HQ 25°C
Thin Walls (TW1-TW5)	4	3	3	3	3	3	2	2	0	2
Rectangular boss (RB1-RB5)	3	4	3	3	3	3	2	1	1	3
Pins (P1-P5)	2	3	3	4	2	4	3	3	2	3
Small Holes (SH1-SH5)	3	3	3	3	2	3	2	2	0	3
Total	**12**	**13**	**12**	**13**	**10**	**13**	**9**	**8**	**3**	**11**

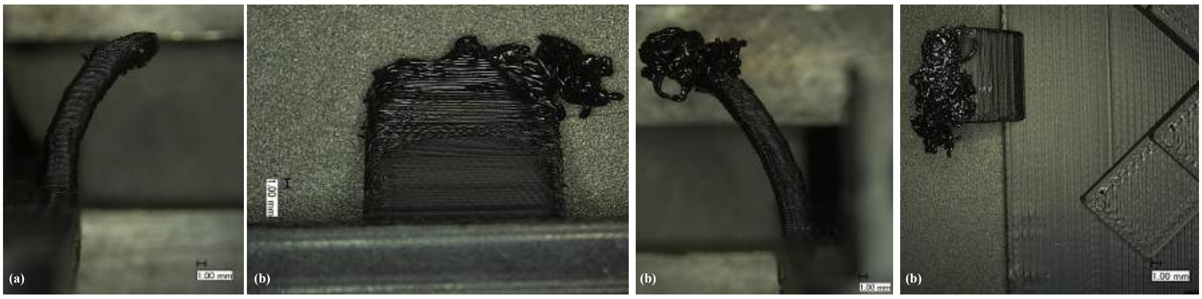
Tab. 4.14 – Comparison of the various EAM equipment based on the fabrication of the benchmark's thin features under different printer settings (5=very good, 4=Good, 3=Satisfactory, 2=Poor, 1=Worst, 0=Fail).

6.3.Overhangs evaluation

As for accuracy, also in the case of overhangs the score will be assigned taking as a reference the results obtained with the Stratasys uPrint, which is not only the best printer, as confirmed by the results above, but has also used support material for the realization of these two specific features. In this case the scale of evaluations will be from 0 to 2. These are indeed particular features that will be evaluated qualitatively by analyzing the images collected at the SEM and an overextension of the scores scale with this premises would have only risked favoring a part rather than a other. Will be assigned a score of:

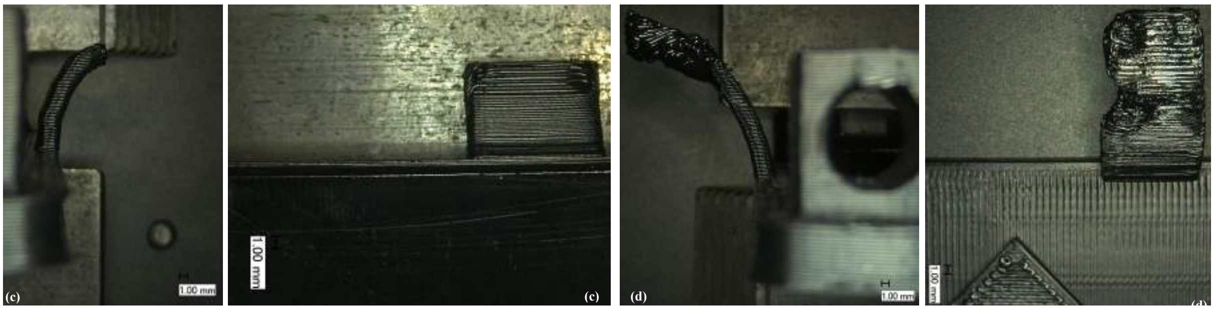
- **2**, when the part has been manufactured with great accuracy and precision depositing one layer on top of another without significant distortion
- **1**, the features were created for all its extension, but the layer bonding did not happen correctly or there are some deformations
- **0**, feature made only partially or not realized

Below, in fig. 4.20 and fig. 4.21, the most significative pictures of the overhangs collected with microscope are illustrated.



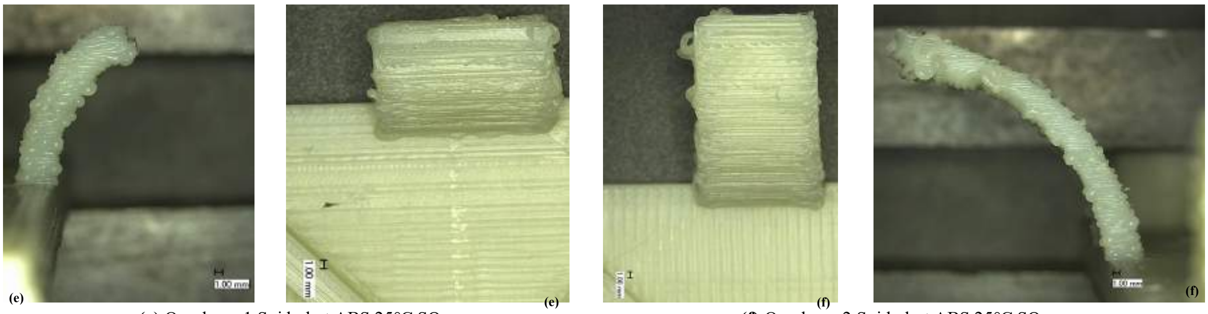
(a) Overhang 1 Prusa ABS HQ

(b) Overhang 2 Prusa ABS HQ



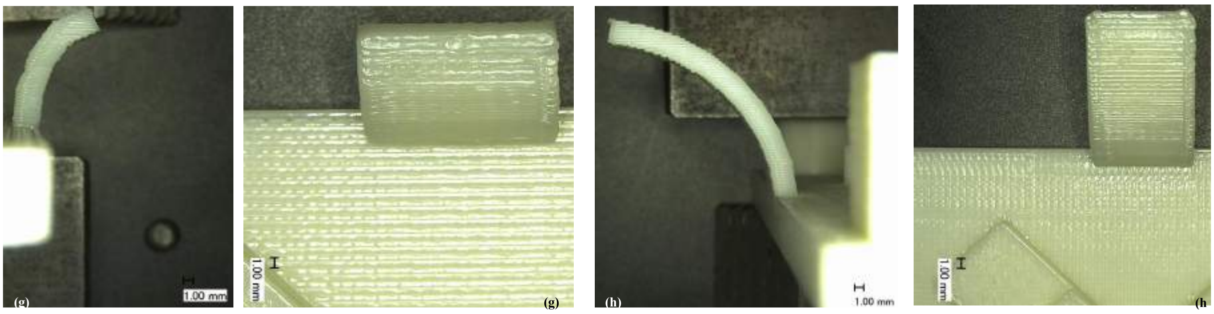
(c) Overhang 1 Prusa ABS SQ

(d) Overhang 2 Prusa ABS SQ



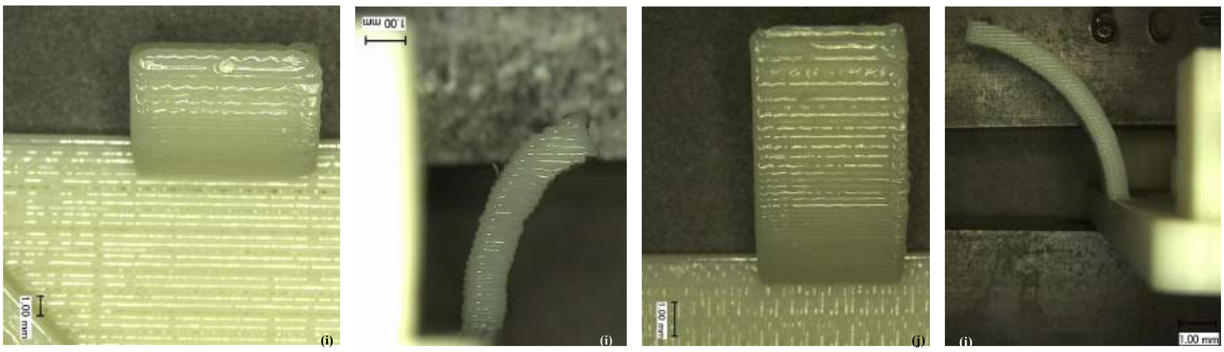
(e) Overhang 1 Spiderbot ABS 25°C SQ

(f) Overhang 2 Spiderbot ABS 25°C SQ



(g) Overhang 1 uPrint ABS HQ

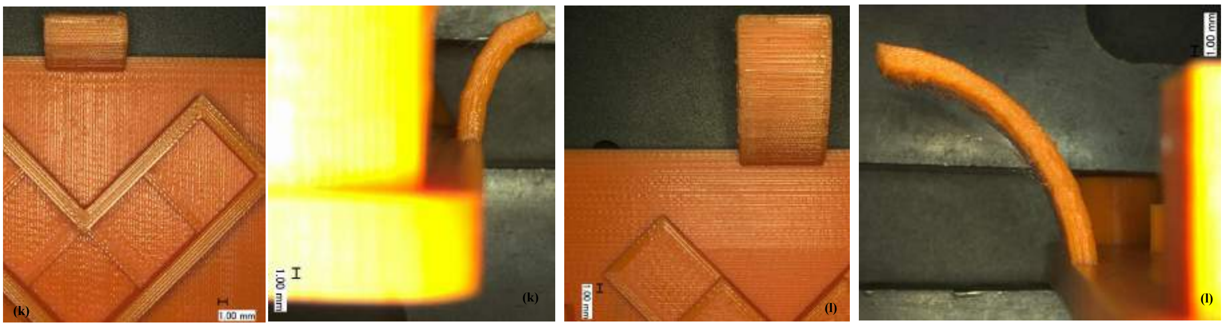
(h) Overhang 2 uPrint HQ



(i) Overhang 1 uPrint ABS SQ

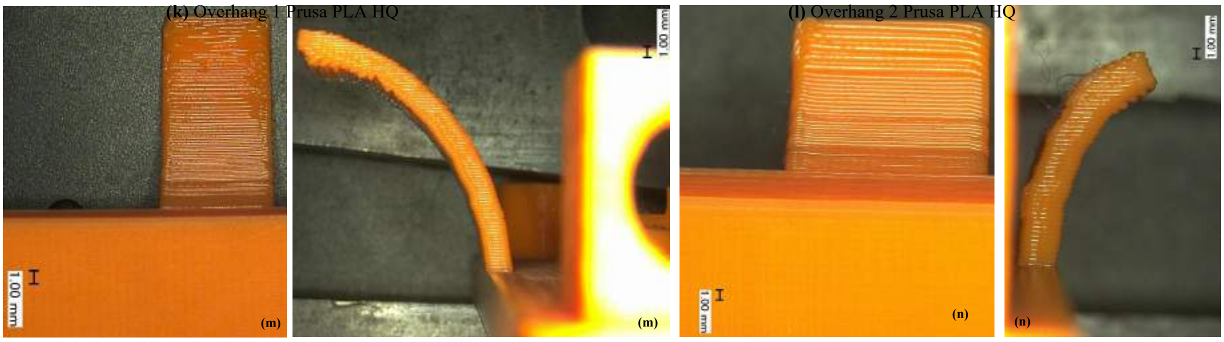
(j) Overhang 2 uPrint SQ

Fig. 4.20 – Pictures showing in detail the overhangs in the benchmark parts



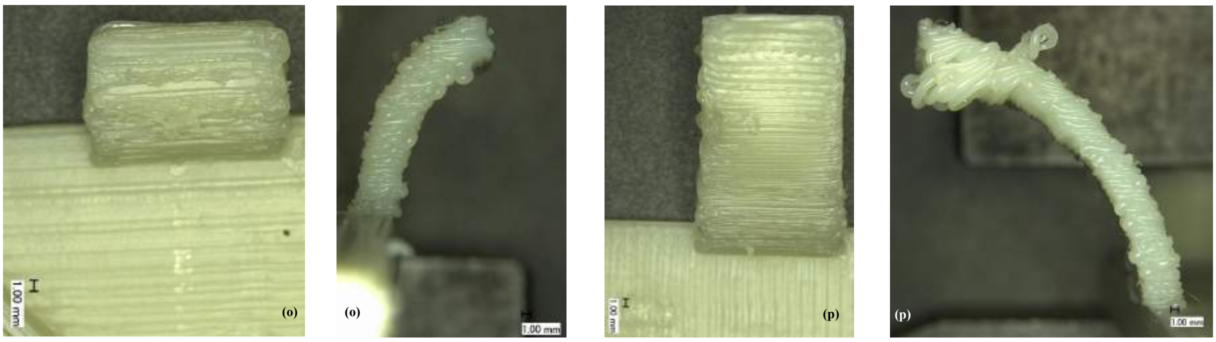
(k) Overhang 1 Prusa PLA HQ

(l) Overhang 2 Prusa PLA HQ



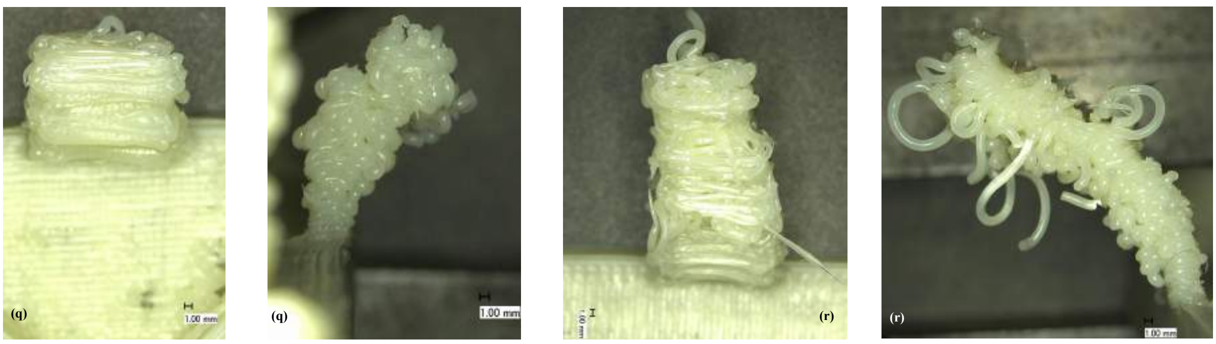
(m) Overhang 1 Prusa PLA SQ

(n) Overhang 2 Prusa PLA SQ



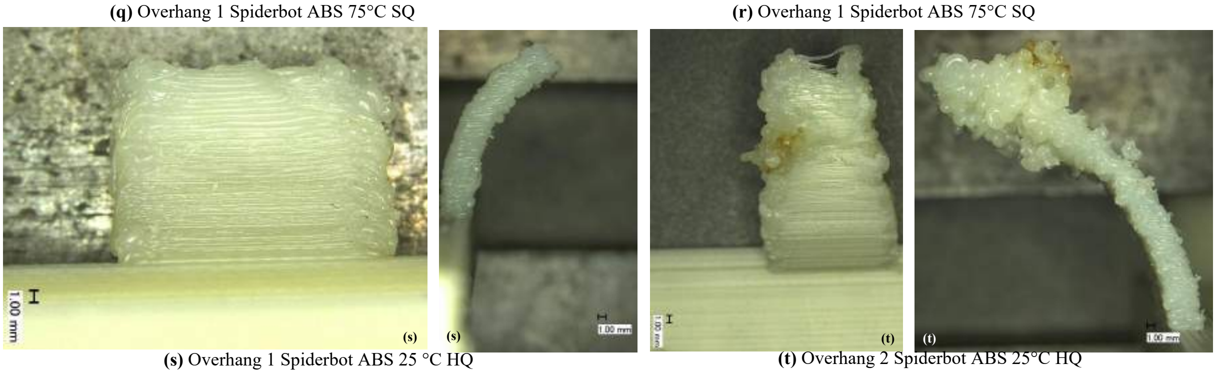
(o) Overhang 1 Spiderbot ABS 50°C SQ

(p) Overhang 2 Spiderbot ABS 50°C SQ



(q) Overhang 1 Spiderbot ABS 75°C SQ

(r) Overhang 1 Spiderbot ABS 75°C SQ



(s) Overhang 1 Spiderbot ABS 25 °C HQ

(t) Overhang 2 Spiderbot ABS 25°C HQ

Fig. 4.21 – Pictures showing in detail overhangs in the benchmark parts.

Based on the data collected with the SEM each of the two features for each part was evaluated (tab. 4.15) exploiting the rating scale described above. The best results were obviously obtained with the uPrint, the reference used to establish the rating scale values. Good also the behavior of the Prusa with the PLA. On the other hand, the remaining benchmarks, in particular for the second overhangs, showed poor or non-sufficient results. Finally, it is possible to state that, in general, all the printers seem to behave well for the manufacture of features that have an inclination of 45 degrees. The problems start to become consistent instead for inclinations greater than 45°, for which there is generally a lack of proper bonding between the layers.

	Prusa i3 MK3 PLA		**Prusa i3 MK3 ABS**		**Stratasys uPrint SE**		**Spiderbot HT 4.0**			
Features	SQ	HQ	SQ	HQ	SQ	HQ	SQ 25°C	SQ 50°C	SQ 75°C	HQ 25°C
Overhangs 1	1	2	2	2	2	2	1	1	0	1
Overhangs 2	1	2	0	0	2	2	1	1	0	0
Total	**2**	**4**	**2**	**2**	**4**	**4**	**2**	**2**	**0**	**1**

Tab. 4.15 – Overhangs evaluation of the various benchmark parts produced with different device under different printer settings (2=very good, 1=Satisfactory, 2=Poor, 0=Worst/Fail).

6.4.Warpage evaluation

The objective of this section is to do a qualitative evaluation of the warpage on the base for each benchmark part manufactured. No part is characterized by massive or compromising warping. As mentioned at the beginning of the chapter, indeed, for each benchmark parts, after several tests, the best printing conditions were individuated. Despite this, some pieces still have small deformations. Therefore, it was decided to evaluate all the parts assigned a score from 0 to 2, depending on the quality of the results (tab. 4.16). Also, for this classification the benchmark part taken as reference is the one manufactured by uPrint with the raft and high-quality printer settings. In particular, it will be assigned a score of:

- **2**, when there is no warping
- **1**, when there is warping, but this is limited to a single corner or edge
- **0**, there is warping in at least two different point of the part or the geometry of the figure to print is compromise.

	Prusa i3 MK3 PLA		Prusa i3 MK3 ABS		Stratasys uPrint SE		Spiderbot HT 4.0			
Features	SQ	HQ	SQ	HQ	SQ	HQ	SQ 25°C	SQ 50°C	SQ 75°C	HQ 25°C
Warping	1	1	1	0	2	2	1	2	0	0

Tab. 4.16 – Warping evaluation of the various benchmark parts produced with different device under different printer settings (2=very good, 1=Satisfactory, 2=Poor, 0=Worst/Fail).

With the exception of the parts made by the uPrint not many others can achieve a full score, not even the parts made in PLA by the Prusa, that until now have held discrete evaluations. In particular these parts do not show warping on the corners or sides of the component, but rather an accumulation of tensions in the center of part that make it warps. As can be partially seen in figure 4.22, the edges are perfectly adherent to the worktop, but the central part is slightly raised. Discreet results were registered also for the parts produced by the Spiderbot, in particular for the benchmark part printed at 50°C which does not have the slightest deformation.

Fig. 4.21 – Pictures showing in detail benchmark part warping. **(a)** Prusa PLA high quality part, **(b)** Spiderbot ABS standard quality 75°C, **(c)** Prusa ABS high quality

7.Qualitative and quantitative evaluation overall ranking

An attempt has been made to rank the benchmark parts according to a weighting of the performances with respect to the different features evaluated: accuracy, warping, thin features and overhangs. In the event of a tie in the scores in one of the assessed performances, the same score will be assigned to the two parts, reducing the ranking scale extension (tab. 4.17). Then depending on the ranking position for each group of performances evaluated a score from 1 to 10 will be awarded, 10 to the first classified and 1 to the last. Finally, it will find the average score weighted on the number of features belonging to each group for each benchmark part (tab. 4.18).

	Prusa i3 MK3 PLA		**Prusa i3 MK3 ABS**		**Stratasys uPrint SE**		**Spiderbot HT 4.0**			
Group of features	SQ	HQ	SQ	HQ	SQ	HQ	SQ 25°C	SQ 50°C	SQ 75°C	HQ 25°C
Accuracy	4	3	5	6	2	1	8	9	10	7
Thin feature	2	1	2	1	4	1	5	6	7	3
Overhangs	2	2	2	3	1	1	2	1	3	3
Warping	2	1	2	2	1	1	2	2	3	1

Tab. 4.17 – Ranking table of different benchmark parts taking into account the different performances measure and evaluated.

	Prusa i3 MK3 PLA		**Prusa i3 MK3 ABS**		**Stratasys uPrint SE**		**Spiderbot HT 4.0**			
Group of features	SQ	HQ	SQ	HQ	SQ	HQ	SQ 25°C	SQ 50°C	SQ 75°C	HQ 25°C
Accuracy	4,56	5,21	3,26	3,91	5,86	6,52	1,95	1,3	0,65	2,6
Thin feature	2,72	3,03	2,73	3,03	2,12	3,03	1,81	1,51	1,21	2,42
Overhangs	0,14	0,14	0,14	0,12	0,15	0,15	0,14	0,15	0,12	0,12
Warping	0,27	0,3	0,27	0,27	0,3	0,3	0,27	0,27	0,24	0,3
Total score	**7,69**	**8,68**	**6,4**	**7,33**	**8,43**	**10**	**4,17**	**3,23**	**2,22**	**5,44**

Tab. 4.17 – Total average score for each benchmark parts weighted on the number of features belonging to each group.

Obviously, the best part manufactured is the one made in high quality by the uPrint which, at least in terms of accuracy and overhangs, has been taken as a reference to evaluate the other benchmark parts manufactured. On the second and third position there are the benchmark part printed by the Prusa in high quality made of PLA and the other part manufactured by the uPrint, respectively. The last positions instead are occupied by the parts made by the Spiderbot.
However, from a customer point of view, consider only the geometric features could not be enough to provide the complete picture of the situation. Also, aspects like manufacturing time, post-processing time and printer reliability should take into account. In the following table, thus, in addition to the total score achieved by each part, the actual production time of the piece will be reported together with the post-processing time if present. As far as reliability is concerned, only the number of machine failures occurred during the production of the parts will be considered.

<table>
<tr><th>Printer</th><th>Material</th><th>Printer quality settings</th><th>Total score</th><th>Manufacturing time (h)</th><th>Post-processing time (h)</th><th>Number of machine failures</th></tr>
<tr><td rowspan="4">Prusa</td><td rowspan="2">PLA</td><td>standard quality</td><td>7,69</td><td>02:41</td><td rowspan="2">00:00</td><td rowspan="4">1</td></tr>
<tr><td>high quality</td><td>8,68</td><td>04:55</td></tr>
<tr><td rowspan="2">ABS</td><td>standard quality</td><td>6,4</td><td>02:48</td><td rowspan="2">00:00</td></tr>
<tr><td>high quality</td><td>7,33</td><td>04:50</td></tr>
<tr><td rowspan="2">uPrint</td><td rowspan="2">ABSplus</td><td>standard quality</td><td>8,43</td><td>02:13</td><td rowspan="2">03:56</td><td rowspan="2">0</td></tr>
<tr><td>high quality</td><td>10</td><td>03:12</td></tr>
<tr><td rowspan="4">Spiderbot</td><td rowspan="4">ABS</td><td>standard quality (25°C)</td><td>4,17</td><td>03:13</td><td rowspan="4">00:00</td><td rowspan="4">1</td></tr>
<tr><td>standard quality (50°C)</td><td>3,23</td><td>03:13</td></tr>
<tr><td>standard quality (75°C)</td><td>2,22</td><td>03:12</td></tr>
<tr><td>high quality</td><td>5,44</td><td>08:51</td></tr>
</table>

Tab. 4.18 – Benchmark parts manufacturing process overall evaluation.

Some additional consideration can now be done:

- As to the manufacturing time the parts produced by uPrint are those with the lowest producing times of the respective categories, standard quality and high quality. The result is even more surprising if we hold that the volume of extruded material from the Strasasys is greater than that extruded by the other printers, since in addition to the actual benchmark part, also raft and supports must be built. On the other hand, the printed parts with the uPrint are the only ones that require an extremely time-consuming post-processing.

- During the tests phase and the production of the benchmarks the Prusa and the Spiderbot broke down. In the first case the extruder clogged, in the second the extruder head has fallen from the magnetic supports, precipitating into the plate, damaging it immediately.
- The high-quality parts are always better compared to the corresponding standard quality printed part from the machine
- The higher quality is always accompanying by an increase in the manufacturing time that can more than double, as with the Spiderbot. The relationship between accuracy and production time is not constant but varies from machine to machine.
- As to the Prusa, the benchmark parts made of PLA are better in terms of accuracy than the parts made of ABS and require the same manufacturing time. The ABS on the other hand guarantees better mechanical properties and can be used at higher temperatures.

8.Comparison between data collect with Caliper and Profile Projector

As previously mentioned for some groups of features, in particular the holes H1-H3 (excluding H4) and the rectangular notches RN1-RN6, the accuracy measurements, as well as with the digital caliber, were also taken with the Nikon profile projector V-16-E with a measurement degree of 0.001mm. In the following subchapters a statistical analysis of the data will be presented first and then the comparison between these measurements and those taken with the caliper.

8.1.Statistical analysis

With the profile projector the measurements of the rectangular notches and the holes were detected, with the exception of H4 for which, due to its position, it was not possible to put the image in focus. For each feature 10 measurements were taken as it was done with the caliper. Therefore, a total of 900 were taken, 90 for each benchmark part (Appendix 2). Using the nominal value of each feature represented in tab. 4.10 it was possible to establish the probability of the machine for making features that fall within a particular range of dimensional percentage change. Then for each one of them, the percentage deviation from the nominal value was then measured and a frequency histogram was created (fig 4.22), as it was done for the caliper (fig. 4.13).

The bell-shaped curve not fairly fit the distribution of the collected data, although, probably, this mismatch is only due to the low number of taken measurements. In general, the tendency of a uniform shrinkage of the parts is confirmed and strengthened by these measurements. The mean now has a value of -12.239% compared to -0.138% calculated from the statistical analysis of the data taken with the caliber. although unfortunately, other considerations cannot be made since the number of the two samples measurements are completely different, not to mention that the measures taken with the profile projector concern only two particular groups of features. The dispersion of measurements instead (fig. 4.13) appears more extended, but also more homogenous between the different benchmark parts, than the data takes with the Caliper.

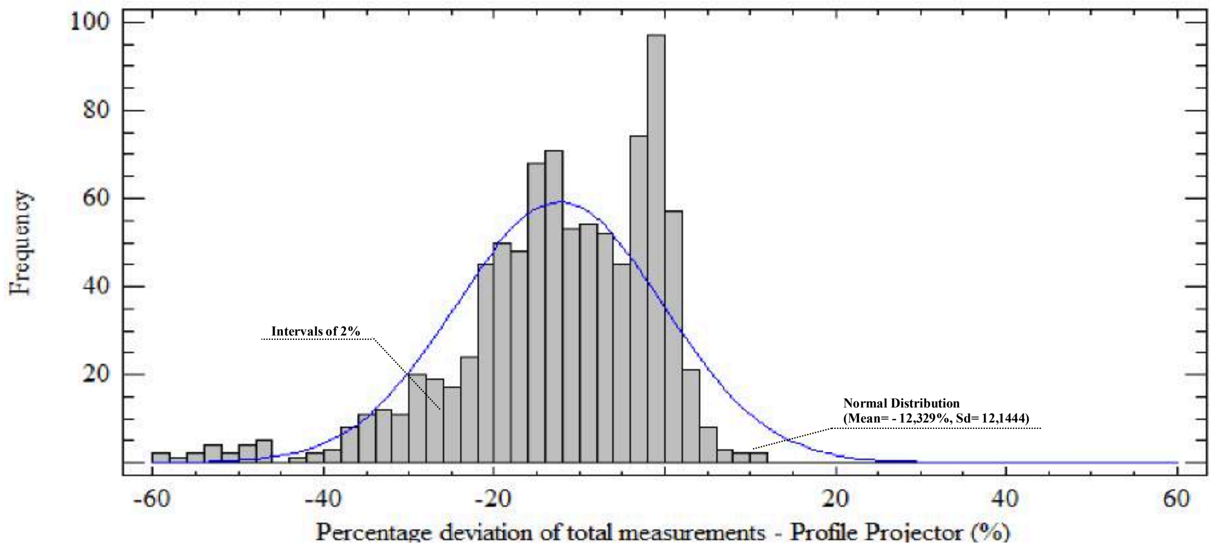


Fig. 4.22 – Distribution of the total Profile Projector measurements of percentage deviation.

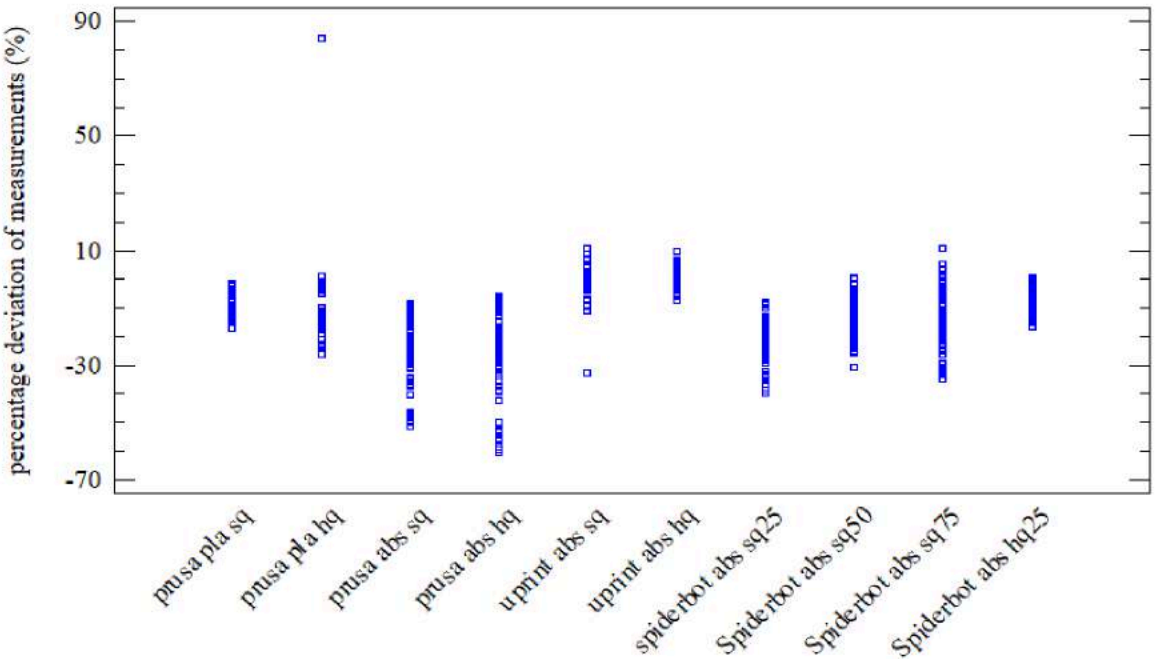


Fig. 4.23 – Scatter chart of total profile projector measurements percentage deviation divided according to the printer used to manufacture the benchmark part and the printer settings.

Finally, it should be emphasized that this probability was obtained from a different quantity of data N, compared to what was done with the caliper. The comparison should therefore always take into consideration that the results derive from a significantly different amount of data

8.2.International tolerance

Particularly interesting is the comparison between the data collected with the caliber and those collected with the profile projector in terms of IT grades tolerance. Using the equations shows in the subchapter 5.2, the maximum value *ni* among the set of measures obtained from the two group of features of the 10 parts is yielded and compared to result already obtained with Caliper (fig 4.24).

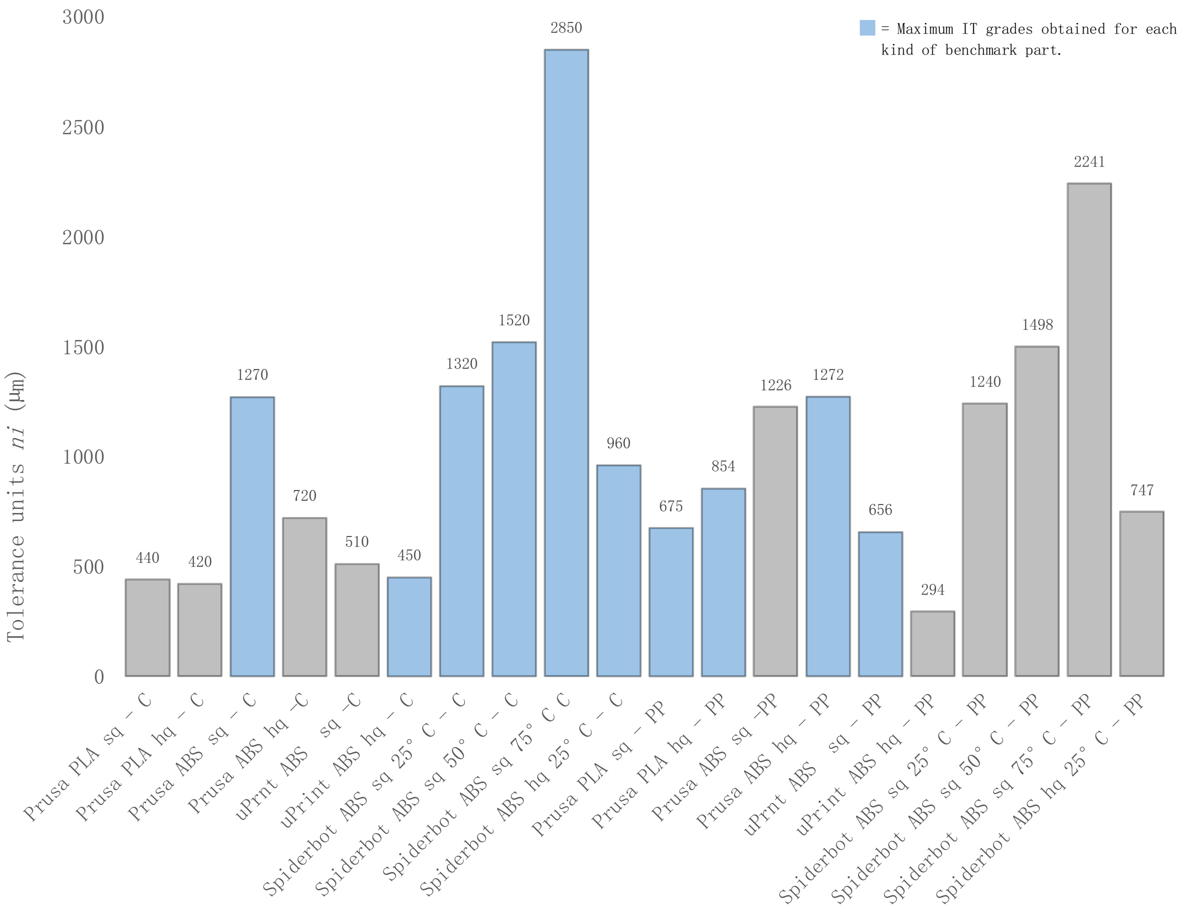


Fig. 4.24 – Comparison of the maximum tolerance grades achieved on 10 benchmark parts taking into account two different measurement tools. (C= Caliper, PP= Profile Projector)

In most cases the results obtained with the profilometer tend to confirm the results obtained with the gauge, even if the measurements taken with the caliber seem to be closer to the nominal value of those taken with the profilometer, except for the two parts printed in high quality with the Prusa in ABS and PLA. Both of these parts have a maximum tolerance grades level that is almost the double compared to the data collected with the caliber, making the accuracy achievable with the Prusa very similar to that obtained with the Spiderbot. The parts produced by the Stratasys always remain the best, with the maximum it grades obtained from the high-quality printed piece that is even almost halved.

8.3.Accuracy evaluation

The method proposed in chapter 5.1 for measurements processing has been put forth again with the same evaluation scoring adopt before and illustrate in table 4.12. The results are shown in table 4.19 below.

	Prusa i3 MK3 PLA		Prusa i3 MK3 ABS		Stratasys uPrint SE		Spiderbot HT 4.0			
Features	SQ	HQ	SQ	HQ	SQ	HQ	SQ 25°C	SQ 50°C	SQ 75°C	HQ 25°C
H1	2	3	0	0	5	5	0	0	0	0
H2	2	4	0	0	4	5	0	0	0	0
H3	3	3	0	0	4	5	0	0	0	0
RN1	0	0	0	0	4	5	0	0	0	0
RN2	0	0	0	0	0	5	0	0	0	0
RN3	0	0	0	0	5	5	0	2	0	4
RN4	0	0	0	0	5	5	0	0	0	0
RN5	0	0	0	0	4	5	0	0	1	3
RN6	0	0	0	0	5	5	0	0	0	0
Total PP	**7**	**10**	**0**	**0**	**36**	**45**	**0**	**2**	**1**	**7**
Total C	**27**	**29**	**15**	**10**	**27**	**45**	**7**	**3**	**5**	**25**

Index: **Total PP**: total score of measures taken with the profile projector **Total C**: total score of measures taken with the profile projector

Tab. 4.19 – Comparison of the various EAM equipment based on the fabrication of the geometric benchmark part under different printer settings (5=very good, 4=Good, 3=Satisfactory, 2=Poor, 1=Worst, 0=Fail).

The trend of the data collected with the profile projector seems to follow the trend traced by the data collected with the caliber. The highest scores were totalized by the parts produced with the industrial printer, in a completely analogous way to what was found with the caliber. On the second and third place as before we find the Prusa with its PLA parts. In this analysis the only exception occurs for the positions in the ranking, however that are no longer occupied by the parts produced by the Spiderbot but by those manufactured by the Prusa in ABS. The divergence in the results of the data in the latter case is attributable to the strategy used with Prusa for the manufacturing of the printed parts first layer. This layer, especially when the heated printing chamber is missing as in our case, is generally extruded at higher temperatures, with wider layers and with excess of extruded material, so as to favor a better adhesion to the print bed. However, the main drawback to this strategy is the possibility that this excess of material extruded at higher temperature come out the position where the layer was deposited going slightly over the others, or in case of the outer edges layers, overflowing beyond the defined geometry of the parts base, resulting with those crushed effect also visible in figure 4.25. Therefore, the first larger layer that is always detected by the profile projector, detecting the latter the projection of our piece, but not always by the caliber instead, and whose measurements are closely related to where the jaws are supported

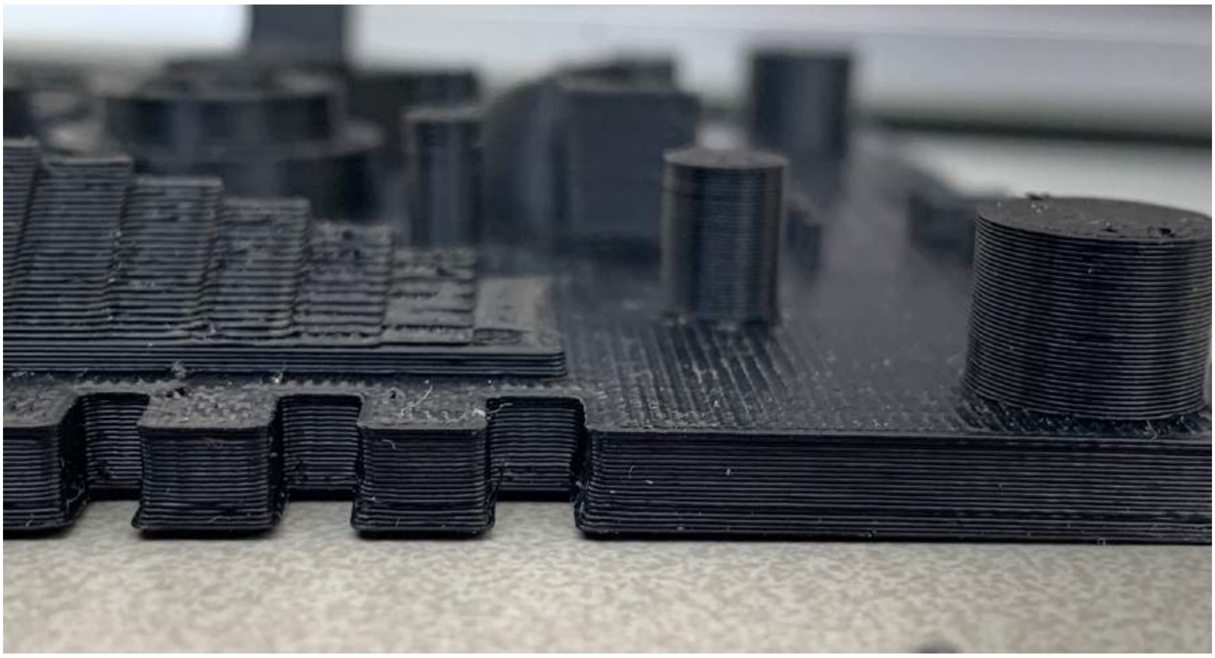


Fig. 4.25 –Detail of the first layer of the ABS benchmark part printed in standard quality with Prusa.

9.Direct cost analysis

In this section the building cost of the benchmarking parts will be computed, based on 3 aspects:

- Filaments cost, F_{cost}

- EAM equipment running cost. This cost takes into account the depreciation/usage of machine, electricity, maintenance, and other overhead cost in part fabrications stage. It can be estimated based on the part fabrication time and the machine running rate.
- Post-processing cost

9.1.Filaments cost

The material cost can be divided into two items: the cost for the part building and the cost for building the support structure, as follows:

$$F_{cost} = V_{bp} * C_{bm} + V_{ss} * C_{sm}$$

Where V_{bp} and V_{ss} represent the volume of the part and the external support respectively, while C_{bm} and C_{sm} denotes the unit price of the part material and support material. The data provided by the slicing software was taken as reference for the volume, neglecting the minimal difference between prediction and material actually used because not relevant for the purpose of analysis. For each printed benchmark part, the total material cost was then calculated as illustrated in tab. 4.20. The price of the material used by the Stratasysy is about 10 times more expensive than the other materials used for the other benchmarks, so it is not surprising the difference between the parts manufactured by the Stratasys and the others.

Printer	Quality settings	Material (brand)	Support material	Total material costs (€)
Prusa	standard quality	PLA (ICE)	-	6,27
	high quality			6,25
	standard quality	ABS (ICE)		6,89
	high quality			6,87
uPrint	standard quality	ABS-P430XL (Stratasys)	SR-30XL (Stratasys)	63,66
	high quality			36,88
Spiderbot	standard quality 25°C	ABS (ICE)	-	6,2
	standard quality 50°C			6,2
	standard quality 75°C			6,2
	high quality			6,8

Tab. 4.20 – Total material cost for each printed benchmark parts.

9.2.EAM equipment running cost

The machine running cost R_{mc} was calculated based on the equations illustrated by Xu *et all.* [103] for a given part can be evaluated based on the machine running rate and the fabrication time. The former reflects the capital cost of an EAM equipment, power consumption, labor cost, maintenance cost, and other overheads in the machine running. The latter was calculated during the manufacturing of the part.

The machine running rate can be computed using the following equation:

$$M_{rr} = (1 + o_{op}) * w_o + (1 + o_{mch}) * \frac{P_{mch}}{8760 * T_{mch}}$$

Where:

- o_{op} and o_{mch} are the overhead costs of the operator and the machine, respectively
- w_o is hourly salary of the operator
- P_{mch} is the original cost of the EAM equipment
- T_{mch} is the amortization period

Realistically assumed that the hourly wage is 15€, the amortization period is three years, operator overhead is 100% and machine overhead is 150%. Given then the machine running rate, the running cost for a specific part can be computed based on the real fabrication time t_f, as follows:

$$R_{mc} = t_f * M_{rr}$$

The result are presented in the following table 4.21.

Printer	Quality settings	Machine cost (€)	Machine running rate (€/h)	Fabrication time (h)	Machine running cost (€/part)
Prusa	standard quality	999	30,09503425	02:41	72,53
	high quality		30,09503425	04:55	136,93
	standard quality		30,09503425	02:48	74,64
	high quality		30,09503425	04:50	135,43
uPrint	standard quality	19000	31,80745814	02:13	67,75
	high quality		31,80745814	03:12	99,24
Spiderbot	standard quality 25°C	8000	30,76103501	03:13	96,28
	standard quality 50°C		30,76103501	03:13	96,28
	standard quality 75°C		30,76103501	03:12	95,97
	high quality		30,76103501	08:51	261,78

Tab. 4.21 – Machine hourly running rate and cost per part.

9.3.Post processing cost

The cost in the post processing stage is related to the complexity of post-processing work, the equipment, the electricity consumed and the labor cost. In our case only the parts printed with the Stratasys have undergone post-processing manufacturing. Using the same equation and assumptions than before considering the price of the ultrasonic heater EMAG Emmi D-60 equal to 850 € [125] it is possible to calculate the post-processing cost as illustrated in table 4.22.

Printer	Quality settings	Post-processing machine cost (€)	Machine running rate (€/h)	Post-processing time (h)	Machine running cost (€/part)
Prusa	standard quality	-	.	-	-
	high quality				
	standard quality				
	high quality				
uPrint	standard quality	850	30,06468798	03:56	107,03
	high quality				
Spiderbot	standard quality 25°C	-	.	-	-
	standard quality 50°C				
	standard quality 75°C				
	high quality				

Tab. 4.22 –Post-processing hourly running rate and cost per part

Once all the costs have been sorted out it is possible to collect them as shown in table 4.23 to get a complete picture of the situation.

Printer	Quality settings	Material cost (€/part)	Printer running cost (€/part)	Post-processing cost (€/part)	Total cost (€/part)
Prusa	standard quality	6,27	72,53	-	78,80
	high quality	6,25	136,93		143,18
	standard quality	6,89	74,64		81,53
	high quality	6,87	135,43		142,30
uPrint	standard quality	63,66	67,75	107,03	238,44
	high quality	36,88	99,24	107,03	243,15
Spiderbot	standard quality 25°C	6,2	96,28	-	102,48
	standard quality 50°C	6,2	96,28		102,48
	standard quality 75°C	6,2	95,97		102,17
	high quality	6,8	261,78		268,58

Tab. 4.22 –Benchmark parts manufacturing cost analysis

Conclusion

The final chapter of this thesis concludes the study by discussing the main contributions of the research. The implication of the study and the future directions of research are provided.

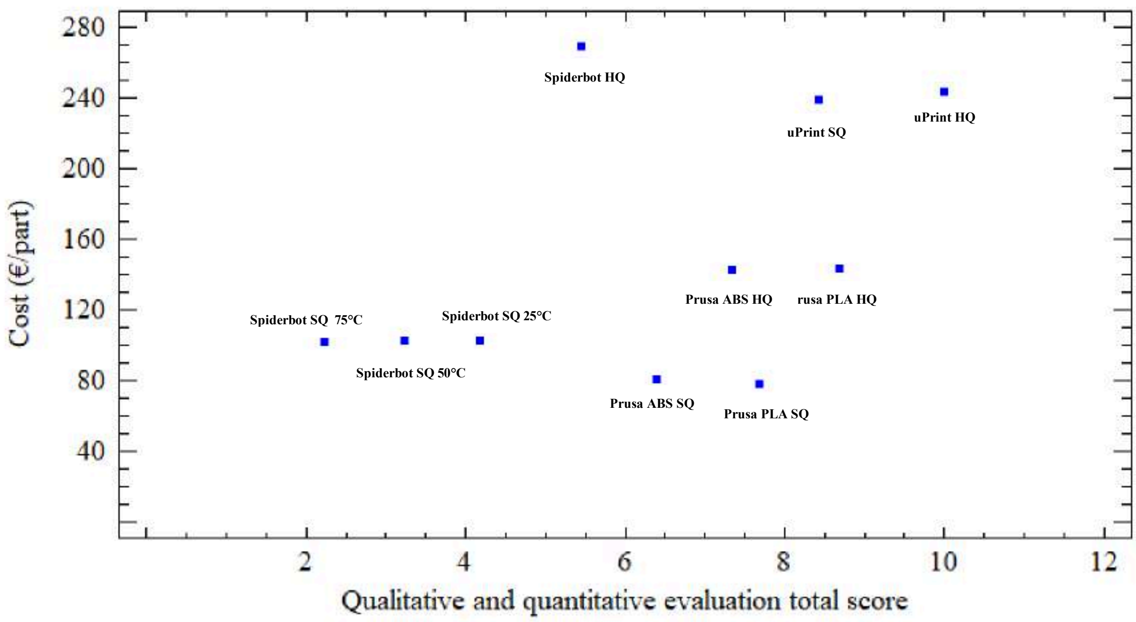
The objectives set out in the introduction of the thesis have been fulfilled. After a general overview on additive technologies with a particular focus on the extrusion process the state of art of the benchmark parts has been presented. The first objective then was achieved developed a new benchmark part with a greater number of measurable features than all the parts designed in the literature up to now. Moreover, it also has a shorter printing time than the comparable artifacts. For instance, at the same printing settings and EAM equipment the printing time is 27% and 38% lower than that employed for manufacturing the benchmark part developed by the NIST and by Minetola et all. respectively. The objective, quick and complete performance measurement and the quality standards setting is a fundamental step to check the progress and measure the degree of success of a technology, in particular when it comes to technologies, not so new, but certainly in continuous development and evolution.

Finally, the second objective, the comparison between a low-end, medium-end and high-end 3D printer, was achieved through the new developed benchmark part manufacturing, the measurement of the same and the comparison between the different performances of each machine through a sort of Round Robin test involving not different scientist, but only different measurement systems. In addition to geometric terms, the comparison was also carried out in qualitative terms on some special features and in terms of direct costs. Moreover, exploiting the results obtains, the three additive manufacturing equipment was compared with other common manufacturing technologies.

Specifically, as can be seen in figure 4.23, the parts that record the most expensive total cost are the high-quality models of the Spiderbot followed by the two parts printed with the uPrint in HQ and SQ respectively. In general, it can be stated that the higher the manufacturing plus the post-processing time, the higher the total cost as illustrated in figure highlighting how the direct labor cost of the technical staff assigned to the EAM equipment are mostly affected the final result that constituted a percentage that varies from 94 to 99.8% overall. In this regard, however, it should be emphasized for the sake of completeness that an operator can simultaneously deal with a number *n* of machines, where *n* is greater, the greater the EAM equipment reliability.

It is also interesting to pointed out the spot occupied in the graph by the benchmark parts manufactured by the Spiderbot, the medium-end printer, that instead should have been placed

between those printed with the Stratasys and the Prusa both in terms of quality and costs. These position is probably due to the rigidity of the machine that was which has been designed and optimized to print exclusively PEEK and PEI and no other materials.
Future research should try to expand the field of tested additive manufacturing technologies. A comparison that should be expanded not only in purely technological terms, but also as concerned materials. As it was pointed out in the previous chapters it is possible to print almost anything from food to metals, but without shared reference standards the advantages of this technology would risk remaining limited to the main market players, counteracting their widespread use.



Tab. 4.23 – Benchmark parts cost – performance scatter chart

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Appendix 1

The benchmark part feature measurements collected with the digital caliper.

	Benchmark part measurements Prusa PLA standard quality (mm)									
Circumference (diameter)1	19,86	19,81	19,79	19,9	19,89	19,88	19,99	20	19,91	19,88
Circumference (diameter)2	14,94	14,98	14,99	15	14,94	14,92	14,97	14,97	14,97	14,82
Circumference (diameter)3	4,1	4,13	4,05	3,97	4,06	4,05	4,05	4,09	3,98	4,03
Circumference (diameter)4	5,78	5,92	5,88	6	6,07	6,03	5,98	6,01	5,83	6,09
Circumference (diameter)5	10,07	9,96	10	9,96	9,91	10,01	10,03	10,06	9,98	9,85
Circumference (diameter)6	4,01	4,05	3,94	3,93	3,98	4	4,02	4,06	3,87	4,08
Circumference (diameter)7	5,93	5,75	5,98	5,96	5,96	6,02	5,99	5,89	5,92	5,95
Circumference (diameter)8	9,77	9,97	9,98	9,92	10,02	10,1	10,03	9,89	9,79	9,91
Circular hole 1	9,7	9,73	9,73	9,75	9,85	9,76	9,82	9,68	9,72	9,62
Circular hole 2	3,63	3,65	3,66	3,7	3,77	3,64	3,66	3,68	3,68	3,77
Circular hole 3	5,81	5,81	5,79	5,68	5,6	5,78	5,82	5,83	5,75	5,8
Circular hole 4	5,76	5,89	5,76	5,78	5,77	5,84	5,83	5,87	5,74	5,67
Rectangular notch 1	1,45	1,46	1,43	1,42	1,44	1,46	1,46	1,48	1,41	1,45
Rectangular notch 2	1,93	1,94	1,94	1,95	1,95	1,91	1,92	1,94	1,96	1,92
Rectangular notch 3	2,4	2,42	2,44	2,41	2,42	2,43	2,41	2,44	2,44	2,44
Rectangular notch 4	2,92	2,9	2,94	2,92	2,92	2,88	2,84	2,92	2,88	2,92
Rectangular notch 5	3,35	3,41	3,4	3,33	3,37	3,43	3,38	3,09	3,39	3,41
Rectangular notch 6	3,83	3,92	3,93	3,91	3,9	3,94	3,93	3,91	3,92	3,91
Square Base 1 a	4,01	3,99	4,02	4,13	4,08	4,11	4,05	4,11	4,01	3,99
Square base 2 a	5,9	5,93	5,95	6,03	6,05	6,01	6,09	6,07	5,92	5,94
Square Base 3 a	10,02	9,93	9,97	9,96	10,01	10,06	10,05	10,02	10,02	10,03
Square Base 1 b	4,02	4	4,08	4,07	4,06	4,03	4,03	4,05	4	3,99
Square base 2 b	5,91	5,94	5,95	5,98	5,99	5,96	6,02	5,97	5,92	5,9
Square Base 3 b	9,96	9,94	9,93	10	9,96	9,97	10	10,02	9,97	9,92
Negative Staircase H 1	6,96	7,03	6,96	6,98	7,03	6,99	7	6,97	7,01	7
Negative Staircase H 2	6,05	6,01	6,06	6,11	6,06	6,11	6,02	6,01	6,07	6
Negative Staircase H 3	4,13	4,07	4,02	4,07	4,03	4,01	4,03	4,05	4,02	4
Negative Staircase H 4	5,03	4,99	5,05	5	5,03	5,01	4,99	5	5,04	5,01
Negative Staircase H 5	3,01	2,98	3,02	3,1	2,99	3,03	3,02	3,01	3,08	3,01
Positive Staircase H 1	3,14	3,01	3,01	3,01	3,1	3,11	3	3,01	3,02	3,12
Positive Staircase H 2	5,02	5,02	5,05	5,02	5,09	4,97	5,04	5,04	5,03	5,13
Positive Staircase H 3	6,9	6,97	6,95	7,02	7,04	6,98	7,07	7	7,04	7,02
Positive Staircase H 4	6,02	5,98	6,01	6,05	6,06	6	6,01	6,05	6,02	5,99
Positive Staircase H 5	4,1	4,15	3,98	4,08	3,99	4,06	4,18	4,12	4,08	4,06
Wall 1	2,1	1,97	1,98	1,96	2	1,99	1,99	1,99	1,95	2,01
Base feature height 1	4,01	4,02	4,09	4,03	4,03	4,14	4,11	4,03	4,11	4,03
Base feature height 2	4,1	4,06	4,07	4,1	4,05	4,06	4,08	4,07	4,09	4,08
Base feature height 3	4,06	4,08	4,08	4,07	4,06	4,05	4,06	4,06	4,06	4,08
Base feature height 4	4,08	4,1	3,99	4,04	3,97	3,98	4,04	4,03	3,99	3,97
Base feature width 1	99,76	99,78	99,78	99,74	99,66	99,69	99,73	99,74	99,77	99,79
Base feature width 2	99,69	99,69	99,7	99,68	99,69	99,65	99,69	99,74	99,75	99,74
Base feature width 3	99,61	99,62	99,59	99,57	99,56	99,57	99,63	99,65	99,64	99,64
Base feature width 4	99,77	99,75	99,75	99,74	99,68	99,8	99,67	99,72	99,78	99,78

	Benchmark part measurements Prusa PLA – standard quality (mm)									
Circumference (diameter)1	19,81	19,89	19,8	19,86	19,96	19,88	19,94	19,84	19,78	19,79
Circumference (diameter)2	14,8	14,87	14,85	14,91	14,95	14,93	14,93	14,92	14,94	14,95
Circumference (diameter)3	4	4,08	4,04	4,05	4,06	3,99	4,04	4,07	4,01	3,99
Circumference (diameter)4	5,97	5,93	5,96	5,98	6,04	6,02	5,99	6,05	5,94	5,89
Circumference (diameter)5	9,98	9,97	9,7	10,01	9,98	9,97	10,02	9,95	9,96	9,95
Circumference (diameter)6	3,93	3,94	3,96	3,93	3,98	4	3,96	3,98	3,94	3,95
Circumference (diameter)7	5,91	5,93	5,94	5,95	5,91	5,95	5,95	5,94	5,93	5,94
Circumference (diameter)8	9,99	9,95	9,96	9,93	9,94	10	10	9,96	9,9	9,93
Circular hole 1	9,89	9,75	9,83	9,81	9,72	9,78	9,65	9,86	9,73	9,79
Circular hole 2	3,83	3,81	3,87	3,83	3,88	3,78	3,85	3,83	3,72	3,85
Circular hole 3	5,88	5,79	5,81	5,88	5,75	5,85	5,78	5,89	5,82	5,81
Circular hole 4	5,9	5,69	5,87	5,81	5,8	5,6	5,62	5,92	5,77	5,94
Rectangular notch 1	1,5	1,44	1,46	1,52	1,44	1,35	1,41	1,35	1,38	1,35
Rectangular notch 2	1,91	1,92	1,93	1,92	1,87	1,96	1,98	1,96	1,95	1,9
Rectangular notch 3	2,4	2,49	2,41	2,44	2,41	2,42	2,39	2,41	2,42	2,4
Rectangular notch 4	2,93	2,96	2,99	2,95	2,93	2,92	2,9	2,9	2,91	2,9
Rectangular notch 5	3,36	3,4	3,4	3,42	3,41	3,44	3,38	3,43	3,51	3,43
Rectangular notch 6	4	3,98	4,01	3,98	3,87	4,03	3,92	3,89	3,9	3,92
Square Base 1 a	4,02	4,03	4,01	4,04	4,04	4,07	4,05	4,04	4,03	4,03
Square base 2 a	5,95	5,96	6	6,07	6,08	6,06	6,04	6,03	5,97	5,98
Square Base 3 a	9,96	9,95	10,01	9,95	10,02	10,1	10,03	10	10	9,97
Square Base 1 b	4,01	4,03	4,02	4,03	4,02	4,02	4,01	4,02	4,02	4,01
Square base 2 b	5,96	5,96	5,97	5,99	5,97	5,99	6,01	6	5,94	6
Square Base 3 b	9,97	9,98	9,97	10,01	9,98	9,96	9,99	9,94	9,96	10
Negative Staircase H 1	7,08	7,02	7	7,04	7,12	7,06	7,06	7,12	7,04	7,07
Negative Staircase H 2	6,04	6,02	6,01	6,03	6,02	6,02	6,02	6,02	6,07	6,02
Negative Staircase H 3	4,02	4	3,99	4,04	4,01	4,01	4,01	4,03	4,02	4,02
Negative Staircase H 4	5,04	5,02	5,06	5,04	5,02	5,05	5,04	5,06	5,03	5,05
Negative Staircase H 5	3,07	3,04	3,06	3,05	3,04	3,04	3,03	3,05	3,04	3,08
Positive Staircase H 1	3	2,99	2,98	3	2,96	3,02	3,01	3,08	3,04	3,02
Positive Staircase H 2	5,01	5,07	5,08	5,12	5,03	5,08	4,98	5,03	5,02	4,95
Positive Staircase H 3	6,98	7,01	6,96	7,05	6,97	7,03	7,03	7,03	7,05	7,05
Positive Staircase H 4	6,04	5,97	6,01	5,94	5,95	5,96	6,04	6,04	6,11	6,13
Positive Staircase H 5	4,06	4,01	3,99	4,07	4,13	3,99	4,08	3,91	3,94	4,09
Wall 1	2,03	1,94	2	2,01	1,97	2,02	1,93	1,98	2,04	1,99
Base feature height 1	4,01	4,03	4,02	4,01	4,02	4,02	4,06	4,04	4,07	4,07
Base feature height 2	4,06	4,07	4,07	4,06	4,07	4,07	4,05	4,07	4,09	4,06
Base feature height 3	4,06	4,04	4,04	4,07	4,03	4,04	4,06	4,03	4,06	4,06
Base feature height 4	4,06	4	3,97	4,03	4,05	4,01	3,98	3,96	3,99	4
Base feature width 1	99,89	99,94	99,74	99,81	99,79	99,81	99,73	99,83	99,77	99,84
Base feature width 2	99,72	99,84	99,8	99,76	99,83	99,84	99,83	99,83	99,8	99,78
Base feature width 3	99,58	99,6	99,8	99,64	99,76	99,69	99,66	99,67	99,72	99,71
Base feature width 4	99,78	99,81	99,88	99,72	99,81	99,74	99,78	99,75	99,85	99,73

	Benchmark part measurements Prusa ABS – standard quality (mm)									
Circumference (diameter)1	19,82	19,91	19,93	19,77	19,8	19,82	19,73	19,73	19,82	19,85
Circumference (diameter)2	14,99	15,05	14,95	15,15	14,82	14,94	14,97	14,95	15,07	15,08
Circumference (diameter)3	4,13	4,1	4,12	4,19	4,13	4,1	4,11	4,11	4,1	4,11
Circumference (diameter)4	6,07	6,04	6,03	6,08	6,08	6,13	6,04	6,11	6,08	6,04
Circumference (diameter)5	10,11	10,02	10,01	10,17	9,97	9,94	10,18	10,15	10,08	10,11
Circumference (diameter)6	4,13	4,13	4,17	4,19	4,16	4,18	4,14	4,4	4,15	4,16
Circumference (diameter)7	6,03	6,06	5,99	6,08	6,08	6	6,05	5,95	6,01	6,02
Circumference (diameter)8	9,9	10,06	10,02	10,03	10,08	10,1	10,05	9,94	10,08	9,96
Circular hole 1	9,45	9,68	9,25	9,38	9,4	9,48	9,44	9,45	9,47	9,39
Circular hole 2	3,72	3,53	3,55	3,68	3,77	3,68	3,73	3,69	3,64	3,68
Circular hole 3	5,63	5,73	5,68	5,68	5,22	5,25	5,48	5,36	5,48	5,78
Circular hole 4	5,68	5,87	5,72	5,8	5,76	5,92	5,78	5,64	5,8	5,95
Rectangular notch 1	1,44	1,41	1,47	1,38	1,33	1,45	1,47	1,48	1,32	1,21
Rectangular notch 2	1,97	1,85	1,93	1,9	1,87	1,98	1,9	1,97	1,96	1,87
Rectangular notch 3	2,4	2,42	2,39	2,41	2,33	2,3	2,45	2,48	2,35	2,4
Rectangular notch 4	2,83	2,2	2,77	2,55	2,79	2,79	2,84	2,9	2,83	2,93
Rectangular notch 5	3,37	3,29	3,32	3,12	3,4	3,14	3,41	3,43	3,42	3,26
Rectangular notch 6	3,95	3,2	3,99	3,9	3,97	3,93	3,77	3,73	3,64	3,74
Square Base 1 a	4,07	4,05	4,1	4,11	4,06	4,11	4,17	4,11	4,05	4,11
Square base 2 a	6,01	6,03	5,98	6,17	6,21	6,17	6,1	6,01	5,97	5,99
Square Base 3 a	9,99	10,32	10,38	10,45	10,39	10,3	10,24	10,26	10,5	10,33
Square Base 1 b	4,16	4,1	4,09	4,19	4,26	4,14	4,19	4,18	4,1	4,17
Square base 2 b	6,04	6,07	6,27	6,33	6,3	6,29	6,18	6,13	6,05	6,1
Square Base 3 b	10,13	10,42	10,32	10,64	9,97	10,21	10,28	10,24	10,16	10,12
Negative Staircase H 1	6,93	6,94	7,03	7,07	6,97	6,94	6,94	6,96	6,95	7,01
Negative Staircase H 2	6,04	5,97	5,98	5,99	5,91	5,92	5,92	5,89	5,91	5,99
Negative Staircase H 3	3,95	3,95	3,96	3,97	3,9	3,96	3,96	3,94	3,92	3,95
Negative Staircase H 4	4,96	4,95	4,97	4,94	4,97	4,96	4,96	5,02	4,98	4,98
Negative Staircase H 5	2,93	2,95	2,84	2,96	2,93	2,92	2,94	2,92	2,94	2,9
Positive Staircase H 1	3,09	3,02	3,07	3,07	3,11	2,94	2,93	3,08	3,01	2,99
Positive Staircase H 2	5	5,14	5,03	5,18	5,15	5	5,1	5,03	5,01	5,11
Positive Staircase H 3	7,12	7,02	7,1	7,09	6,99	7,02	7,04	7,12	7,14	6,99
Positive Staircase H 4	6,12	6,16	6,15	6,12	6,07	6	5,97	6,06	6,1	6,06
Positive Staircase H 5	4,07	4,07	4,07	4,19	4,05	4,11	4,09	4,03	4,08	3,97
Wall 1	2,05	2,2	2,12	2,16	2,08	2,14	2,05	2,1	2,05	2,08
Base feature height 1	3,9	3,9	3,94	3,92	3,9	3,88	3,98	3,95	4,05	4,08
Base feature height 2	3,94	3,82	3,96	3,96	3,84	3,86	3,93	3,98	3,86	3,94
Base feature height 3	4,22	3,97	3,98	3,99	4,03	4,07	4	3,99	4,05	4,09
Base feature height 4	3,83	3,84	3,87	3,87	3,88	3,9	3,9	3,91	3,92	3,86
Base feature width 1	99,66	99,43	99,38	99,46	99,52	99,4	99,41	99,51	99,36	99,41
Base feature width 2	99,79	99,82	99,84	99,82	99,88	99,86	99,8	99,89	99,73	99,77
Base feature width 3	99,73	99,79	99,46	99,56	99,45	99,44	99,69	99,7	99,69	99,63
Base feature width 4	99,53	99,7	99,58	99,05	99,04	99,35	99,62	99,4	99,47	99,65

	Benchmark part measurements Prusa ABS – high quality (mm)									
Circumference (diameter)1	19,84	19,94	19,98	19,95	19,94	20,01	19,93	19,95	20	19,89
Circumference (diameter)2	14,96	14,92	14,99	15	14,98	14,98	14,92	14,92	14,96	14,98
Circumference (diameter)3	4,03	4,08	4,02	4,05	4,06	4,02	4,01	4,05	4,06	3,96
Circumference (diameter)4	6,06	6,03	6,03	6	6,04	6,06	6,04	6,02	6	6,01
Circumference (diameter)5	9,98	10,04	10,05	10,06	10,03	10,04	10,03	10,03	10,07	9,99
Circumference (diameter)6	4,01	4,03	4	3,96	4,02	3,95	4,03	4,05	4,03	3,97
Circumference (diameter)7	5,87	6	5,93	6,06	6,01	6,07	6,02	6,07	5,95	6,06
Circumference (diameter)8	10,01	9,9	10,1	9,96	10,02	10,01	10,01	10	9,97	9,98
Circular hole 1	9,46	9,53	9,28	9,7	9,52	9,45	9,65	9,53	9,76	9,32
Circular hole 2	3,67	3,69	3,46	3,68	3,75	3,69	3,53	3,57	3,4	3,55
Circular hole 3	5,74	5,68	5,41	5,79	5,6	5,59	5,49	5,76	5,64	5,62
Circular hole 4	5,93	5,6	5,83	5,82	5,45	5,49	5,85	5,83	5,96	5,46
Rectangular notch 1	1	1,06	1,05	1,07	1,08	1,09	1,25	1,27	1,33	0,99
Rectangular notch 2	1,9	1,85	1,68	1,82	1,65	1,63	1,78	1,68	1,62	1,79
Rectangular notch 3	2,22	2,25	2,23	2,38	2,25	2,25	2,26	2,23	2,23	2,24
Rectangular notch 4	2,8	2,77	2,77	2,8	2,8	2,78	2,78	2,75	2,96	2,53
Rectangular notch 5	3,16	3,23	3,3	3,3	3,13	3,17	3,3	3,15	3,47	3,22
Rectangular notch 6	4	3,61	3,86	3,61	3,55	3,86	3,61	3,68	3,71	3,78
Square Base 1 a	4,14	4,13	4,06	4,15	4,12	4,18	4,17	4,2	4,07	4,06
Square base 2 a	6	6,03	6,04	6,18	6,11	6,07	6,02	6,01	6,1	6,08
Square Base 3 a	10,15	9,75	9,9	10,13	10,04	10,28	10,43	10,03	10,16	10,16
Square Base 1 b	4,12	4,05	4,18	4,15	4,11	4,07	4,13	4,08	4,11	4,1
Square base 2 b	6,06	6,16	6,08	6,04	6,02	6,03	6,06	6,05	6,06	6,02
Square Base 3 b	10,05	10,02	10,03	10,08	10,01	10,03	10,12	10,02	10,04	10,11
Negative Staircase H 1	6,96	6,96	6,95	6,99	6,96	6,95	7	7,01	7,01	6,94
Negative Staircase H 2	6,11	6,05	6,13	6,09	6,05	6,11	6,02	6,02	6,05	6,02
Negative Staircase H 3	4,1	4,13	4,04	4,13	4,06	4,02	4,03	4,06	4,08	4,05
Negative Staircase H 4	5	5,07	5,06	5,1	5,01	4,99	4,99	4,97	5,01	4,98
Negative Staircase H 5	3	3	3	2,98	3,03	2,98	3,07	3,06	3,05	3,01
Positive Staircase H 1	3,05	3	3,02	2,98	2,96	3	3	2,97	2,99	2,94
Positive Staircase H 2	5,01	4,96	4,97	4,98	4,95	4,93	4,98	4,96	4,95	5
Positive Staircase H 3	6,99	7,01	7	6,94	6,93	6,9	6,91	6,92	6,94	6,87
Positive Staircase H 4	5,94	6,11	6,13	6,01	5,98	5,9	6,15	6	6,05	5,96
Positive Staircase H 5	3,9	3,93	4,05	4,09	3,99	3,92	4,01	4,04	3,9	4,1
Wall 1	2,01	2,12	2	1,99	2,06	2,03	2,07	2,04	2,04	2,06
Base feature height 1	3,81	3,9	3,84	3,82	3,83	3,83	3,85	3,92	3,87	3,85
Base feature height 2	3,9	3,87	3,86	3,86	3,88	3,86	3,84	3,93	3,85	3,98
Base feature height 3	3,91	3,94	3,94	3,92	3,92	3,94	4,03	3,97	4	3,95
Base feature height 4	4,06	3,93	4,04	4,05	4	3,97	3,91	3,95	4	3,84
Base feature width 1	99,98	99,95	99,78	99,77	99,61	99,62	99,76	99,77	99,96	99,91
Base feature width 2	100	100,01	100,03	99,81	99,82	99,98	99,99	99,78	99,9	99,89
Base feature width 3	99,83	99,71	99,69	99,69	99,64	99,68	99,78	99,77	99,76	99,95
Base feature width 4	99,72	99,69	99,79	99,53	99,54	99,89	99,92	99,82	99,8	99,55

	Benchmark part measurements uPrint ABS – standard quality (mm)									
Circumference (diameter)1	19,92	19,91	19,88	19,82	19,94	19,9	19,88	19,96	19,92	19,91
Circumference (diameter)2	14,96	14,9	14,96	15,16	14,91	15,01	14,89	14,97	14,93	14,95
Circumference (diameter)3	4,04	3,99	3,98	3,99	4,02	4,02	3,95	3,9	3,99	3,95
Circumference (diameter)4	5,93	6,09	6,1	5,94	6,05	6,06	5,95	5,99	6	5,97
Circumference (diameter)5	10,25	10,05	9,991	9,98	9,98	9,95	10,1	9,98	9,94	10,01
Circumference (diameter)6	3,96	4,06	3,93	4,04	3,95	4,03	3,97	4,01	3,95	4,06
Circumference (diameter)7	5,96	5,87	6,07	5,96	6,03	6,04	6	5,97	5,9	5,92
Circumference (diameter)8	9,9	10,21	10,04	9,98	10,16	10,01	9,97	9,99	9,99	10,1
Circular hole 1	9,73	9,72	9,81	9,8	9,68	9,82	9,73	9,7	9,79	9,59
Circular hole 2	3,76	3,82	3,83	3,62	3,81	3,85	3,49	3,67	3,69	3,76
Circular hole 3	5,73	5,83	5,7	5,74	5,89	5,67	5,65	5,92	5,84	5,58
Circular hole 4	5,87	5,84	5,86	5,62	5,95	5,97	5,79	5,84	5,76	5,83
Rectangular notch 1	1,48	1,47	1,45	1,48	1,41	1,4	1,35	1,43	1,42	1,46
Rectangular notch 2	1,86	1,87	1,87	1,89	1,97	1,93	1,9	1,92	1,94	1,91
Rectangular notch 3	2,47	2,37	2,42	2,37	2,45	2,37	2,41	2,44	2,4	2,46
Rectangular notch 4	2,93	2,95	2,96	2,92	2,95	2,96	2,96	2,95	2,88	2,92
Rectangular notch 5	3,41	3,46	3,47	3,48	3,39	3,41	3,39	3,47	3,46	3,38
Rectangular notch 6	3,9	3,91	3,93	3,9	3,95	3,93	3,88	3,98	3,85	3,96
Square Base 1 a	4,04	4,06	4,09	4,06	4,09	4,08	4,09	4,07	4,09	4,07
Square base 2 a	6,07	6,05	6,08	6,06	6,05	6,06	6,05	6,13	6,02	6,08
Square Base 3 a	10,13	10,01	10,26	10,13	10,05	10,03	10,1	10,08	10,1	10,2
Square Base 1 b	4,02	4	4,01	4	4	4,11	4,02	3,98	4,09	4,07
Square base 2 b	6,05	6,01	6,02	6,07	5,98	5,96	6	5,97	6,04	6,1
Square Base 3 b	10,02	9,99	9,95	9,99	10,08	10,01	10,01	9,97	10,05	10,1
Negative Staircase H 1	7,07	7,1	7,04	7,1	7,14	7,16	7,13	7,08	7,1	7,15
Negative Staircase H 2	6,07	6,08	6,1	6,04	6,02	6,12	6,11	6,09	6,05	6,03
Negative Staircase H 3	4,03	4,1	4,13	4,16	4,09	4,09	4,13	4,03	4,09	4,06
Negative Staircase H 4	5,09	5,09	5,08	5,09	5,06	5,11	5,07	5,12	5,06	5,08
Negative Staircase H 5	3,06	3,12	3,15	3,11	3,11	3,06	3,12	3,1	3,09	3,09
Positive Staircase H 1	3	2,99	3,05	3	3,07	3,06	3,03	3,03	2,95	3,01
Positive Staircase H 2	5,07	5,09	5,05	4,98	5,02	5,03	5,08	4,99	4,99	5,08
Positive Staircase H 3	7,03	6,98	6,97	6,97	7,03	7,04	7,07	7,1	7,04	7,07
Positive Staircase H 4	5,99	6,02	5,98	5,95	6,12	6,09	5,97	6,05	6,02	6
Positive Staircase H 5	4,01	3,95	3,98	3,94	4,14	4,09	4,12	3,96	3,99	3,94
Wall 1	2	2,05	2	1,98	1,95	1,93	2,03	2,06	2,03	2,06
Base feature height 1	4,15	4,18	4,04	4,1	4,09	4,12	4,04	4	4,1	4,11
Base feature height 2	4,05	4,08	4,03	4,06	4,06	4,08	4,09	4,04	4,01	4,02
Base feature height 3	4,09	4,04	4,06	4,09	4,07	4,08	4,03	4,04	4,02	4,08
Base feature height 4	4,15	4,12	4,1	4,08	4,09	4,08	4,07	4,1	4,1	4,1
Base feature width 1	99,92	99,93	99,92	99,91	99,93	99,93	99,91	99,93	99,94	99,9
Base feature width 2	99,94	99,95	99,94	99,95	99,95	99,96	99,95	99,95	99,95	99,96
Base feature width 3	99,95	99,96	99,97	99,96	99,98	99,97	99,97	99,96	99,94	99,95
Base feature width 4	99,95	99,95	99,96	99,97	99,97	99,97	99,96	99,96	99,95	99,96

	Benchmark part measurements uPrint ABS – high quality (mm)									
Circumference (diameter)1	19,96	19,99	19,94	19,9	19,9	19,89	19,98	19,94	20,01	19,99
Circumference (diameter)2	15	14,98	14,96	15,14	14,99	14,97	14,91	14,96	15,03	15,04
Circumference (diameter)3	3,97	4,01	4	3,96	4	4,05	4,02	4,08	3,98	4,09
Circumference (diameter)4	5,96	5,98	5,98	6,07	5,98	5,97	5,95	5,93	5,9	6,05
Circumference (diameter)5	9,95	9,95	9,96	10,18	9,93	10,04	10,01	9,96	10,01	9,98
Circumference (diameter)6	3,96	4,08	4	3,92	3,95	4,18	3,91	3,92	3,96	4,01
Circumference (diameter)7	6,08	5,9	5,97	5,96	5,96	6,11	5,99	5,93	6	6,02
Circumference (diameter)8	10,27	9,95	10,03	9,95	10,25	10,04	9,98	9,94	10,07	9,98
Circular hole 1	9,62	9,89	9,66	9,68	9,88	9,76	9,78	9,72	9,83	9,87
Circular hole 2	3,9	3,91	3,9	3,8	3,69	3,68	3,89	3,88	3,8	3,67
Circular hole 3	5,62	5,94	5,92	5,66	5,68	5,89	5,84	5,55	5,72	5,82
Circular hole 4	5,9	5,88	5,86	5,93	5,92	5,77	5,75	5,97	5,77	5,87
Rectangular notch 1	1,49	1,49	1,4	1,47	1,48	1,43	1,5	1,53	1,48	1,53
Rectangular notch 2	1,99	1,99	1,95	2,01	1,94	1,91	1,94	1,98	2,01	2,04
Rectangular notch 3	2,48	2,47	2,45	2,48	2,49	2,45	2,41	2,46	2,47	2,54
Rectangular notch 4	2,98	2,93	2,97	2,98	2,94	2,9	2,95	3,04	2,98	2,93
Rectangular notch 5	3,48	3,45	3,38	3,49	3,48	3,48	3,43	3,46	3,49	3,5
Rectangular notch 6	3,95	3,95	3,89	3,97	3,94	3,98	3,98	4,05	4,08	3,96
Square Base 1 a	4,05	4,01	4,01	4,08	4,02	4,05	4,07	4,03	4,04	4
Square base 2 a	6,12	6,07	6,05	6,08	6,04	6,09	6,1	6,03	6,05	6,08
Square Base 3 a	10,19	10,09	10,06	10,11	10,09	10,09	9,97	10,07	10	10
Square Base 1 b	4,07	3,99	4,04	4,01	4,06	4,02	4,05	4,07	4	4,02
Square base 2 b	5,99	6,01	6	6,01	6,09	6,05	5,97	6,02	6,04	6,03
Square Base 3 b	10,07	10,02	10,03	10	9,95	9,98	10,02	9,94	10,01	9,99
Negative Staircase H 1	6,93	6,99	6,84	6,99	7	7	7,04	7,07	6,98	6,99
Negative Staircase H 2	5,99	5,96	5,94	6,01	5,98	5,93	5,93	5,93	5,91	5,9
Negative Staircase H 3	3,94	3,98	3,94	3,9	3,94	3,95	4	4,01	3,92	4,06
Negative Staircase H 4	4,96	4,95	4,95	4,98	4,92	4,95	5	5	4,97	4,96
Negative Staircase H 5	2,92	2,91	2,91	2,91	2,91	2,87	2,93	2,86	2,96	2,9
Positive Staircase H 1	3,1	2,98	3,06	3,07	3,11	3,12	2,96	3,01	3,12	3,11
Positive Staircase H 2	5,11	5,08	5,14	5,02	5,08	5,03	5,04	5,03	5,01	4,99
Positive Staircase H 3	6,88	6,96	6,88	6,88	6,93	6,85	6,82	6,86	6,91	6,89
Positive Staircase H 4	6,1	6,02	6,1	6,13	6,11	6,14	6,11	6,1	6,04	6,14
Positive Staircase H 5	4	3,99	4,05	4,08	4,03	4,02	4,1	4,02	4,07	4,1
Wall 1	2,03	2,06	2	1,97	1,96	1,93	2,08	1,98	2,04	2,06
Base feature height 1	4,08	4,12	4,09	4,1	4,1	4,08	4,09	4,08	4,08	4,08
Base feature height 2	4,05	4,07	4,03	4,02	4,01	4,04	4,05	4,04	4,08	4,04
Base feature height 3	4,05	4,06	4,03	4,05	4,05	4,04	4,03	4,09	4,02	4,04
Base feature height 4	4,08	4,1	4,11	4,12	4,08	4,1	4,09	4,08	4,08	4,07
Base feature width 1	99,93	99,94	99,93	99,91	99,93	99,91	99,94	99,95	99,93	99,92
Base feature width 2	99,94	99,93	99,97	99,95	99,96	99,93	99,92	99,93	99,93	99,94
Base feature width 3	99,95	99,96	99,95	99,95	99,96	99,95	99,98	99,95	99,94	99,96
Base feature width 4	99,99	99,99	100,02	100	100,01	100	100	99,99	100	99,99

	Benchmark part measurements Spiderbot ABS – standard quality 25°C (mm)									
Circumference (diameter)1	20,02	20,01	19,84	19,84	19,68	19,96	19,92	19,97	20,1	19,97
Circumference (diameter)2	15,17	15,48	15,15	15,3	15,18	15,16	15,22	15,28	15,22	15,28
Circumference (diameter)3	4,84	4,69	4,55	4,76	4,41	4,21	4,37	4,57	4,85	4,67
Circumference (diameter)4	6,42	6,66	6,33	6,43	6,51	6,41	6,35	6,3	6,41	6,32
Circumference (diameter)5	10,29	10,29	10,41	10,58	10,36	10,25	10,46	10,27	10,52	10,28
Circumference (diameter)6	4,68	4,8	4,65	4,5	4,78	4,81	4,25	4,68	4,15	4,8
Circumference (diameter)7	6,76	6,42	6,57	6,4	6,94	6,51	6,53	6,57	6,96	6,63
Circumference (diameter)8	10,27	10,39	10,26	10,89	10,54	10,33	10,35	10,36	10,34	10,62
Circular hole 1	9,3	9,11	9,17	9,16	8,86	9,17	8,98	9,25	9,31	8,9
Circular hole 2	3,46	3,22	3,23	3,16	3,51	3,52	3,32	3,06	3,47	3,24
Circular hole 3	4,69	5,22	5,25	4,68	4,92	4,76	5,22	5,27	4,94	4,88
Circular hole 4	5,1	5,37	5,3	5,27	5,35	5,57	5,64	5,46	5,24	5,6
Rectangular notch 1	1,35	1,34	1,1	1,35	1,35	1,35	0,92	1,21	1,44	1,4
Rectangular notch 2	1,9	1,88	1,62	1,78	1,82	1,75	1,78	1,37	1,82	1,38
Rectangular notch 3	2,33	2,28	1,94	2,29	2,31	2,32	2,39	2,32	2,12	2,39
Rectangular notch 4	2,99	3,01	2,71	2,87	2,83	2,75	2,73	2,76	2,76	2,84
Rectangular notch 5	3,25	3,21	3,36	3,31	3,36	3,46	3,5	3,28	3,44	3,23
Rectangular notch 6	3,81	3,83	3,87	3,8	3,86	4,07	3,96	3,76	3,78	3,95
Square Base 1 a	4,92	4,58	4,97	4,71	4,57	4,73	4,74	4,56	4,78	4,58
Square base 2 a	6,45	6,7	6,59	6,6	6,6	6,5	6,69	6,69	6,61	6,53
Square Base 3 a	10,68	10,13	10,54	10,69	10,31	10,65	10,6	10,75	10,66	10,65
Square Base 1 b	4,53	4,6	4,49	4,66	4,54	4,45	4,43	4,63	4,54	4,46
Square base 2 b	6,87	6,44	6,59	6,83	6,6	6,24	7,14	6,83	6,36	6,45
Square Base 3 b	10,23	10,33	10,23	10,67	10,22	10,23	10,2	10,36	10,4	10,36
Negative Staircase H 1	6,86	6,87	6,84	6,84	6,86	6,85	6,88	6,87	6,91	6,88
Negative Staircase H 2	5,97	5,86	5,78	5,99	5,85	6,01	5,95	5,95	6,02	6,04
Negative Staircase H 3	3,99	3,98	3,9	3,97	3,93	3,94	3,92	3,94	3,92	3,96
Negative Staircase H 4	5,02	5,03	5,01	5	4,9	4,92	4,95	5,06	4,85	4,89
Negative Staircase H 5	2,96	2,92	2,91	2,89	2,94	2,96	2,9	2,95	2,97	2,95
Positive Staircase H 1	3,12	3,07	3,23	3,21	3,28	3,05	3,03	3,03	3,12	2,96
Positive Staircase H 2	4,87	5,08	5,18	5,18	5,11	5,14	5,02	5,2	4,88	5,04
Positive Staircase H 3	6,91	7,01	7,15	6,92	7,12	7,11	7,06	6,94	6,94	7,07
Positive Staircase H 4	6,15	6,2	6,06	6,23	6,19	6,15	6,19	6,11	6,08	6,23
Positive Staircase H 5	4,05	4,28	4,19	4,16	4,07	4,06	4,26	3,98	4,1	4,04
Wall 1	2,32	2,32	2,38	2,2	2,24	2,11	2,37	2,36	2,33	2,31
Base feature height 1	4,1	3,89	4	3,97	4,13	4,02	3,91	4,04	3,91	3,85
Base feature height 2	3,9	3,84	3,79	3,95	3,83	3,82	3,82	4,02	3,85	3,85
Base feature height 3	3,94	3,95	3,97	4,03	3,94	3,92	3,99	3,92	3,97	3,99
Base feature height 4	4,05	4	3,96	4,03	4,02	4,04	4,06	4,06	4	4,02
Base feature width 1	99,7	99,83	99,69	99,33	99,35	99,35	99,36	99,36	99,64	99,69
Base feature width 2	100,22	100,25	99,94	100,04	100,18	100,04	100,06	99,94	100,11	100,17
Base feature width 3	100,16	100,17	100	99,83	99,86	100,03	99,88	99,82	99,77	100,06
Base feature width 4	99,66	99,86	99,76	99,66	99,67	99,68	99,89	99,45	99,75	99,71

	Benchmark part measurements Spiderbot ABS – standard quality 50°C (mm)									
Circumference (diameter)1	20,16	19,73	19,82	19,84	19,91	20,01	19,78	19,85	20,06	20,35
Circumference (diameter)2	15	15,15	15,13	15,16	15,56	15,17	15,09	15,08	15,05	15,04
Circumference (diameter)3	4,65	4,36	4,45	4,56	4,35	4,6	4,55	4,47	4,13	4,37
Circumference (diameter)4	6,38	6,68	6,43	6,9	6,26	6,81	6,81	6,39	6,61	6,34
Circumference (diameter)5	10,19	10,38	10,3	10,48	10,16	10,3	10,18	10,08	10,27	10,21
Circumference (diameter)6	4,44	4,45	4,5	4,51	4,5	4,41	4,76	4,49	4,43	4,48
Circumference (diameter)7	6,5	6,68	6,26	6,65	6,53	6,21	6,09	6,36	6,57	6,55
Circumference (diameter)8	10,58	10,16	10,15	10,3	10,63	10,3	10,29	10,34	10,4	10,34
Circular hole 1	8,85	9,1	9,05	9,2	9,01	9,02	9,11	9,07	8,73	9,14
Circular hole 2	3,21	2,94	3,11	3,23	3,26	3,26	3,13	2,91	3,29	3,14
Circular hole 3	4,6	5,43	4,79	4,7	4,48	5,25	5,32	5,03	5,13	4,79
Circular hole 4	5,54	5,27	5,49	5,41	5,29	5,43	5,2	5,35	5,41	5,47
Rectangular notch 1	1,27	1,32	1,26	1,1	1,37	1,26	1,36	1,32	1,37	1,28
Rectangular notch 2	1,83	1,84	1,89	1,86	1,68	1,84	1,62	1,83	1,69	1,82
Rectangular notch 3	2,34	2,39	2,13	2,62	2,3	2,31	2,29	2,3	2,31	2,35
Rectangular notch 4	2,81	2,91	3,01	2,64	2,7	2,46	2,6	2,69	2,64	2,66
Rectangular notch 5	3,3	3,3	3,46	3,29	3,07	3,28	3,14	3,27	3,3	3,19
Rectangular notch 6	3,99	3,94	3,97	3,73	3,75	3,78	3,73	3,75	3,77	3,81
Square Base 1 a	4,66	4,59	4,74	4,96	4,53	4,61	4,78	4,34	4,37	4,52
Square base 2 a	6,56	6,42	6,44	6,28	6,56	6,54	6,43	6,44	6,43	6,33
Square Base 3 a	10,19	10,01	10,39	10,21	10,3	10,36	10,34	10,22	10,2	10,33
Square Base 1 b	4,65	4,41	4,31	4,66	4,45	4,69	4,67	4,46	4,51	4,34
Square base 2 b	6,49	6,3	6,59	6,7	6,71	6,45	6,32	6,45	6,44	6,38
Square Base 3 b	10,19	10,12	10,1	10,53	10,4	10,18	10,16	10,15	10,62	10,39
Negative Staircase H 1	6,89	6,84	6,9	6,88	6,85	6,78	6,75	6,81	6,83	6,78
Negative Staircase H 2	5,82	5,9	5,85	5,84	5,84	5,83	5,85	5,75	5,85	5,96
Negative Staircase H 3	3,84	3,82	3,92	3,89	3,89	3,93	3,92	3,93	3,89	3,89
Negative Staircase H 4	4,89	4,75	4,8	4,77	4,72	4,87	4,83	4,82	4,87	4,82
Negative Staircase H 5	2,97	2,9	2,88	2,92	2,81	2,95	2,82	2,95	2,92	2,94
Positive Staircase H 1	2,93	3,1	3,21	3,01	2,92	3,14	2,88	3,03	2,87	2,95
Positive Staircase H 2	4,92	4,96	5,14	5,29	5,12	5,12	5,2	5,21	4,82	4,8
Positive Staircase H 3	7,01	7,13	7,16	7,03	6,86	7,02	6,99	7,04	7,16	6,95
Positive Staircase H 4	5,9	6,18	6,2	5,98	5,83	6,24	6,25	6,16	6,06	5,84
Positive Staircase H 5	4,12	4,03	4,21	3,97	4,18	4,24	4,12	4,16	4,08	4,03
Wall 1	2,32	2,16	2,02	1,99	2,14	2,13	2,07	2,05	2,15	2,18
Base feature height 1	4,22	4,1	4,18	4,25	4,12	4,21	4,22	4,18	4,23	4,13
Base feature height 2	4,11	4,11	4,03	4,17	4,08	4,02	4,14	4,17	4,2	4,25
Base feature height 3	4,23	4,09	4,15	4,13	4,21	4,16	4,38	4,14	4,25	4,34
Base feature height 4	4,25	4,18	4,16	4,27	4,21	4,21	4,23	4,17	4,23	4,15
Base feature width 1	99,66	99,58	99,47	99,65	99,67	99,55	99,65	99,74	99,49	99,62
Base feature width 2	99,71	99,71	99,7	99,96	99,87	99,74	99,89	99,71	99,7	100,75
Base feature width 3	99,48	99,55	99,48	99,59	99,6	99,39	99,55	99,53	99,52	99,51
Base feature width 4	99,38	99,44	99,54	99,35	99,39	99,37	99,38	99,36	99,57	99,39

	Benchmark part measurements Spiderbot ABS – standard quality 75°C (mm)									
Circumference (diameter)1	17,73	17,6	17,86	17,9	18,69	18,02	17,8	18,15	17,74	18
Circumference (diameter)2	14,7	14,68	14,66	14,56	14,52	14,64	14,5	14,6	14,72	14,51
Circumference (diameter)3	4,48	5,09	4,8	5,7	4,98	4,82	4,56	4,84	5	5,14
Circumference (diameter)4	6,2	6,11	6,44	6,35	6,2	6,24	6,06	5,86	5,89	6,09
Circumference (diameter)5	9,24	9,28	9,72	9,44	9,51	9,46	8,9	8,88	8,93	9,14
Circumference (diameter)6	5,16	4,41	4,69	4,35	4,5	5,24	4,5	4,65	4,28	4,66
Circumference (diameter)7	5,58	5,95	5,82	6,25	5,75	5,72	5,82	5,62	5,5	5,63
Circumference (diameter)8	9,1	8,93	8,72	8,69	9,3	8,77	8,62	9,25	9,44	8,85
Circular hole 1	7,7	7,91	7,43	7,77	7,6	7,64	7,65	7,6	7,75	7,76
Circular hole 2	2,5	2,67	2,54	2,7	2,5	2,55	2,63	2,6	2,51	2,63
Circular hole 3	4,54	4,58	4,26	4,24	4,39	4,5	4,49	4,23	4,46	4,24
Circular hole 4	3,68	4,16	3,97	3,15	4,08	4,24	3,59	3,47	3,7	4,08
Rectangular notch 1	2,2	2,07	2,44	1,43	1,77	1,52	1,48	1,66	1,82	2,38
Rectangular notch 2	2,52	1,88	2,1	2,18	2	2,16	1,91	1,84	1,91	1,83
Rectangular notch 3	2,39	2,33	2,45	2,53	2,3	2,49	2,13	2,41	2,25	2,5
Rectangular notch 4	2,63	2,64	2,68	2,64	2,87	2,85	2,7	3	2,54	2,8
Rectangular notch 5	3,33	3,49	3,19	3,32	3,33	3,19	3,18	3,38	3,2	3,23
Rectangular notch 6	4	4,19	4,36	3,97	3,8	3,89	3,9	3,83	4,09	4,71
Square Base 1 a	4,52	4,58	4,49	4,59	4,64	4,65	4,68	4,4	4,52	4,66
Square base 2 a	5,73	5,87	6,01	6,15	6,03	5,95	5,94	6,05	5,87	6
Square Base 3 a	9,96	9,73	9,72	9,43	9,86	10,03	9,88	9,62	10,24	9,85
Square Base 1 b	4,88	5	4,99	4,96	4,8	5	5,01	4,7	4,91	4,77
Square base 2 b	6,58	6,28	6,56	6,7	6,7	6,26	6,3	6,28	6,26	6,62
Square Base 3 b	11,02	11,25	10,41	10,98	11	11,12	11,65	11,07	11,07	11,71
Negative Staircase H 1	6,05	6,63	6,63	7,98	8,25	8,24	8,68	7,15	8,26	8,16
Negative Staircase H 2	5,43	6,37	5,43	6,13	6,75	6,49	6,03	5,3	5,78	6,88
Negative Staircase H 3	3,8	3,36	3,7	4,18	3,88	3,2	3,59	5,39	3,59	3,59
Negative Staircase H 4	5,38	5,09	4,94	4,92	5,01	5,11	4,96	4,98	5,08	5,12
Negative Staircase H 5	3,84	3,18	3,26	3,71	3,86	3,65	3,68	2,92	2,88	3,33
Positive Staircase H 1	3,18	3,33	3,67	3,18	3,6	3,53	2,95	3,27	3,33	2,59
Positive Staircase H 2	5,06	5,08	5,17	5,17	5,21	5,34	5,24	5,17	5,29	5,04
Positive Staircase H 3	5,69	8,21	6,41	5,87	5,39	6,84	6,84	7,37	6,85	8,19
Positive Staircase H 4	6,03	6,08	6,35	6,07	5,96	6,28	6,13	6,16	6,22	6,14
Positive Staircase H 5	4,51	4,45	4,5	4,07	4,48	4,23	4,37	4,61	4,44	4,48
Wall 1	3,06	2,67	2,89	2,82	2,48	3,35	2,5	2,18	3,5	2,5
Base feature height 1	4,62	4,37	4,76	4,62	4,58	4,7	4,46	4,39	4,4	4,35
Base feature height 2	4,28	4,27	4,28	4,7	4,46	4,43	4,38	4,28	4,49	4,28
Base feature height 3	4,72	4,56	4,9	4,43	4,51	4,41	4,45	4,58	4,56	4,45
Base feature height 4	4,55	4,73	4,71	4,39	4,67	4,92	4,43	4,56	4,6	4,45
Base feature width 1	99,13	99,21	99,07	98,91	99,3	99,21	98,91	99,03	99,22	99,23
Base feature width 2	99,53	99,75	99,38	99,82	99,8	99,78	99,93	99,96	99,61	99,63
Base feature width 3	99,07	98,48	99,06	99,35	98,81	99,22	98,84	98,38	99,12	99,19
Base feature width 4	98,87	98,77	99,2	99,04	98,54	98,75	98,7	99,02	98,96	99,2

	Benchmark part measurements Spiderbot ABS – standard quality 75°C (mm)									
Circumference (diameter)1	19,95	19,99	19,89	19,99	20	19,94	20	20,04	19,86	19,97
Circumference (diameter)2	14,99	14,98	15,03	15	15,06	15,12	15,06	15,2	15,07	15,02
Circumference (diameter)3	4,48	4,37	4,31	4,3	4,27	4,2	4,3	4,35	4,46	4,16
Circumference (diameter)4	6,48	6,22	6,29	6,05	6,06	6,38	6,24	6,32	6,23	6,24
Circumference (diameter)5	10,14	10,09	10,1	10,14	10,26	10,04	10,04	10,15	10,08	10,04
Circumference (diameter)6	4,26	4,35	4,14	4	4,12	4,23	4,08	4,08	4,19	4,26
Circumference (diameter)7	6,1	5,94	6,12	6,22	6,09	6,12	6,09	6,02	6,32	6,09
Circumference (diameter)8	10,22	10,06	10,04	9,95	10,13	9,98	10,03	10,02	10,07	10,16
Circular hole 1	9,33	9,56	9,49	9,46	9,47	9,51	9,49	9,55	9,36	9,33
Circular hole 2	3,45	3,56	3,48	3,48	3,52	3,54	3,47	3,33	3,42	3,48
Circular hole 3	5,59	5,54	5,27	5,6	5,61	5,14	5,62	5,41	5,39	5,38
Circular hole 4	5,29	5,71	5,26	5,63	5,77	5,19	5,35	5,11	5,53	5,23
Rectangular notch 1	1,46	1,55	1,54	1,44	1,38	1,64	1,42	1,46	1,43	1,45
Rectangular notch 2	2,03	1,97	1,99	1,92	1,93	2,05	1,92	1,9	1,95	1,93
Rectangular notch 3	2,47	2,47	2,46	2,42	2,31	2,4	2,32	2,44	2,45	2,45
Rectangular notch 4	2,88	2,96	2,91	2,83	2,77	2,77	2,78	2,79	2,87	2,82
Rectangular notch 5	3,35	3,51	3,5	3,32	3,31	3,31	3,81	3,79	3,82	3,78
Rectangular notch 6	3,93	4,01	3,99	3,82	3,84	3,82	3,82	3,95	3,8	3,81
Square Base 1 a	4,31	4,36	4,19	4,2	4,21	4,34	4,23	4,3	4,22	4,26
Square base 2 a	6,18	6,35	6,27	6,3	6,32	6,32	6,23	6,31	6,31	6,21
Square Base 3 a	10,8	10,01	10,75	10,91	10,96	9,26	9,34	9,61	10,79	9,3
Square Base 1 b	4,53	4,52	4,46	4,39	4,39	4,45	4,4	4,42	4,48	4,43
Square base 2 b	6,32	6,29	6,22	6,34	6,4	6,32	6,4	6,38	6,32	6,37
Square Base 3 b	10,25	10,34	10,6	10,35	10,28	10,36	10,38	10,16	10,22	10,12
Negative Staircase H 1	6,89	6,92	6,98	7,08	7	7,02	6,98	6,87	6,93	7,02
Negative Staircase H 2	5,88	5,91	5,99	6,08	6,05	5,94	5,96	5,97	5,98	5,99
Negative Staircase H 3	4,03	4,08	4,02	4,15	4,09	4,07	3,98	4,01	4,02	4,03
Negative Staircase H 4	4,95	5,02	5	4,99	5,07	5	4,95	4,95	4,96	4,96
Negative Staircase H 5	3,11	3,09	3,08	3,15	3,16	3,15	3,02	3,04	3,02	3,04
Positive Staircase H 1	3,01	2,91	2,95	2,94	2,93	2,87	3,03	3,12	3,11	3,12
Positive Staircase H 2	4,93	4,97	5,11	4,88	4,88	4,92	5,09	4,98	5,11	5,09
Positive Staircase H 3	6,99	6,88	6,94	7,13	7,11	7,01	6,93	6,87	7,07	6,9
Positive Staircase H 4	5,97	5,96	5,93	5,95	5,7	5,93	5,6	5,86	6,11	6,06
Positive Staircase H 5	3,84	3,97	3,98	3,99	4,03	4,18	3,93	4,03	4,13	4,03
Wall 1	2,14	2,1	2,21	2,15	2,1	2,12	2,24	2,24	2,2	2,3
Base feature height 1	4,44	4,3	4,29	4,2	4,28	4,11	4,15	4,35	4,28	4,35
Base feature height 2	4,33	4,2	4,15	4,17	4,19	4,18	4,12	4,24	4,11	4,19
Base feature height 3	4,39	4,38	4,4	4,45	4,13	4,27	4,24	4,29	4,26	4,23
Base feature height 4	4,28	4,26	4,32	4,25	4,45	4,31	4,27	4,27	4,35	4,26
Base feature width 1	99,45	99,36	99,31	99,46	99,28	99,27	99,33	99,34	99,34	99,32
Base feature width 2	99,52	99,54	99,54	99,58	99,67	99,68	99,57	99,58	99,78	99,78
Base feature width 3	99,26	99,35	99,7	99,36	99,27	99,28	99,27	99,52	99,28	99,25
Base feature width 4	99,33	99,49	99,31	99,38	99,39	99,35	99,34	99,32	99,33	99,3

Appendix 2

The benchmark part feature measurements collected with the profile projector.

	Benchmark part measurements Prusa PLA standard quality (mm)									
Circular hole 1	9,791	9,81	9,797	9,858	10	10	10	9,826	10	10
Circular hole 2	3,757	3,792	3,793	3,806	3,705	3,777	3,821	3,791	3,789	3,726
Circular hole 3	5,893	5,897	5,897	5,918	5,923	5,908	5,863	5,869	5,841	5,917
Rectangular notch 1	1,288	1,346	1,343	1,331	1,288	1,309	1,313	1,332	1,307	1,387
Rectangular notch 2	1,702	1,745	1,811	1,742	1,743	1,769	1,759	1,807	1,821	1,792
Rectangular notch 3	2,14	2,264	2,223	2,198	2,165	2,161	2,172	2,191	2,193	2,235
Rectangular notch 4	2,55	2,574	2,546	2,623	2,6	2,603	2,58	2,62	2,618	2,634
Rectangular notch 5	3,03	3,068	3,067	3,071	3,042	3,06	3,085	3,099	3,096	3,156
Rectangular notch 6	3,325	3,547	3,591	3,615	3,579	3,584	3,6	3,575	3,576	3,475

	Benchmark part measurements Prusa PLA – standard quality (mm)									
Circular hole 1	9,886	9,843	9,851	9,828	9,888	9,849	9,865	9,836	9,859	9,856
Circular hole 2	3,801	3,844	3,839	3,851	3,856	4,053	3,91	3,955	3,847	3,86
Circular hole 3	5,857	5,869	5,888	5,901	5,9	6,065	5,896	5,833	5,888	5,913
Rectangular notch 1	1,303	1,299	1,285	1,315	1,307	1,287	1,291	1,32	1,296	1,351
Rectangular notch 2	1,541	1,545	1,733	1,733	1,692	1,699	1,708	1,716	1,728	1,765
Rectangular notch 3	2,221	2,06	2,072	2,109	2,103	2,141	1,908	2,105	2,095	2,071
Rectangular notch 4	2,212	2,497	2,505	2,503	2,552	2,581	5,522	2,545	2,577	2,567
Rectangular notch 5	2,903	2,925	2,946	2,935	2,95	2,968	2,981	3,084	2,837	3,047
Rectangular notch 6	3,332	3,146	3	3,403	3,429	3,463	3,464	3,492	3,481	3,509

	Benchmark part measurements Prusa ABS – standard quality (mm)									
Circular hole 1	8,978	9	9,058	8,98	8,954	9,039	9,074	9,119	9,168	9,011
Circular hole 2	3,08	3,1	3,186	2,959	2,859	3,116	3,141	3,165	3,166	3,091
Circular hole 3	5,147	5,1	5,14	5,331	5,159	5,198	5,184	5,218	5,213	5,16
Rectangular notch 1	0,786	0,748	0,771	0,8	0,803	0,725	0,779	0,807	0,756	0,796
Rectangular notch 2	1,314	1,318	1,3	1,193	1,268	1,268	1,259	1,249	1,28	1,317
Rectangular notch 3	1,781	1,796	1,766	1,737	1,752	1,757	1,793	1,72	1,778	1,735
Rectangular notch 4	2,253	2,277	2,257	2,22'	2,286	2,27	2,285	2,293	2,261	2,251
Rectangular notch 5	2,738	2,758	2,731	2,274	2,752	2,7	2,539	2,779	2,755	2,795
Rectangular notch 6	3,296	3,3	3,27	3,338	3,254	3,261	3,224	3,252	3,296	3,265

	Benchmark part measurements Prusa ABS – high quality (mm)									
Circular hole 1	9,227	9,257	9,3	8,281	9,273	9,336	9,391	9,393	9,368	9,296
Circular hole 2	3,208	3,22	3,29	3,255	3,286	3,27	3,176	3,24	3,284	3,26
Circular hole 3	5,326	5,316	5,527	5,21	5,258	5,34	5,358	5,4	5,446	5,257
Rectangular notch 1	0,711	0.716	0,592	0,7	0,706	0,606	0,62	0.679	0,668	0,659
Rectangular notch 2	1,005	1,279	1,283	1,284	1,348	1,412	1,397	1,255	1,436	1,413
Rectangular notch 3	1,727	1,786	1,826	1,718	1,794	1,799	1,823	1,51	1,651	1,535
Rectangular notch 4	2,197	2,294	2,282	2,298	2,325	2,279	2,243	2,17	2,192	1,728
Rectangular notch 5	2,835	2,855	2,856	2,82	2,827	2,832	2,838	2,795	2,78	2,97
Rectangular notch 6	3,206	3,42	3,295	3,478	3,185	3,251	3,3	3,265	3,166	2,793

	Benchmark part measurements uPrint ABS – standard quality (mm)									
Circular hole 1	9,766	9,88	10,1	9,81	9,795	9,942	9,996	9,863	10,13	10,1
Circular hole 2	4,041	4,035	3,931	3,948	3,959	3,88	3,852	3,628	3,9	3,91
Circular hole 3	5,984	6	5,99	5,953	5,922	5,753	5,793	5,916	6,05	6,02
Rectangular notch 1	1,57	1,607	1,66	1,395	1,447	1,49	1,496	1,47	1,629	1,56
Rectangular notch 2	1,995	1,965	2,08	2,032	1,847	1,957	2,047	1,344	1,953	1,95
Rectangular notch 3	2,433	2,506	2,479	2,435	2,447	2,487	2,514	2,494	2,49	2,43
Rectangular notch 4	2,913	3,06	3,045	3,026	3,001	2,989	2,955	2,9	3	2,99
Rectangular notch 5	3,46	3,47	3,56	3,441	3,455	3,486	3,115	3,413	3,55	3,48
Rectangular notch 6	3,877	3,98	3,982	4,039	4,065	3,972	4,004	3,965	4,025	3,96

	Benchmark part measurements uPrint ABS – high quality (mm)									
Circular hole 1	10,04	10,16	9,9	9,952	10	9,733	9,766	9,972	9,953	10,01
Circular hole 2	4,05	4,046	3,9	3,802	3,764	3,843	3,994	3,973	3,948	4,01
Circular hole 3	6,11	6,09	5,8	5,966	5,98	5,971	5,706	6,025	5,821	6,1
Rectangular notch 1	1,6	1,6	1,65	1,454	1,521	1,563	1,473	1,453	1,388	1,59
Rectangular notch 2	2,07	2,08	2,01	1,922	1,95	1,99	1,986	1,896	2,08	2,08
Rectangular notch 3	2,62	2,596	2,637	2,517	2,478	2,522	2,525	2,47	2,632	2,56
Rectangular notch 4	3,031	3,102	3,13	2,929	2,933	3,019	3,029	2,94	3,088	3,06
Rectangular notch 5	3,57	3,618	3,58	3,359	3,532	3,556	3,527	3,466	3,605	3,55
Rectangular notch 6	4,05	4,118	4,098	3,962	3,781	4,077	3,995	4,034	4,12	4,05

	Benchmark part measurements Spiderbot ABS – standard quality 25°C (mm)									
Circular hole 1	9,124	9,135	9,2	9,01	8,986	8,996	9,123	9,106	9,151	9,21
Circular hole 2	3,234	2,936	3,264	2,901	2,882	2,954	2,9	3,017	3,061	2,95
Circular hole 3	4,973	4,917	4,796	4,789	4,76	4,827	4,835	4,83	4,837	4,89
Rectangular notch 1	1	1	1,017	0,97	0,985	0,972	0,944	0,9	0,997	0,92
Rectangular notch 2	1,42	1,505	1,555	1,497	1,475	1,433	1,442	1,323	1,598	1,65
Rectangular notch 3	2,011	2,066	2,027	1,921	2,039	2,013	1,994	1,985	2,011	2
Rectangular notch 4	2,486	2,459	2,46	2,52	2,466	2,432	2,418	2,4	2,54	2,39
Rectangular notch 5	2,971	2,994	3	2,926	2,952	2,954	2,976	3,017	2,998	2,99
Rectangular notch 6	3,446	3,46	3,455	3,377	3,411	3,42	3,405	3,378	3,471	3,61

	Benchmark part measurements Spiderbot ABS – standard quality 50°C (mm)									
Circular hole 1	9,098	9,147	9,156	8,56	8,66	9,1	9,159	9,156	8,502	8,79
Circular hole 2	3,27	3,31	3,1	3,284	3,304	3,288	3,121	3,139	3,13	3,28
Circular hole 3	4,988	5,03	5,29	5,285	5,31	4,933	5,008	5	5,353	4,97
Rectangular notch 1	1,183	1,174	1,138	1,04	1,112	1,126	1,176	1,192	1,22	1,37
Rectangular notch 2	1,695	1,73	1,742	1,748	1,653	1,682	1,66	1,582	1,716	1,72
Rectangular notch 3	2,24	2,256	2,308	2,258	2,261	2,326	2,319	2,273	2,289	2,45
Rectangular notch 4	2,7	2,73	2,838	2,722	2,705	2,744	2,727	2,577	2,739	2,84
Rectangular notch 5	3,3	3,295	3,29	3,139	3,234	3,295	3,271	3,266	3,316	3,259
Rectangular notch 6	4,01	3,927	4,02	3,792	3,798	3,85	3,848	3,858	3,52	3,829

	Benchmark part measurements Spiderbot ABS – standard quality 75°C (mm)									
Circular hole 1	7,88	7,93	8,157	7,832	7,759	7,857	7,882	8	8,114	8,317
Circular hole 2	2,841	2,764	2,823	2,684	2,667	2,663	2,734	2,707	2,768	2,814
Circular hole 3	4,526	4,617	4,856	4,438	4,485	4,74	4,718	4,871	4,942	4,6
Rectangular notch 1	1,286	1,223	1,18	1,179	1,29	1,205	1,129	0,978	1,482	1,664
Rectangular notch 2	1,538	1,665	1,786	1,473	1,582	1,614	1,683	1,732	2,07	1,915
Rectangular notch 3	2,07	2,151	2,2	2,408	2,316	2,194	2,095	1,934	2,32	2,52
Rectangular notch 4	2,564	2,671	2,82	2,109	2,51	2,568	2,886	2,832	2,79	2,866
Rectangular notch 5	3,138	3,174	3,366	3,627	3,4	3,282	3,13	3,036	3,544	3,677
Rectangular notch 6	3,629	3,722	3,751	3,583	3,708	3,759	3,978	4,153	3,959	4,132

	Benchmark part measurements Spiderbot ABS – standard quality 75°C (mm)									
Circular hole 1	9,381	9,268	9,305	9,292	9,321	9,382	9,405	9,253	9,426	9,274
Circular hole 2	3,502	3,59	3,335	3,435	3,419	3,394	3,522	3,482	3,407	3,516
Circular hole 3	5,453	5,498	5,637	5,634	5,645	5,419	5,425	5,483	5,659	5,71
Rectangular notch 1	1,297	1,332	1,372	1,33	1,332	1,358	1,285	1,277	1,361	1,34
Rectangular notch 2	1,827	1,833	1,961	1,778	1,891	1,916	1,926	1,952	1,922	1,86
Rectangular notch 3	2,317	2,35	2,51	2,378	2,449	2,457	2,337	2,306	2,496	2,431
Rectangular notch 4	2,831	2,9	2,873	2,723	2,796	2,823	2,881	2,913	2,905	3,01
Rectangular notch 5	3,332	3,448	3,383	3,396	3,382	3,398	3,397	3,332	3,472	3,449
Rectangular notch 6	3,74	3,84	3,843	3,784	3,812	3,843	3,832	3,845	3,873	3,877