

POLITECNICO DI TORINO

Master's degree in Management Engineering

Quality Control on FDM process



Supervisor

Prof. Maurizio Galetto

.....

Candidate

Simona Tomaselli

.....

Year 2017/2018

*A mio nonno
sempre vicino
nella lontananza*

Acknowledgments

I especially want to thank the professor Robert Schmitt for giving me the chance to work in a prestigious institute as WZL. I would also like to thank my supervisor Marco Fuhrmann for his vast knowledge, guidance, and support throughout my thesis' work. Many more at WZL institute have helped me during my project, Henning Voet and Thomas Fischer to name a few.

From Politecnico of Turin I would like to express my sincere gratitude to my professor Maurizio Galetto, for giving me the opportunity to work on this thesis and for his help and support during the work. I would also like to thank Elisa Verna and Gianfranco Genta for their expertise knowledge and suggestions.

It has been a very insightful work, getting to know more about additive manufacturing and giving me new skills.

This accomplishment would not have been possible without the support of my family who have given me constant moral and economical support and advice during my graduate academic career. Your support and belief has been immeasurable, thank you.

I would like to say a particular thank also to my friends without whom this goal would not have been achieved. Thank you for your support, conversations, laughs that made our relationship unique during all these years.

Table of contents

1. Introduction	1
1.1 Problem statement and derivation of question researches.....	2
1.2.1 Methodology	3
2. Additive Manufacturing Processes Categories.....	5
2.1 The Generic AM Process	5
2.2 Overview of AM technologies	7
2.2.1 Directed Energy Deposition.....	7
2.2.2 Binder Jetting	8
2.2.3 Sheet Lamination.....	9
2.2.4 Material Jetting.....	11
2.2.5 Vat Photopolymerization.....	12
2.2.6 Powder Bed Fusion	14
2.2.7 Material Extrusion.....	17
3. System Modeling	26
3.1 Shape chosen.....	26
3.1.1 Construction of the CAD models	27
3.2 Output parameters	29
3.2.1 Printing time.....	29
3.2.2 Energy consumption.....	30
3.2.3 Surface roughness	31
3.2.4 Dimensional accuracy	32
3.3 Input parameters.....	33
3.4 Feedback, Control and Environment.....	36
4. Experimental execution of the test and analysis of results.....	39
4.1: Elaboration of experimental plan.....	40
4.1.1 Adopted experimental design.....	41
4.2 Execution of experimental plan.....	43
4.3 Analysis of functions.....	47
4.4 Optimization.....	63
5. Conclusions	69
Bibliography.....	71
Sitography	73
List of Acronyms and Abbreviations	79
Appendix	80

1. Introduction

Additive Manufacturing (AM) represent all the processes of joining materials to make objects from 3D model data, layer upon layer and without the usage of any tools (EPMA 2015). A machine called 3D printer, under computer control, [1] can carry out this process with good precision and accuracy.

Originally AM was known as Rapid prototyping (RP). ‘Prototyping’ because it was only used in the production of complex geometric prototypes with a very restricted choice of materials and ‘Rapid’ because the process was faster in comparison with the traditional ones. (Hopkinson 2003) After, it changed its name to Rapid Casting, Rapid Tooling and today is best known as Additive Manufacturing, because it used additive processes and above all it started to be used also to produce finished products with a wider range of available materials. The new challenge became the fast production of aesthetically appealing end use products that were functionally reliable although the core purpose was to produce prototypes.

AM has simplified a lot the way to create the objects, in particular the most complicated ones. Traditional subtractive manufacturing processes rely on methods of cutting or drilling to carve out objects, so they need a detailed analysis of the geometric piece and process used. (Kumar L, Kumar V, Haleem A. 2016). In contrast, the AM’s processes need only some basic dimensional details. In addition, they have a greater design freedom, even though there are still rules that must be followed per technology. [2]

The rapid growth and improvements in Additive Manufacturing technologies have enabled many industries to benefit from it. In the recent years, AM has become a suitable process usable in various industrial sectors such as aerospace, architecture, design, energy, automotive, medical and dental, tooling and jewelry. (EPMA 2015) As the costs began to lower, as a result of the developments in the technology, it is also used by hobbyists and anyone willing to try out the new technology. [3]

According to the printer used, the considered material and how the layers are created and bonded to each other, there are different technologies. [1] Such differences will determine factors like the accuracy of the final piece plus its material and mechanical properties. Furthermore, they will also determine how quickly a part can be made, how much postprocessing is required, the size of the AM machine used, and the overall cost of the machine and process. (Gibson et al. 2010)

To summarize, nowadays exist various Additive Manufacturing technologies that allow the realization of complex geometric, customized products, from a wide variety of different shapes, sizes and a combination of multiple materials. (Wohlers 2014)

It is easy to understand that there are several benefits connected with these technologies, this is why AM is currently considered one of the most promising manufacturing techniques and it is believed that it will be the cause of the next industrial revolution.

1.1 Problem statement and derivation of question researches

AM processes enable the creation of products with complex geometries, sometimes unmatched by conventional manufacturing processes. Using these methods, you can: undercut complicated component realizing them with a plurality of materials, testing ideas at low cost, minimizing weight or build customized products at competitive cost. (Wahlström e Sahlström 2016)

On the other hand, exist barriers in the usage of this technology. A decisive disadvantage is represented by the skills expertise and the high investments required, even if in the near future are expected to get less expensive. (Mellor Stephen 2014) The potential of these processes has only been insufficiently exploited in industries because uncertainty in the quality of the components produced and lack of experience or know-how represent obstacles. The last one, in particular, is necessary for process monitoring and control, since the degree of automation of generative production technologies is not yet fully developed (Wahlström e Sahlström 2016) and do not exist software applications that provide supported setup experiment after the purchase of a printer. (Frank et al. 2015)

The challenge is to provide to the users a better understanding of the mechanism of action of their printer reducing the need of know-how. Researches exist in this direction and allow to predict the systems behavior, modeling the cause-and-effect relationships within the 3D printing system but cover all the issues connected to all AM process and AM printers is difficult.

The aim of this work is to discover and optimize the purpose-dependent relationship among the changeable parameters and the target values in the FDM process, using the MakerBot z18 printer, when are printed critical shapes (overhang and bridge). It would try to find an answer to these research questions:

The structure of the component (bridges, overhangs) affect the target values? Why?

How can the quality targets of parts printed by FDM, be modeled as a function of the input parameters of the process?

How is possible to optimize the target variables starting from the input ones?

1.2.1 Methodology

Within this research work an experiment was performed to model and optimize the relationship among input and target factors.

To conduct a successful analysis is needed a structured approach. A set of guidelines should be respected. (Design and analysis of experiments 2013) In figure 1, the flowchart illustrates the procedure.

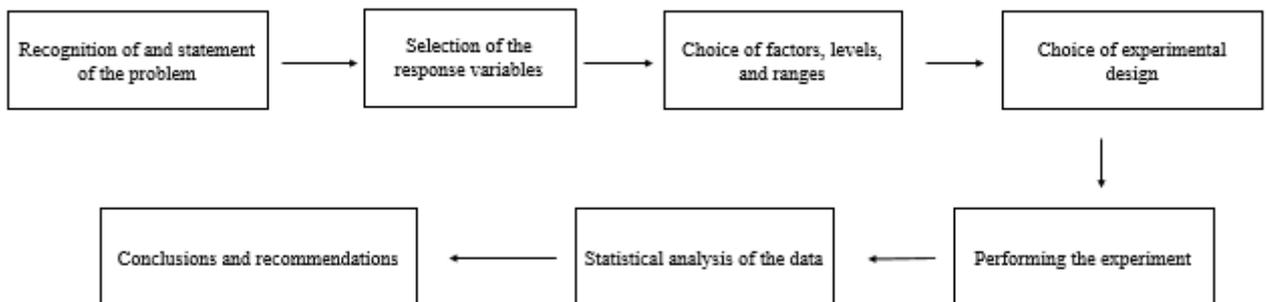


Figure 1: Flow chart of a DOE (Design and analysis of experiments 2013)

Detailing the steps:

1. Recognition of and statement of the problem:

This research is focused on the FDM-process using the MakerBot z18 printer, since the printer is relatively new and it is not yet known the relationship among input and output parameters.

The statement of this work has been defined by the literature, finding out what have been done already and in which way this thesis could contribute with original content.

The researches have been conducted in both web based and physical libraries, by information available internally at RWTH Aachen Universitätsbibliothek and by browsing the internet. The web based library has been the main source of information and include Elsevier, ScienceDirect and Springer Journals.

2.- 3. Selection of response variables and the choice of factors:

The possible parameters of influence and the target variables conditioned by these parameters were found, as well, through a careful literature research, that include the preliminary works and research projects conducted by WZL Institute of RWTH Aachen University and examining the MakerBot site to understand how the system works, which parameters can be changed and in which range has sense to change them.

4. Choice of experimental design:

The experimental plan (DOE) designed was a two-level factorial design with 6 factors ($2^6 = 64$ trials). To reduce the experimental effort the number of trials was reduced to 32 using a fractional factorial experimental design. Furthermore, four central points were included to investigate the linearity of the model. ($32+4=36$)

5. Performing the experiment:

The execution of the experiment has happened according to the programmed plan. Several copies of the shapes chosen have been printed, and for each of them the factors were varied according to plan.

6.-7. Statistical analysis of the data and conclusions:

When the 36 parts have been printed, and data have been collected, a qualitative analysis to discover the relationship among input and output variables has been done, through the main effect plot and interaction plot. Then, a regression model for each target was defined to verify quantitatively these relationships. Found the models, 5 scenarios were considered and optimized, varying the set of responses analyzed, in order to evaluate the different predictability achievable. At the end, the conclusions summarized the work.

2. Additive Manufacturing Processes Categories

The aim of this chapter is to give an overview of the generic AM process and to explain the mechanism behind how AM processes work. It provides a summary of the most common Additive Manufacturing methods, how they additively manufacture parts and their common applications. Each has his own benefits and limitations, and it is able to print part with different materials, so is suitable for a specific design. Then, the chapter will go on discussing the extrusion process and the FDM technology in detail.

2.1 The Generic AM Process

AM involves a number of steps that move from the virtual CAD model to the physical resultant part. Different products will have more or less the same steps, depending on the complexity of the part. Although each AM method produces part in different way, at least, most of the AM processes involve these steps shown in figure 2.1. (Gibson et al. 2010)

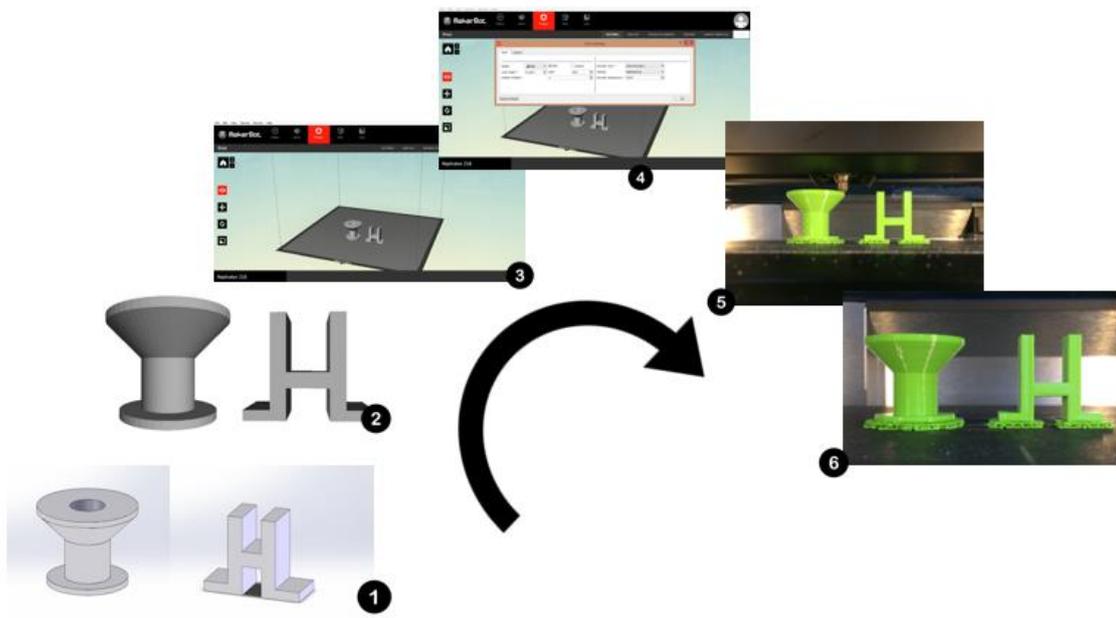


Fig.2.1 Generic process of CAD to part, showing all 6 stages

The first step is the modelling, to create a 3D model of the object that you would print. This model can be designed with computer-aided design (CAD) software like Blender, Sketchup, Solidworks, or through 3D engineering equipment, such as Go!SCAN 3D or you can

download it directly from internet. It should contain all the information about the shape, the dimensions and physical features. The idea of the modelling process is to create a real, physical object and give its a volume in a desirable way. (Gibson et al. 2010) [4]

The second step is the conversion of the CAD file into a standard additive manufacturing file format, an STL file through the program that you use for modeling or through specific software like Meshlab. This file describes the external closed surfaces of the original CAD model. (Gibson et al. 2010) [4]

Then, the model is digitally sliced into layers. There are two methods of slicing adaptive and constant. The slicing process is the intermediate step among modelling and printing and it is crucial to achieve a print close to the first idea of the designer. The slicer's software allows to convert your 3D model in the final G-code file that the printer could recognize. It is a numerical control programming language used in CAM to control automated machines like 3D printer. You can choose from several slicing applications in the market, like Slic3r, Netfabb or free ones such as ReplicatorG, Cura and KISSlicer. The aim of the slicing process is to set and optimize some characteristics of the model, this is why STL format uses triangles of different size to describe the surfaces to be built in order to follow the profile of the model and to give a better final product. Each triangle is described as three points and a facet normal vector indicating the outward side of the triangle. [5] There are some problems connected to the usage of this format but thanks to several corrective software actually, it is the most usable standard. (Gibson et al. 2010) [6]

The third and fourth steps require the transfer of the STL file and setting up of the machine. In order to print economically, maximize cost savings and reduce material waste (Chua et al., 2010), the positioning, the orientation and sizing of the object on the build platform should be checked before the print. Also, the building parameters like the layer thickness, printing speed etc., must be setted up in a properly way prior to the build process. (Gibson et al. 2010)

In the fifth step, the machine, which is only controlled by a computer, builds the model layer by layer. The process can largely carry on without supervision. A monitoring is required to ensure that no errors have taken place. (Gibson et al. 2010) [4]

After building the part and potentially applying cooling and curing periods, the model can be removed from the machine. Clearly, there are safety interlocks just to be sure that for example there are no actively moving parts, or the temperature of the chamber is enough low. This process could be easy for some AM's technologies, because it is simple to remove the printed

part from the build platform but difficult for others and could require highly skilled machine operators along with safety equipment and controlled environments.

Additional post processing operations can occur before the object is ready for use. Operations such as cleaning, removing the supports, painting and finishing of the surface maybe are required to achieve the desired standard. This depends by the technologies used and may involve the use of other machines and tools, and careful manual manipulation. [4]

At the end the parts are ready to be used or required to be assembled together to form a final model or product. (Gibson et al. 2010)

2.2 Overview of AM technologies

The ISO/ASTM 52900 Standard was created in 2015 to standardize all terminology as well as classify each of the different methods of AM technologies. A total of seven process categories were established.

2.2.1 Directed Energy Deposition

“Directed Energy Deposition is a manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.” (Technologies et al. 2012)

Directed Energy Deposition (DED) is commonly used to add or fix additional material to existing components (Gibson et al. 2010). Unlike material extrusion, technologies under the directed energy deposition category are often combined with multi-axis motion systems and robotic arms. This means that the build is not limited to horizontal layers and could follow complicated surfaces. [6]

A typical DED machine consists of a nozzle mounted on a multi axis arm, in general 4 or 5 axis arms, that moves around a fixed object (1) and deposits melted material onto the existing surfaces of the part. (2) In most cases, it is the arm that moves and the object remains in a fixed position but is also possible that the platform moves and the arm remain in a fixed position. The build material could be either provided in wire or powder form and is melted using a laser, electron beam or plasma welding torch, upon deposition. Further material is added layer by layer and solidifies, (3) creating or fixing new material features on the existing

object. The process happens in a controlled chamber with a reduce oxygen levels. (Wohlers e Caffrey 2015), [7]

Table 1: Overview on the Directed Energy Deposition category [7]:

Benefits and limitations	<p>BENEFITS:</p> <ul style="list-style-type: none"> • Ability to control the grain structure to a high degree, which lends the process to repair work of high quality or functional parts; • A balance is needed between surface quality and speed, although with repair applications, speed can often be sacrificed for a high accuracy and a pre- determined microstructure; (Gibson et al. 2010) <hr/> <p>LIMITATIONS:</p> <ul style="list-style-type: none"> • Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect; • Fusion processes require more research;
Materials	<p>Polymers, ceramics can be used but it is typically used metals, for example cobalt chrome, titanium, stainless steel in the form of either powder or wire. Wire is less accurate due to the nature of a pre-formed shape but is more material efficient when compared to powder (Gibson et al. 2010)</p>
Applications	<p>Repairing, maintaining structural parts and adding material to the existing components;</p>

2.2.2 Binder Jetting

“Binder Jetting (BJ) is an Additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials” (Technologies et al. 2012)

Exists two categories of binder jetting: sand printing and metal printing, both have a powder bed as seen in figure 2.2. (Redwood et al. 2017) A roller spread, for each layer, this powder over the whole build surface (1). Then, the binder adhesive is deposited by a print head on top of the powder where required (2) and the powder particles bind together. The build plate is lowered for the next layer (3). This process is repeated until the part is finished (4). The cure of the adhesive is made faster thanks to a heated build chamber that could speed up the process.

When the build is completed, and the binder agent is fully cured, the part can be removed from the machine and the bound powder is removed from the part through compressed air. As the component only will be as strong as the glue holding it

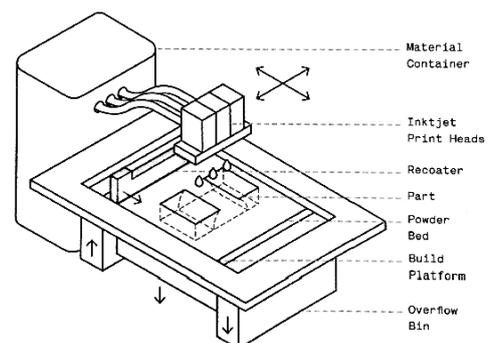


Figure 2.2 A basic schematic of the binder jetting process category (Redwood et al. 2017)

together, the structural and mechanical properties might have to be improved by additional consolidation processes such as sintering or infiltration. The cost and quality of the end part generally defines which secondary process is most appropriate for a certain application.

All of this means that though the BJ process is relatively quick, the necessary post processing might add significant time to the overall process. (Wohlers e Caffrey 2015), (Redwood et al. 2017), (Wahlström e Sahlström 2016), [8] [9]

Table 2: Overview on the Binder Jetting category [8]:

Benefits and limitations	<p>BENEFITS:</p> <ul style="list-style-type: none"> • Doesn't require support structures to be printed, as parts are surrounded by powder during the printing process; • Large, complex geometries can be done at a relatively low cost and in general the process is faster than others; • Don't use any heat meaning parts don't suffer from the residual stresses; • Large number of different binder-powder combinations in terms of colours and materials are allowed and various mechanical properties; • The binder agents are inexpensive; • Machines have some of the largest build volumes of all AM technologies; <hr/> <p>LIMITATIONS:</p> <ul style="list-style-type: none"> • Not always suitable for structural parts, due to the use of binder material the parts are fragile; • Additional post processes are always required if a functional part is required, so this add significant time to the overall process; • The powder used in metal printing can significantly increase the cost of the process;
Materials	Polymers, polymer blends, composites, metals and ceramics. Some examples are stainless steel, copper, tungsten, Inconel, nickel, ABS, PA, PC, glass;
Applications	It is used for a range of applications: Full color modelling and prototyping. Sand casting molds and cores. Functional metal parts when are used secondary processes in conjunction with BJ;

2.2.3 Sheet Lamination

Sheet lamination is defined as an “Additive manufacturing process in which sheets of material are bonded to form a part” (Technologies et al. 2012)

In the sheet lamination process category, sheets of material are joined together to build a part. The material is cutted through a laser or knife and the sheets are bonded together by an adhesive (2). A knife or a laser cuts the layer obtaining the required shape and the next layer is added. Alternatively, the material can be cut before being positioned and bonded. The process is also called ultrasonic additive manufacturing (UAM) in case the building material

used is metal sheets. The variation of the process in which papers are used for making the 3D models is known by the name - Laminated Object Manufacturing (LOM).

UAM joins sheets of metal by a sonotrode. The sonotrode vibrates in high frequencies which causes the layers to melt (by friction). The metal cannot be easily removed by hand and unwanted material must be removed by machining. To ease the post processing and to achieve better surface finish it could be combined with a mill head. [10] [11] [12]

LOM instead uses sheets pre-laminated with heat sensitive adhesive instead of welding. The layers are then heated selectively, and the contour of the cross section can be cut e.g. using a knife or cutting by laser. The process does not require any specialist tools and is time efficient. Whilst the structural quality of parts is limited, adding adhesive, paint and sanding can improve the appearance, as well as further machining. [10] [11] [12]

Table 3: Overview on the Sheet Lamination category [10]:

<p style="text-align: center;">Benefits and limitations</p>	<p>BENEFITS: Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used (Krar e Gill 2003)</p> <p>UAM:</p> <ul style="list-style-type: none"> • The process can bond different materials and requires relatively little energy, as the metal is not melted; <p>LOM:</p> <ul style="list-style-type: none"> • Available and inexpensive A4 papers are used; • Relatively simple and inexpensive setup; <hr/> <p>LIMITATIONS: Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect;</p> <p>UAM:</p> <ul style="list-style-type: none"> • The limitation is that the strength and durability of the model created depends largely on the finish of the welding; <p>LOM:</p> <ul style="list-style-type: none"> • the strength and durability of the model created depends largely on the quality of adhesive;
<p style="text-align: center;">Materials</p>	<p>UAM: metals like aluminum, copper, stainless steel and titanium; LOM: A4 paper;</p>
<p style="text-align: center;">Applications</p>	<p>It is used for a range of applications: Full color modelling and prototyping. Sand casting molds and cores. Functional metal parts when are used secondary processes in conjunction with BJ;</p>

2.2.4 Material Jetting

“Material jetting is an additive manufacturing process in which droplets of material are selectively deposited” (Technologies et al. 2012)

One or multiple printhead, positioned above build platform, dispense drops of photosensitive material or waxes to create each layer (1) that is then cured or hardened through ultraviolet (UV) light becoming a solid component. (2) After one layer has been deposited and cured, the platform will drop down (3) and the procedure is repeated until the 3D part is complete. (4) Material Jetting operations deposit build material in a rapid, linewise fashion as it is visible in figure 2.3

For this technology exists a particular printer, the DOD Drop on Demand (DOD) printer, that has 2 print jets, one to deposit the build materials and another for dissolvable support material.

Due to the high accuracy of the process technology, the part that has been completed doesn't require as much hand finishing and post finishing after. Support material must be built below any overhanging surfaces (B. Stucker 2012) and can be removed by hand, by a sodium hydroxide solution, using a high-powered water jet station or immersing the part in a water-based liquid. [14]

Machines vary in complexity and in their methods of controlling the deposition of material. Furthermore, they have a system in place to clean jets or notify operators if cleaning is required. (Wohlers e Caffrey 2015), (Redwood et al. 2017), [8] [13] [14] [15]

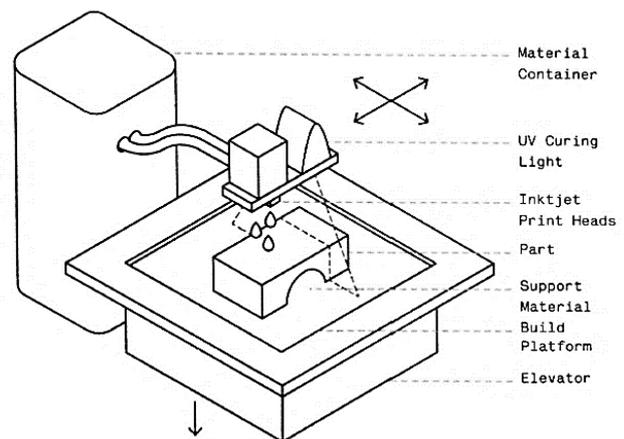


Figure 2.3 A basic schematic of the material jetting process category (Redwood et al. 2017)

Table 4: Overview on the Material Jetting category [15]:

<p>Benefits and limitations</p>	<p>BENEFITS:</p> <ul style="list-style-type: none"> • High accuracy of deposition of droplets with a very smooth surface finish; • If parts are correctly placed and the space within each build line is optimized, the process is able to produce parts at a much quicker rate than other technologies; • The part is homogeneous because the layers are cured throughout the printing process; • Multiple material can be printed in the same part and in a full color; <hr/> <p>LIMITATIONS:</p> <ul style="list-style-type: none"> • Support material is often required; • A high accuracy can be achieved but materials are limited and only polymers and waxes can be used; • The parts produced have poor mechanical properties and are typically very brittle;
<p>Materials</p>	<p>As material must be deposited in drops, the number of materials available to use is limited and has a higher cost per kilogram. Waxes and polymers, for example Polypropylene, PS, PMMA, PC, ABS, HIPS, EDP, are suitable and commonly used materials, due to their viscous nature and ability to form drops. Viscosity is the main determinant in the process and is always controlled during printing.</p>
<p>Applications</p>	<p>It is often utilized to print support structures from a different material during the build phase. It is ideal for creating realistic visual and haptic model and prototypes with very smooth surfaces. Applications of multimaterial parts range from parts with controlled hardness and flexibility to parts with differing electrical properties in various regions (B. Stucker 2012) It is expected that this capability will enable the manufacturing of functional structures within products, such as optical pathways, resulting in radically novel products with unprecedented degrees of functional density (M. Baumann, C. Tuck, P. Dickens, R. Hague 2014).</p>

2.2.5 Vat Photopolymerization

Vat photopolymerization is an “Additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization”. (Technologies et al. 2012)

In the vat photopolymerization process category, the model is constructed using a liquid photopolymer resin in a vat cured or hardened by a light source, that could be a lamp, a laser or a LED (1). The light is directed across the surface of the resin with the use of motor-controlled mirrors, where necessary. The light could be either under the liquid container or from above, meaning that the component either can be built from the bottom-up or top-down.

Whilst each new layer is cured above the previous one, the platform moves downwards by the layer thickness. (2) After completion, the vat is drained of resin and the object removed. (3)

Some machines use a blade or a recoating blade which moves between layers in order to provide a smooth resin base to build the next layer on and to be ensure that there are no defects in the resin for the construction of the next layer.

The most common forms of VAT Polymerization are SLA and DLP and since they have similar mechanism they will have the same benefits and limitations and required the same post processing.

Stereolithography apparatus (SLA) technology was the first AM technology to be commercialized and has a high level of accuracy and good finish. It uses mirrors to rapidly aim a laser beam across a vat, curing and solidifying resin as it goes along. This process breaks down the layer by layer design in a series of points and lines that are given to the mirrors as a set of coordinates. Figure 2.4

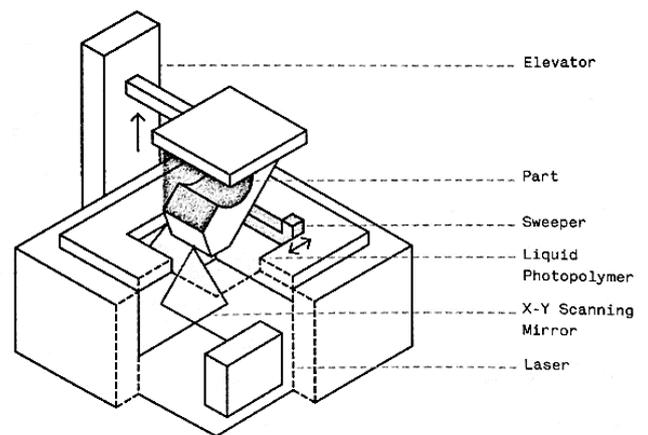


Figure 2.4: A basic schematic of the vat photopolymerization process using the SLA technology. (Redwood et al. 2017)

The photo-polymerisation process and support material may have likely caused defects such as air gaps, which need to be filled with resin in order to achieve a high-quality model. Also, if a structural part is required post curing treatments are needed.

DLP follows a similar method of producing parts as SLA. The main difference is that DLP uses a digital light projector screen to flash a single image of each layer all at once so, it can achieve faster print times compared to SLA.

Light is projected onto the resin using light emitting diode (LED) screens or a UV light source that is directed to the build surface by a

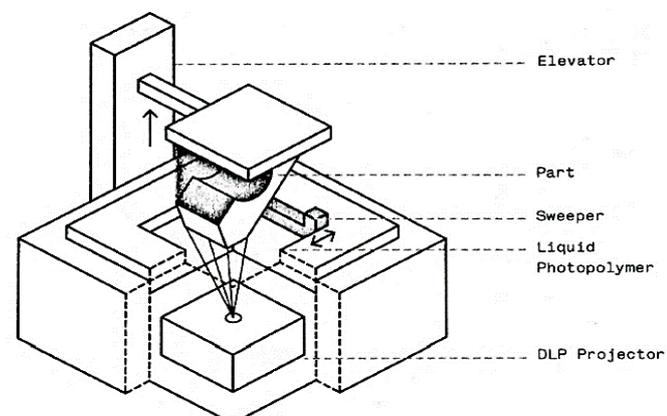


Figure 2.5: A basic schematic of the vat photopolymerization process using the DLP technology. (Redwood et al. 2017)

DMD (Digital Micromirror Device) that control where the light is projected and generate the light pattern on the build surface. (Figure 2.5) (Redwood et al. 2017), [9] [16]

Table 5 Overview on the vat photopolymerization category [16] :

Benefits and limitations	<p>BENEFITS:</p> <ul style="list-style-type: none"> • High level of accuracy, finest details can be print; • Smooth surface finish; • Typically, large build areas: objects 1000: 1000 x 800 x 500 and max model weight of 200 kg; <hr/> <p>LIMITATIONS:</p> <ul style="list-style-type: none"> • Expensive if are used particular resin; • Large flat surfaces and long unsupported spans are most likely to shrink or warp; • Lengthy post processing time due to the resin; • Limited material and color and shelf life of one year in average; • Requires support structures and these can leave marks on the surface and create uneven ones; • Post curing for parts to be strong enough for structural or functional use are required because the photopolymers are brittle; (Redwood et al. 2017)
Materials	Photopolymers, Resin that according to the application could be: transparent, high temperature resistant, dental, cast.
Applications	Parts are most suitable for visual applications and prototyping due to the smooth surface finish is capable to print. Some of the most common applications are: Jewelry, Dental applications, Injection mold like prototypes, hearing aids. (Redwood et al. 2017)

2.2.6 Powder Bed Fusion

Powder bed fusion is an “Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed”. (Technologies et al. 2012)

In the powder bed fusion process category, powder is sintered by thermal energy and solidify in the cross sections of the part.

A typical process provides for: (1) powder is distributed over the build surface, (2) a laser or an electron beam hits the cross section of the part and the material is melted and fused with the previous layer (3) the build plate is lowered for the next layer and (4) the process is repeated until the build is finished. The final component is enclosed in powder that is removed, after a period of cool down, with compressed air and a blasting medium. The parts are then ready to use or are further post processed. There are several printing techniques based on this technology. [16]

Selective laser sintering (SLS) is a technique that uses a high-power laser to sinter powdered material, typically nylon. SLS machines are made up of three components (Gibson et al. 2010): a heat source to fuse the material, typically a laser, a method to control this heat source and a mechanism to add new layers of material over the previous, in general is used a recoating blade. See figure 2.6 for a basic scheme.

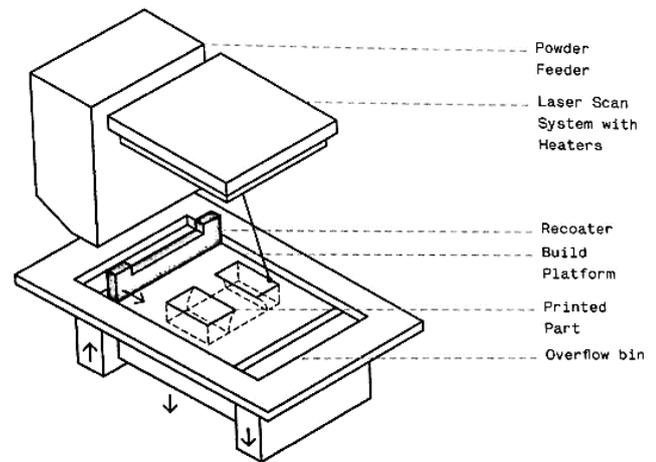


Figure 2.6: A basic schematic of the powder bed fusion process using the SLS technology. (Redwood et al. 2017)

The chamber is thermally controlled, the temperature is usually a few degrees below the melting point of the polymer and, is often filled with nitrogen to maximize oxidation and end quality of the model. Models require a cool down period to ensure a high tolerance and quality of fusion. SLS does not need special support structures because the part being constructed is surrounded by unsintered powder at all times.

Direct metal laser sintering (DMLS) technology prints in metals and produce parts in a similar method as SLS. DMLS doesn't melt the powder but heats it to a point so that the molecules can fuse together. The part produced with DMLS is denser than SLS due to the material used and it is possible to do infiltration to make it fully dense if needed.

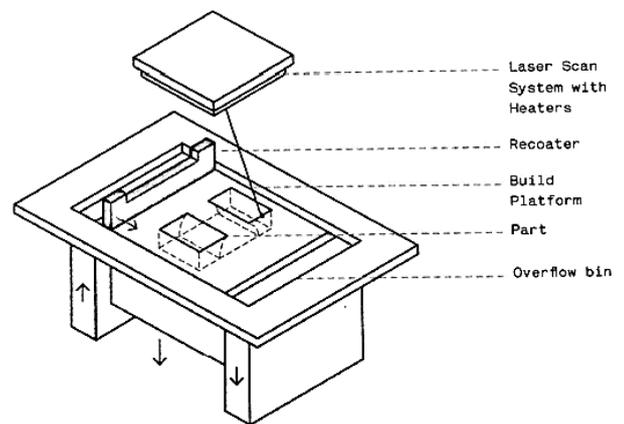


Figure 2.7: A basic schematic of the powder bed fusion process with the DMLS/SLM technology. (Redwood et al. 2017)

Selective laser melting (SLM) technology prints in metals as well and functions similarly to SLS. See figure 2.7. Unlike DMLS, it fully melts the metal material, so the resultant part has a single melting temperature. In comparison with SLS, SLM can produce stronger parts because of reduced porosity and greater control over crystal structure. Furthermore, SLM is often

faster, but has higher energy costs and typically has a poor energy efficiency of 10 to 20 %. (Gibson et al. 2010).

At the end, electron beam melting (EBM) technology uses a high-energy electron beam instead of a laser to fuse metal powders. Inside the working room there must be the vacuum in order to prevent the deflection of the beam caused by the air molecules and to eliminate the impurities, to give strength properties to the material. It has superior build speed and more uniform heat handling than SLM so it is possible to achieve material characteristics similar to cast materials. (Redwood et al. 2017), [8] [17]

Table 6: Overview on the powder bed fusion category [17]:

Benefits and limitations	<p>BENEFITS:</p> <p>SLS:</p> <ul style="list-style-type: none"> • No support structure is needed • Multiple products could be produced simultaneously • Parts are homogeneous due to the initial heating of the build powder • Height level of dimensional accuracy, good strength and often function as end use parts. <p>DMLS:</p> <ul style="list-style-type: none"> • quickly produce a unique part without special tooling • It produces parts with great mechanical properties • Height level of dimensional accuracy • Height level of customization <p>SLM:</p> <ul style="list-style-type: none"> • quickly produce a unique part without special tooling • It produces parts with great mechanical properties • Height level of dimensional accuracy • Height level of customization <p>EBM:</p> <ul style="list-style-type: none"> • high level of accuracy in the trajectory control • high scan speed • material wasted is minimized <p>LIMITATIONS:</p> <ul style="list-style-type: none"> • Size limitations • Finish is dependent on powder grain size <p>SLS:</p> <ul style="list-style-type: none"> • Shrinkage usually occurs in the 3%-3.5% range • Post processing is required due to the powdery grainy finish • Few colours are available • Machines are expensive and need highly skilled operators • LT can be longer than other technologies <p>DMLS:</p> <ul style="list-style-type: none"> • Need support structures • Risk of warping and shrinkage due to the high temperature that produces residual stress • Highly skilled operators are required • Post process is required if is needed a smooth surface finish • Highly cost of material <p>SLM:</p> <ul style="list-style-type: none"> • Need support structures • Risk of warping and shrinkage due to the high temperature that produces residual stress • Highly skilled operators are required • Post process is required if is needed a smooth surface finish
--------------------------	---

	<ul style="list-style-type: none"> Highly cost of material <p>EBM:</p> <ul style="list-style-type: none"> The process can be only used with conductive materials that has expensive powders
Materials	<p>SLS: Material with low thermal conductivity, like thermoplastic material, for example nylon or composite powder of nylon and aluminum or glass or carbon.</p> <p>Any metal that is able to be welded can be used to produce metal parts via DMLS or SLM technology.</p> <p>DMLS: Stainless steel, cobalt chrome, aluminum and titanium.</p> <p>SLM: Stainless steel, cobalt chrome, aluminum and titanium, gold, tungsten, copper. Also precious metal can be use by these two technologies there are deeply used in jewelry field.</p> <p>EBM: Titanium, cobalt chrome, stainless steel, aluminum and copper.</p>
Applications	<p>Modelling and prototyping. Are used increasingly for end use products.</p> <p>SLS: Its usage is increasing in art and industries such as in the aerospace industry, where is needed to create functional parts or hollow sections.</p> <p>DMLS: It is used to manufacture direct parts for a variety of industries including aerospace, dental, jewelry, medical and tooling industry to make direct tooling inserts.</p> <p>SLM: It is used to manufacture direct parts for a variety of industries including aerospace, dental, jewelry, medical and tooling industry to make direct tooling inserts.</p> <p>EBM: The high finish quality of the process makes the part suited to be used in aeroplanes and medical applications.</p>

2.2.7 Material Extrusion

In the material extrusion process category, the material contained in a reservoir is pushed out through a heated nozzle when pressure is applied. If the pressure remains constant the roads that is the resulting extruded material, will flow at a constant rate and will have a constant cross-sectional diameter. Before the material goes out of the nozzle, it is heated (for hot or warm extrusion) and must be in a semi-melted state. Then, it is deposited layer by layer. First layer is built as nozzle deposits material following a pattern, on a build platform. The following layers are added on top of previous layers, meanwhile the platform is lowered to give room for the next layer. These steps are repeated until the build is finished. (Wahlström e Sahlström 2016) Metal extrusion processes may be performed hot, warm, or cold. Each method has its own unique operating parameters.

Schematically, there are several key features that are common to any extrusion-based system:

- Loading of material: the chamber that contains the material must be preloaded.
- Liquification of the material: this step is essential to allow the material to go out through the die or nozzle. The material inside the chamber should be kept in a molten state but should be taken care to maintain it at as low temperature as possible since

some polymers degrade quickly at higher temperatures and could also burn, leaving residue on the inside of the chamber.

- Application of pressure to move the material through the nozzle
- Extrusion
- Plotting according to a predefined path and in a controlled manner: the control software determines the path that the nozzle will follow and furthermore it is responsible of how to fill the material within the outline. This is crucial for the process because there must be clear access for the extrusion head to deposit fill material within the outline without compromising the material that has already been laid down. Additionally, if the material is not laid down close enough to adjacent material, it will not bond effectively.
- Bonding of the material to itself or secondary build materials to form a coherent solid structure (Gibson et al. 2010)

There are two approaches to control the material state. An approach is to use a chemical change to cause solidification. This approach could be helpful, for example, in context where the choice of material is very restricted like biochemical applications. Alternatively, the most commonly used approach is to use the temperature. Inside a reservoir, material is melted so that it can flow out through the nozzle and bond with material pre-deposited, before solidifying. (Gibson et al. 2010)

Extrusion may be continuous and is then cut to a convenient stock size or semi-continuous, producing many pieces. A detailed explanation of all the extrusion's ways is outside the scope of this thesis.

Commonly extruded materials include metals, polymers, some ceramics, composites. Among polymers, the most common are: ABS (Acrylonitrile butadiene styrene), Nylon, PC, AB.

This is one of the most economical and widespread method. It is easily accessible and creates objects that have good structural properties, close to a final production model with a good surface finish.

On the other hand, the speed is low in comparison with other processes and also, the accuracy of the final model is limited by nozzle thickness. (Krar e Gill 2003) Furthermore, the nozzle has a radius and as it is not possible to make a perfectly square nozzle this will affect the final quality of the printed object (Chua et al. 2010)

2.2.7.1 Fused Deposition Model (FDM)

Fused deposition modelling (FDM) is the arguably most prominent technology that goes under the material extrusion process category. The first commercialized and developed fused layer modelling process was registered by Stratasys, USA. [18]

This process is one of the most widely used by consumers, in particular for non-commercial use, due to its ability to build functional parts having complex geometry in reasonable build time (Rayegani e Onwubolu 2014) and because it employs inexpensive machinery and durable part materials. In the last years not just big companies but also engineering, designers, architects and hobbies, give a professional interest to it.

The process utilizes the simple idea of the melting, extrusion, and resolidification of thermoplastic materials. (Wohlers 2014) A spool of thermoplastic material is loaded into the extrusion head and when the nozzle has reached the desire temperature, it is heated to a semi molten state by an electric heating system. Then, it is extruded from the tip of the nozzle as an ultrathin filament and it is deposited, in a prescribed manner, on the platform, where it re-solidifies at chamber temperature. The properties of built parts depend on the settings of various process parameters fixed at the time of fabrication.

The extrusion nozzle moves according to a path defined and the material is deposited on top of the existing layer. When a layer is fully deposit and forms a solid layer, the platform is lowered by the amount of one-layer thickness (Gebhardt 2012), on the z-axis, and the nozzle continues filling until the entire model is filled completely, obtaining an entire three-dimensional object. (Li et al. 2017), [18]

Material layers can be bonded by temperature control or through the usage of chemical agents, as for all the extrusion techniques.

The process has many factors that influence the final model quality. An unexperienced user might find difficulties to set up a 3D-printer, because it requires a deep understanding of the working mechanisms to achieve an accurate print. Potential problems vary from setting the printer, to design of the 3D-model or to configurate the printing software. Consequently, inappropriate setup can lead to various quality problems of the printed part, such as bad surface quality, poor dimensional accuracy, etc. This means that is needed a careful attention in the choice of the process parameters, fixed at the time of fabrication, in order to make the system more precise and repeatable.

FDM has great potential and viability, but it is important to be aware of some limitations and constraints, that can be read as challenges to overcome, to take full advantage of this AM technology. Three of these key limitations [19] are:

- the range of materials you can replicate, you cannot use glass or metals, even if some researches starts in this field with Metal X machine from Markforged;
- difficulties to create finely-detailed items;
- finished product quality issues: The final product is removed manually from the 3D printer, so this operation can adversely impact the quality of the finished product. A careful removing is requested, but despite this, there is no 100% guarantee that you remove the support material without scratching or even more seriously damaging the object;

Support Structures

All AM systems must have a means for supporting free-standing and disconnected features and for keeping all features of a part in place during the fabrication process. In the extrusion-based systems such features must be kept in place by the additional fabrication of supports. (Gibson et al. 2010) Sometimes the use of support can impact the design decision making process. These supports are usually calculated and added to the part by the system's software. They may be formed using the same material of the part, or a different material. (Jacobs e Reid 1992)

The downside of supports is that they can be difficult to remove from small, intricate features without breaking the model and they can also increase the total cost of the print job. Furthermore, they leave imperfections on the surface they are in contact with, resulting in a rougher surface finish that always need post processing to become smoother. (Redwood et al. 2017) [20] This is why the most effective way to remove supports from the part is to fabricate them in a different material.

Many new FDM printers offer dual extrusion, with two printed heads and are able of printing multi-material parts. For these printers two materials are used. The former constitutes the final product, while a dissolvable material could be used as scaffolding. The variation in material properties can be exploited so that supports are easily distinguishable from part material, either chemically, visually or mechanically. Because the support is dissolved in water or solvent, rather than mechanically removed, the surface of the print that was in contact with the support has a superior finish. But, on the other hand, the cost of a build using dissolvable support generally increases because of the price of dissolvable filament. (Redwood et al.

2017) [20] Among the dissolvable polymers the widely used is PVA, a Polyvinyl alcohol water soluble.

If the system is simpler and has just one extruder, supports and parts have to be carefully designed and placed with respect to each other so that they can be separated at a later time.

In general, are used two kinds of support: the most common is a sort of flat accordion, or lattice, and is best suited for most FDM prints. The other type, less popular but preferred by some printers, is a 'tree-like' support. This method has less contact with the print surface and the result is a better surface finish but at the same time it offers less stability. (Redwood et al. 2017) [20]

The printer operator will generally specify the type of support that best suits the application and thus minimizes the aesthetic impact on the design. The location and the amount of support needed by a print are dependent upon part orientation, but it could also be fine a limited amount of support placed in the correct location to allow an accurate finish part.

In general, supports are needed if the model is complex due to layers that have no material to build on, like bridges, or overhanging features that are shallower than 45 degrees relative to the build plate. New layer needs a solid scaffold to hold it up because it cannot be deposited on the thin air.

When there is no layer below to print on, support is added. This allows to print also features that would otherwise not possible to create. [20]

Applications

FDM technologies is challenging the status quo in manufacturing, health care, education. It is the most common Additive manufacturing technologies used to create functional prototype, for commercial and non-commercial use, and rapid tooling pattern. It also suited for creating concept models.

It was employed in aerospace defense industry by TDF (Trainer Development Flight) to produce a large quantity of internal and external elements of the copies of airplanes that they produce in order to train repair technicians. [21]

Also, Soft Play is using FDM to provide small models of large playground equipment and BMW to make ergonomically designed assembly aids that perform better than conventionally made tools. Ducati started to use it to build both concept models and functional prototypes from ABS, polycarbonate. [22] [23]

To categorize some of the most common applications of this technique there are:

Electronics Housing: These are one of the most popular applications for FDM printing. FDM allows the maximum flexibility in terms of design and hours needed. 3D printed enclosures, for examples, offer an effective method of confirming design geometry and several of the materials that can be used for printing enclosures are suitable for end use applications.

Investment casting patterns: Due to the ability of FDM to produce complex geometries and to create parts with no solid infill structure inside, it is a good solution for investment casting patterns.

Homemade prints, jigs and fixture: The high level of customization and complexity that FDM allows with the speed and accuracy given, to make this process suitable for homemade applications, jigs and fixture. Volkswagen Autoeuropa used jigs and fixtures every day on the assembly line. [24]

Form and fit testing: FDM allows to create curves and shapes which otherwise would be difficult to produce using traditional manufacturing techniques. So, this is one of the commonest FDM applications because it provides haptic feedback to the designer and is useful to showcase the geometry. (Redwood et al. 2017)

Materials

Today, printers that use FDM technology are the most widespread, economical and suitable for home and office use. Thanks to this technology is possible to mix material to create objects with different properties and even color in different parts. This fact has led over the years to an important development and marketing of materials with different properties and these researches are continuing due to the necessity to give new properties to final products.

Choosing the right type of material to print objects is becoming increasingly difficult as a result of the wide range of possibilities. PLA and ABS have historically been the two main polymers used but today also other thermoplastic materials, such as PS, PET, Nylon, are available. These materials have very different mechanical characteristics (stiffness, tensile strength, impact resistance), and furthermore can be combined with thermoplastic elastomers with lower stiffness, allowing to obtain products with very different mechanical properties. These materials have different properties and potential and are chosen considering the function of the object to be created and the desired characteristics.

In this study, we focus on the main pure polymers that exist in the market today: PLA, ABS, PET, Nylon, TPU (Flexible) and PC.

In the table 7 is provided a spider graph of the polymer's properties, a short representation of the material, the argument for and against the usage of that material and the field of application. This analysis is done considering that materials are usually graded along 3 categories: mechanical performance, visual quality and process.

[25] The material properties, that will be compared, are:

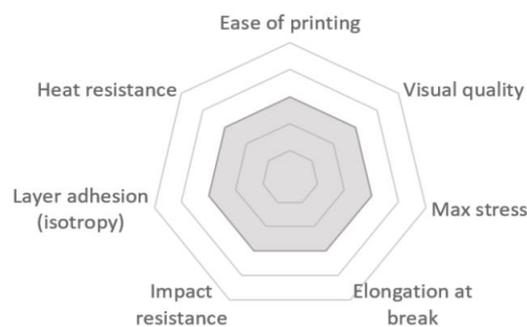
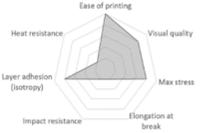
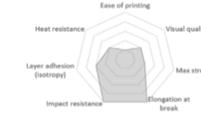
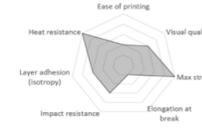


Figure 2.8: Spider graph with material properties

- **Ease of printing:** How easy it is to print a material: bed adhesion, max printing speed, frequency of failed prints, flow accuracy etc.
- **Visual quality:** How good the finished object looks. It is tested without post-processing.
- **Max stress:** Maximum stress the object can undergo before breaking when slowly pulling on it.
- **Elongation at break:** Maximum length the object has been stretched before breaking.
- **Impact resistance:** Energy needed to break an object with a sudden impact.
- **Layer adhesion:** How good the adhesion between layers of material is. It is linked to “isotropy”, uniformity in all directions: better is the layer adhesion, more isotropic the object will be.
- **Heat resistance:** Max temperature the object can sustain before softening and deforming.

Each material has been ranked along the following criteria on a 1 (low) to 5 (high) scale, using the data from [Optimatter](#). [26] The data considered are for an average polymer. (Redwood et al. 2017)

Table 7: Material's overview. [25] [27], [28]:

Material	PLA	ABS	PET	Nylon	TPU	PC
Spider graph						
Characteristics	<p>PLA is the easiest polymer to print. It is a thermoplastic polymer, typically generated by the fermentation of corn or wheat. It is odorless and strongly hygroscopic, so it must be kept in a dry environment because it is water-soluble at temperatures higher than 70 ° C. Its extrusion temperature is between 200 ° - 230 ° C and does not require a heated floor as it has no withdrawal problems. PLA is heavier and less deformable than ABS but has a retraction index of 2-3% and is used to make large and linear objects, where no significant mechanical properties are required. It is very rigid and actually quite strong but is very brittle.</p>	<p>Acrylonitrile-butadiene-styrene (ABS) is a thermoplastic copolymer. It is derived from the polymerized styrene together with the acrylonitrile in the presence of polybutadiene. Styrene gives the ABS a good workability, acrylonitrile the stiffness and the thermal and chemical resistance, while butadiene makes the material more tenacious and resilient, even at low temperatures. ABS doesn't have great resistance to UV rays and is not suitable for contact with food. The extrusion temperature is between 240-260 ° C. It requires a heated surface to be molded, in order to slow down the solidification and allow the base to adhere to the surface avoiding detachment or shrinkage problems.</p>	<p>PolyEthylene Terephthalate (PET) is slightly softer polymer, very light and with good impact resistance. It has good adhesion to the printing surface. Its glass transition temperature is about 60 °C, while the extrusion temperature is about 260 ° C; if the temperature of the process is too high temperature is possible to obtain objects with filamentary surfaces.</p> <p>The Dutch producer FormFutura has developed a new formula of PET, called HDglass, with which very transparent objects are obtained. HD means 'heavy duty' because it is a flexible and extremely resistant material. It has the same strength, durability and heat resistance qualities as other PET filaments, but allows 90% of visible light to pass through, with only 1% distortion.</p>	<p>Nylon is the trade name of a polymer with polyamide base. Nylon possesses great mechanical properties, unlike ABS and PLA, it is less fragile and more resistant. It has a great elongation at break (about 300%), good resistance to abrasion and good resilience. However, Nylon have greater deformations and withdrawals in comparison with ABS, so it needs a heated surface for a better layer adhesion. Moreover, it is a very fibrous material, so the printing speed is limited because it could compromise the realization of the object. The Nylon's extrusion temperature is between 235 ° and 260 ° C.</p> <p>The spider graph is referred to Nylon 6.</p>	<p>Thermoplastic polyurethane (TPU) is mostly used for flexible applications but its very high impact resistance can open for other applications. It has great elasticity, shear and abrasion strength. It does not emit toxic fumes or odors during extrusion and it is printed with temperatures between 240 °C and 260 °C.</p>	<p>Polycarbonate (PC) is the strongest material of all and can be an interesting alternative to ABS as the properties are quite similar. It is a thermoplastic polymer obtained from carbonic acid. Unlike many thermoplastic polymers, it can withstand large plastic deformations without breaking. It has a glass transition temperature of about 150 °C, but to be extruded requires temperatures higher than 260 °C. It needs a 100 °C heated build plate because it has adhesion problems. Polycarbonate absorbs humidity, so it must be kept in airtight containers. If it has absorbed water, the filament becomes white and bubbles are formed during extrusion. To avoid a print quality compromised, it must always be dried.</p>
For Against	<p>FOR:</p> <ul style="list-style-type: none"> Biosourced, Biodegradable Odorless Can be post-processed with sanding paper and painted with acrylics Good UV resistance <p>AGAINST:</p> <ul style="list-style-type: none"> Can't be glued easily Low humidity resistance 	<p>FOR:</p> <ul style="list-style-type: none"> Can be post-processed with acetone vapors for a glossy finish Can be post-processed with sanding paper and painted with acrylics Acetone can also be used as strong glue Good abrasion resistance <p>AGAINST:</p> <ul style="list-style-type: none"> UV sensitive Odor when printing Potentially high fume emissions 	<p>FOR:</p> <ul style="list-style-type: none"> Food safe (FDA pproved) High humidity resistance High chemical resistance Recyclable Good abrasion resistance Can be post-processes with sanding paper and painted with acrylics Can be glued 	<p>FOR:</p> <ul style="list-style-type: none"> Good chemical resistance <p>AGAINST:</p> <ul style="list-style-type: none"> Very low humidity resistance Potentially high fume emissions 	<p>FOR:</p> <ul style="list-style-type: none"> Good abrasion resistance Good resistance to oil and grease <p>AGAINST:</p> <ul style="list-style-type: none"> Can't be glued easily Difficult to post process 	<p>FOR:</p> <ul style="list-style-type: none"> Easy to post-process (sanding) Can be sterilized <p>AGAINST:</p> <ul style="list-style-type: none"> UV sensitive
Applications	General applications	Widely used to create light and rigid objects such as pipes, car parts and toys.	It is suitable for making light objects, it is largely used in food industry.	Thanks to its self-lubricating properties it is used for the production of gears.	It has many applications in the construction of panels for automotive, wheels, power tools and medical devices	It is the ideal filament for printing complex parts, as it does not leave smudges; for this it is widely used in the automotive and aerospace industries.

3. System Modeling

The system analysis is a problem-solving technique that breaks down a system into its component to simplify it. It is essential if exists a need to understand how well the parts of a system are working and are interacting to accomplish their purpose.

If this analysis is well done, it can help a decision maker to make a better decision especially when problems have to be solved or when checks are required.

The aim of this chapter is to explain the choice of the shapes printed and furthermore, describe the system in which the print happens, defining the input parameters, the target values and the work's conditions (feedback, controlling, environment).

This work has been made analyzing carefully literature researches, the preliminary works and research projects conducted by WZL Institute of RWTH Aachen University and examining the MakerBot site to understand how the system works and which parameters can be changed.

3.1 Shape chosen

Although FDM is considered one of the simplest additive manufacturing technique, there are some design limitations and constrains that have to be considered in the early stage of the planning. There are several rules that can be followed in order to achieve a better result. In the table 8 are shown some geometric features, critical for FDM technique and the associated description:

Table 8: Critical geometric features for FDM process (Redwood et al. 2017), [29]:

Wall thickness	A minimum wall thickness of 2 mm is recommended.
Unsupported edges	They cannot be too long otherwise they lose quality and fail to print. Unsupported edges should be no longer then 3.0mm.
Pins	Vertical pins should be no smaller than 3.0 mm in diameter, if an accurate print is required and they have functional task. Smaller diameter pins, less than 5mm diameter, can be made up of only perimeter prints with no infill. This can create a discontinuity between the pin and the rest of the print, resulting in a weak connection that is susceptible to breaking. Nonetheless, a good setting of the parameters can reduce the probability of small pins failing.

Features size	The minimum feature size when printing with FDM is 2.0mm
Clearance	A spacing of 0.5mm should be used when clearance is required between parts. This can be varied depending of the type of fit that is required.
Holes	In particular vertical axis holes are problematic. Holes smaller than 2.0 mm in diameter should be avoided, but in general, if accurate holes are required, after printing is recommended drilling.
Bridges	Unsupported horizontal bridges produced via FDM should have a span no longer than 10mm to avoid sagging. This aspect would be detailed in the second part of this paragraph.
Overhangs	An overhang is when a layer extends outward, potentially unsupported, over the previous layer. Overhanging features less than 45° relative to the horizontal require support material to be accurately print. This aspect would be detailed in the second part of this paragraph.
Embossed and engraved details	If they have to be readable, all embossed and engraved details produced via FDM should be no smaller than 0.6mm wide and 2.0mm high.
Corner	Because the printing nozzle in FDM is circular, corners and edges will have a radius that is equal to the size of the nozzle so cannot never be perfectly precise.

3.1.1 Construction of the CAD models

In this study it was decided to design two shapes that are considered ‘limited features’ by literature and to analyze how the printer works under stressed conditions. It was printed an overhang and a bridge that can be seen as a simply prototype respectively of a connector for a pomp (figure 3.1) and a door hinge (figure 3.2).

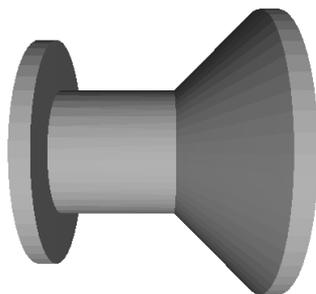


Figure 3.1: Prototype of a connector for a pomp

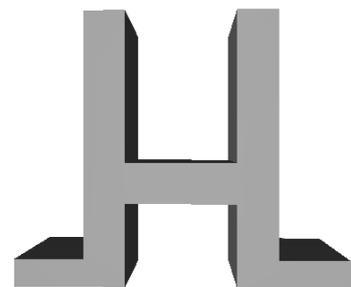


Figure 3.2: Prototype of a door’s hinge

OVERHANG

When the material on the printer layer is partially supported by the layer below there is an overhang.

If the angle, relative to the horizontal, is smaller than 45° it can sag and although it is possible to print it without support material, due to the inherent stickiness of the molten filament, the angled surface begins to suffer in quality so is better to use it. Support allows overhanging features, that are below the 45° threshold, to be printed with precision.

It was decided to print a shape that has a printed layer supported by 50% of the previous layer, so with an overhang of 45° . 45° represents the limit under which is recommended not to print without supports in order to achieve an accurate print, with a smooth surface finish.

Issues with overhang are one of the most common print quality problems relating to FDM. Another issue that occurs when printing overhangs is curling; the newly printed layer becomes increasingly thinner at the edge of the overhang, resulting in differential cooling causing it to deform upward. [29] [30], (Redwood et al. 2017)

BRIDGE

When the printer has to print between two supports or anchor points, bridging occurs.

If the print is done without using support structures there is nothing to build upon, so it is required to 'bridge' a gap, and the material will tend to sag. In general, shorter is the length of the bridge greater is the chance that the bridge will succeed structurally. Instead, longer the bridge is more post processing and support it will require. (Redwood et al. 2017) The bridge printed has a length of 24mm and it has been printed without supports.

Material also plays a role in the maximum length of the bridge that can be printed at.

The usage of supports offers a temporary build platform for the bridging layer to be built upon but needs to be removed once the print has been completed. This can leave marks or damage on the surface where the support was connected to the final part. An advanced solution is to split the design into separate parts or consider some form of post processing if a level and smooth surface is required. [29] [30]

Similar to overhangs, the inadequate support provided by the surface below the build layer can result in poor layer adhesion, bulging or curling. [29] [30]

3.2 Output parameters

To evaluate the final quality of the components produced, it has been selected, from the literature, 4 target variables: printing time, energy consumption, surface roughness and dimensional accuracy.

At the beginning also the mechanical properties such as tensile strength, compressive strength, warping and Young's module were considered but, it hasn't been possible to collect all these data for several reasons.

Warping represent a permanent alteration of the original, regular configuration of a form. In general, it happens when the plastic cools rapidly, contracting itself.

From the definition it is easy to understand that this variable is too generic, it isn't specific, so it is difficult to evaluate. It doesn't exist a standard warping indicator yet.

Compressive strength is the capacity of a material or structure to withstand loads tending to reduce size. Some materials deform irreversibly at their compressive strength limit, others fracture. [31] It wasn't possible to collect these data due to the lack of time, even though there were tools to do it.

Tensile strength is the capacity of a material or structure to withstands loads tending to elongate. [32] It wasn't possible to conduct the test because the parts haven't a shape that can be attached to the arms of the tool and furthermore it would be difficult because the parts were printed in plastic.

The Young's modulus, also known as the elastic modulus, is a measure of the stiffness of a solid material. It is a linear elastic property of solid materials. It is defined by the relationship between stress (force per unit area) and strain (proportional deformation) in a material. [33] For the same reason of the tensile strength, it was not possible to estimate the value of this variable.

3.2.1 Printing time

Printing time was chosen as the first target, due to the generally high influence on manufacturing costs.

It has been considered as an output target to optimize in other works.

For example, Frank et Al. designed that an experiment to model the FDM process. Among the four optimization target variables that were defined, there was also the printing time. (Frank et al. 2015)

Fuhrmann et Al. in their trying to develop a mathematical model of FDM process by two different approaches, have considered printing time as one response to optimize. (2016 IEEE International Symposium on Intelligent Control (ISIC) 2016)

In this work, the data for the printing time have been collected during the printing process, using the MakerBot Desktop software. In fact, setted the input parameters, it was possible to have a preview of the printing time and the quantity of material required. Figure 3.3

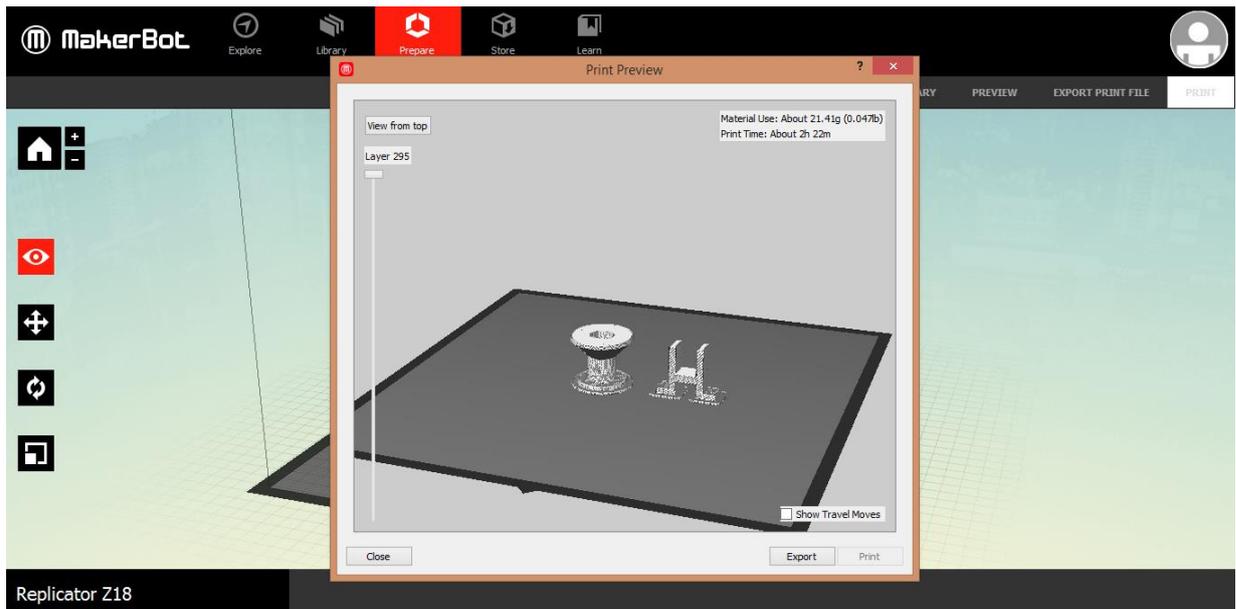


Figure 3.3: Print Preview

3.2.2 Energy consumption

The other target chosen was the energy consumption of the printing process. This choice can be reasoned by the increasing importance of energy efficiency in manufacturing processes in the past years. (Author 2005)

Several authors discussed about it and tried to optimize this and other variables defining a cause-and-effect relationship among input factors and output variables.

Griffiths et Al., for example, used energy consumption as one of the six target variables to optimize. They chose four input parameters and through a full factorial experiment derived which ones were significant for each target variable (Griffiths et al. 2016).

Fuhrmann et Al. created a model of prediction for the output variables, including energy consumption, first defining empirical models based on a specific application scenario and

after analyzing their transferability to other application scenarios. (2017 25th Mediterranean Conference on Control and Automation (MED) 2017)

In this work, the data for the energy consumption have been collected during the process using the Energy Logger 4000 EKM device of VOLTCRAFT. (Attachment 1) Thanks to this device it was possible to acquire the values of energy consumed every minute by the printer. For the scope of the thesis, it was required to cumulate the data related to a single print obtaining just one value of energy consumption for each print. An example of the graph obtained is provided in the attachments. (Attachment 2)

The values of printing time and energy consumption are not representative of a single object printed but being the two parts printed together, represent the values of a single print. Furthermore, it is important to say that printing time and energy consumption can be expected to be heavily influenced by the build size, different for different geometries.

3.2.3 Surface roughness

Surface roughness represents a component of surface texture, so it is an important target used to evaluate the final quality of the part printed. In particular in FDM method is difficult and expensive to control it, because decreasing the roughness of the surface usually increase its manufacturing cost. [34]

In literature, several authors have tried to model the surface roughness as a function of different input parameters.

In 2001, Anitha et Al. analyze the effect of layer thickness, road width and speed deposition on surface roughness of the component produced by FDM, in order to minimize it. To statistically evaluate the data, the authors used the ANOVA method. (Anitha et al. 2001)

Ahn et Al., as well, proposed a new approach to model surface roughness in FDM process. Considering the effects of surface angle, layer thickness, cross-sectional shape of the filament, and overlap interval, the authors formulated the expression that, subsequently have been validated through empirical data. (Ahn et al. 2009)

In this work, the values of surface roughness of each print were measured afterward through a surface roughness tester. It has been taken two measures for the overhang and three for the bridge. Figure 3.4

The parts measured have been chosen in order to show how much important is the orientation of the printing part, using this technique. It was expected that under the bridge and the body of the overhang were rougher than the upperpart of the overhang and of the bridge because they have been printed in the orientation of the figure. This expectation was confirmed analyzing the Ra values, the mean roughness that quantifies the quality.

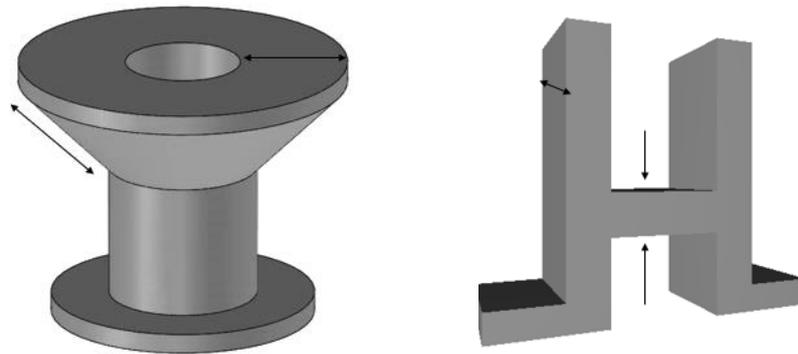


Figure 3.4: Measurements for the surface roughness

In order to achieve a better measurement, it was marked, in each part, the point where to start the measurement and this point was the same in every shape. An example of the graph obtained by surface roughness tester is provided in the attachments. (Attachment 3)

3.2.4 Dimensional accuracy

The objects printed were measured using a digital caliber with precision hundredth of a millimeter. The parts were marked, and it was taken one measure for each dimension, afterwards.

The parts measured have been chosen considering the ones on which a minimum tolerance had to be applied and the classical ones (total height, total width and total length). (Figure 3.5). For the analysis' purpose, just the first ones (in red in Figure 3.5) have been considered because since they were created as prototypes of fittings, the dimensions can vary within certain limits.

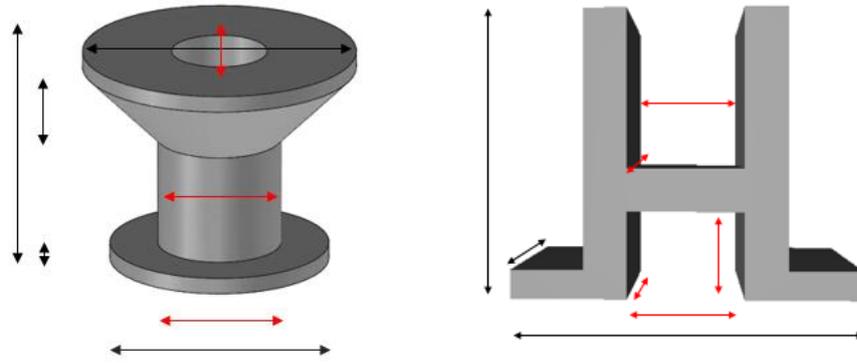


Figure 3.5: Measurements of dimensional accuracy

Various research projects investigate the effect of process variables on the dimensional accuracy. For example, in 2005, Pennington et Al. investigated the dimensional accuracy of prototypes built using FDM through a fully factorial experiment. Here the component size, the position on the working surface and the envelope temperature were found to be significant influences on dimensional stability. (Pennington et al. 2005)

In 2015, Huang et Al. developed an approach to model and predict part shrinkage and derive an optimal shrinkage compensation plan, changing the CAD model design, in order to achieve a better dimensional accuracy. Their approach was demonstrated in stereolithography process. (Huang et al. 2015)

3.3 Input parameters

A list of significant input variables has been done analyzing several literary papers. In categories:

- *Process-specific influencing variables*: Layer height, Bed temperature, Nozzle Temperature, Fill Density, Print Speed, Infill speed, Retraction distance, Retraction speed, Initial layer thickness, Initial layer line width, Bottom layer speed, Raster angle, Raster width, Air gap, Number of shells, Shell thickness, Bottom/Top thickness, Outer shell speed, Inner shell speed
- *Machine-specific influencing variables*: Nozzle diameter, Speed of material feeding rollers, Filament width, Layer thickness, Platform adhesion type, Temperature of removal, Filament diameter
- *Geometries-specific influencing variables*: Part orientation, Particular features.

These parameters were first reduced checking the MakerBot website, <https://www.makerbot.com>, finding the ones effectively changeable on the printer and second creating a qualitative matrix of correlation to eliminate the parameters not statistically significant. A qualitative scale of 1-5 has been used.

5 means that it has been found three or more authors that have discussed about that correlation, so it has been supposed that really exists a relationship among the two variables considered.

4 means that it has been found two papers that show the existence of a correlation among the variables.

3 means that it has been found one paper that shows a correlation among the variables.

2 one paper suggests that it doesn't exist a correlation.

1 more papers suggest that there isn't a correlation.

This matrix was also filled out by experts so, the final one represented a weighted mix of literature and practical experience. (Attachment 4)

At the end, were chosen the six input parameters that had at least one 4 in the correlation matrix. The part orientation variable resulted difficult to evaluate so it has been decided to delete it.

1. Layer height:

Layer height represents the thickness of each printed layer. It is basically equivalent to vertical resolution in 3D printed objects. Thinner is the layer smoother is the texture of object printed but more time is required. [35] [36]

It depends upon the type of nozzle used. (Sood et al. 2012) The standard nozzle diameter on MakerBot is .4 mm so, this is the slightest layer height you can print with this nozzle.

This variable has strongly been used in literature researches. Some investigations were conducted by Frank et Al., Onwubolu et Al., Griffiths et Al., Pandey et Al., Ziemian et Al., Pennington et Al., Anitha et Al. Sood et Al. (Frank et al. 2015), (Onwubolu e Rayegani 2014), (Griffiths et al. 2016), (Pandey et al. 2003), (Ziemian e Crawn 2001), (Pennington et al. 2005), (Anitha et al. 2001), (Sood et al. 2012).

2. Fill density:

The infill percentage gives the support structure inside the object. It can be varied depending on the application of the part.

The density of a print change, changing the infill percentage. A higher percentage will result in a stronger object, while 0% infill will make the object hollow. If there is the necessity to create a prototype only used for form and fit testing, the infill percentage can be decreased, allowing the part to be made at a lower cost and faster. (Redwood et al. 2017), [37] [38] [36]

Griffiths et Al. used this variable, as one of the four parameters, trying to investigate if exists a correlation among these and target variables. (Griffiths et al. 2016)

3. Temperature of extruder:

The temperature of the extruder is the temperature of the nozzle. It affects the viscosity of the polymer. [39]

In Frank et Al.'s research has been shown that the high temperature of the nozzle strongly impacts the shrinkage. (Frank et al. 2015)

Kaveh et Al. investigated the effect of the temperature of the extruder on precision and internal cavity of geometries printed with FDM. The results showed that the temperature have effect on both target. (Kaveh et al. 2015)

4. Number of shells:

A shell is a border that is printed for each layer. It makes up the surface of your prints. The minimum number of shells printed per layer is one. (Griffiths et al. 2016) Adding more shells does not affect its external dimensions but can make your object stronger. [37] [36]

The number of shells was the other variable that Griffiths et Al. used in the research. (Griffiths et al. 2016)

5. Print speed:

This factor specifies the printing speed that is used during printing. It influences the speed with which material is deposited. [37]

Frank et Al., for example, included print speed as one of the seven input parameters for the experiment and discovered that this factor had a statistic influence on the overall time needed to finish a printed part. (Frank et al. 2015)

6. Retraction speed:

The retraction speed parameter gives information on how fast the filament is retracted. This parameter is not so often considered in investigations but, since two parts were printed together it has been supposed that set how rapid the filament retract could have a significant impact on the final quality of the print.

3.4 Feedback, Control and Environment

The system under consideration was the MakerBot z18, that is considered one of the easier to use printer available in the market, due to the customer support offered by the producer and the big community that used it.

It provides an answer to the challenge of fast speed, better reliability and free design with an impressive build volume (30.0 L x 30.5 W x 45.7 H cm). [40] Figure 3.6.



Figure 3.6: Makerbot z18

Released alongside the Replicator Mini and 5th Generation Replicator, the Z18 offers a layer resolution of 100 microns and an on-board camera to remotely monitor the print progress.

Shortly, in the FDM process that uses MakerBot z18, the filament is fed into the extruder of printer, where it is heated to a temperature high enough to melt it. Then, it is extruded from the nozzles to create an object each layer at a time. The nozzle had the diameter of 0.4 mm.

This printer hasn't a heated build plate, it operates in a temperature among 15-24°C so with a room temperature.

In order to achieve an accurate print, before the printing process is important to check some aspects like the cleanliness of the nozzle, if there are any plastic debris off on the build plate, if the extruder cooling fan works well or if the threaded rods within print chamber are lubricate and not squeak.

During the process, the system provides some feedback as well. It cannot start to print if the lid isn't locked or if the filament is not sufficiently pulled in the extruder. Furthermore, it gives a message if the filament is jammed or runs out and if the temperature of the extruder is higher than 50°C after the printing. [41]

Through the MakerBot Desktop application it is allowed to prepare, manage and monitor the print. There are two tabs to set the variables, the quick tab (figure 3.7) and the custom settings tab (figure 3.8). Apart from the input variables chosen, all the other variables have been left as suggested by the producer. Furthermore, the prints have been realized with the rafts on in order to ensure a perfect adhesion with the build plate and because is easy to remove it once the print is finished, avoid ruining the surface.

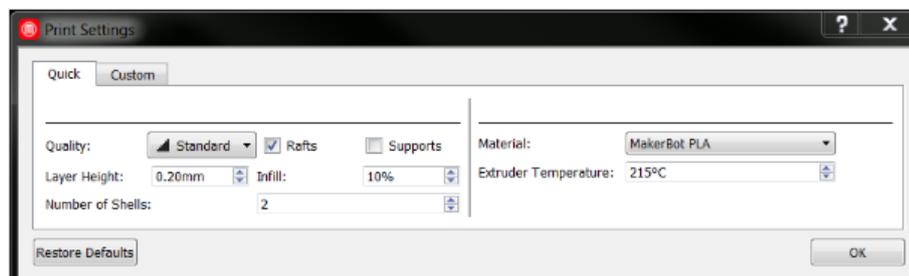


Figure 3.7: Quick setting Tab

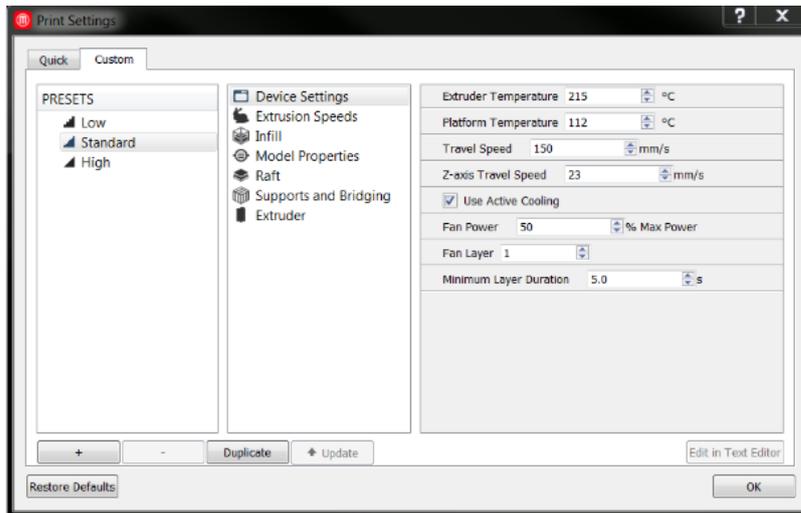


Figure 3.8: Custom Settings Tab

4. Experimental execution of the test and analysis of results

In this chapter will be analyzed the last steps of the design of experiment started in the chapter 2 and 3 with the recognition and the statement of the problem and the selection of the response variables and factors. It will be given a reason for the values chose as levels of factors, for the type of experiment selected and furthermore, it will explain how the experiment was performed and how the data have been analyzed.

To plan the experiment, it has been studied the book of Montgomery, “Design and Analysis of Experiments” about the design of experiment’s technique.

The design of experiment investigates the effects of several input variables (factors) on an output variable (response) at the same time and in a system not yet known. Factors are varied together, instead of one at a time. Practically, it consisted of a series of runs in which the input variables are changed purposefully. [42]

Experimental design methods are deeply used in engineering design activities or in early stages of a process development because it could improve the quality and save design cost by reducing re-work, if performed in the initial design phase. Its common applications include the evaluation and comparison of basic design configurations, selection of key product design parameters that impact product performance, identification of the process conditions in a system not known in order to make improvements in process yields or reductions of the overall costs. (Design and analysis of experiments 2013)

To obtain an accurate experiment is needed a clear idea in advance in terms of what to study, how the data will be collected and must be followed some basic principles like randomization, replication and blocking. (Design and analysis of experiments 2013)

Randomizing properly the runs is possible to reduce the effects factors not included in the model but that maybe exist, averaging out the bias. Minitab provides a randomization by default, except Taguchi designs.

The replication principle consists of repeating each run within an experiment. Replications allow to estimate experimental errors ad furthermore the variance decrease if the numbers of replications increase.

The last principle is blocking. A block is a group of relatively homogeneous experimental conditions, used to reduce the variability transmitted from nuisance factors, improving the precision with which comparisons among the factors of interest are made. Nuisance factors

are factors not directly interesting for the analysis but that may impact the responses. (Design and analysis of experiments 2013)

In this work, to create, analyze and visualize the designed experiment it has been used the commercial software Minitab, a complete software that offers several analytical tools, graph tools and statistics to help the understanding and interpretations of the results.

4.1: Elaboration of experimental plan

Among the designed experiments offered by Minitab, it has been chosen a fractional factorial design.

A factorial design is the simplest type of multivariate experimental plan. It is a randomized k-factors experiment in which it is wished to study k factors and where each factor can occur on only 2 levels. Complete a full factorial design would take too long so, it was assumed that certain interactions of high-order are negligible, so it is possible to execute only a fraction of the complete factorial experiment.

This design choice is justified by the multiple factors being tested and by the fact that using a factorial design, there is the possibility to build the factorial portion of the design up into a central composite design that make possible the estimation of the curvature by adding axial points.

Furthermore, these fractional factorial designs are commonly used in screening applications, experiment in which for example the process is new, and the goal is to find a relationship (if exists) among input and output.

Created the experimental plan then, the response surface methodology has been used to create the regression models, defining the relationships among input and output parameters.

The Response surface methodology (RSM) represents a useful technique to model and analyze problems in which an interest response is influenced by several variables and the goal is to optimize this response. (Design and analysis of experiments 2013)

In general, in the problem in which RSM technique is used, the form of the relationship between the response and the independent variables is unknown and the aim is to find a suitable approximation or the 'true' functional relationship between y and the set of independent variables.

4.1.1 Adopted experimental design

In this work it was decided to use a $2^{(6-1)}$ factorial experiment, that consists precisely of half the complete 2^6 factorial experiment.

The preceding $2^{(6-1)}$ design is called a resolution VI design. These are designs in which no main effect or two-factor or three factor interactions is aliased with any other main effect or two-factor interaction or three factor interactions but three factor interactions are aliased with four factor interactions.

Minitab offers several designs, depending on the requirements of the experiment. As already discussed was chosen the factorial design, in particular the 2-level factorial design. In the main 'create factorial design dialog box' it was possible to set 6 as the number of factors and to select a resolution VI design. Figure 4.1

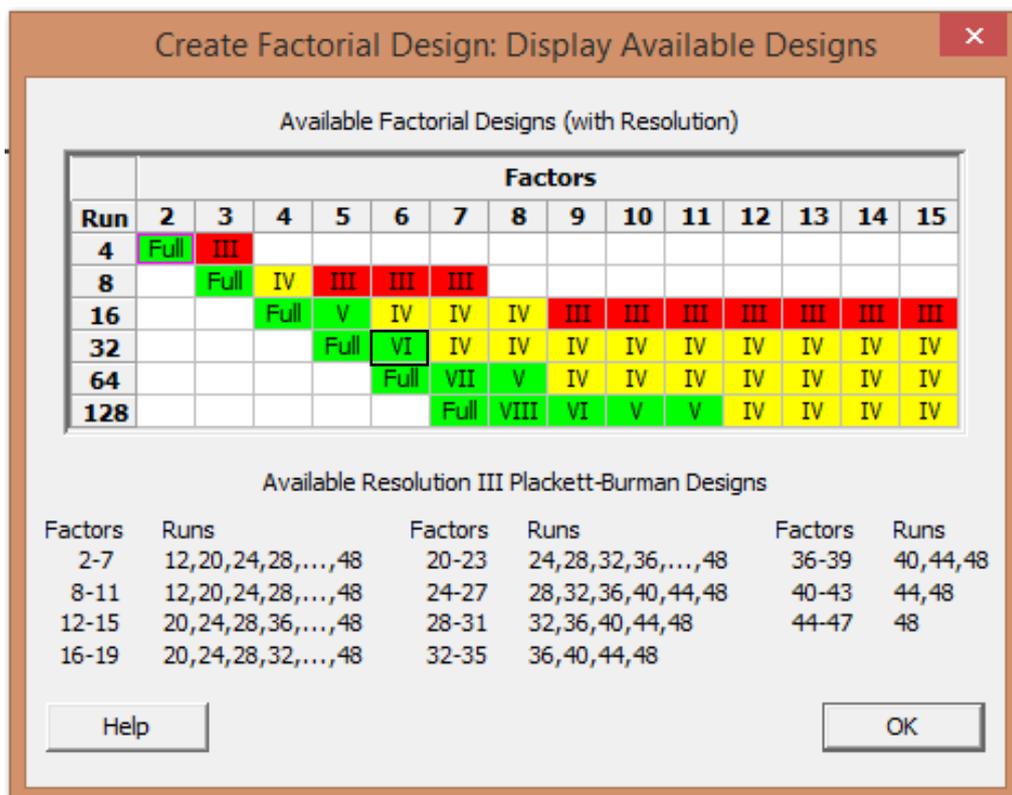


Figure 4.1: Design chosen

Consequently, the number of required experimental runs were 32, in each run, the factors were varied together.

To these there were added 4 center point. The way Minitab adds center points to the design depends on the type of data: text, numeric, or a combination of text and numeric factors. [43] [44]

In a central composite design and in a response surface design in general, is possible to designate a low level and a high level for each factor. These factor levels define the proportions of the "cube" around which the design is built. [45]

The levels chosen for each factor have been named “minimum value” and “maximum value” and they have been obtained within a range of the default values, giving a weight to the values recommended by the producer, to used values in literature and empirical tests of these parameters. (Table 9)

Table 9: Levels of factors

Number	Factor	Minimum value	Maximum value	Default
1	Layer height	0.12mm	0.31mm	0.20mm
2	Fill density	5%	20%	10%
3	Temperature of extruder	205°C	220°C	215°C
4	Number of shells	1	3	2
5	Print speed	140mm/s	160mm/s	150mm/s
6	Retraction speed	45mm/s	60mm/s	50mm/s

As Minitab uses the factor names as the labels for the factors on the analysis output and graphs, in order to make the functions more readable it has been preferred to use just one letter for factors.

Below, the legend for each factor:

L: layer height;

F: fill density;

T: temperature of extruder;

S: number of shells;

P: print speed;

R: retraction speed;

Created the design, Minitab stores design information and factors and the experiment can start.

4.2 Execution of experimental plan

During the execution, the silver filament of PLA that it was being using, finished so it was necessary to change it. It was decided to use another PLA filament with the same characteristics (same diameter, 1.75mm, same producer) of the silver one but that had different batch and color.

In order to prove that the behavior of the filament has not changed, an analysis of variance (ANOVA One-Way) was done, even if the analysis of variance has a much wider application than this. [46] The aim was to compare if exists a significant difference in the results between the two filaments.

It was printed other 4 prints at the end of the experiment. These prints had the same values of factors respectively of: 1th, 9th, 17th and 25th print.

The principle behind the One-Way ANOVA is to test the equality of two or more population means when you have one categorical factor. In the case analyzed the two filaments were considered as two levels of the same factor and each response was considered separately.

Some assumptions were made in order to ensure valid results: the continuity of the response variable, the independence of each observation from the others and the normality of the sample data. [47] Furthermore, to verify the equality of the variance it has been considered the Levene test [48] because it has been used a small sample. The results showed that the null hypothesis of equality of variance could not be refused so, it was assumed an equal variance among filaments.

Generally, in the ANOVA test, the null hypothesis states the equality of the population means instead the alternative one states that at least one of them is not equal.

In figure 4.2 is represented an example of the test for the equality of the variance and an ANOVA output for DA5.

To determine whether any of the differences between the means were statistically significant or if it was possible to say that exist no difference among the variances, it has been compared the significance level ($\alpha=0.05$) with the p-value.

P-value represents the probability that the statistic test takes the value that is at least as extreme as the observed value of the statistic when the null hypothesis H_0 is true. In other words, it is the smallest level of significance that would lead to rejection of the null hypothesis H_0 and furthermore, it is the smallest level at which the data are significant. (Design and analysis of experiments 2013)

If $p\text{-value} > 0.05$: The differences between the means are not statistically significant, the null hypothesis cannot be rejected;

If $p\text{-value} \leq 0.05$: The differences between some of the means are statistically significant, the null hypothesis is rejected, the two means are not equal;

Usually, a significance level (denoted as α or alpha) of 0.05 works well. This significance level indicates a 5% risk of concluding that a difference exists when there is no actual difference. (Error I type).

Figure 4.2: An example of the equality of the variance test for DA5

Test for Equal Variances: DA5 (Internal Bottom Height) versus Group

Method

Null hypothesis All variances are equal
 Alternative hypothesis At least one variance is different
 Significance level $\alpha = 0,05$

95% Bonferroni Confidence Intervals for Standard Deviations

Group	N	StDev	CI
1	4	0,197379	(0,0378503; 2,34112)
2	4	0,037417	(0,0080535; 0,39540)

Individual confidence level = 97,5%

Tests

Method	Test	
	Statistic	P-Value
Multiple comparisons	4,28	0,039
Levene	1,10	0,335

One-way ANOVA: DA5 (Internal Bottom Height) versus Group

Method

Null hypothesis All means are equal
 Alternative hypothesis At least one mean is different
 Significance level $\alpha = 0,05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Group	2	1; 2

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Group	1	0,001012	0,83%	0,001012	0,001012	0,05	0,830
Error	6	0,121075	99,17%	0,121075	0,020179		
Total	7	0,122087	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,142053	0,83%	0,00%	0,215244	0,00%

Means

Group	N	Mean	StDev	95% CI
1	4	10,2225	0,1974	(10,0487; 10,3963)
2	4	10,2000	0,0374	(10,0262; 10,3738)

Pooled StDev = 0,142053

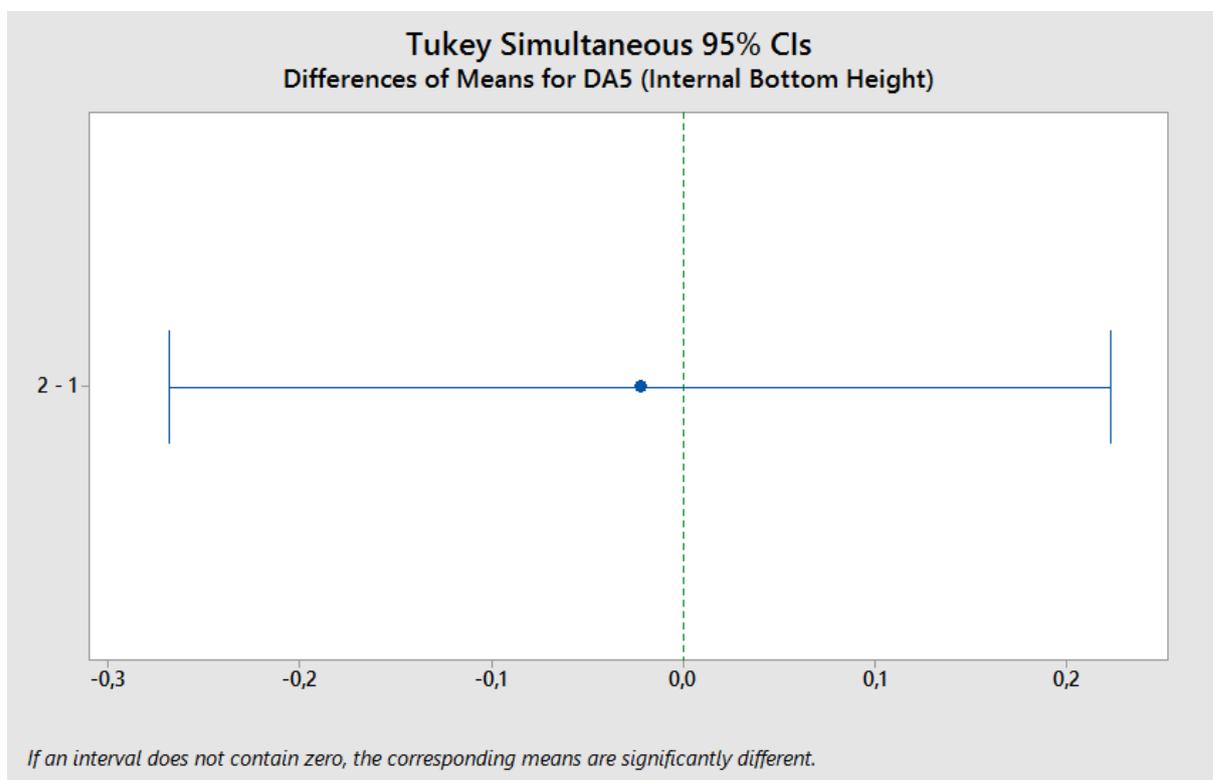
Quoting all the analysis only serves to weigh down the text so, it was thought to summarize in a table the p-value found for each One-Way ANOVA run.

Response	p-value
SR1 (Overhang Bottom)	0.817
SR3 (Internal Bottom)	0.495
SR4 (Internal Top)	0.661
SR5 (Lateral)	0.712
DA1 (Internal Diameter Top)	0.130
DA2 (Internal Diameter Bottom)	0.202
DA3 (Cylinder diameter)	0.222
DA4 (Internal Bottom Width)	0.681
DA5 (Internal Bottom Height)	0.830
DA6 (Internal Bottom Length)	0.824
DA7 (Internal Top Length)	0.823
DA8 (Internal Top Width)	0.409

All p-values have confirmed that the null hypothesis could not be rejected at that level of significance so, it cannot be affirmed that the two population means were different.

Furthermore, also the Tukey comparison results confirmed that it cannot be said that the filament behavior is not the same. The graph that include the Tukey simultaneous confidence intervals shows a range that include zero, which indicates that the difference between the means is not significant. [49] The data were analyzed with a significant level of 5%, so Minitab gives a 95% confidence interval. An example of the graph obtained is provided in figure 4.3.

Figure 4.3: Graph with the Tukey Simultaneous Confidence intervals



NOTE: the response energy consumption and printing time were not considered because in both cases assumed the same values.

The response SR2 has not be considered because the upper part of the overhang was ruined. In fact, while the nozzle extruded the filament, the piece was moving because there was a lack of adhesion with the build plate.

4.3 Analysis of functions

Following the execution, the 36 parts were printed, and data collected. The printing time and the energy consumption data were measured during the printing process for each print, as already discussed. Instead, the surface roughness and the dimensional accuracy data were measured afterwards.

Thought the software Minitab, all the data from the 36 trials were statistically analyzed to reveal the cause-and-effect relationships between the six factors and the fifteen responses.

First a qualitative analysis for each target was done. It was used the 'Main effect plot' and the 'Interaction plot', two factorial plots to illustrate the main effects and interaction effects respectively.

The main effect plot is helpful to examine differences among level means for one or more factors. It graphs the response mean for each factor level connected by a line, but it does not show any interactions that are present.

If there is no main effect present, the line is horizontal, parallel to the x-axis. Each level of the factor affects the response in the same way, and the response mean is the same across all factor levels. [45]

Otherwise, if there is a main effect present the line is not horizontal. Different levels of the factor affect the response differently. The steeper is the slope of the line, the greater is the magnitude of the main effect. [50]

The interaction plot is used to visualize possible interactions, so when the effect of one factor depends on the level of the other factor. Minitab drew a matrix of interaction plots because there entered 6 factors.

If there is no interaction, the lines in the plot are parallel.

If there is, the higher is the degree of interaction, the greater is the difference in slope between the lines. [46]

However, the interaction plot does not tell if the interaction is statistically significant. [51]

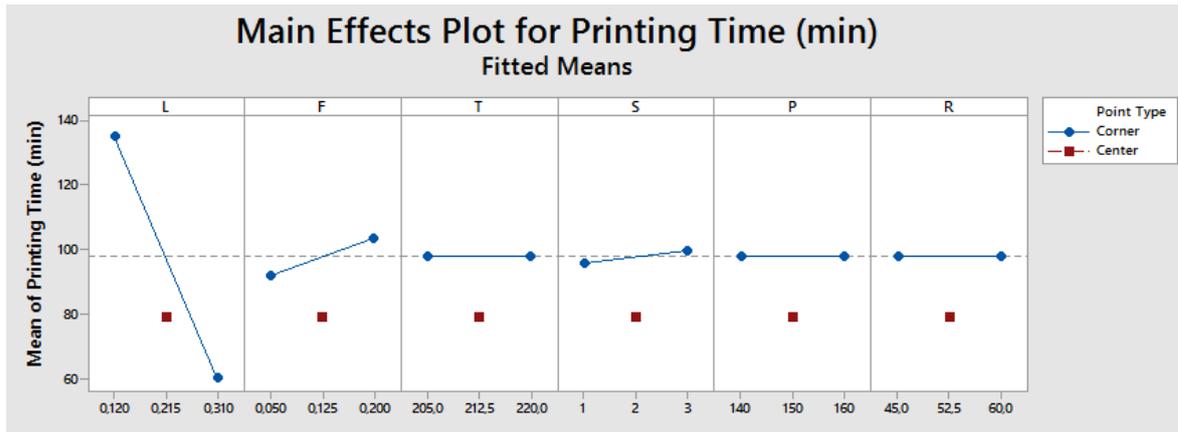
In figure 4.4 are shown the main effect plot and the interaction plot for Printing Time.

In figure 4.5 are shown the main effect plot and the interaction plot for Energy Consumption.

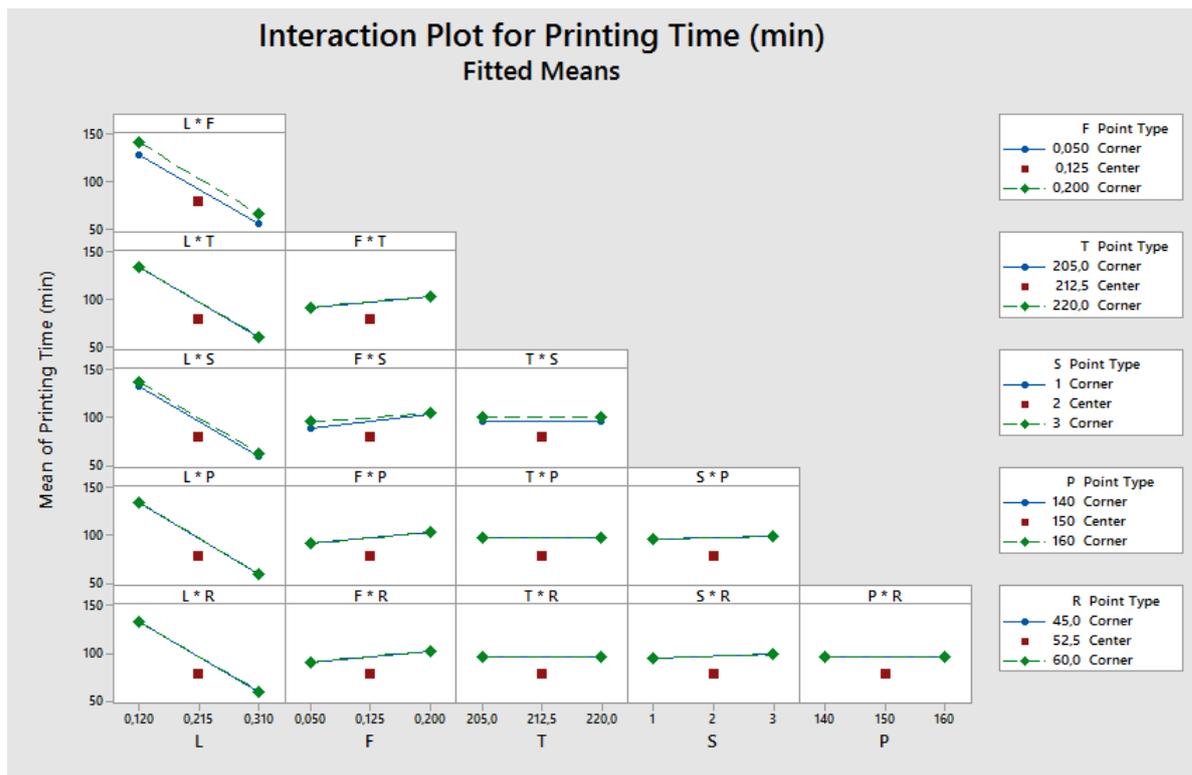
In figure 4.6 are shown the main effect plot and the interaction plot Surface Roughness SR1

and in figure 4.7 are shown the main effect plot and the interaction plot dimensional accuracy DA1.

Figure 4.4: Main effect plot and interaction plot for PT



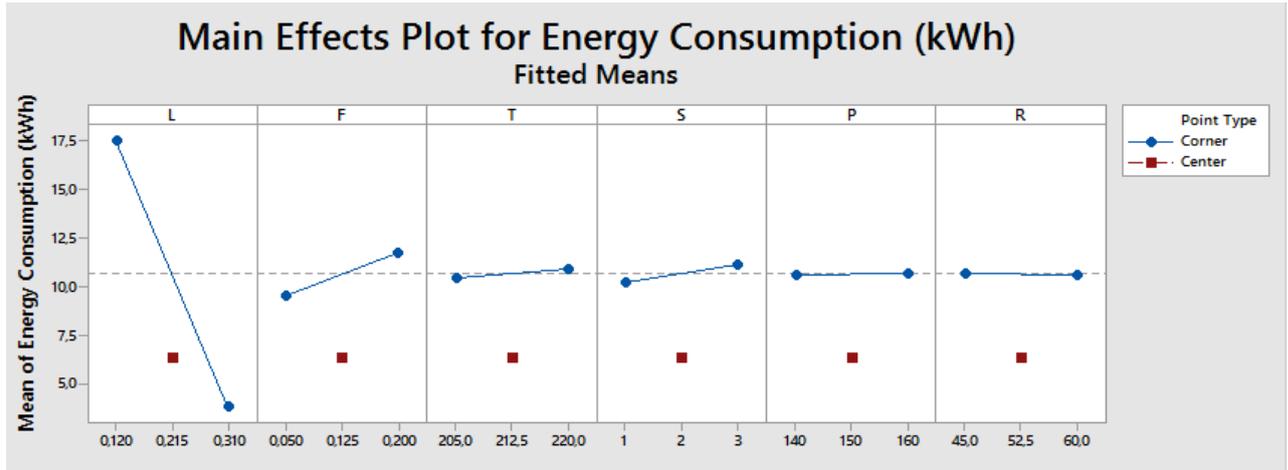
Layer height appears to strongly affect the Printing Time because the line is not horizontal. 0.120 has a higher Printing Time mean than 0.310. Fill density also affects the printing time but less than layer height. 0.200 has a higher Printing Time mean than 0.05. The other ones are almost horizontal lines. The reference line represents the overall mean.



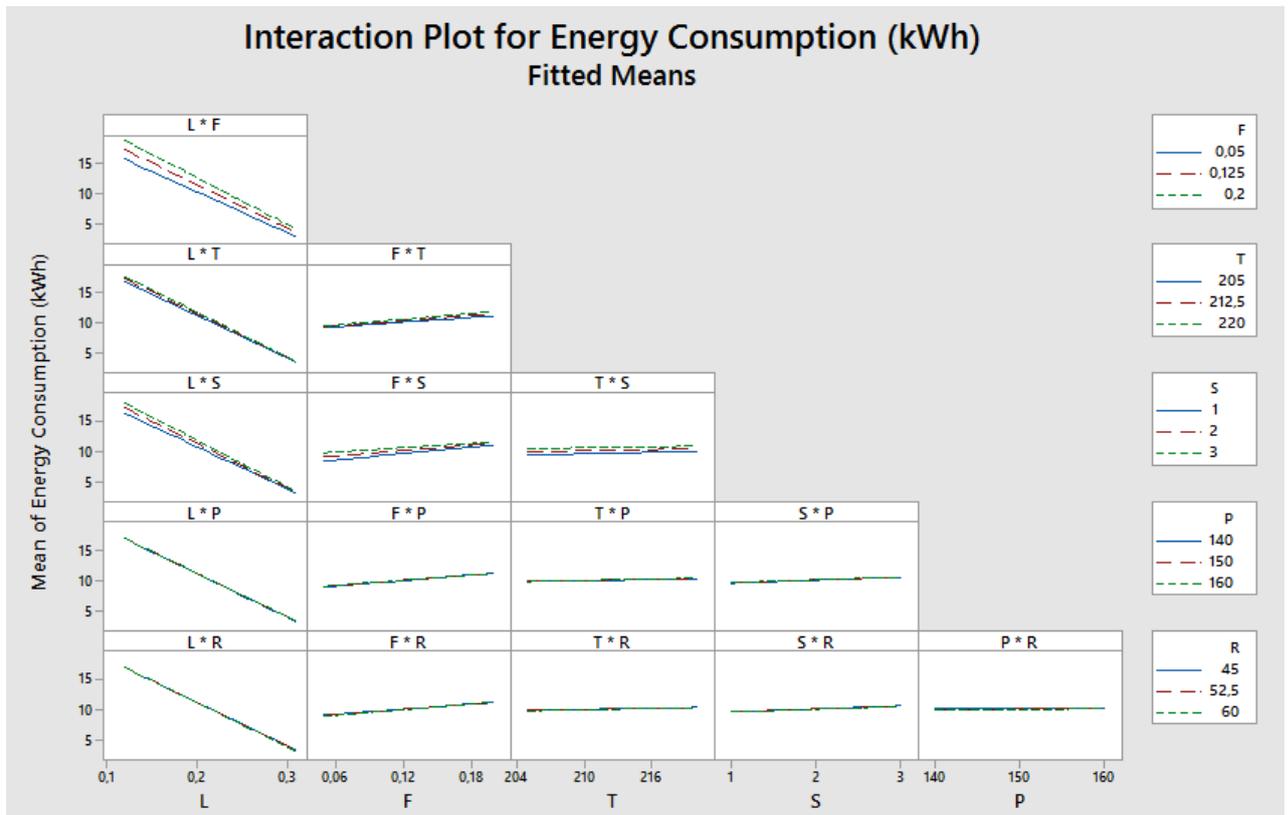
This plot indicates a small interaction between the Fill Density (F) and the Numbers of shell (S).

The other factors seem to have no interactions.

Figure 4.5: Main effect plot and interaction plot for EC

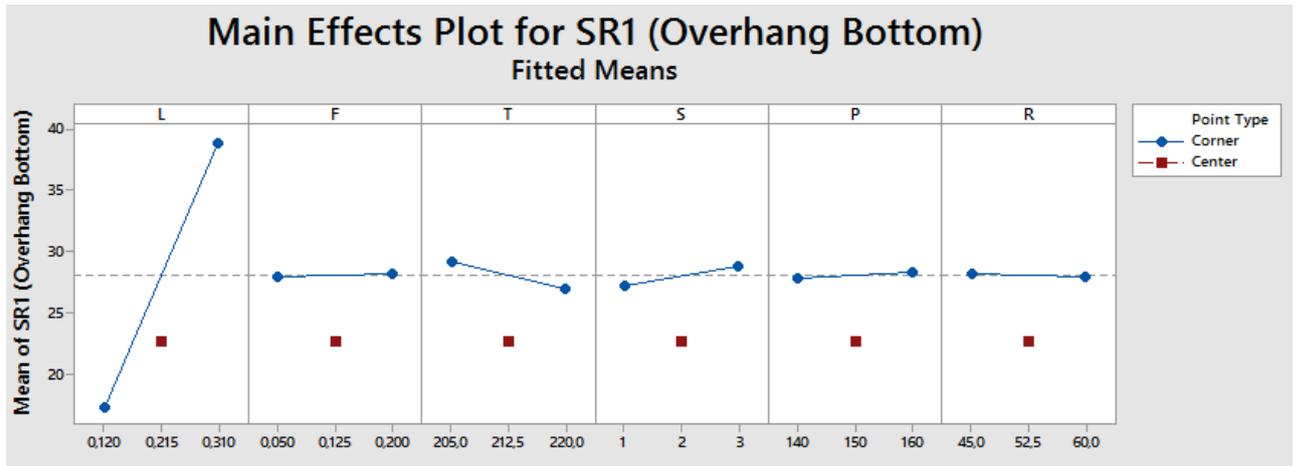


Also for Energy Consumption, layer height appears to strongly affect it (the line is not horizontal). Again, 0.120 has a higher Energy Consumption mean than 0.310. Fill density affects the Energy Consumption as well but less than layer height. 0.200 has a higher Energy Consumption mean than 0.05. The other ones are almost horizontal lines, except for the number of shells that has a small slope.

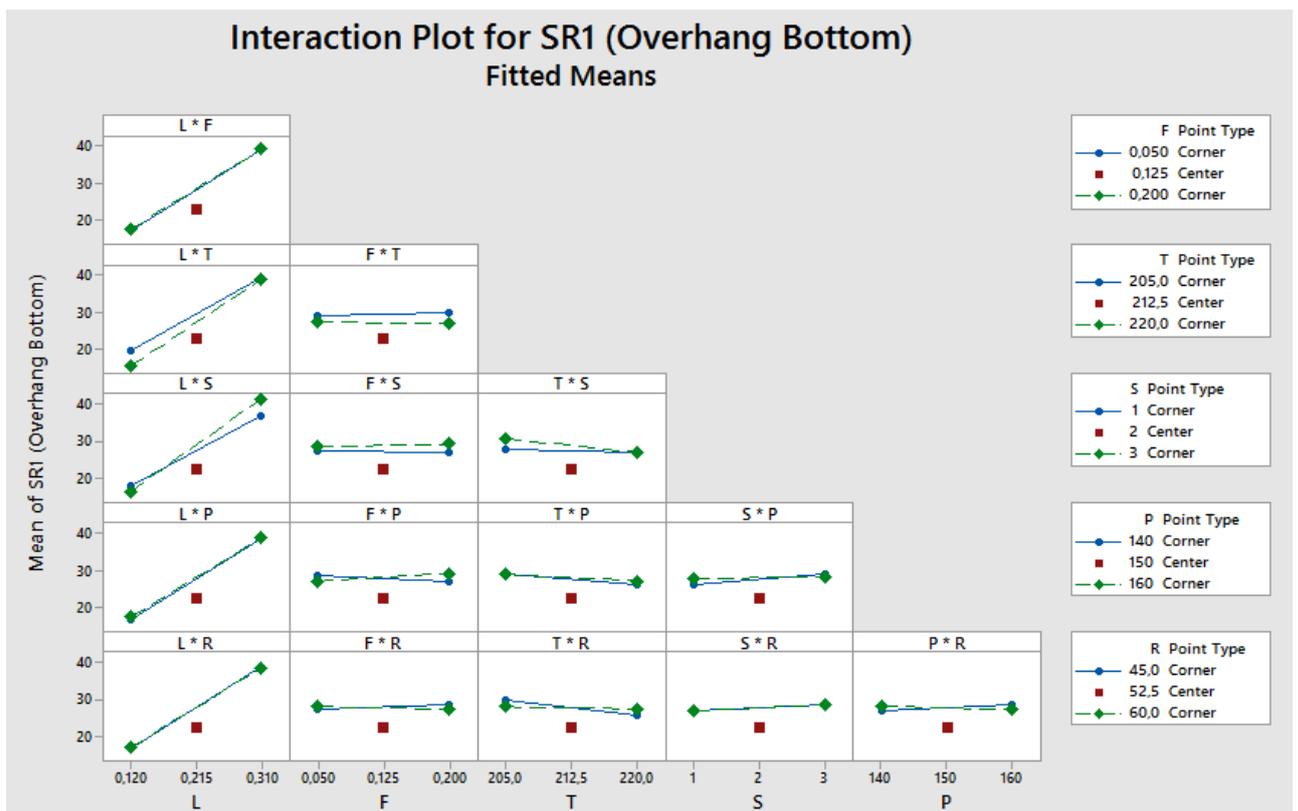


This plot indicates that no factors have interactions.

Figure 4.6: Main effect plot and interaction plot for SR1

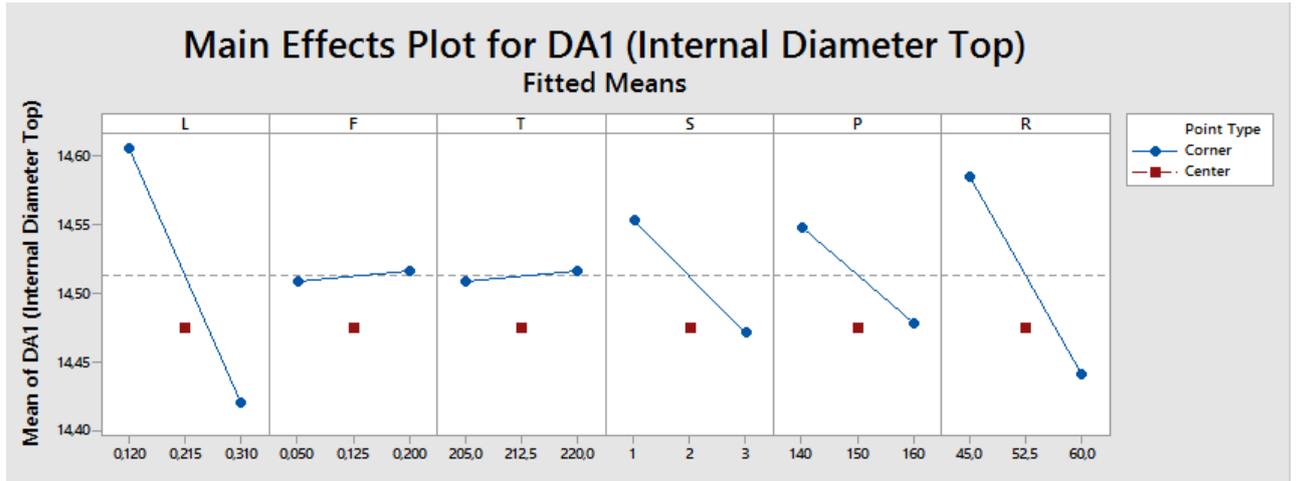


For SR1, layer height appears to strongly affect it. But this time, 0.310 has a higher SR1 mean than 0.120. Temperature of extruder and the Number of shells affect the SR1 but less than layer height. The other ones are almost horizontal lines.

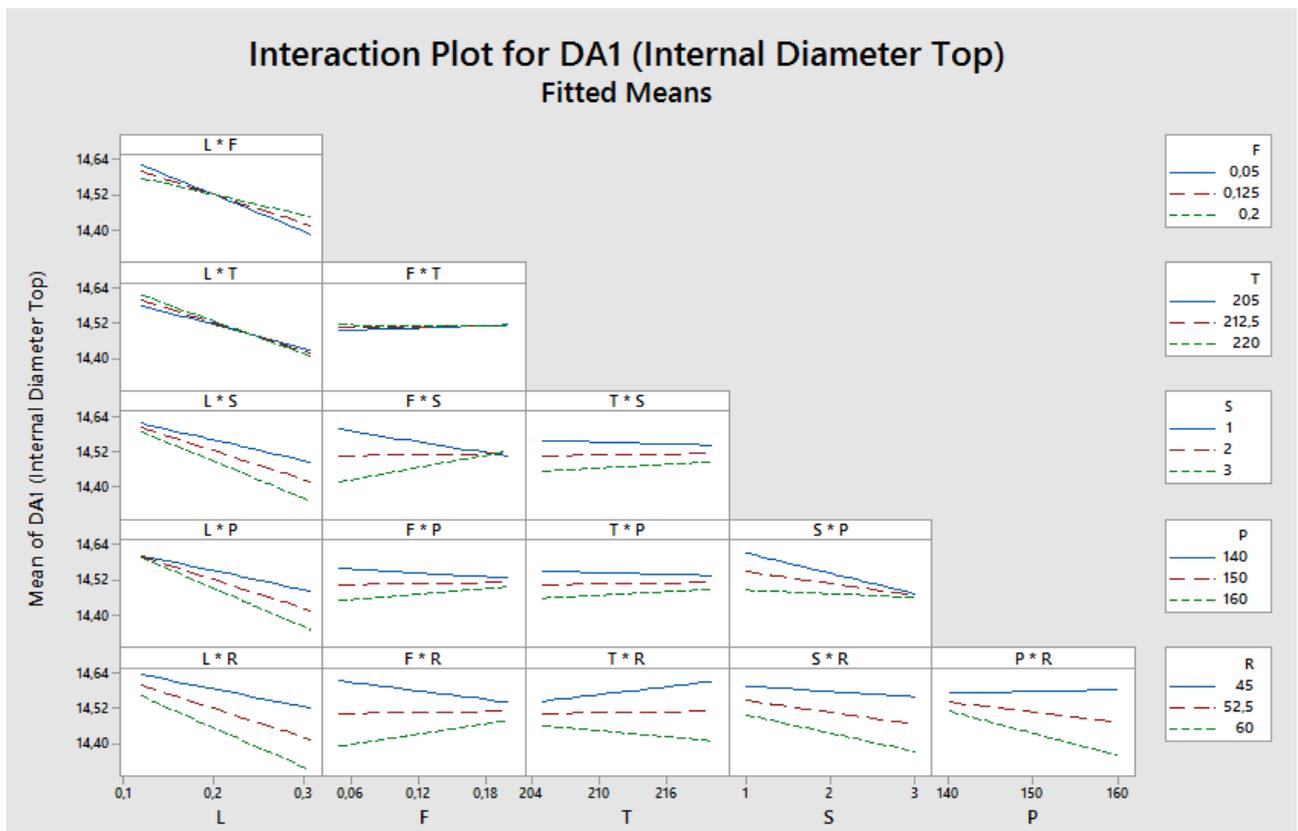


This graph indicates a small interaction between the Layer height (L) and Number of shells (S), between Number of shells (S) and Printing speed (P), between Temperature of extruder (T) and Retraction speed (R) and between Printing speed (P) and retraction speed (R). The highest interaction seems to be the one among Fill density (F) and Printing Speed (P), the other factors seem to have no interactions.

Figure 4.7: Main effect plot and interaction plot for DA1



Retraction speed and Layer height looks to strongly affect the DA1. 0.120 has a higher DA1 mean than 0.310 and, 60 has a lower DA1 mean than 45. Number of Shells and Printing Speed also affect the DA1 but less than the first two. Fill density and Temperature of extruder are almost horizontal lines.



This plot shows an interaction between the Layer height (L) and Fill Density (F) and a smaller one between Fill density (F) and the numbers of shell (S).

Subsequently, it has been used the analyzer tool for Response Surface design of Minitab in order to confirm these results and fit the data, finding the regression model for each target. Since there were 35 degrees of freedom (DF), it was possible to include in the model only the linear and the interactions terms. An example of the regression model for the printing time is displayed below.

To determine whether a factor was significant the p-values of every single main effect and of interactions between two factors were evaluated.

Response Surface Regression: Printing Time (min) versus L; F; T; S; P; R

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	21	45628,0	2172,8	24,30	0,000
Linear	6	45558,0	7593,0	84,91	0,000
L	1	44402,0	44402,0	496,51	0,000
F	1	1058,0	1058,0	11,83	0,004
T	1	0,0	0,0	0,00	1,000
S	1	98,0	98,0	1,10	0,313
P	1	0,0	0,0	0,00	1,000
R	1	0,0	0,0	0,00	1,000
2-Way Interaction	15	70,0	4,7	0,05	1,000
L*F	1	18,0	18,0	0,20	0,661
L*T	1	0,0	0,0	0,00	1,000
L*S	1	2,0	2,0	0,02	0,883
L*P	1	0,0	0,0	0,00	1,000
L*R	1	0,0	0,0	0,00	1,000
F*T	1	0,0	0,0	0,00	1,000
F*S	1	50,0	50,0	0,56	0,467
F*P	1	0,0	0,0	0,00	1,000

F*R	1	0,0	0,0	0,00	1,000
T*S	1	0,0	0,0	0,00	1,000
T*P	1	0,0	0,0	0,00	1,000
T*R	1	0,0	0,0	0,00	1,000
S*P	1	0,0	0,0	0,00	1,000
S*R	1	0,0	0,0	0,00	1,000
P*R	1	0,0	0,0	0,00	1,000
Error	14	1252,0	89,4		
Lack-of-Fit	11	1252,0	113,8	*	*
Pure Error	3	0,0	0,0		
Total	35	46880,0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
9,45667	97,33%	93,32%	94,48%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		95,67	1,58	60,70	0,000	
L	-74,50	-37,25	1,67	-22,28	0,000	1,00
F	11,50	5,75	1,67	3,44	0,004	1,00
T	0,00	0,00	1,67	0,00	1,000	1,00
S	3,50	1,75	1,67	1,05	0,313	1,00
P	0,00	0,00	1,67	0,00	1,000	1,00
R	0,00	0,00	1,67	0,00	1,000	1,00
L*F	-1,50	-0,75	1,67	-0,45	0,661	1,00
L*T	-0,00	-0,00	1,67	0,00	1,000	1,00
L*S	-0,50	-0,25	1,67	-0,15	0,883	1,00

L*P	-0,00	-0,00	1,67	-0,00	1,000	1,00
L*R	0,00	0,00	1,67	0,00	1,000	1,00
F*T	-0,00	-0,00	1,67	-0,00	1,000	1,00
F*S	-2,50	-1,25	1,67	-0,75	0,467	1,00
F*P	0,00	0,00	1,67	0,00	1,000	1,00
F*R	-0,00	-0,00	1,67	-0,00	1,000	1,00
T*S	-0,00	-0,00	1,67	-0,00	1,000	1,00
T*P	0,00	0,00	1,67	0,00	1,000	1,00
T*R	-0,00	-0,00	1,67	-0,00	1,000	1,00
P*R	0,00	0,00	1,67	0,00	1,000	1,00

Regression Equation in Uncoded Units

$$\begin{aligned}
 \text{Printing Time (min)} = & 159 - 374 L + 133 F - 0,00 T + 4,4 S - 0,00 P + 0,00 R - 105 L*F \\
 & - 0,00 L*T - 2,6 L*S + 0,00 L*P + 0,00 L*R - 0,00 F*T - 16,7 F*S \\
 & - 0,00 F*P + 0,00 F*R - 0,000 T*S + 0,0000 T*P - 0,0000 T*R - 0,000 S*P \\
 & - 0,000 S*R - 0,0000 P*R
 \end{aligned}$$

For the sake of readability, it is not possible to show all the ANOVA test, so the p-value of these analysis have been summarized and shown in Table 10.

It has done a differentiation among the factors which have p-value ≤ 0.01 (a very significant influence), which have p-value ≤ 0.05 (a significant influence) and which have p-value > 0.05 (no influence).

The factors with p-value ≤ 0.01 were double asterisked and the factors with p-value ≤ 0.05 were asterisked.

At the bottom of Tab. 10 the model qualities are displayed (R-Sq (%), R-Sq_{adj} (%)). These values indicate whether the model fits the data adequately or not. The R-Sq value always increases when you add additional predictors to a model whereas, the R-Sq_{adj} shows in percentage how much the model explains the variance of the responses considering the numbers of predictors. (Vicario e Levi 2008)

The adjusted R-squared increases only if the new term improves the model more than would be expected by chance. It decreases when a predictor improves the model by less than expected by chance. The adjusted R-squared can be negative, but it's usually not. It is always lower than the R-squared [52]

The adjusted coefficients of determination for the printing time (93,32%) and the energy consumption (89.6 %) were good.

For the dimensional accuracy of the bridge the R-Sq_{adj} varied from 15.42 % to 68.52 % and of the overhang from 22.05% to 80.43%.

Concerning the surface roughness, the adjusted coefficients of determination for the overhang were 88,56% and 30,26%, for the bridge varied from 19.8% to 66.77%.

Table 10: p-value table.

		PT	EC	SR1	SR2	SR3	SR4	SR5	DA1	DA2	DA3	DA4	DA5	DA6	DA7	DA8
1	L	0**	0**	0**	0,285	0**	0,072	0**	0**	0,031*	0**	0,010*	0,238	0**	0**	0,148
2	F	0,004*	0,014*	0,818	0,766	0,105	0,005*	0,793	0,857	0,436	0,010*	0,749	0,569	0,014*	0,034*	0,937
3	T	1,000	0,534	0,093	0,777	0,774	0,521	0,312	0,857	0,618	0,870	0,621	0,029*	0,028*	0,044*	0,257
4	S	0,313	0,243	0,289	0,146	0,519	0,843	0,575	0,066	0,003*	0**	0,001*	0,605	0,225	0,370	0,337
5	P	1,000	0,932	0,723	0,870	0,255	0,377	0,168	0,108	0,943	0,261	0,930	0,280	0,738	0,907	0,916
6	R	1,000	0,923	0,928	0,023*	0,179	0,971	0,418	0,003*	0,736	0,898	0,705	0,077	0,693	0,762	0,812
7	L*F	0,661	0,248	0,969	0,042*	0,886	0,048*	0,626	0,218	0,536	0,784	0,112	0,177	0,225	0,474	0,325
8	L*T	1,000	0,654	0,161	0,719	0,750	0,574	0,648	0,474	0,214	0,549	0,124	0,031*	0,271	0,834	0,979
9	L*S	0,883	0,419	0,038*	0,197	0,787	0,525	0,010*	0,229	0,576	0**	0**	0,155	0,022*	0,283	0,218
10	L*P	1,000	0,988	0,827	0,987	0,667	0,670	0,448	0,147	0,201	0,128	0,372	0,269	0,297	0,420	0,449
11	L*R	1,000	0,902	0,781	0,203	0,609	0,327	0,015*	0,114	0,632	0,784	0,581	0,013*	0,099	0,114	0,958
12	F*T	1,000	0,791	0,730	0,145	0,016*	0,645	0,904	0,763	0,706	0,038*	0,091	0,760	0,225	0,798	0,162
13	F*S	0,467	0,609	0,733	0,294	0,347	0,500	0,100	0,029*	0,894	0,004*	0,101	0,107	0,204	0,123	0,301
14	F*P	1,000	0,919	0,168	0,950	0,126	0,624	0,839	0,343	0,959	0,841	0,705	0,989	0,488	0,346	0,363
15	F*R	1,000	0,872	0,419	0,111	0,311	0,772	0,092	0,066	0,413	0,623	0,152	0,681	0,045*	0,420	1,000
16	T*S	1,000	0,911	0,248	0,478	0,560	0,600	0,857	0,569	0,976	0,437	0,152	0,720	0,036*	0,134	0,015*
17	T*P	1,000	0,909	0,786	0,109	0,506	0,312	0,922	0,589	0,814	0,549	0,749	0,947	0,649	0,798	0,350
18	T*R	1,000	0,970	0,153	0,266	0,116	0,201	0,246	0,171	0,604	0,437	0,749	0,006*	0,738	0,370	0,480
19	S*P	1,000	0,969	0,307	0,031*	0,850	0,809	0,340	0,189	0,293	0,015*	0,074	0,662	0,111	0,048*	0,085
20	S*R	1,000	0,949	0,910	0,796	0,683	0,120	0,374	0,288	0,100	0,324	0,581	0,193	0,247	0,981	0,169
21	P*R	1,000	0,945	0,382	0,878	0,228	0,909	0,285	0,066	0,359	0,956	0,663	0,302	0,649	0,474	0,547
	R-Sq	97,33 %	95,85 %	95,42 %	72,10 %	86,71 %	67,93 %	79,51 %	83,30 %	68,82 %	92,17 %	83,55 %	77,98 %	87,41 %	80,53 %	66,17 %
	R-Sq adj	93,32 %	89,63 %	88,56 %	30,26 %	66,77 %	19,83 %	48,77 %	58,25 %	22,05 %	80,43 %	58,88 %	44,96 %	68,52 %	51,33 %	15,42 %

Based on the results shown in Table 10, the model was subsequently reduced by neglecting factors which had no effect on at least one target. (Table 11) The purpose of the reaction was to simplify the model, eliminating insignificant terms.

To reduce the model, it was considered the hierarchical principle so, first it has been removed the most complex terms that were statistically insignificant.

However, if a statistically insignificant term represented part of an interaction term or a higher-order term, then the term was left in the model. [53]

Table 11: p-value table reduced

		PT	EC	SR1	SR2	SR3	SR4	SR5	DA1	DA2	DA3	DA4	DA5	DA6	DA7	DA8
1	L	0**	0**	0**	0,285	0**	0,072	0**	0**	0,031*	0**	0,010**	0,238	0**	0**	0,148
2	F	0,004**	0,014*	0,818	0,766	0,105	0,005**	0,793	0,857	0,436	0,010**	0,749	0,569	0,014*	0,034*	0,937
3	T	1,000	0,534	0,093	0,777	0,774	0,521	0,312	0,857	0,618	0,870	0,621	0,029*	0,028*	0,044*	0,257
4	S	0,313	0,243	0,289	0,146	0,519	0,843	0,575	0,066	0,003**	0**	0,001**	0,605	0,225	0,370	0,337
5	P	1,000	0,932	0,723	0,870	0,255	0,377	0,168	0,108	0,943	0,261	0,930	0,280	0,738	0,907	0,916
6	R	1,000	0,923	0,928	0,023*	0,179	0,971	0,418	0,003**	0,736	0,898	0,705	0,077	0,693	0,762	0,812
7	L*F	0,661	0,248	0,969	0,042*	0,886	0,048*	0,626	0,218	0,536	0,784	0,112	0,177	0,225	0,474	0,325
8	L*T	1,000	0,654	0,161	0,719	0,750	0,574	0,648	0,474	0,214	0,549	0,124	0,031*	0,271	0,834	0,979
9	L*S	0,883	0,419	0,038*	0,197	0,787	0,525	0,010**	0,229	0,576	0**	0**	0,155	0,022*	0,283	0,218
10	L*R	1,000	0,902	0,781	0,203	0,609	0,327	0,015*	0,114	0,632	0,784	0,581	0,013*	0,099	0,114	0,958
11	F*T	1,000	0,791	0,730	0,145	0,016*	0,645	0,904	0,763	0,706	0,038*	0,091	0,760	0,225	0,798	0,162
12	F*S	0,467	0,609	0,733	0,294	0,347	0,500	0,100	0,029*	0,894	0,004**	0,101	0,107	0,204	0,123	0,301
13	F*R	1,000	0,872	0,419	0,111	0,311	0,772	0,092	0,066	0,413	0,623	0,152	0,681	0,045*	0,420	1,000
14	T*S	1,000	0,911	0,248	0,478	0,560	0,600	0,857	0,569	0,976	0,437	0,152	0,720	0,036*	0,134	0,015*
15	T*R	1,000	0,970	0,153	0,266	0,116	0,201	0,246	0,171	0,604	0,437	0,749	0,006**	0,738	0,370	0,480
16	S*P	1,000	0,969	0,307	0,031*	0,850	0,809	0,340	0,189	0,293	0,015*	0,074	0,662	0,111	0,048*	0,085
	R-Sq	97,33%	95,84%	94,42%	66,07%	81,90%	58,08%	75,49%	72,77%	55,77%	89,89%	81,64%	71,14%	84,20%	77,40%	54,3%
	R-Sq adj	95,08%	92,34%	89,72%	37,5%	66,66%	22,78%	54,86%	49,85%	18,52%	81,38%	66,19%	46,83%	70,89%	58,37%	15,81%

To compare if the model reduced maximized the precision of predictions or not, it has been considered the R-Sq_{adj}.

Except the R-Sq_{adj} of DA1, all the indexes increased, indicating that the terms deleted were not significant. Maybe the reason why the R-Sq_{adj} of DA1 decreased was due to the removal of the interaction among P*R from the model. Even if it had a p-value not significant (0.066), it was near the level of significance.

Below are shown all the regression model for each target.

The general model is a linear combination of the significant factors with a corresponding weighting factor (a₀ – a₂₁):

$$y = a_0 + a_1 * L + a_2 * F + a_3 * T + a_4 * S + a_5 * P + a_6 * R + a_7 * L * F + a_8 * L * T + a_9 * L * S + a_{10} * L * R + a_{11} * F * T + a_{12} * F * S + a_{13} * F * R + a_{14} * T * S + a_{15} * T * R + a_{16} * S * P$$

$$\begin{aligned} \text{Printing Time (min)} = & 159 - 374 L + 133 F + 0,00 T + 4,4 S + 0,000 P + 0,00 R - 105 L * F \\ & - 0,00 L * T - 2,6 L * S + 0,00 L * R - 0,00 F * T - 16,7 F * S + 0,00 F * R \\ & - 0,000 T * S - 0,0000 T * R - 0,000 S * P \end{aligned}$$

$$\begin{aligned} \text{Energy Consumption (kWh)} = & 5,2 - 0 L - 11 F + 0,062 T + 3,0 S + 0,0064 P - 0,06 R - 65,8 L * F \\ & - 0,250 L * T - 3,41 L * S - 0,069 L * R + 0,187 F * T - 2,71 F * S \\ & + 0,114 F * R - 0,0059 T * S + 0,00026 T * R - 0,0015 S * P \end{aligned}$$

$$\begin{aligned} \text{SR1 (Overhang Bottom)} = & 213 - 194 L + 135 F - 1,116 T + 29,8 S + 0,163 P - 3,58 R - 3,6 L * F \\ & + 1,365 L * T + 15,83 L * S - 0,261 L * R - 0,41 F * T + 3,05 F * S - 0,97 F * R \\ & - 0,1056 T * S + 0,0177 T * R - 0,0697 S * P \end{aligned}$$

$$\begin{aligned} \text{SR2 (Overhang Top)} = & 67,0 + 58,2 L + 197 F - 0,240 T - 13,99 S - 0,1385 P - 1,10 R + 87,2 L * F \\ & - 0,143 L * T - 3,97 L * S - 0,522 L * R - 0,764 F * T - 4,05 F * S - 0,842 F * R \\ & + 0,0270 T * S + 0,00574 T * R + 0,0669 S * P \end{aligned}$$

$$\text{SR3 (Internal Bottom)} = -338 - 238 L + 961 F + 2,13 T - 15,7 S - 0,088 P + 6,27 R + 22 L * F$$

$$+ 0,50 L*T - 3,2 L*S + 0,80 L*R - 5,30 F*T + 14,2 F*S + 2,04 F*R$$

$$+ 0,087 T*S - 0,0325 T*R - 0,021 S*P$$

$$SR4 (Internal Top) = -391 + 405 L + 264 F + 1,81 T - 16,2 S - 0,058 P + 7,40 R - 423 L*F$$

$$- 1,13 L*T + 9,5 L*S - 1,98 L*R - 1,16 F*T - 12,8 F*S + 0,73 F*R$$

$$+ 0,100 T*S - 0,0332 T*R - 0,034 S*P$$

$$SR5 (Lateral) = 17,0 - 4,6 L + 12,3 F - 0,0905 T + 1,37 S + 0,0042 P - 0,281 R + 5,7 L*F$$

$$+ 0,054 L*T + 2,559 L*S - 0,317 L*R + 0,018 F*T - 1,92 F*S - 0,262 F*R$$

$$- 0,0020 T*S + 0,00176 T*R - 0,00806 S*P$$

$$DA1 (Internal Diameter Top) = 10,23 + 6,11 L - 3,49 F + 0,0307 T - 0,823 S - 0,00912 P$$

$$+ 0,1027 R + 3,68 L*F - 0,0211 L*T - 0,270 L*S - 0,0482 L*R$$

$$- 0,0111 F*T + 0,658 F*S + 0,0722 F*R + 0,00158 T*S$$

$$- 0,000522 T*R + 0,00281 S*P$$

$$DA2 (Internal Diameter Bottom) = 9,14 + 12,67 L + 2,8 F + 0,0315 T - 0,543 S - 0,00678 P$$

$$+ 0,058 R - 2,68 L*F - 0,0548 L*T - 0,181 L*S - 0,0206 L*R$$

$$- 0,0206 F*T + 0,054 F*S + 0,0450 F*R - 0,00013 T*S$$

$$- 0,000283 T*R + 0,00328 S*P$$

$$DA3 (Cylinder diameter) = 21,21 + 1,78 L - 13,26 F - 0,0148 T + 1,138 S + 0,00734 P$$

$$- 0,0538 R + 0,66 L*F - 0,0145 L*T + 0,859 L*S + 0,0066 L*R$$

$$+ 0,0683 F*T - 0,763 F*S + 0,0150 F*R - 0,00179 T*S + 0,000239 T*R$$

$$- 0,00466 S*P$$

$$DA4 (Internal Bottom Width) = 13,72 - 5,94 L - 4,64 F - 0,0027 T + 0,722 S + 0,00397 P$$

$$+ 0,0142 R - 2,50 L*F + 0,0241 L*T + 0,510 L*S + 0,0083 L*R$$

$$+ 0,0339 F*T - 0,246 F*S - 0,0283 F*R - 0,00212 T*S$$

$$- 0,000061 T*R - 0,002031 S*P$$

$$DA5 (Internal Bottom Height) = -0,46 - 13,24 L + 1,39 F + 0,0449 T - 0,526 S + 0,00053 P$$

$$+ 0,3101 R + 4,61 L*F + 0,0776 L*T + 0,365 L*S - 0,0925 L*R$$

$$\begin{aligned}
& - 0,0128 F*T + 0,529 F*S - 0,0172 F*R + 0,00112 T*S \\
& - 0,001328 T*R + 0,00103 S*P
\end{aligned}$$

$$\begin{aligned}
\text{DA6 (Internal Bottom Length)} &= 23,64 + 2,55 L + 6,56 F + 0,0000 T - 0,475 S + 0,00378 P \\
& + 0,0120 R - 1,80 L*F - 0,0162 L*T + 0,273 L*S + 0,0250 L*R \\
& - 0,0228 F*T + 0,179 F*S - 0,0394 F*R + 0,00312 T*S \\
& - 0,000061 T*R - 0,001719 S*P
\end{aligned}$$

$$\begin{aligned}
\text{DA7 (Internal Top Length)} &= 27,64 - 0,20 L + 1,62 F - 0,0192 T - 0,224 S + 0,00584 P \\
& - 0,0508 R - 1,36 L*F - 0,0039 L*T + 0,155 L*S + 0,0311 L*R \\
& - 0,0061 F*T + 0,288 F*S - 0,0194 F*R + 0,00279 T*S \\
& + 0,000217 T*R - 0,00284 S*P
\end{aligned}$$

$$\begin{aligned}
\text{DA8 (Internal Top Width)} &= 14,32 + 0,77 L + 13,01 F + 0,0027 T - 2,421 S - 0,00887 P \\
& + 0,0641 R - 3,33 L*F - 0,0009 L*T - 0,316 L*S + 0,0018 L*R \\
& - 0,0611 F*T + 0,333 F*S - 0,0000 F*R + 0,00858 T*S - 0,000300 T*R \\
& + 0,00431 S*P
\end{aligned}$$

For every regression model defined, it has been created the residual plot. The residual plot is used to analyze the goodness of model fit.

Examining residual plots is important to understand if the ordinary least squares assumptions are being met. If these assumptions are satisfied, then the regression produce unbiased coefficient estimates with the minimum variance. [54] [55]

The residual plot available in Minitab are:

Normal Probability Plot of residuals. The points in this plot should generally form a straight line if the residuals are normally distributed. If the points on the plot deviate from a straight line, the normality assumption may be invalid. [56]

Residuals Versus Fitted Values. This plot should show a random pattern of residuals on both sides of 0. If a point is far from the majority of points, it may be an outlier. There should not be any recognizable patterns in the residual plot. If not, the spread of residual values may violate the constant variance assumption. [56]

Histogram of the Residuals. An exploratory graph that shows general characteristics of the residuals (typical values, spread, shape). It should show if the residuals are normally distributed. A long tail on one side may indicate a skewed distribution. If one or two bars are far from the others, those points may be outliers. [56]

Residuals Versus Order of Data. This is a scatter plot of all residuals in the order that the data was collected and can be used to find non-random error, especially of time-related effects. This plot helps to check the assumption that the residuals are uncorrelated with each other. These plot is only appropriate if you know the order in which the data were collected. [57]

As examples, in figure 4.8 is shown the Residual plot for the SR1 Overhang Bottom and in figure 4.9 the Residual plot for DA1 (Internal Diameter Top)

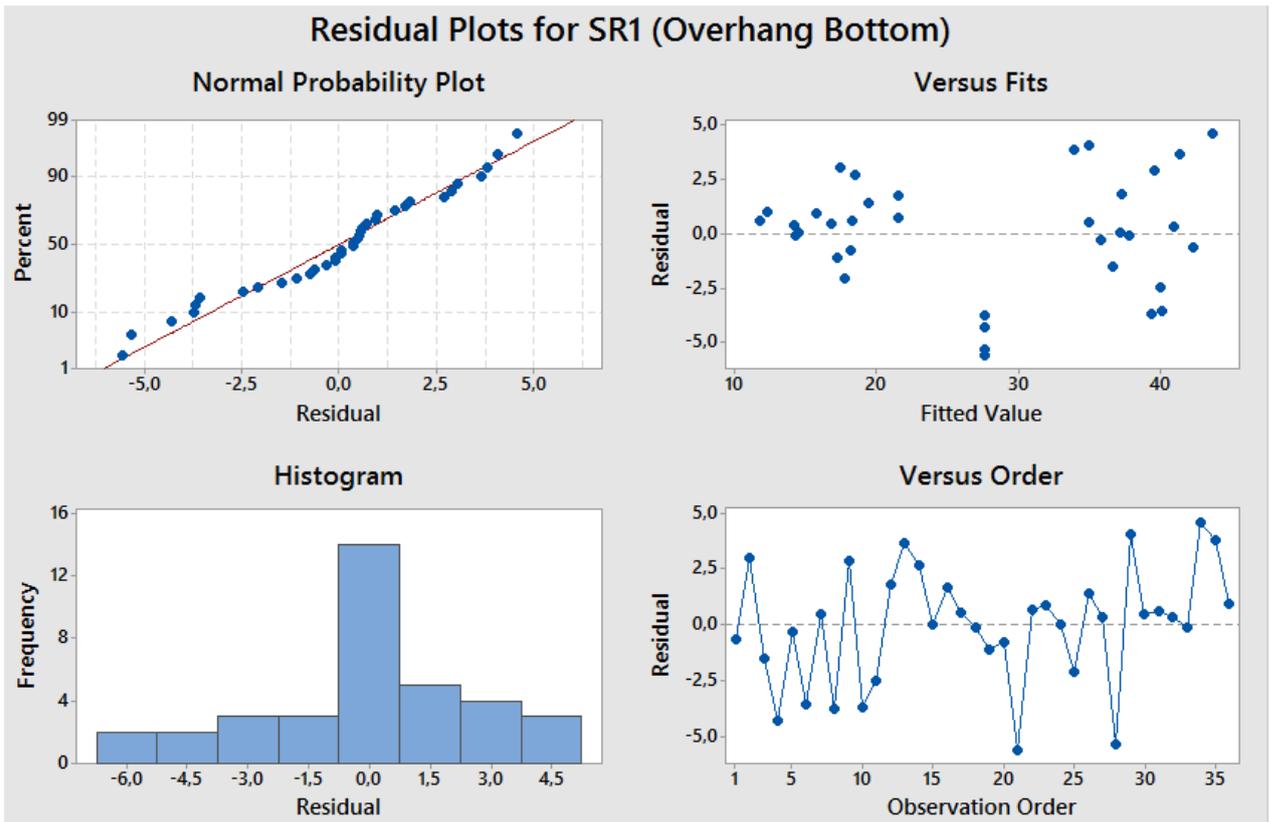


Figure 4.8: Residual plot for SR1

The assumption of normality seemed to be true, even if at the beginning the points departed from a straight line. The Versus Fit plot showed a trend. In the left and in the right of the plot, the points were arranged under a random pattern while in the center were lined up. The assumption of constant variance was violated. It could be better to add runs to investigate the curvature.

The Residuals Versus Order Data plot as well, did not have a satisfactory trend.

The histogram seemed to be approximately bell-shaped, even if the mean was higher than the others. This behavior confirmed the tails of the normal probability plot.

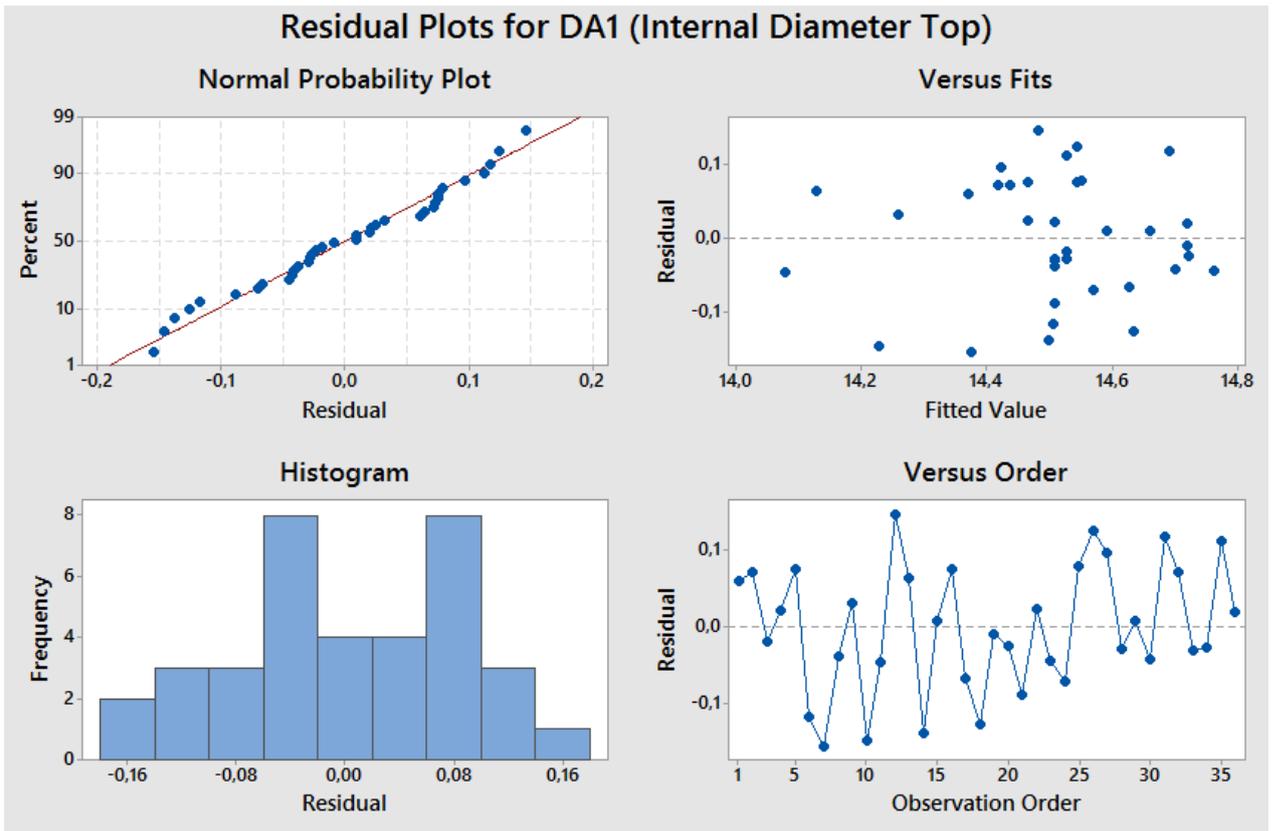


Figure 4.9: Residual plot for DA1

The assumption of normality seemed to be correct, the points followed the straight line. The Versus Fit plot showed a trend. Therefore, in the left there were just few points while in the right of the plot, the points were more concentrated and did not follow a random pattern. It should be added other points to investigate the curvature.

The histogram had a bell-shaped. This behavior confirmed the normal probability plot, the assumption of normality was respected.

In the end, the Residuals Versus Order Data plot seemed to confirm the assumption that the residuals were uncorrelated. The residual bounce was randomly distributed around the residual zero line.

4.4 Optimization

The final regression models were used to generate the combination of input variable settings that jointly optimize first all responses (scenario 1) and then a set of responses (scenario 2-5).

Since the joint optimization must satisfy the requirements for all the responses in the set, more are the responses to optimize, more is difficult to achieve a high predictability due to the conflicting objectives that could exist. Therefore, it has been decided to analyze other scenarios in order to improve the percentage of predictability of responses.

Minitab offers a numerical optimization tool called “Response Optimizer”, that calculates an optimal solution and afterwards, draws a plot using the solution found. [58] [59] This optimization plot is interactive, it shows how different experimental settings affect the predicted responses but at the same time, allows to change these settings. Actually, the reasons to vary these parameters are different, for example, maybe there is an interest in found the input variable settings with a higher composite user-defined desirability or it is wished to explore variable settings in the neighborhood of a local solution. [60]

Within these research, the levels of factors were not changed but it has been analyzed several scenarios, changing the set of responses to optimize.

In the first scenario all responses were considered and optimized. In detail, the printing time was minimized, the energy consumption and surface roughness as well, while the dimensional accuracy was maximized. The importance and the weight of responses were left at the default value of 1 and no constrains were put. Figure 4.10 is shown the Response Optimizer setup and in Figure 4.11 the Optimization Plot.

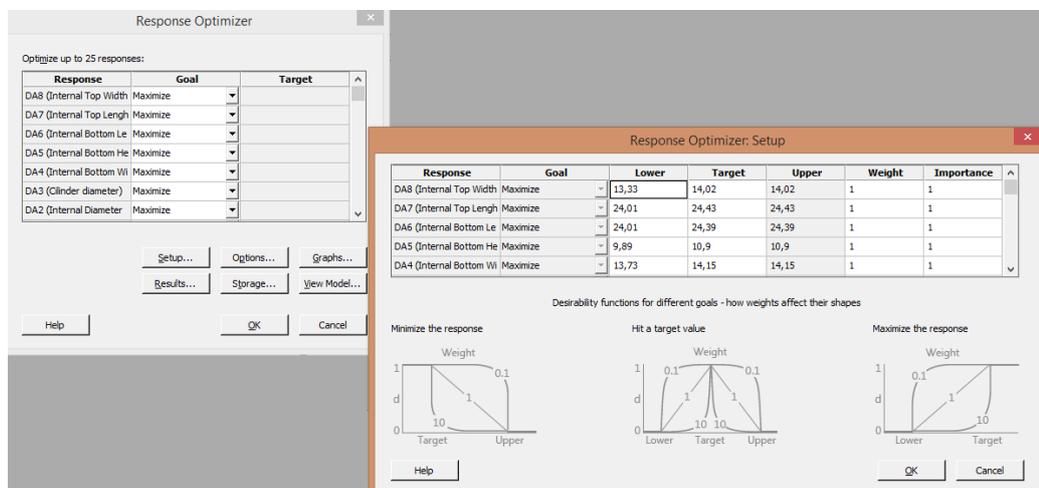


Figure 4.10: Response Optimizer Setup

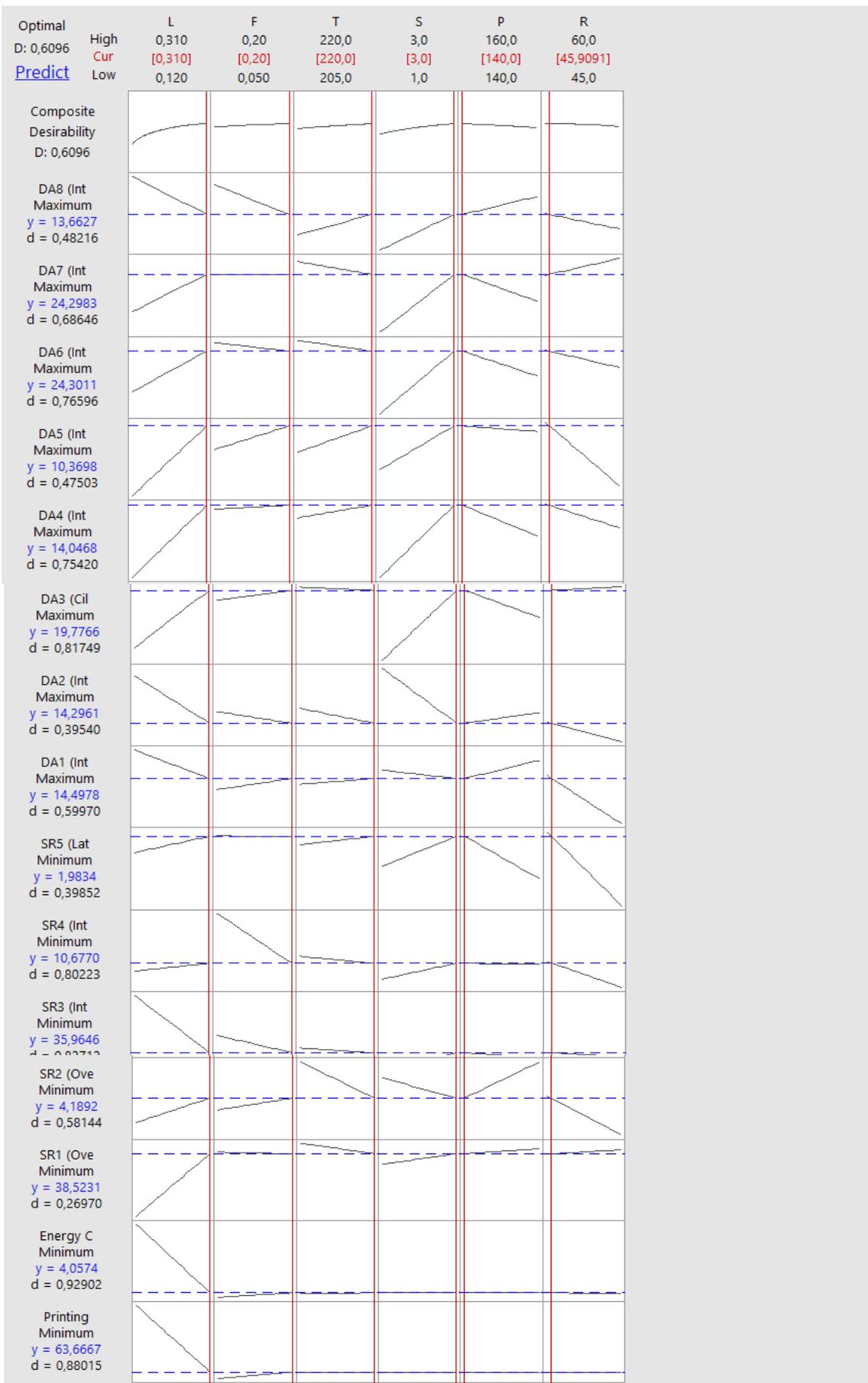


Figure 4.11: Optimization plot

The optimization plot showed the effect of each factor (columns) on the responses and on the composite desirability. The index 'd' represents the individual desirability and evaluates how the settings optimize a single response. The index 'D', instead is the composite desirability and evaluates how the settings optimize the set of responses overall. The optimal solution is achieved when the composite desirability obtains its maximum. [61]

The numbers in red displayed at the top of a column show the current factor level settings. The vertical red lines on the graph represent the current factor settings and can be moved in interactive mode to see how the level of factors impact on the responses. The horizontal blue lines and numbers represent the responses for the current factor level. [60]

When all the responses are considered the composite desirability is D=60% and most factors are at their highest settings (Layer height = 0.310, Fill density = 20%, Temperature of extruder = 220, Number of shells = 3, Printing speed = 140 and Retraction speed = 45,909).

In order to improve the composite desirability of each macro target, it has been analyzed each response separately, creating other 4 scenarios. In the second scenario it has been considered just the minimization of the printing time and the other responses were not optimized. Figure 4.12

In the third the minimization of energy consumption was the goal while the others target variables were not optimized. Figure 4.13

In the fourth it has been minimized first the targets for surface roughness of the overhang and then the ones for the bridge Figure 4.14. In the fifth it has been maximized first the responses for the dimensional accuracy of the overhang then the ones for the bridge. Figure 4.15

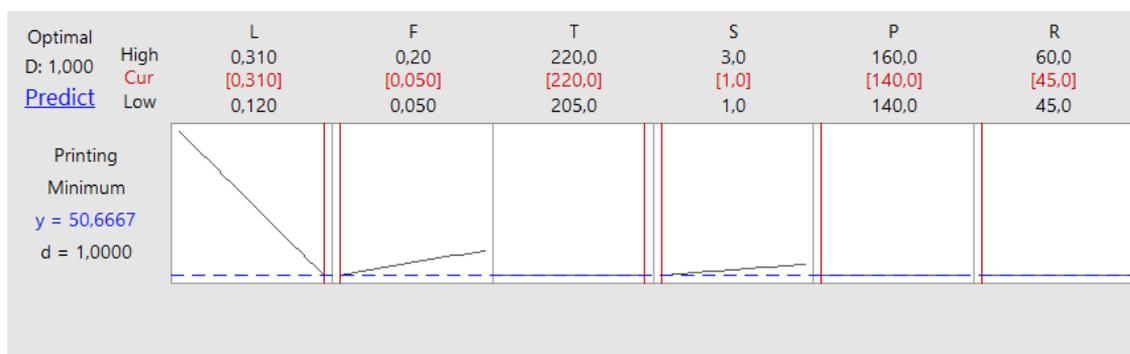


Figure 4.12: Optimization plot for PT (scenario 2)

Here, the composite desirability is 1. This indicates that the settings achieve favorable result for the response. It has been obtained the same result (D=1) with the minimization of energy consumption. Figure 4.13

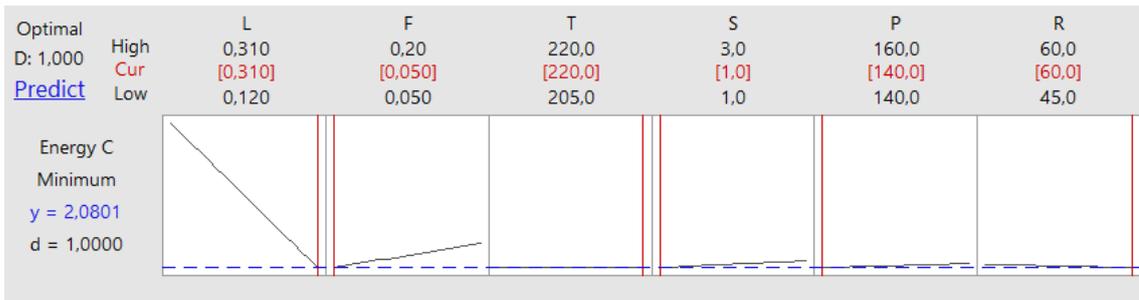


Figure 4.13: Optimization plot for EC (scenario 3)

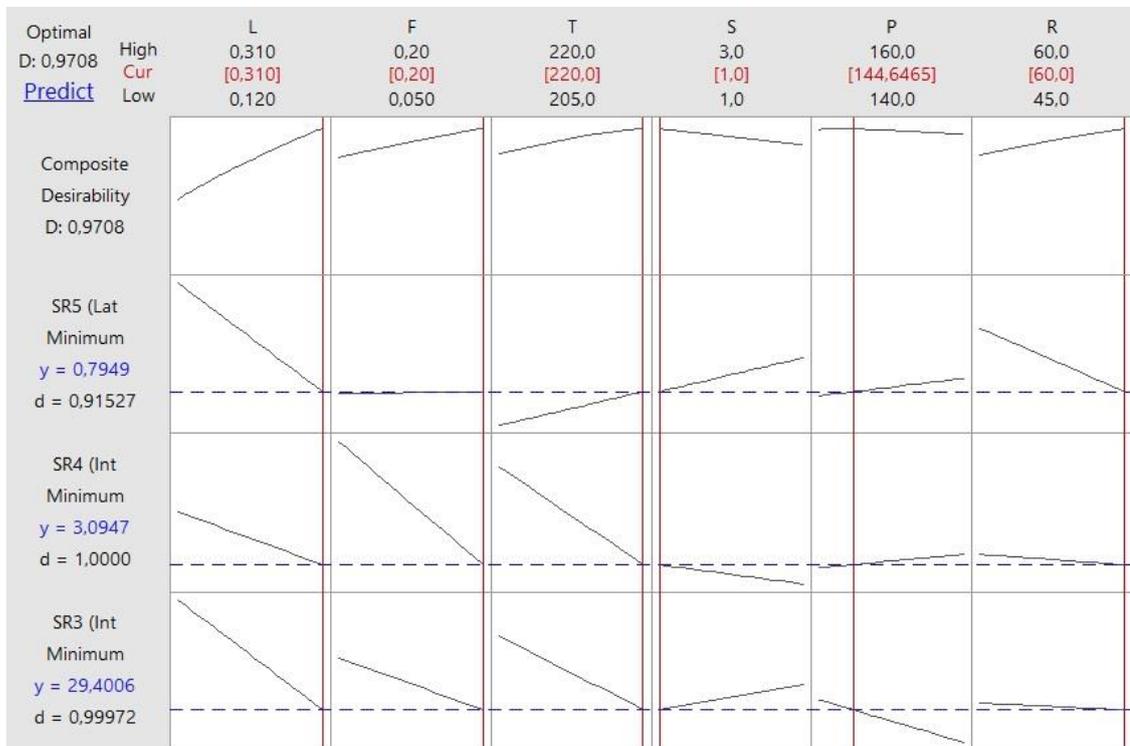
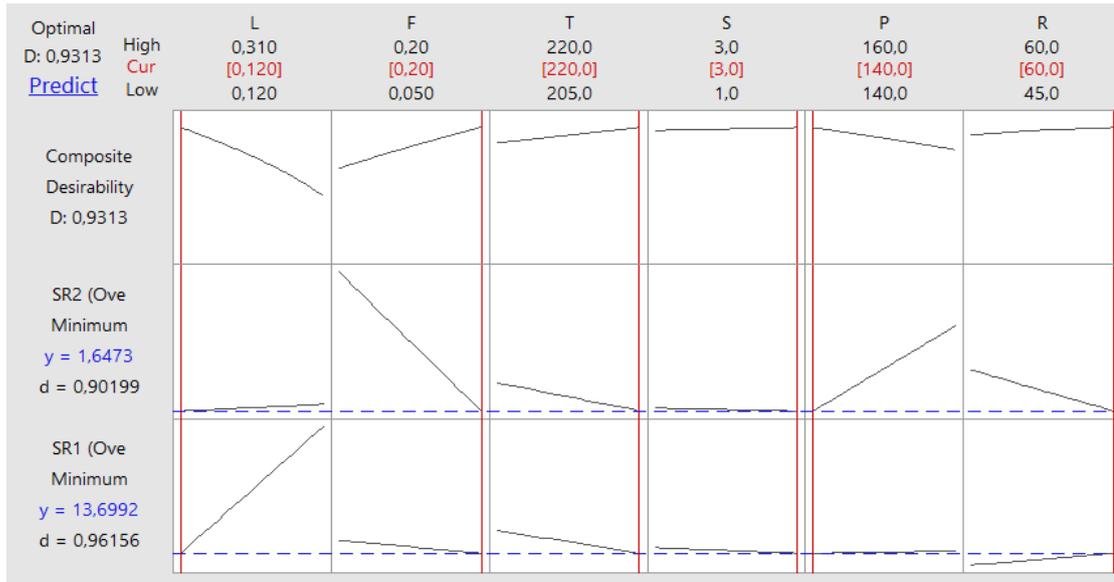


Figure 4.14: Optimization plot for SR (scenario 4)

A differentiation among overhang and bridge has been done. Both have the composite desirability close to 1 (0.9313, 0.9708) and this indicate positive results for the responses.

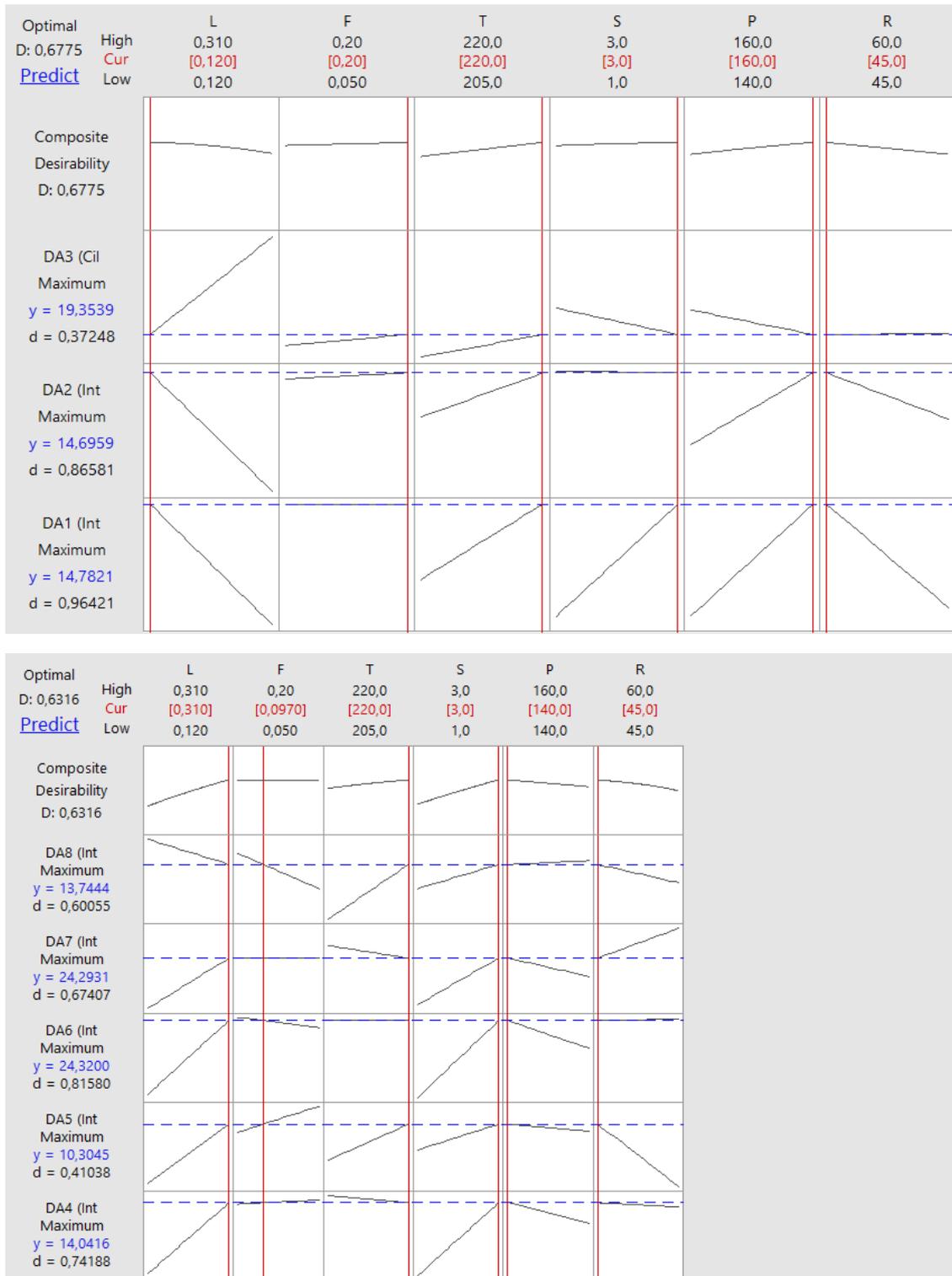


Figure 4.15: Optimization plot DA (scenario 5)

For the dimensional accuracy target also has been done a differentiation among overhang and bridge. For the overhang responses the individual desirability indicates that the settings were more effective at maximizing DA1 (0.96421) than at maximize DA2 (0.86581) or at maximize DA3 (0.37248). If maximize DA3 is more important, the settings need to be adjusted.

The composite desirability is 0.6775. This indicates that the requirements for all the responses choice are not satisfied. Since the composite desirability represent the weighted geometric mean of the individual desirabilities, if a higher value is required the weight of the targets has to be changed.

For the bridge responses as well, the optimization plot shows a low composite desirability, $D = 0.6316$. The response better maximized within the set of factors used is DA6 ($d=0.8158$).

5. Conclusions

This thesis presents a statistical analysis to investigate the cause-and-effect relationships among selected input and output variables, within the MakerBot z18 system and the applicability of experimental models on the generation of optimum printing parameters for FDM process.

The macro responses analyzed included printing time, energy consumption, surface quality and dimensional accuracy. These targets were split into fifteen responses and measured as the result of each trial. The dimension and orientation part in which the objects have been evaluated strongly impact the data. Six factors were selected and varied together in a design of thirty-six runs, in order to study their effects and interaction on the mentioned target parameters. The six factors were: layer height, fill density, temperature of extruder, number of shells, printing speed and retraction speed.

First a qualitative analysis was done, then a quantitative. Factors yielding not significance values (level of significance, $\alpha=5\%$) for any of the target variables from the ANOVA were disregarded from the final model.

Obtained the final regression models, five scenarios were analyzed (one general and four specific), and optimum settings factors were determined for each goal selected.

It can be concluded that optimum process parameters generated from experimental models varied in accordance with the goal considered and optimizing all the responses, if heterogeneous lead to the reduction of the percentage of their predictability.

To conclude, this model should be widen:

- 1) Validating the model equations of the target parameters though other prints;
- 2) Including the star points in addition to center points to investigate the curvature and to estimate quadratic terms that cannot be included in the model due to the lack of degree of freedom;
- 3) Changing the weights of responses, giving more importance to some goals and less to others;

The next step of the research could be to evaluate these models using other complex geometries, other materials or other printers to test their adaptability to other use cases, gaining more knowledge about prediction using experimental models.

Furthermore, other scenarios could be tested changing the grouping of the targets or modifying interactively the levels of factors.

In addition, other modeling approaches (gray box, white box) could be used to combine the statistical knowledge with the physical relationships.

Bibliography

- 2016 IEEE International Symposium on Intelligent Control (ISIC) (2016). 2016 IEEE International Symposium on Intelligent Control (ISIC). Buenos Aires, Argentina, 19/09/2016 - 22/09/2016: IEEE.
- 2017 25th Mediterranean Conference on Control and Automation (MED) (2017). 2017 25th Mediterranean Conference on Control and Automation (MED). Valletta, Malta, 03/07/2017 - 06/07/2017: IEEE.
- Ahn, Daekeon; Kweon, Jin-Hwe; Kwon, Soonman; Song, Jungil; Lee, Seokhee (2009): Representation of surface roughness in fused deposition modeling. In: *Journal of Materials Processing Technology* n. 15-16, 209, pp. 5593–5600. DOI: 10.1016/j.jmatprotec.2009.05.016.
- Anitha, R.; Arunachalam, S.; Radhakrishnan, P. (2001): Critical parameters influencing the quality of prototypes in fused deposition modelling. In: *Journal of Materials Processing Technology* n. 1-3, 118, pp. 385–388. DOI: 10.1016/S0924-0136(01)00980-3.
- B. Stucker (2012): Additive manufacturing technologies: technology introduction and business implications. in *Frontiers of Engineering: Reports on Leading-Edge Engineering From the 2011 Symposium*. Washington, DC. Disponibile online in <http://www.bjchinesetranslation.com/upload/484265361.pdf>.
- Chua, Chee Kai; Leong, Kah Fai; Lim, Chu Sing (2010): *Rapid prototyping. Principles and applications*. 3. ed. New Jersey: World Scientific.
- Design and analysis of experiments (2013). Eighth edition. Hoboken NJ: John Wiley & Sons Inc.
- EPMA (2015): *Introduction to additive manufacturing technology*.
- Frank, Daniel; Chandra, Raymond L.; Schmitt, Robert (2015): An Investigation of Cause-and-Effect Relationships Within a 3D-Printing System and the Applicability of Optimum Printing Parameters from Experimental Models to Different Printing Jobs. In: *3D Printing and Additive Manufacturing* n. 3, 2, pp. 131–139. DOI: 10.1089/3dp.2015.0010.
- Gebhardt, Andreas (2012): *Understanding additive manufacturing. Rapid Prototyping - Rapid Tooling - Rapid Manufacturing*. Munich: Hanser.
- Gibson, Ian; Rosen, David W.; Stucker, Brent (2010): *Additive manufacturing technologies. Rapid prototyping to direct digital manufacturing*. New York: Springer.
- Griffiths, C. A.; Howarth, J.; Rowbotham, G. de-Almeida; Rees, A. (2016): Effect of Build Parameters on Processing Efficiency and Material Performance in Fused Deposition Modelling. In: *Procedia CIRP*, 49, pp. 28–32. DOI: 10.1016/j.procir.2015.07.024.
- Hopkinson, Dickens (2003): *Analysis of rapid manufacturing—using layer manufacturing processes for production*.
- Huang, Qiang; Zhang, Jizhe; Sabbaghi, Arman; Dasgupta, Tirthankar (2015): Optimal offline compensation of shape shrinkage for three-dimensional printing processes. In: *IIE Transactions* n. 5, 47, pp. 431–441. DOI: 10.1080/0740817X.2014.955599.
- Jacobs, Paul F.; Reid, David T. (1992): *Rapid prototyping & manufacturing. Fundamentals of stereolithography*. 1st ed. Dearborn MI: Society of Manufacturing Engineers in cooperation with the Computer and Automated Systems Association of SME.
- Kaveh, Mahdi; Badrossamay, Mohsen; Foroozmehr, Ehsan; Hemasian Etefagh, Ardeshir (2015): Optimization of the printing parameters affecting dimensional accuracy and internal

- cavity for HIPS material used in fused deposition modeling processes. In: *Journal of Materials Processing Technology*, 226, pp. 280–286. DOI: 10.1016/j.jmatprotec.2015.07.012.
- Krar, Stephen F.; Gill, Arthur (2003): Exploring advanced manufacturing technologies. 1st ed. New York: Industrial Press.
- Kumar L, Kumar V, Haleem A. (2016): RapidPrototypingTechnologyforNewProductDevelopmentIJSET_V3_I1_39. International journal of innovative science, engineering and technology.
- Li, Hongbin; Wang, Taiyong; Sun, Jian; Yu, Zhiqiang; Campbell, R. Ian; Gibson, Ian (2017): The effect of process parameters in fused deposition modelling on bonding degree and mechanical properties. In: *Rapid Prototyping Journal* n. 1, 34, p. 0. DOI: 10.1108/RPJ-06-2016-0090.
- M. Baumers, C. Tuck, P. Dickens, R. Hague (2014): How Can Material Jetting Systems Be Upgraded for More Efficient Multi-material Additive Manufacturing. Proceedings of the Solid Freeform Fabrication (SFF) Symposium. The University of Texas at Austin. Texas. Disponibile online in <https://sffsymposium.engr.utexas.edu/sites/default/files/2014-016-Baumers.pdf>.
- Mellor Stephen (2014): An implementation framework for additive manufacturing. University of Exeter, United Kingdom.
- Onwubolu, Godfrey C.; Rayegani, Farzad (2014): Characterization and Optimization of Mechanical Properties of ABS Parts Manufactured by the Fused Deposition Modelling Process. In: *International Journal of Manufacturing Engineering*, 2014, pp. 1–13. DOI: 10.1155/2014/598531.
- Pandey, Pulak M.; Venkata Reddy, N.; Dhande, Sanjay G. (2003): Improvement of surface finish by staircase machining in fused deposition modeling. In: *Journal of Materials Processing Technology* n. 1-3, 132, pp. 323–331. DOI: 10.1016/S0924-0136(02)00953-6.
- Pennington, R. C.; Hoekstra, N. L.; Newcomer, J. L. (2005): Significant factors in the dimensional accuracy of fused deposition modelling. In: *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* n. 1, 219, pp. 89–92. DOI: 10.1243/095440805X6964.
- Rayegani, Farzad; Onwubolu, Godfrey C. (2014): Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE). In: *Int J Adv Manuf Technol* n. 1-4, 73, pp. 509–519. DOI: 10.1007/s00170-014-5835-2.
- Redwood, Ben; Gerret, Brain; Schöffner, Filemon (2017): The 3D Printing Handbook. Technologies, design and applications. Amsterdam: 3D Hubs B.V.
- Sood, Anoop K.; Ohdar, Raj K.; Mahapatra, Siba S. (2012): Experimental investigation and empirical modelling of FDM process for compressive strength improvement. In: *Journal of Advanced Research* n. 1, 3, pp. 81–90. DOI: 10.1016/j.jare.2011.05.001.
- Technologies, ASTM Committee F42 on Additive Manufacturing; International, ASTM; Terminology, ASTM Committee F42 on Additive Manufacturing Technologies Subcommittee F42 91 on (2012): Standard Terminology for Additive Manufacturing Technologies. Designation F2792-12a: ASTM International (ASTM-Standards). Disponibile online in <https://books.google.de/books?id=f-ATswEACAAJ>.
- Vicario, Grazia; Levi, Raffaello (2008): Metodi statistici per la sperimentazione. Bologna: Progetto Leonardo.

- Wahlström, Terese; Sahlström, Johan (2016): Additive Manufacturing in Production - for the Automotive Industry.
- Wohlers, Terry (2014): Wohlers Report 2014. 3D printing and additive manufacturing state of the industry; annual worldwide progress report. Fort Collins, Colo.: Wohlers Associates.
- Wohlers, Terry T.; Caffrey, Tim (2015): Wohlers report 2015. 3D printing and additive manufacturing state of the industry annual worldwide progress report. Fort Collins Colo.: Wohlers Associates.
- Ziemian, C. W.; Crawn, P. M. (2001): Computer aided decision support for fused deposition modeling. In: *Rapid Prototyping Journal* n. 3, 7, pp. 138–147. DOI: 10.1108/13552540110395538.

Sitography

- [1] «Instructables,» June 2015. [Online]. Available: <http://www.instructables.com/id/3D-Printing-Basics/>.
- [2] «3dinsider,» 3dinsider, [Online]. Available: <http://3dinsider.com/3d-printing-guide/#chapter1>.
- [3] C. Carelli, «Ridible,» 04 Maggio 2015. [Online]. Available: <https://www.ridible.com/stampa-3d/>.
- [4] B. Redwood, «3dhubs: The Additive Manufacturing Process,» 3dhubs, [Online]. Available: <https://www.3dhubs.com/knowledge-base/additive-manufacturing-process>.
- [5] C. Orban, «3Dstampa3Dforum,» 21 Luglio 2014. [Online]. Available: <https://www.stampa3d-forum.it/introduzione-software-slicer/>.
- [6] 3D Printing school, «Stampiamo in 3D Inventa progetta e crea,» 3D Printing school, [Online]. Available: <http://stampiamoin3d.com/3d-printing-school-introduzione-alla-stampa-3d/primi-passi-per-stampare-in-3d/>.
- [7] AM Research Group , Loughborough University, [Online]. Available: <http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directenergydeposition/>.
- [8] AM Research Group, Loughborough University, [Online]. Available: <http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/>.
- [9] ALL3DP, «ALL3DP: 3D Printing Technology Guide – Types of 3D Printing Explained,» [Online]. Available: <https://all3dp.com/1/types-of-3d-printers-3d-printing-technology/>.
- [10] AM Research Group, loughborough university, [Online]. Available: <http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/heatlamination/>.

- [11] N. A, «engineersgarage,» [Online]. Available: <https://www.engineersgarage.com/articles/3d-printing-processes-sheet-lamination>.
- [12] N. A, «engineersgarage: 3D Printing Processes - Sheet Lamination,» [Online]. Available: <https://www.engineersgarage.com/articles/3d-printing-processes-sheet-lamination>.
- [13] «DREAMS,» [Online]. Available: <http://seb199.me.vt.edu/dreams/material-jetting/>.
- [14] Stratasys Direct Manufacturing, 16 March 2016. [Online]. Available: <https://www.youtube.com/watch?v=kbiIdTVz6bA>.
- [15] AM Research Group, loughborough university, [Online]. Available: <http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/>.
- [16] AM Research Group, loughborough university, [Online]. Available: <http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/vatphotopolymerisation/>.
- [17] AM Research Group, loughborough university, [Online]. Available: <http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/>.
- [18] E. Palermo, «LiveScience,» 19 September 2013. [Online]. Available: <https://www.livescience.com/39810-fused-deposition-modeling.html>.
- [19] M. C. w. H. Fraiss, «Consumables,» 19 November 2015. [Online]. Available: <https://consumables.ic3dprinters.com/fused-deposition-modeling-fdm-and-its-main-limitations/>.
- [20] P. Chain, «3dhubs: Supports in 3D Printing: A technology overview,» 3dhubs, [Online]. Available: <https://www.3dhubs.com/knowledge-base/supports-3d-printing-technology-overview>.
- [21] Stratasys, «Stratasys,» [Online]. Available: <http://www.stratasys.com/it/resources/case-studies/defense/sheppard-air-force-base>.
- [22] Stratasys, «Stratasys,» [Online]. Available: <http://www.stratasys.com/resources/case-studies/commercial-products/soft-play?returnUrl=http://www.stratasys.com/resources/case-studies?technologies=FDM>.
- [23] Stratasys, «Stratasys,» [Online]. Available: <http://www.stratasys.com/resources/search/case-studies/sheppard?returnUrl=http://www.stratasys.com/resources/case-studies?industries=Aerospace&technologies=FDM>.
- [24] Ultimaker, «Ultimaker,» [Online]. Available: <https://ultimaker.com/en/stories/43969-volkswagen-autoeuropa-maximizing-production-efficiency-with-3d-printed-tools-jigs-and-fixtures>.

- [25] 3dmatter, «3dmatter: What is the best type of plastic for my 3D printing application?,» 8 July 2016. [Online]. Available: <http://my3dmatter.com/what-is-the-best-type-of-plastic-for-my-3d-printing-application/>.
- [26] Optimatter, Optimatter, [Online]. Available: <https://www.optimatter.com/>.
- [27] Fabbricafuturo, «fabbricafuturo: Materiali polimerici per la stampa 3D con tecnologia FDM,» 8 January 2016. [Online]. Available: <https://www.fabbricafuturo.it/nateriali-polimerici-la-stampa-3d-tecnologia-fdm/>.
- [28] 3dhubs, «3dhubs: FDM 3D Printing Materials Compared,» 3dhubs, [Online]. Available: <https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared>.
- [29] B. Hudson, «3dhubs: How to design parts for FDM 3D Printing,» 3dhubs, [Online]. Available: <https://www.3dhubs.com/knowledge-base/how-design-parts-fdm-3d-printing?action>.
- [30] E. Tyson, «Rigid.ink: How to Print Overhangs, Bridges and Exceeding the 45° Rule,» 16 January 2017. [Online]. Available: <https://rigid.ink/blogs/news/how-to-print-overhangs-bridges-and-exceeding-the-45-rule>.
- [31] wikipedia, «wikipedia: Compressive strength,» wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Compressive_strength.
- [32] wikipedia, «wikipedia: Tensile strength,» wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Ultimate_tensile_strength.
- [33] Wikipedia, «Wikipedia: Young module,» Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Young%27s_modulus.
- [34] apsleyeng, «apsleyeng: Surface roughness,» apsleyeng, [Online]. Available: <http://www.apsleyeng.co.uk/technical-advice/surface-roughness/>.
- [35] makerbot, «makerbot: Layer height,» makerbot, [Online]. Available: https://support.makerbot.com/learn/3d-printing/3d-printing-terms/layer-height_12672.
- [36] MakerBot, «MakerBot:LEARN THE BASICS OF 3D PRINTING,» MakerBot, [Online]. Available: <https://www.makerbot.com/learn/>.
- [37] MakerBot, «MakerBot: CUSTOM SETTINGS,» MakerBot, [Online]. Available: https://support.makerbot.com/learn/makerbot-desktop-software/print-settings/custom-settings_11912.
- [38] E. Tyson, «Rigid: How to Use 3D Print Infill Settings - Increase Strength, Save Filament,» Rigid, 05 May 2017. [Online]. Available: <https://rigid.ink/blogs/news/optimum-infill>.
- [39] J. FRANKLAND, «ptonline: Extrusion: The Facts About Barrel-Temperature Override,» ptonline, 31 August 2017. [Online]. Available: <https://www.ptonline.com/columns/extrusion-the-facts-about-barrel-temperature->

override.

- [40] CNET, «Youtube,» MakerBot, 6 January 2014. [Online]. Available: <https://www.youtube.com/watch?v=Xlu1-jbbR7A&t=92s>.
- [41] 3dhubs, «3dhubs: Makerbot z18,» 3dhubs, [Online]. Available: <https://www.3dhubs.com/3d-printers/makerbot-replicator-z18>.
- [42] M. support, «Minitab support: Designing an Experiment,» Minitab support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/getting-started/designing-an-experiment/>.
- [43] M. Blog, «Minitab Blog: DOE Center Points: What They Are & Why They're Useful,» Minitab Blog, [Online]. Available: <http://blog.minitab.com/blog/michelle-paret/doe-center-points-what-they-are-why-theyre-useful>.
- [44] M. Blog, «Minitab Blog: Gummi Bear DOE: What Do the Center Points Show?,» Minitab Blog, [Online]. Available: <http://blog.minitab.com/blog/statistics-and-quality-improvement/gummi-bear-doe-what-do-the-center-points-show>.
- [45] S. Minitab, «Support Minitab: What factor values should I use in a response surface design?,» Support Minitab, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/doe/supporting-topics/response-surface-designs/what-factor-values-should-i-use/>.
- [46] M. Support, «Minitab Support: Delve Deeper into Survey Data with Minitab: 2-Sample t-Tests, Proportion Tests, ANOVA and Regression,» Minitab Support, [Online]. Available: <http://www.minitab.com/en-us/Published-Articles/Delve-Deeper-into-Survey-Data-with-Minitab--2-Sample-t-Tests,-Proportion-Tests,-ANOVA-and-Regression/>.
- [47] M. support, «Minitab support: Data considerations for One-Way ANOVA,» Minitab support, [Online]. Available: <http://support.minitab.com/en-us/minitab-express/1/help-and-how-to/modeling-statistics/anova/how-to/one-way-anova/before-you-start/data-considerations/>.
- [48] S. Minitab, «Support Minitab: Should I use Bonett's method or Levene's method for 2 Variances?,» Support Minitab, [Online]. Available: <http://support.minitab.com/en-us/minitab-express/1/help-and-how-to/basic-statistics/inference/supporting-topics/tests-of-proportions-and-variances/bonett-s-method-or-levene-s-method/>.
- [49] M. support, «Minitab support: Example of One-Way ANOVA,» Minitab support, [Online]. Available: <http://support.minitab.com/en-us/minitab-express/1/help-and-how-to/modeling-statistics/anova/how-to/one-way-anova/before-you-start/example/>.
- [50] M. Support, «Minitab Support: Interpret the key results for Main Effects Plot,» Minitab Support, [Online]. Available: <http://support.minitab.com/en-us/minitab-express/1/help-and-how-to/modeling-statistics/anova/how-to/main-effects-plot/interpret-the-results/>.
- [51] M. support, «Minitab support: Interpret the key results for Interaction Plot,» Minitab

- support, [Online]. Available: <http://support.minitab.com/en-us/minitab-express/1/help-and-how-to/modeling-statistics/anova/how-to/interaction-plot/interpret-the-results/>.
- [52] M. support, «Minitab support: Multiple Regression Analysis: Use Adjusted R-Squared and Predicted R-Squared to Include the Correct Number of Variables,» Minitab support, [Online]. Available: <http://blog.minitab.com/blog/adventures-in-statistics-2/multiple-regression-analysis-use-adjusted-r-squared-and-predicted-r-squared-to-include-the-correct-number-of-variables>.
- [53] S. Minitab, «Support Minitab: Model reduction,» Support Minitab, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/regression/supporting-topics/regression-models/model-reduction/>.
- [54] M. Support, «Minitab Support: Residual plots in Minitab,» Minitab Support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/regression/supporting-topics/residuals-and-residual-plots/residual-plots-in-minitab/>.
- [55] statwing, «statwing: Interpreting residual plots to improve your regression,» statwing, [Online]. Available: <http://docs.statwing.com/interpreting-residual-plots-to-improve-your-regression/>.
- [56] M. support, «Minitab support: Residual plots for Fit Regression Model,» Minitab support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/regression/how-to/fit-regression-model/interpret-the-results/all-statistics-and-graphs/residual-plots/>.
- [57] E. c. o. science, «Eberly college of science: Residuals vs. order plot,» Eberly college of science, [Online]. Available: <https://onlinecourses.science.psu.edu/stat501/node/39>.
- [58] M. support, «Minitab support: Response Optimizer,» Minitab support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/doe/how-to/mixtures/response-optimizer/>.
- [59] M. support, «Minitab support: Overview for Response Optimizer,» Minitab support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/using-fitted-models/how-to/response-optimizer/before-you-start/overview/>.
- [60] M. support, «Minitab support: What is an optimization plot?,» Minitab support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/using-fitted-models/supporting-topics/response-optimization/what-is-an-optimization-plot/>.
- [61] M. support, «Minitab support: What are individual desirability and composite desirability?,» Minitab support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/using-fitted-models/supporting-topics/response-optimization/what-are-individual-desirability-and-composite-desirability/>.
- [62] E. Tyson, «Rigid: How to Use 3D Print Infill Settings - Increase Strength, Save

Filament,» Rigid, 5 May 2017. [Online]. Available:
<https://rigid.ink/blogs/news/optimum-infill>.

- [63] M. Support, «Minitab Support: What are response surface designs, central composite designs, and Box-Behnken designs?,» Minitab Support, [Online]. Available:
<https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/doe/supporting-topics/response-surface-designs/response-surface-central-composite-and-box-behnken-designs/#what-is-a-central-composite-design>.
- [64] M. Support, «Minitab Support: Example of Analyze Response Surface Design,» Minitab Support, [Online]. Available: <https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/doe/how-to/response-surface/analyze-response-surface-design/before-you-start/example/>.
- [65] N. sematech, «Nist sematech: Central Composite Designs (CCD),» [Online]. Available: <https://www.itl.nist.gov/div898/handbook/pri/section3/pri3361.htm>.
- [66] M. Support, «Minitab Support: What are response surface designs, central composite designs, and Box-Behnken designs?,» Minitab Support, [Online]. Available:
<https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/doe/supporting-topics/response-surface-designs/response-surface-central-composite-and-box-behnken-designs/#what-is-a-central-composite-design>.

List of Acronyms and Abbreviations

ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
ANOVA	analysis of Variance
BJ	binder jetting
CAD	computer aided design
CCD	central composite design
DED	directed energy deposition
DLP	digital light processing
DMLS	direct metal laser sintering
DOE	design of Experiment
EBM	electron beam melting
FDM	fused deposition modeling
LOM	laminated object manufacturing
MJ	material jetting
PC	polycarbonate
PET	polyethylene terephthalate
PLA	polylactic acid
Ra (μm)	surface roughness average
RM	rapid manufacturing, when AM is used for end products
RP	rapid prototyping, when AM is used for prototyping
R-sq(adj)%	adjusted coefficient of determination
RT	rapid tooling, when AM is used for tools or tooling
SL	sheet lamination
SLA	stereolithography apparatus
SLM	selective laser melting
SLS	selective laser sintering
TPU	thermoplastic polyurethane
UAM	ultrasonic additive manufacturing
3D	3-Dimensional

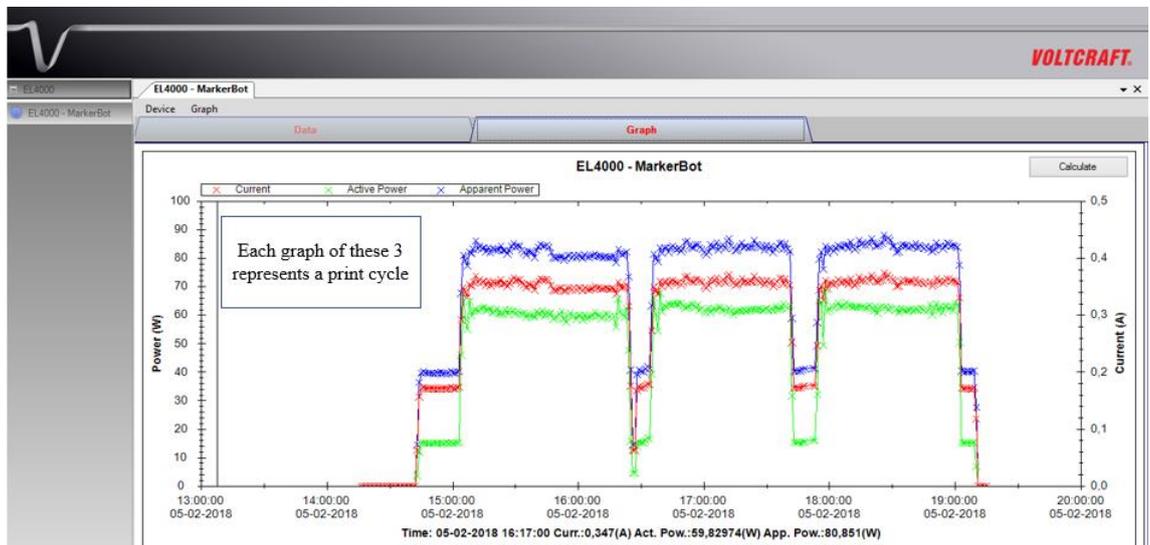
Appendix

- I.** Energy Device
- II.** Energy Consumption Graph
- III.** Surface Roughness Graph
- IV.** Final correlation matrix

I. Energy Device

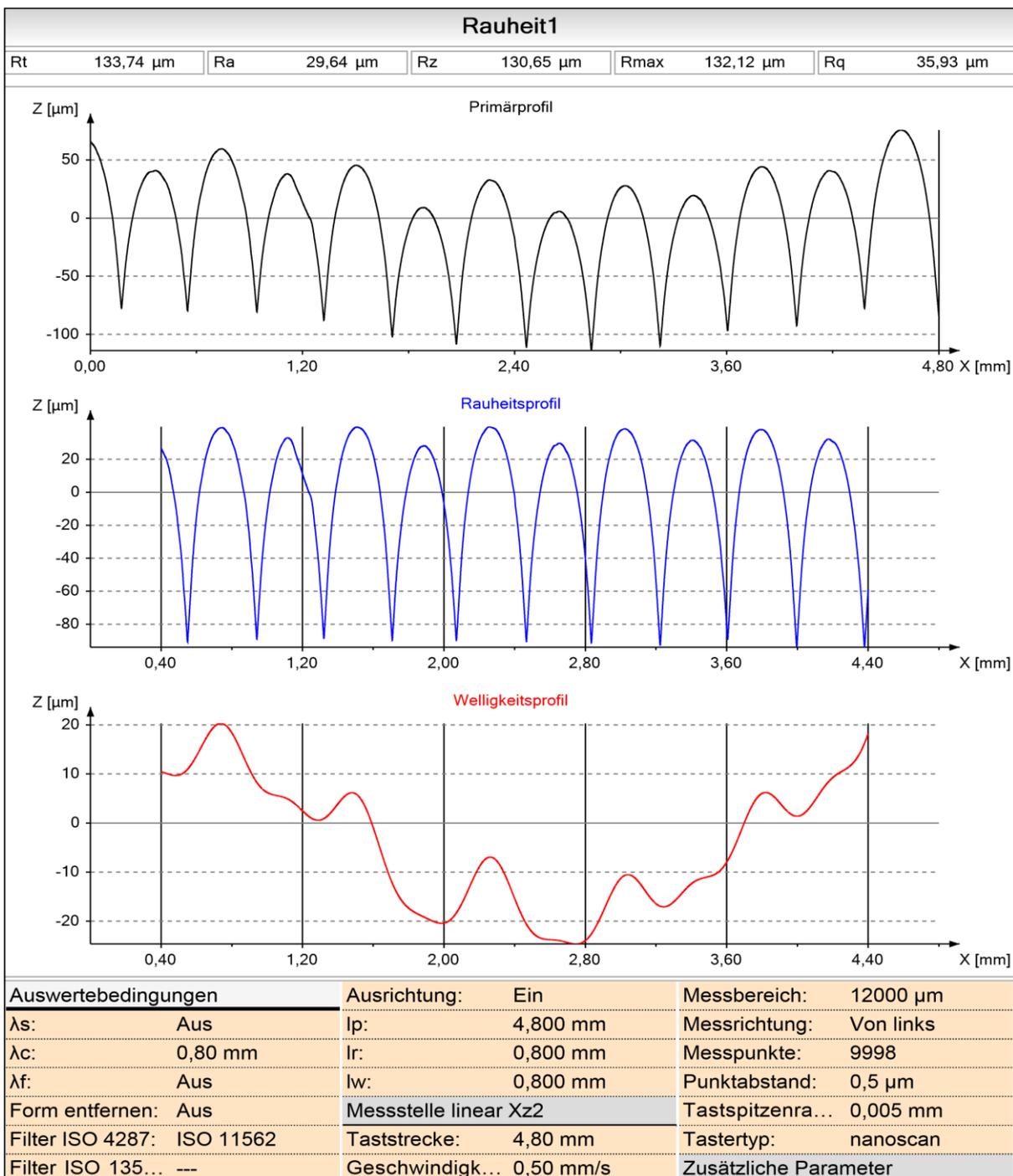


II. Energy Consumption Graph



III. Surface Roughness Graph

Kunde	Werkstück	
Auftrag	Zeichnungsnummer	
Prüfer	Seriennummer	
Bemerkung		



19.02.2018 17:14:56	Hommel-Etamic T8000	EVOVIS 2.00.1.00	Seite 1/1
---------------------	---------------------	------------------	-----------

IV. Final correlation matrix

Parameters	Parameter/ Costant	Printing Time	Energy Consumption	Dimensional Accuracy	Surface Roughness	Compressive Streight	Young's Module	Tensile Streight	Warping
Print Speed	Yes	4	4	4	3	3-nc	nc	3-nc	4
Layer Height	Yes	5	4	4	5	4-3	4	4-3	2-3
Fill Density	Yes	5-4	4	4-3	2-1	5	3	5	4-3
Temperature of extruder	Yes	nc	4	3	2	3-2	2-nc	2	2
Part orientation		1-nc	2-nc	4	4	2	nc	nc	nc
Number of shells	Yes	4	3	3-2	3-1	4-3	3	3	4-2
Bottom/Top thickness	Constant	3-2	2	2	2-1	3-2	2-nc	2	3
Filament diameter	Constant	1-nc	1-nc	2	3-2	3-1	1-nc	3-1	3-1
Retraction speed	Yes	4-1	2-1	3-nc	3-nc	2-nc	nc	nc	nc
Retraction distance	Constant	3-1	2-1	3-nc	3-nc	2-nc	nc	nc	nc