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MASTER'S THESIS

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Parameter optimization in additive manufacturing (3D printing) for optimal mechanical and structural performance

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I Abstract

This master thesis explores the optimization of parameters in resin-based 3D printing to enhance mechanical and structural performance. The main problem was the development of residual stresses in the polymer resin during the 3D SLA printing and post-processing, which led to distortion and affection of the mechanical and structural performance of the printed parts. The study was conducted using the Taguchi method, a statistical approach for enhancing quality of products or processes. Specifically the research focused on print orientation, layer thickness, UV curing temperature, and UV curing time to achieve desired outcomes while minimizing distortion.

Results revealed that print orientation, particularly the vertical setting of 90° had the most significant influence on both the signal-to-noise ratio and flatness of the printed parts. Additionally, lower layer thickness, UV curing time and temperature contributed to a better SNR and surface flatness. These findings offer practical insights to improve the overall quality of printed parts through careful adjustment of these parameters.

The thesis also addresses the environmental and financial highlights related to resin-based 3D printing. With certain limitations and potential sources of error, the study contributes to the existing knowledge in the field of additive manufacturing and provides a foundation for further research and development. It is hoped that these findings will inspire future advancements in the field, leading to improved performance and functionality of 3D printed products.

Key words:

- Additive Manufacturing
- Resin-based 3D Printing
- Parameter Optimization
- Taguchi Method
- Post Processing

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Table of Contents

List of Figures

List of Tables

List of Equations

Nomenclature

Acronyms

3D Three Dimensional

AM Additive Manufacturing

ANOVA Analysis of Variance

ASTM American Society for Testing and Materials

CAD Computer Aided Design

CMM Coordinate Measuring Machine

DLP Digital Light Processing

DLS Digital Light Synthesis

DoC Degree of Cure

DOE Design of Experiments

FDM fused Deposition Modeling

ISO International Organization for Standardization

MJF Mult Jet Fusion

S/N Signal to Noise

SLA Stereolithography

SLM Selective Laser Melting

SLS Selective Laser Sintering

UiS University of Stavanger

USA United States of America

UV Ultra Violet

VIF Variance Inflation Factor

Symbols

GPa Giga Pascal

L Litre

mm Millimeter

MPa Mega Pascal

pH Quantitative measure of the acidity or basicity of aqueous or other liquid solutions

1 Introduction

1.1 Background

The field of additive manufacturing is currently experiencing significant growth, with a wide range of potential applications across multiple industries (Ian Gibson, David Rosen, & Brent Stucker, 2015). The selection of materials for use in additive manufacturing processes is a crucial factor in determining the success of the final product. One such material, the photopolymer resin known as Clear V4 produced by Formlabs, which is the focus of this research project, is prone to deformation during the stereolithography (SLA) process. Form 3 + is a low force stereolithography 3D printer produced by Formlabs (Formlabs, 2023c), and is used in this research to investigate the deformation of the polymer resin during the SLA process. The UV curing process can also lead to the development of residual stresses within the material, which can negatively impact the mechanical and structural properties of the final product. This research aims to investigate and understand the underlying causes of these problems and explore possible solutions to mitigate or eliminate them.

1.2 Problem Formulation

The problem is the development of residual stresses in the polymer resin during the SLA printing process and the UV curing post process, which leads to distortion and affects the mechanical and structural performance of the printed parts.

1.3 Objective and Scope

To optimize the parameters of additive manufacturing to minimize residual stresses and related distortion in the polymer resin, resulting in optimal mechanical and structural performance of printed parts.

1.4 Limitations

Only the Clear V4 polymer resin and the SLA process will be conducted in the study. The research will not cover other types of additive manufacturing techniques, only the Form 3+ 3D printer will be used.

1.5 Structure of Report

Chapter 2 - Theory - This chapter outlines the theories, methods, models, equations, etc. informative to complete the thesis, as well as for the reader. An introduction to the additive manufacturing process is presented, a literature survey on the resin material and the background information on the test methods used are included.

Chapter 3 - Methodology - The chapter outlines the approach used to carry out the research and analysis of the thesis. The material, equipment and technique used are presented.

Chapter 4 - Results - In this chapter all the results obtained are presented.

Chapter 5 - Financial overview - A thorough explanation of the financial aspect of the thesis. Material, machines and equipment used.

Chapter 6 - Environmental account - Impact on the environment regarding the work in the thesis.

Chapter 7 - Discussion - The chapter contains the discussion of the results presented.

Chapter 8 - Conclusion - A brief summary of the results in the thesis and what they can tell us are concluded in this chapter.

2 Theory

2.1 Additive Manufacturing Process

Additive manufacturing, also known as rapid prototyping or 3D printing is a process used to create a model representation quickly (Ian Gibson, David Rosen, & Brent Stucker, 2015). The term rapid prototyping was commonly used to describe such a technology, but improvements in the quality of the fabricated models have led to the development of new applications. The process rely on creating physical models directly from a digital model (CAD), and the term additive manufacturing is a better term to describe it. Fabrication involves using an additive approach, material is added layer by layer, where each layer is a thin section from the original CAD model.

2.1.1 *Step 1 - CAD*

A CAD (computer-aided design) model is a digital representation of the external geometry of the model that is created using specialized software (Ian Gibson, David Rosen, & Brent Stucker, 2015). Typical CAD software includes Autodesk Inventor, Solidworks, and Creo (Apollo, 2021). A CAD consists of a series of interconnected geometric shapes, such as polygons or curved surfaces.

When creating a CAD model from scratch in a specialized program as stated, the file format is usually limited to the specific program. This is to maintain competition and ensure software compatibility (Ian Gibson, David Rosen, & Brent Stucker, 2015). However, CAD software programs allow the user to export their model in an universal format as .STL, .OBJ, or .STEP. The universal format of the models does not allow the user to see the underlying ”building blocks” of the model, i.e the operations done to create the specific model.

2.1.2 *Step 2 - Conversion to STL*

The most common universal format of 3D models is the STL (STereoLithography) format. The generic format was developed by 3D Systems in USA, which was the first company to commercialize additive manufacturing technology and called the file format "STL" after their stereolithography technology (Ian Gibson, David Rosen, & Brent Stucker, 2015). The STL file format models consists of a triangulated mesh illustrated in figure 2, different from the CAD model in figure 1 the STL model does not contain any information about the color, texture, or material properties of the 3D model. The STL file contains only the basic geometry of the object, while the CAD model contains all the details and specifications.

Figure 1: CAD Model

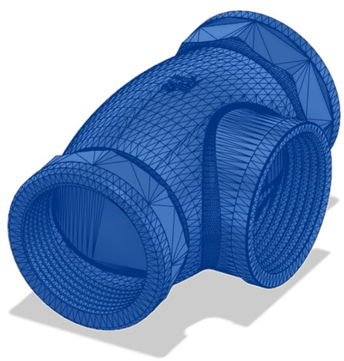


Figure 2: STL Model

As the STL file format consists only of a triangulated mesh, the quality of a 3D print is highly dependent on the number of points in the mesh (Jyothish Kumar, M. Pandey, & Ian Wimpenny, 2019). If creating a mesh of a perfectly round sphere, then the more points the better. If the mesh contains few points, the sphere will be coarse and create edges around.

2.1.3 *Step 3 - Slicing*

The slicing program is the essential program that translates a 3D model into readable code for the 3D printer to execute and print the model (Jyothish Kumar, M. Pandey, & Ian Wimpenny, 2019). The program split the model into thin sections, creating layers for the 3D printer. As the term additive manufacturing states, the model is then created layer by layer of the given material.

In the program, the user can alter different parameters to obtain different qualities of the finished 3D model. Some of the most typical parameters are listed below:

- Orientation of model
- Layer height
- Density
- Print speed
- Infill density

Used in this study is the PreForm slicing program by Formlabs. It is a powerful software concentrating at a user friendly interface.

2.1.4 *Step 4 - SLA 3D Printing*

After slicing, the program is ready for the 3D printer. Stereolithography (SLA) 3D printing uses a liquid resin that is cured by a UV laser beam. The curing process is an exothermic polymerization process characterized by chemical cross-linking reactions that crate and bind to an infusible, insoluble, and highly cross-linked 3D network (Paulo Jorge Bártolo et al., 2011). The resin cures when exposed to the beam, as the printer platform moves up layer by layer at a fraction of a millimeter repeatedly until the model is printed.

In figure 3 an illustration provided by Formlabs explain the unique parts of an SLA 3D printer.

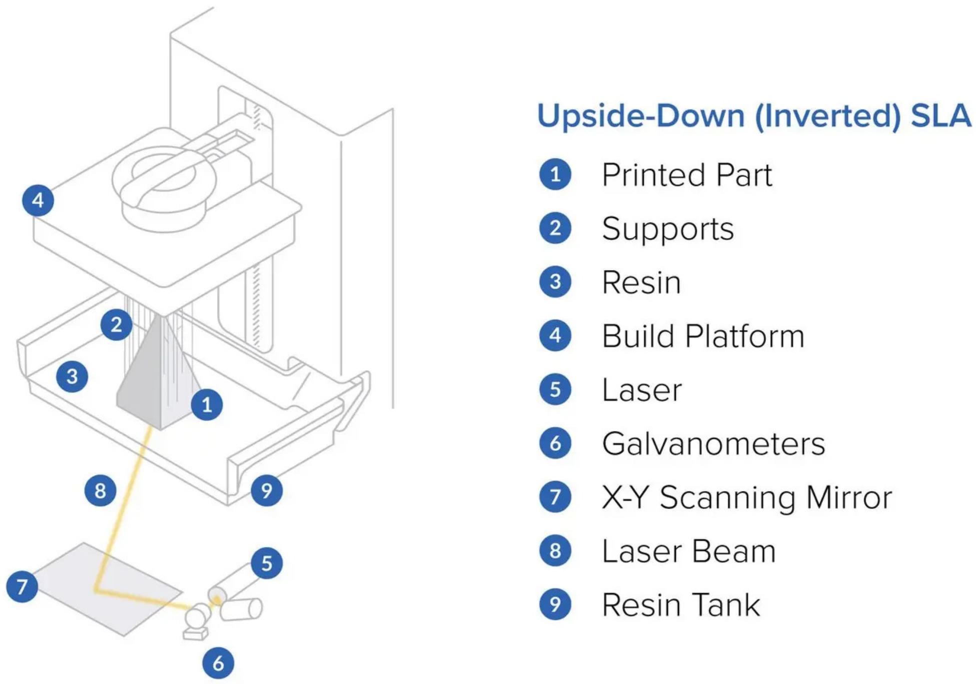


Figure 3: SLA 3D printing schematic illustration (Formlabs, 2023e)

SLA printing delivers high resolution (small layer height) and the ability to create precise parts. The lower the layer height yields a higher level of detail, as well as a smoother surface finish. The uncured resin in the chamber remains liquid and can be reused, minimizing material wastage. The high resolution and accuracy make the 3D printer suitable for applications requiring intricate detail and small models.

2.1.5 *Step 5 - Post Processing*

As the model is finished printing it is not ready for use yet. In SLA printing methods, excess resin is usually left on the printed parts after completion. The printed parts are then rinsed in an alcohol solution to remove any uncured resin left.

The support structure which is created in the printing process to prevent the model from collapsing has to be removed. This is a manual process, having to be careful not to damage the main part.

Finally the parts will be cured in a UV curing chamber to additional cure the parts. Resin models have a sticky surface finish when finished printing, which requires additional UV curing. Depending on the specific resin, the time and temperature are set in the chamber to cure and strengthen the model further.

2.2 Literature Survey - Clear V4 Polymer Resin

2.2.1 *Introduction*

The Clear V4 polymer resin is prone to distortion during the SLA production process. In additive manufacturing, distortion during production is an important topic for several reasons. As additive manufacturing is becoming increasingly more used in various industries such as healthcare, aerospace and automotive, maintaining accuracy and quality of printed parts is a must. Distortion, the deviation of a printed part from its intended shape, can occur both in the printing process and the post processing. This can negatively impact the mechanical and structural performance in the part making it not reasonable for intended use.

The distortion in polymer resin during additive manufacturing can also increase the cost and time required for producing models. Increased production cost, wasted material, delays in delivery, and reduced profitability may be negative factors for a given company.

Understanding and minimizing distortion in polymer resin can help improve the overall efficiency, quality and reliability of additive manufacturing, which is essential for the further development and adoption of the technology.

2.2.2 *Characteristics of The Polymer Resin*

Table 1: Material properties Clear V4 polymer resin

Property	Without additional treatment	Post-Cured	Method
Tensile properties			
Ultimate Tensile strength	38 MPa	65 MPa	ASTM D638-14
Tensile modulus	1.6 GPa	2.8 GPa	ASTM D638-14
Elongation at break	12%	6%	ASTM D638-14
Flexural properties			
Flexural modulus	1.3 GPa	2.2 GPa	ASTM D 790-15
Impact properties			
Notched izod	16 J/m	25 J/m	ASTM D256-10
Thermal properties			
Heat Deflection Temp. @ 1.8 MPa	43 °C	58 °C	ASTM D 648-16
Heat Deflection Temp @ 0.45MPa	50 °C	73 °C	ASTM D 648-16

The material properties of the resin is dependent on the additional UV cure in post-processing. From table 1 (Formlabs, 2023a) it is clearly seen that the post-cured material has a higher ultimate tensile strength, but suffers from a more brittle characteristic relative to elongation. As the post-cure treatment can be set from no additional treatment to fully post cured as in the table 1, one can obtain different characteristics in-between the two extremities.

2.2.3 *Mechanical And Structural Performance of Printed Parts*

According to Baumgarner and Piovesan (2021) testing the ultimate post-cured tensile strength of Clear V4 resin, the experimental results were lower than those reported by Formlabs in table 1. Indicating a value of 47.6 MPa compared to the value of 65 MPa post-cured material property as in the table 1. On the other hand the experimental value found for the uncured resin samples, the ultimate tensile strength was 43 MPa according to Baumgarner and Piovesan

(2021). Indicating a higher strength than Formlabs at 38 MPa for the uncured clear resin.

2.2.4 *Previous Research On Distortion In Polymer Resin During SLA*

According to Zhang et al. (2021) on ”Design for the reduction of volume shrinkage-induced distortion in digital light processing 3D printing”, there is a known shrinkage related to the photocure from liquid into solid. The investigation carried out in the article was on the volume shrinkage-induced distortion of DLP (Digital Light Processing) printed parts. The difference between SLA and DLP is the light source, SLA utilizing a UV laser beam while the DLP utilizes UV light from a projector (Formlabs, 2023e). The DoC (Degree of Cure) of the resin material was used to characterize the properties of the material and volume shrinkage. The study found that reducing the DoC during printing can reduce the residual stress and shape distortion of the printed parts.

2.2.5 *Various Factors On Warping And Distortion*

There are numerous different parameters to choose from when setting up a 3D print. The process has to be split into two different sections, ”Pre-Process” and ”Post-Process”. As these factors have a direct impact on the distortion of the printed parts, they are also related to each other. Various websites and forums indicate the most common preventive solutions to stop 3D resin prints from warping. In the bullet list below are the most common preventive solutions (Michael Dwamena, 2023).

- Models are not supported properly.
- Exposure times during printing process.
- Correct orientation of the model.
- Change the resin material. Alternatively use filler to alter the resins properties.
- Correct wall thickness. Density of the model.
- The models are completely dry before curing.

- Correct layer height.
- UV cure evenly.

2.2.6 *Research On Residual Stresses In Polymer Resin*

Both according to Zhang et al. (2021) and Yankov and Nikolova (2017) state the issue of volumetric changes during the printing process of models. Residual stress development in the material is developed layer by layer by the UV beam or projector in DLP. The DoC stated in the article of Zhang et al. (2021) is illustrated in Figure 4 highlighting the evolution of curing resin material.

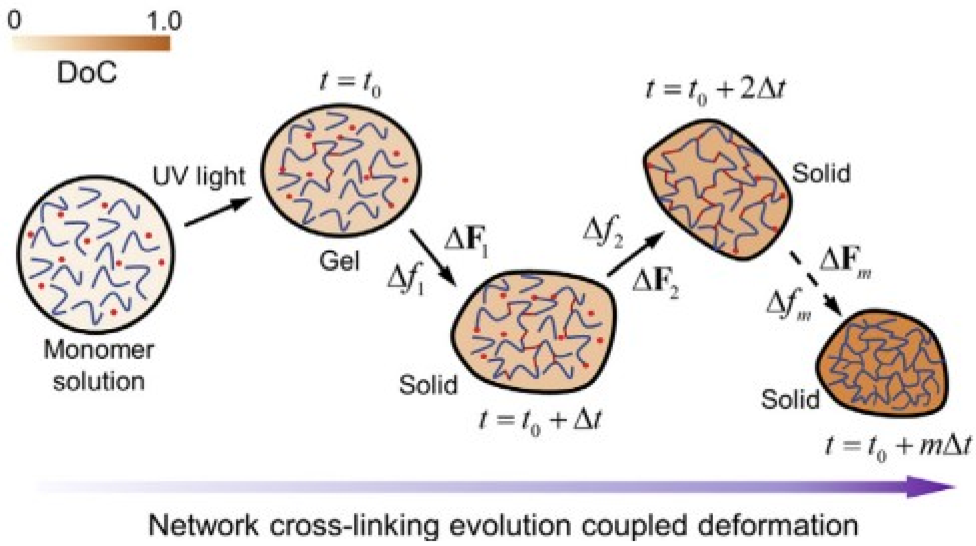


Figure 4: Material evolution process during photo polymerization (Zhang et al., 2021)

2.2.7 *UV Post-Curing Effect On 3D Printed Models*

The study of Štaffová et al. (2022) reveal insights in how UV post curing influences the 3D printed models. The combined method used in the study HDT (Heat Deflection Temperature) and DMA (Dynamic Mechanical Analysis). For a FDM (Fused Deposition Modeling) 3D printer, it was found that printing in the x direction provide higher mechanical resistance, reducing distortions. The study also indicated that post-processing exposure and washing in isopropanol significantly impacted the thermomechanical properties of the models, influencing their distortion.

Longer post-curing time and higher exposure to UV light lead to increase in network density and overall hardness. The network density refers to the degree of cross linking or interconnections in a polymer network (Tanaka Fumihiko, 2011). In additive manufacturing, this can measure the extent to which the polymer has been cured both during the 3D printing process and after.

The study of Guttridge et al. (2022) investigated the impact of post-curing times on photosensitive 3D printing resins. The resins used had special applications in medicine and dentistry. The research revealed that while curing depth generally increased with extended UV exposure, the effect varied significantly based on the opacity of the resin. Opaque resins did not fully cure even when the curing time was extended to five times the duration, in comparison to translucent resins that cured to full depth at the recommended guidance. Stated by Guttridge et al. (2022), it is recommended for users to develop and validate their own post-processing methods to mitigate potential negative effects.

2.2.8 *Preheating Techniques Related To UV Curing From Formlabs Services*

UV curing process is necessary to enhance the mechanical properties of 3D printed models. Formlabs Services suggest preheating the models in the UV curing chamber as the chamber heats up to target temperature. Preheating the model can help reduce the risk of cracking or warping. The size and geometry of the model is also important to consider when selecting a post-cure cycle. For larger, thicker, and more complex parts, it may be necessary to modify the post-curing process to ensure effective and safe curing. Ensuring that the models are completely dry before inserting in the UV curing chamber is important to prevent clouding on the reflective surfaces inside the machine.

2.2.9 *Summary And Conclusions*

The survey conducted on the Clear V4 polymer resin reveals that distortion during the UV curing process is a common problem during the additive manufacturing process. Distortion or warping can negatively impact the mechanical and structural performance of the printed models, making them not suitable for their purpose.

The material properties of the polymer resin depend on the additional UV cure in post-processing. Post-cured models has a higher ultimate tensile strength than non-cured models. The additional treatment can be set from no additional curing to fully post cured, which can make the material obtain characteristics in-between the two extremities.

Previous research has shown that reducing the degree of cure can reduce the residual stress and shape distortion of the printed models.

In conclusion, understanding the factors that contribute to distortion and warping in additive manufacturing is crucial for achieving high-quality parts. The findings of this survey will act as a guide to optimize the printing parameters and post-processing techniques to reduce distortion and improve overall mechanical and structural performance.

2.3 Pareto Analysis

Pareto analysis, also known as the 80/20 Rule, is a powerful technique that identifies the vital factors contributing to a majority of the outcomes or problems (Richard Koch, 2011). The method is applicable in various industries, such as engineering, manufacturing, management and human resources according to Richard Koch (2011). By analyzing on the vital few factors, The Pareto analysis creates an efficient resource and decision making.

2.3.1 *Methodology*

The methodology of Pareto analysis follows the bullet points of Michael L. George et al. (2004).

1. Collecting and organizing relevant data to the problem or outcome of interest.

2. Categorizing the data into different groups.

3. Ranking the categories based on their frequency, or impact.

4. Plotting the Pareto chart to visually represent the vital factors of each category.

5. Identify the vital categories that contribute to the majority of the problem.

2.3.2 *Interpretation*

The results of a Pareto analysis interpretation is important for making the informed correct decisions (Michael L. George et al., 2004). The Pareto chart helps identifying the vital few factors that require attention and resources. By focusing on the vital few categories, it becomes possible to achieve improvement and maximize impact.

2.3.3 *Practical Applications*

Pareto analysis is applicable in various industries as stated. Quality improvements, optimizing resource allocation, identifying bottlenecks, and enhance overall efficiency are some of the main goals of the method. Understanding the most influential factors related to the desired outcome, strategies and interventions can be developed to create better results (Richard Koch, 2011).

2.3.4 *Conclusion*

The usage of a Pareto analysis offers a systematic approach for identifying and addressing the vital factors related to a specific outcome or problem (Richard Koch, 2011). The aim is to gain valuable information and make decisions that will lead to an improved desired outcome and greater efficiency.

2.4 Taguchi Robust Design Approach

2.4.1 *Overview of Taguchi Robust Design Approach*

Taguchi Robust Design Process is a statistical method used in engineering to improve the quality of a product or process by reducing the sensitivity to noise factors (Madhav Shridhar Phadke, 1989). The method was developed by Dr. Genichi Taguchi, a Japanese engineer (Teruo Mori, 2011). The method is widely used, Ford Motor Company decreed in the early 1990s that all engineers and suppliers engineers be trained in the Taguchi methodology (Ranjit K. Roy, 2010). The process involves three stages; system design, parameter design and tolerance design.

In the system design stage, the engineers goal is to identify the important factors that affect the quality characteristics of the product or process (Teruo Mori, 2011). The controllable factors are those that can be adjusted by the experimenter, while the uncontrollable factors cannot be controlled, but can be monitored. Determining the acceptable range of variation, in other words the levels of each key factor are also done in this stage.

In the parameter design stage the optimal combination of the factor levels is determined. The method uses an orthogonal array to conduct a set of experiments with a minimal number of runs. The signal-to-noise (S/N) is used to evaluate the performance of each combination of factor levels. The goal is to find the combination of factor levels that produces the highest S/N ratio and therefore the best performance.

The tolerance design stage is the stage of evaluating the effect of noise factors on the performance of the product or process, this is to ensure the robustness of the optimal design. The noise factors are uncontrollable factors that can affect the quality characteristics of the product or process. The goal is to determine the tolerance levels for the controllable factors so that the optimal design is insensitive to variations in the noise factors.

By utilizing the Taguchi robust design approach engineers can design products and processes that are less sensitive to noise factors, resulting in higher quality and more reliable products (Ranjit K. Roy, 2010).

2.4.2 *Orthogonal Array L9*

The Taguchi L9 design is an experimental setup that involves 4 factors each with 3 levels. In the Taguchi method this setup provides good balance between the number of experiments required and the information that can be gained (Madhav Shridhar Phadke, 1989). For 4 factors with 3 levels the total number of experiments required is $3^4 = 81$. The Taguchi methods usage of orthogonal arrays are designed to minimize the number of experiments, while still providing information to determine the optimal factor settings. Compared to a full factorial design, requiring a total of 81 experiments, the L9 orthogonal array allows for the same amount of information to be gathered with only 9 experiments. This significantly reduce the time, resources and cost to conduct the experiment. This make the Taguchi method a more efficient approach to optimization (Genichi Taguchi, Subir Chowdhury, & Yuin Wu, 2004).

2.4.3 *Signal-To-Noise Ratio*

In the Taguchi method there are three different objective functions to evaluate the performance. In each function the signal-to-noise ratio is the identifier of the quality of the process or product measured. The objective functions are optimized to the desired output determined on the process or product. The three main objective functions are explained relative to the S/N ratios (Ranjit K. Roy, 2010).

Smaller-The-Better is used when the quality of the process or product is improved by reducing the output. Used when minimizing a response variable, such as cost or weight. Equation 1 is the function used for smaller the better analysis of the S/N ratio.

$$S/N_s = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Nominal-Is-Best objective function is used when the target value is known and the goal is to minimize the deviation from the target value. This can be used for example in chemical processes when aiming for a specific pH value. The function for the desired S/N representation is equation 2.

$$S/N_t = 10 \log \left(\frac{\bar{y}^2}{s^2}\right) \tag{2}$$

Larger-The-Better objective function is used when the goal is to maximize a response variable. This can be used for a material process when the goal is to maximize the strength of the material. Equation 3 is the function used for the larger-the-better objective.

$$S/N_L = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}\right) \tag{3}$$

2.4.4 *Taguchi Method Step-By-Step*

The approach of Taguchi method follows the steps according to Madhav Shridhar Phadke (1989). The following are the main steps involved.

Planning the experiment:

1. Identify the primary function of the product or process, as well as any side effects or failure modes that may occur.

2. Determine the testing conditions and noise factors that may affect the quality of the product or process.

3. Identify the quality characteristics that need to be observed and the objective function that needs to be optimized.

4. Identify the control factors and their alternate levels.

5. Design the matrix experiment and define the data analysis procedure.

Performing the experiment:

1. Conduct the matrix experiment.

Analyzing and verifying the experiment results:

1. Analyze the data collected from the experiment and determine the optimal levels for the control factors.

2. Predict the performance of the product or process under the optimal conditions.

3. Conduct a verification or confirmation experiment to validate the results obtained from the matrix experiment.

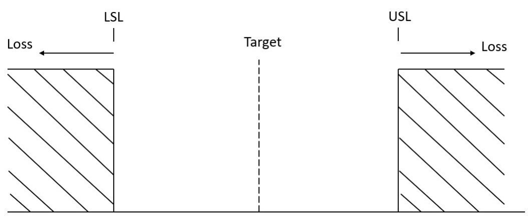
4. Plan future actions based on the results obtained.

2.4.5 *Quality Loss Function*

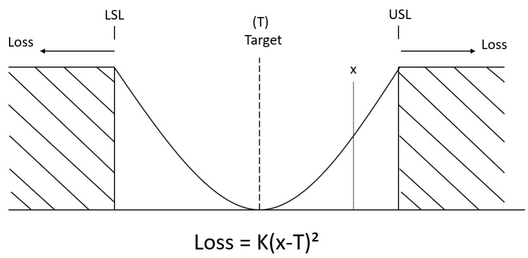
According to Madhav Shridhar Phadke (1989, p.14) ”We have defined the quality level of a product to be the total loss incurred by society due to the failure of the product to deliver the target performance and due to harmful side effects of the product, including its operating cost.” Phadke defines a high-quality product as one that performs well and does not cause harm or additional costs to society.

As Phadke has defined the quality of a product; the products failure to deliver the intended performance. Quantifying this loss can be difficult as customers use the products in various ways and under different conditions. However, it is crucial to measure this loss so the product or process can be evaluated.

The step function illustrated in figure 5 (a) measure that all products that meet the specification are equally good, and those outside specifications are a loss. This measure of quality is often incomplete and misleading. The quality loss function developed by Taguchi is essential for measuring the deviation from the target response continuously (Genichi Taguchi, Subir Chowdhury, & Yuin Wu, 2004, p. 174). The function in figure 5 (b) considers the products performance characteristics and the total loss incurred by society due to the products failure to deliver the intended performance and any negative side effects or operating costs.



(a)



(b)

Figure 5: (a) Conventional loss (b) Taguchi Loss

Taguchi believed that the cost of quality could be reduced by focusing on preventing poor quality by moving engineers to design specifications from inspection and rework (Teruo Mori, 2011) . Designing products designed to perform as closely as possible to the target value, rather than just within the allowable specification limit.

Overall this approach is intended to result in better products that both satisfy the costumers expectations, as well as reducing costs associated with poor quality.

2.4.6 *Advantages and Limitations*

The Taguchi method is a powerful method with several advantages that make it a valuable tool for optimizing product design and improving quality control (Teruo Mori, 2011). The efficiency in experimental design, testing several factors simultaneously with relatively few experiments by the utilization of orthogonal array is one of the main advantages of the method. Where time and resources are limited, the Taguchi method is particularly useful.

The signal-to-noise ratio as a ratio of performance, the Taguchi method can identify the combination of factors that will yield the best overall performance. It is a comprehensive method that can be tweaked by the objective function needed for the product or process being optimized by the smaller/larger-the-better or nominal-the-best functions (Ranjit K. Roy, 2010).

The Taguchi method has several limitations that should be considered when using it for optimization and quality control. The assumption that the system is linear and that the relationship between the factors and output response is additive. This implies that the response of a product is independent of the interactions between its components. This assumption may not be true for all systems, which can lead to inaccurate result if not accounted properly for (Ranjit K. Roy, 2010).

According to Ranjit K. Roy (2010) The Taguchi method requires proactive thinking and working as a group to address the quality improvement issues early in the product/process development. When the design variables are determined and their nominal values are specified, experimental design may not be cost-effective. Additionally if important factors are left out of the experimental design, the results may not be the optimal combination of factors for the desired performance. The Taguchi method may also not be suitable or appropriate for all situations. As stated by Ranjit K. Roy (2010, p.23) "in simulation studies involving factors that vary in a continuous manner, such as the torsional strength of a shaft as a function of its diameter, the Taguchi method may not be the best choice."

2.4.7 *Applications of the Taguchi Method*

The Taguchi method has found many applications in different industries, including mechanical, chemical and electrical manufacturing (Genichi Taguchi, Subir Chowdhury, & Yuin Wu, 2004). As mentioned by Ranjit K. Roy (2010) Ford Motor Company resulted in significant improvements in their production processes. By Ford Motor Company 1990 from 1980 Ford's quality survey showed a 400% improvement in the number of issues that occurred in the first three months of service, reducing the average number of issues per car from three to one. The implementation of the Taguchi method made Ford cars as reliable as many Japanese made automobiles (Genichi Taguchi, Subir Chowdhury, & Yuin Wu, 2004, p.160).

2.4.8 *Relevance Of The Taguchi Method To The Study*

The Taguchi method in relevance to the study is identifying critical control factors in the 3D printing process. Minimizing the quality loss and optimizing the 3D printed part. The methods efficiency in experimental design can help reach the achievement goals quicker than traditional testing.

2.5 Coordinate Measuring Machine

Coordinate measuring machines in modern manufacturing has become an essential tool in quality control and inspection (Carl Zeiss AG, 2023). The automated machines mainly use a probe with a range of sensors to measure physical dimensions of objects. In engineering such machines are vital in ensuring that the manufactured components meet the required specifications and tolerances. This chapter will provide information and an overview of CMM, working principle and application related to engineering quality control.

2.5.1 *Quality of Measuring Instruments*

In regards of quality control, there are specific terms used to describe the quality of measuring instruments. Accuracy, amplification, calibration, drift, linearity, precision, resolution, sensitivity and speed of response are such characteristics (Serope Kalpakjian & Steven Schmid, 2022). The appropriate measuring instrument depends on other factors such as size of machine and part, environment, operator skills and cost.

To assure acceptable manufactured parts, one of the most critical aspects of quality control is dimensional tolerances. Tolerance is the acceptable variation in dimensions, such as height, width, depth etc. of a manufactured part. As it is close to impossible to manufacture two identical parts with the precise same dimensions, tolerances are introduced. Having a close dimensional tolerance can significantly increase product cost.

The selection of dimensional tolerances are very important in manufacturing ensuring parts meet their intended design and functional requirements (Serope Kalpakjian & Steven Schmid, 2022) . Yet, the balance between precision and accuracy against the cost of production is important to maintain. Ultimately, the selection of tolerances should take into account the specific functional requirements of the product, as well as the capabilities and limitations of the manufacturing process being used. By balancing these factors manufacturers can create high quality parts, but also remaining it cost-effective according to Serope Kalpakjian and Steven Schmid (2022).

2.5.2 *Flatness Measuring*

According to Robert J. Hocken and Paulo H. Pereira (2011, p.173) "The flatness of a plane is defined as the minimum separation possible between two parallel planes that contain the surface between them". A part with good flatness will have a smooth and even surface free from any bumps and undulations.

Coordinate measuring machines are often used to measure the flatness of parts not possible to see with the naked eye. According to a set tolerance the part is examined to ensure it is within the specifications.

Checking a parts flatness would follow the steps below according to Robert J. Hocken and Paulo H. Pereira (2011):

1. Place the part on the platform of the CM machine, ensuring it holds its place. Measure the surface of the part with the probe, make sure to get a dense number of points on the surface.

2. Once the measurements have been taken, next is to find the minimum-zone plane. The plane is a mathematical representation of the surface of the part that best fits the data points obtained. This can be done by the software's algorithm.

3. Once the plane has been established, the peak-to-valley is one way to calculate the flatness. This is done by measuring the distance between the highest point on the plane and the lowest point on the plane. The flatness is then calculated, the greatest residual minus the least residual.

4. Finally the flatness of the plane is compared to the flatness tolerance to see if the surface is within the specifications. The flatness tolerance is a specification that determines the allowable deviation from a perfect plane for a particular part.

2.5.3 *Tolerances in 3D printing*

In 3D printing tolerances are the acceptable deviation from the intended dimensions of a part, as the CAD model. The tolerance of a 3D printer depends on various factors. The level of the 3D printer, a desktop- versus an industrial printer may vary in precision and accuracy. Generally higher-end 3D printers with higher resolution have lower tolerances, where lower-end desktop printers have higher tolerances.

Table 2: Tolerances in 3D printing (1)

Source:	(Xometry Europe, 2021)	(MarkusMay, 2018)
Technology	**Tolerance**	
MJF	±0.3% (± 0.2 mm)	
SLS	±0.3% (± 0.3 mm)	± 0,3 % (Low limit ± 0.3 mm)
SLA	**±0.2% (± 0.2 mm)**	**± 0,2 % (Low limit ± 0.2 mm)**
FDM	±0.3% (± 0.3 mm)	± 0,5 % (Low limit ± 0.5 mm)
Carbon DLS	±0.1% (± 0.1 mm)	
DMLS	±0.2% (±0.1 – 0.2 mm)	
Polyjet	±0.05-0.1mm	± 0,1 – 0,2 %)
DLP		± 0,1 – 0,2 %
SLM		± 0,5 %

Table 3: Tolerances in 3D printing (2)

Source:	(Nutma, 2019)	(Hubs, 2023)
Technology	**Tolerance**	
MJF	± 0.1% (Low limit ± 0.05 mm)	
SLS	± 0.3% (Low limit ± 0.3 mm)	± 0.3% (Low limit ± 0.3 mm)
SLA	**± 0.15% (Low limit ± 0.01 mm)**	**± 0.15% (Low limit ± 0.01 mm)**
FDM	± 0.15% (Low limit ± 0.2 mm)	± 0.15% ((Low limit ± 0.2 mm)

In table 2 and 3 are the tolerances indicated from various sources on different 3D printers. It is important to notice that also the design and printing process is a vital part of meeting a set tolerance in any fabrication method. By understanding the limit and factors that influence the tolerance of 3D printers, it is possible to create good quality and accurate parts within the tolerances.

2.6 Minitab Data Analysis Tool

Minitab is statistical software used for data analysis. The software provides a range of statistical tools to analyze data and perform statistical analyses. It has a friendly user interface making it easy for researchers and engineer to operate the program. It is widely used in manufacturing, healthcare and finance(Minitab, 2023).

One of the key features of Minitab is the ability to generate ANOVA, regression analysis and control charts. Minitab also provide a range of tools to visualize the data, such as scatter-plots, histograms, pie-chart etc.

Minitab can be used to evaluate design of experiments (DOE), statistical methods to optimize a process or a product. The program can help define, create and analyse such experiments. The Taguchi method is one of the important tools Minitab can evaluate. The user friendly interface of Minitab along with its ability to handle large data sets, it has become one of the leading statistical data tools for engineers and researches.

3 Methodology

The following chapter outlines the approach used to conduct the research and analysis of the thesis. In this thesis, the methodology chapter will focus on the experimental research approach. Research design, data collection methods and data analysis techniques will be discussed in the chapter with the regards to the book ”Case Study Research and Applications” by Yin Robert K. (2018).

3.1 Research

3.1.1 *Research Method: Experimental Research*

The research method for the study is the experimental approach. This decision was influenced by the nature of the research problem and the objectives of the study. Experimental research is an effective method for investigating the cause-and-effect relationship between different variables, a feature particularly suited to this study.

In experimental research, a controlled environment is constructed, where variables can be manipulated and their effects observed directly (Blog, 2023). In the context of this research, the goal is to investigate the effect of four key parameters; Print orientation, layer thickness, UV curing temperature and UV curing time, on the flatness and mechanical performance of resin based 3D printed parts.

The decision to utilize experimental research is supported by literature. As Yin Robert K. (2018) explains, experimental research is especially helpful in studies about manufacturing and production. Directly observing the effects of modifying process parameters while keeping all other variables kept constant to ensure that any observed differences are due to the manipulated variable and not something else. As in the study of Qin et al. (2022) point out the applicability of experimental research of AM, as they are investigating the use of process simulations for training, in addition to experimental results, in the application of machine learning and additive manufacturing.

The study of Górski et al. (2020) present the results of research conducted on a batch of additive manufactured individualized wrist-hand orthoses made of thermoplastics. Their usage of experimental research provided valuable insights that are difficult to obtain through other studies, such as correlational or observational studies. Likewise, Zeng and Zou (2019) summarizes the types of errors of 3D printing, utilizing experimental research where the variables can be controlled and manipulated to find causes of error.

The adoption of experimental research in this study allows for a rigorous investigation of the cause-and-effect relationship between identified parameters and the performance of 3D printed parts, making it a robust exploration of the research problem.

3.1.2 *Literature Review*

A comprehensive literature review is done to improve the study design and methodology. An overview of the current state of knowledge in the research topic is important before performing the experiments. The theory section is intended to create a foundation of the thesis, as well as providing the reader a clear understanding of the context and background of various aspects.

Conducting the literature review and establishing the background theory, various sources were consulted, including master thesis', academic journals and books. A systematic approach using key search terms to find relevant books and published academic papers using Google Scholar. The supervisors also provided relevant sources of information included in the theory.

3.1.3 *Material*

Only the resin Clear V4 will be conducted in this study. According to Formlabs (2023b), the Clear V4 resin is specifically great for its suitability in applications that require translucency or display internal features. The resin shows it best potential in parts such as fluidics, mold making, optics, lighting and other similar parts. The resin support print resolution of 100, 50 an 25 microns. Post-curing in a UV-curing chamber is recommended. Some illustrative parts by Formlabs can be seen in figure 6. The parts in figure 6 show high complexity and quality in small, intricate parts.

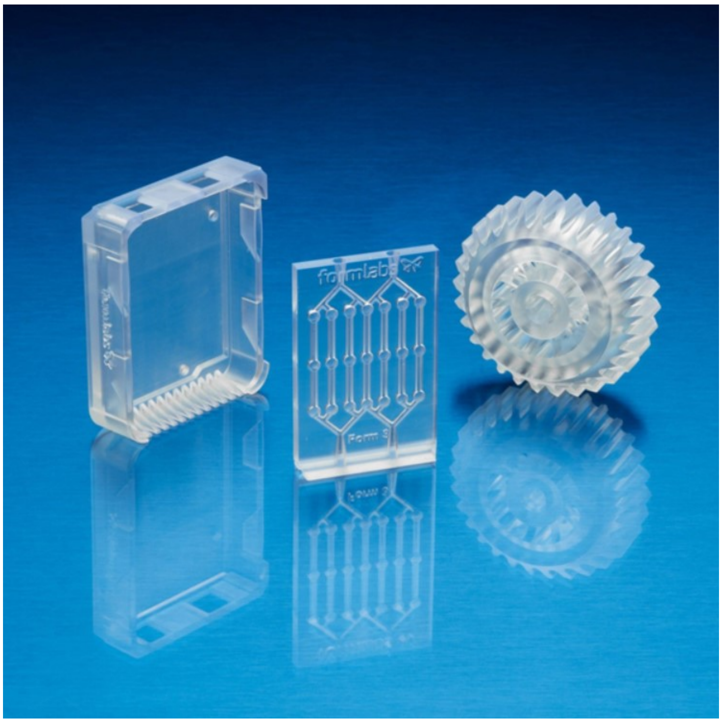


Figure 6: ClearV4 illustration from Formlabs catalogue. (“Formlabs ClearV4 (RS-F2-GPCL-04)”, 2023)

3.1.4 *Equipment*

The research will not cover any other additive manufacturing techniques than SLA. Only the Form 3+ 3D printer will be used, shown in figure 7 (Formlabs, 2023d).

Figure 7: Formlabs Form 3+

The "Form Wash" by Formlabs was used to rinse off any residue after the 3D printing. A large chamber containing isopropanol (2-propanol) dissolved the uncured resin left on the 3D printed models. In figure 8 the cleaning machine Form Wash is pictured, along with the isopropanol used.

Figure 8: Formlabs Form Wash

The curing chamber by Formlabs ”Form Cure” was the machine used to further cure the 3D printed parts. A UV curing chamber with several light sources and a reflective internal to fully submerge the 3D printed part in the ultra violet light. The chamber is shown in figure 9.

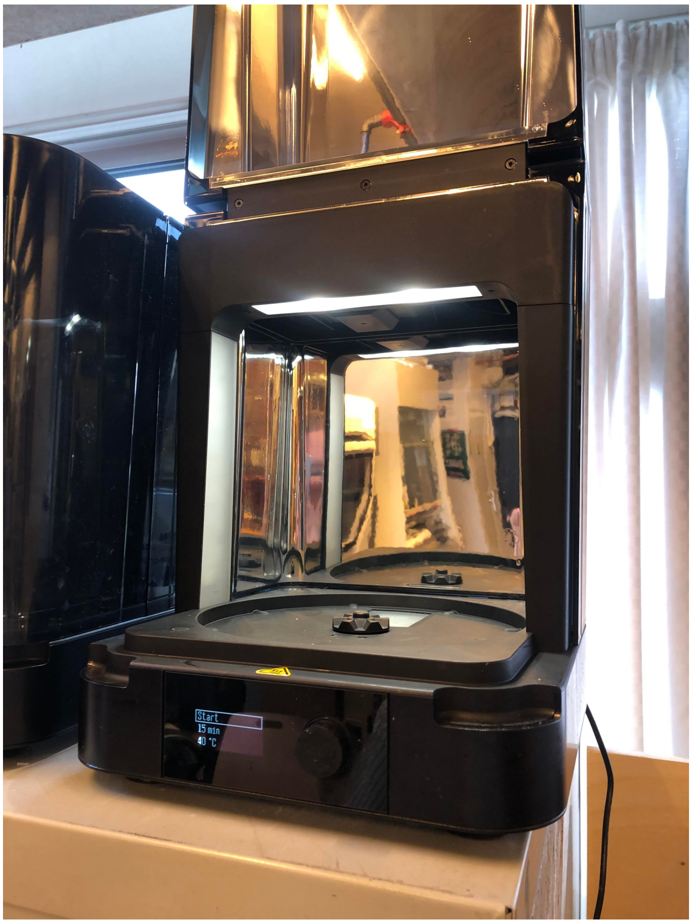


Figure 9: Formlabs UV Cure chamber

The CMM at University of Stavanger is shown in figure 10. The CMM is a crucial piece of equipment in this research, facilitating accurate and precise measurements of the 3D printed parts.

Figure 10: Coordinate Measuring Machine

3.1.5 *3D Models*

Shown in figure 11 is the part being conducted in the experiments. A part used to aid medical experiments. The part hosts a filter in the square center used for filtering urine in medical tests. The structural integrity has to be accurate and precise for the given part to fulfill its purpose. If distortion is present the part will not function properly and cause leakage.

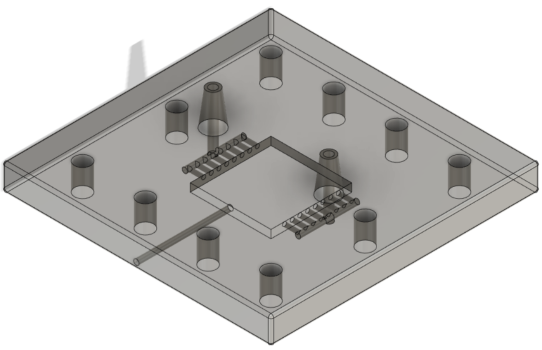


Figure 11: Part

The original size of the part in figure 11 measure 10cm x 10cm x 0.50 cm in size. Due to the size of the printing platform in the 3D printer, together with the time span of printing larger parts the size is scaled. A 50% scaled model of the original is used in the experiment. The internal holes are kept at 1mm in diameter suitable for the 3D printer. By having a smaller model several parts can be created in the same print.

3.2 Analysis

3.2.1 *Method to Implement Experimental Research*

The application of Taguchi method in this study follows the structured process defined in section 2.4.4; problem identification, experimental design, conducting experiment and data analysis. The following flow chart is created by Dr. R.M. Chandima Ratnayake, supervisor on the study. The flowchart in figure 12 define the sequence of the implementation of the Taguchi experimental design in the thesis.

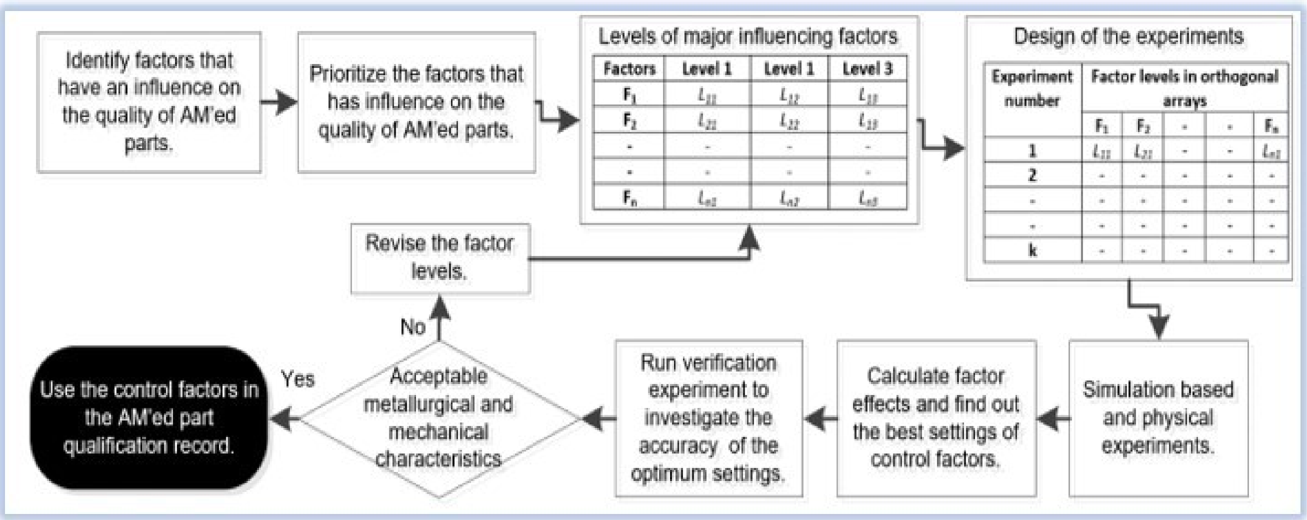


Figure 12: Flow chart of method to implement experimental research

Before implementing the Taguchi method the problem is clearly defined. Here, the primary objective is to understand how different parameters affect the flatness and mechanical performance of resin-based 3D printed parts. This stage involves identifying factors that are likely to influence the desired output, in this case, the quality of 3D printed parts.

The experimental design involves planning the experiments using orthogonal arrays, a feature of the Taguchi method described in section 2.4.2. The orthogonal array allow for an efficient exploration of the effect of multiple factors in the output by minimizing the number of experiments required.

Conduction the physical experiments according to the experimental design is the next step. Each experiment involves setting the control factors to the specific levels, running the 3D printing process, and measuring the resulting flatness and performance of the 3D printed part. Ensuring consistent and accurate measuring is important at this stage.

The final step is analysing the results using statistical methods. The aim is to identify the most significant effect on the output and determine the optimal levels for these factors. A verification experiment is run to validate the optimal combination of factors to investigate the accuracy of the optimum settings. Finally, if the desired output has the acceptable desired flatness and mechanical characteristics, document the favorable outcomes in the parts qualification record.

3.2.2 *Test Experiments*

A Pareto analysis was set up to identify the factors that have the greatest impact on the output. The experiments were set up to find the ”vital few” factors that need to be optimized in order to improve the output, as opposed to the ”trivial many” factors that have a minimal output.

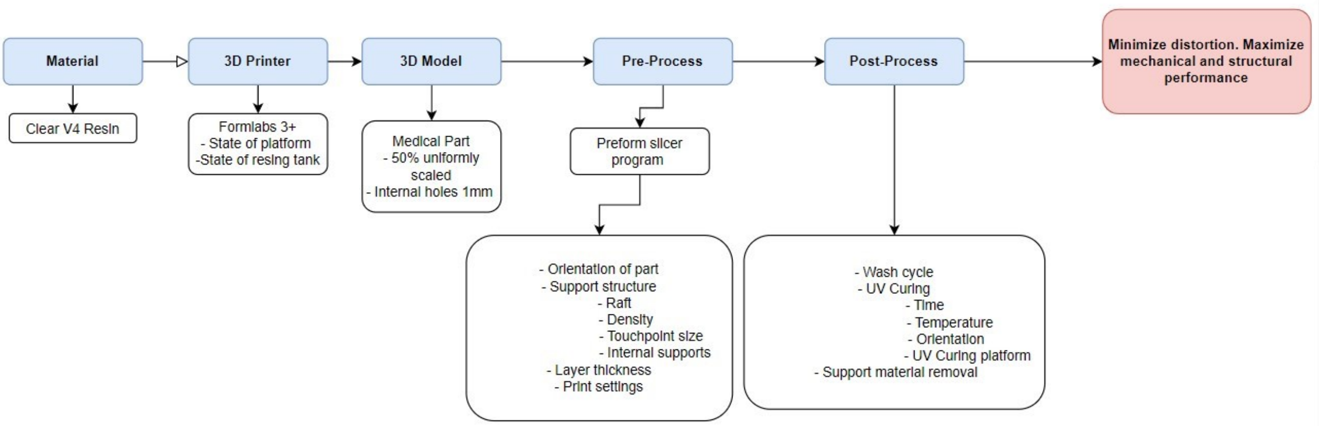


Figure 13: Fishbone diagram

Figure 13 presents a standardized fishbone diagram. The figure illustrate the many factors related to each of the different steps in 3D printing. The usage of a fishbone diagram is to visualize and categorize the different sub-causes in each category. The diagram is also intended to help understand the intricate relationships within the whole process.

3.2.3 *Taguchi Method - Statistical Experimentation Setup*

The setup of the Taguchi experiment was done by behalf of the research and test experiments done. The L9 orthogonal matrix was chosen due to the factors and levels. In table 4 the chosen variable parameters are illustrated.

Table 4: Factors and Levels - Variable parameters

	Variable Parameters					
	Factors		**Level**			**Unit**
			1	**2**	**3**	
Pre-Process	A	**Layer Thickness**	0.025	0.050	0.100	[mm]
	B	**Print Orientation**	20	45	90	[° Rotational degree]
Post-Process	C	**UV Curing Time**	5	15	30	[min]
	D	**UV Curing Temperature**	40	60	80	[° Celsius]

There are several other parameters in the process not as influential as the chosen ones in table 4. The other parameters in the process are kept constant and highlighted in table 5.

Table 5: Constant parameters

Constant Parameters			
Pre-Process	**Setting**	**Post-Process**	**Setting**
Support Raft	Full Raft	**Wash Cycle - Isopropanol**	10 min
Support Density	1.00	**Preheat**	Preheat part in chamber
Support Touchpoint size	0.50	**Support**	Removed before UV curing
Internal supports	On	**Support platform**	Yes
Print Settings	Default v2.1	**Cure Chamber**	2 -Old

The matrix is set up according to the L9 Orthogonal Taguchi setup as shown in table 6

Table 6: Experiment setup L9 Taguchi matrix

	Control Factors and Levels Setup			
	A	**B**	**C**	**D**
Experiment	**Layer Thickness**	**Print Orientation**	**UV Curing Time**	**UV Curing Temperature**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The experiement variable factors and levels inserted in the L9 Taguchi setup is done in table 7.

Table 7: Experiment setup L9 with parameters

	Control Factors and Levels			
	A	**B**	**C**	**D**
Experiment	**Layer Thickness**	**Print Orientation**	**UV Curing Time**	**UV Curing Temperature**
1	0.025	20	5	40
2	0.025	45	15	60
3	0.025	90	30	80
4	0.050	20	15	80
5	0.050	45	30	40
6	0.050	90	5	60
7	0.100	20	30	60
8	0.100	45	5	80
9	0.100	90	15	40

The experiments in the Taguchi matrix were run each a total of 3 times. In order to do this a total of $3 \cdot 9$ to total 27 test specimens. This is done to get a more accurate representation of the true behavior of each experiment. Running each experiment multiple times can reduce the impact of random errors or variations, which can lead to inaccurate results.

The overall power of the statistical analysis is increased by running multiple experiments and taking an average. This means that we can be more confident in the results obtained and more easily identify any significant differences or trends in the data.

3.2.4 *3D Printing*

The 3D printing process follows the outline of the process as in Section 2.1. The process of 3D printing with the Formlabs printer is a relative straight forward process. The printer was already set up as it was used beforehand. With this in mind, the printer cartridge was changed to a brand new to remove any possibility of left over residue in the resin. A new tank of Clear V4 resin was changed, so that the material was not exposed to air and light as much as possible. The printing bed of the machine was changed to a brand new one, a clean printing bed set the foundation for good quality prints.

The 3D printer was cleaned and prepped for testing and experimental test specimens. This kept the process constant.

The parts were rinsed in the Form Wash in isopropanol alcohol prior to UV curing. The washer was cleaned thoroughly by hand, and not used by any other material than the Clear V4 throughout the process. The chamber was filled with new isopropanol alcohol to get a really good rinse of the uncured resin left on the parts.

Between the Form wash and UV curing chamber, the parts were handled with care and kept out of light as much as possible. The parts were dried off by hand, rinsed in isopropanol and cleaned with pressurized air. This was done to completely dry the parts before UV curing, as well as to keep the internal holes open.

The 3D printer could produce three of the same experiments in one print. This was done not only to minimize potential errors but also to reduce the printing time. In figure 14 is the PreForm slicer setup of experiment 2.

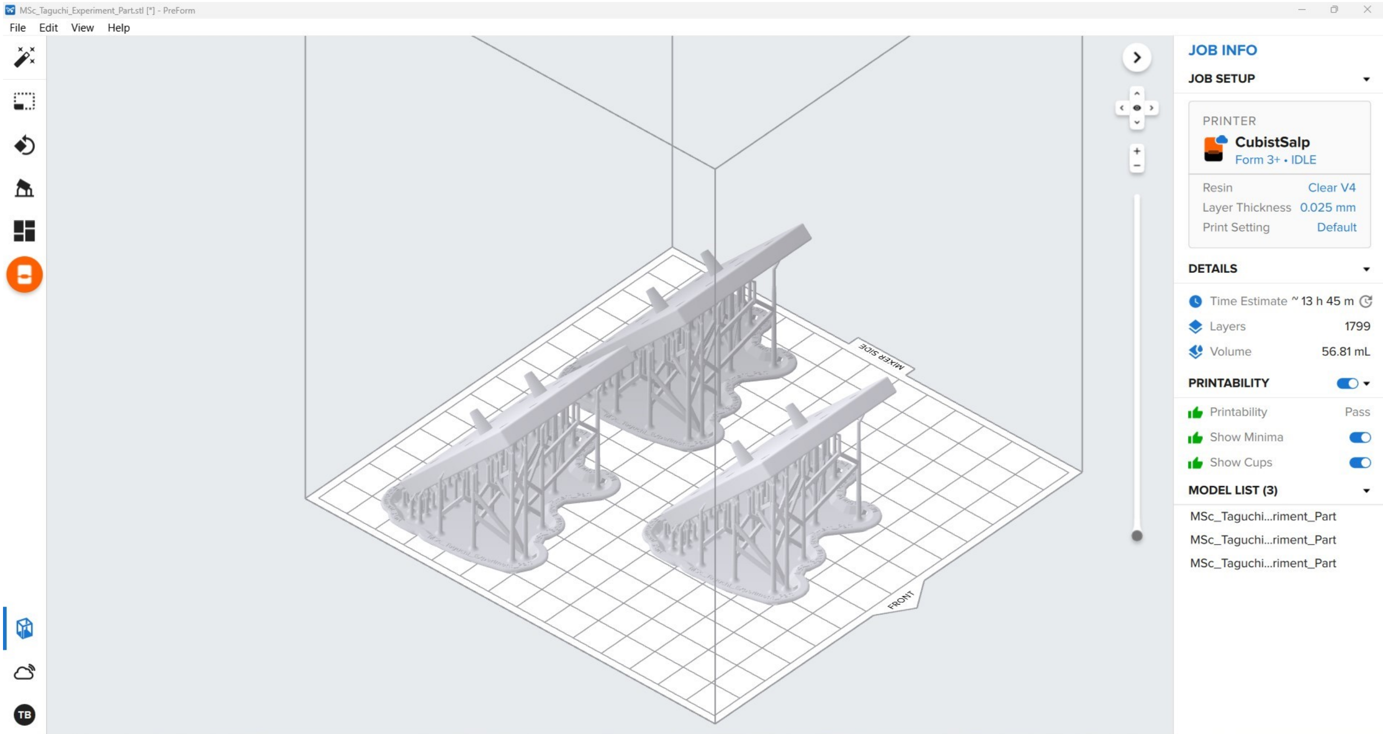


Figure 14: PreForm slicer setup

3.2.5 *Distortion Measurement - CMM*

The CMM measurement was conducted using a Zeiss CMM with the Calypso interface software. Measurements were CNC-programmed for execution, and a specific program was designed to check the top surface for flatness to control distortion. Additionally, the four sides of each specimen were examined for straightness.

To measure the flatness of the surface, a grid was constructed as shown in figure 15. A 2.5mm ball probe was used to follow the grid lines and collect points in the XYZ direction. About 9000 points were collected from each specimen's top surface to control its flatness.

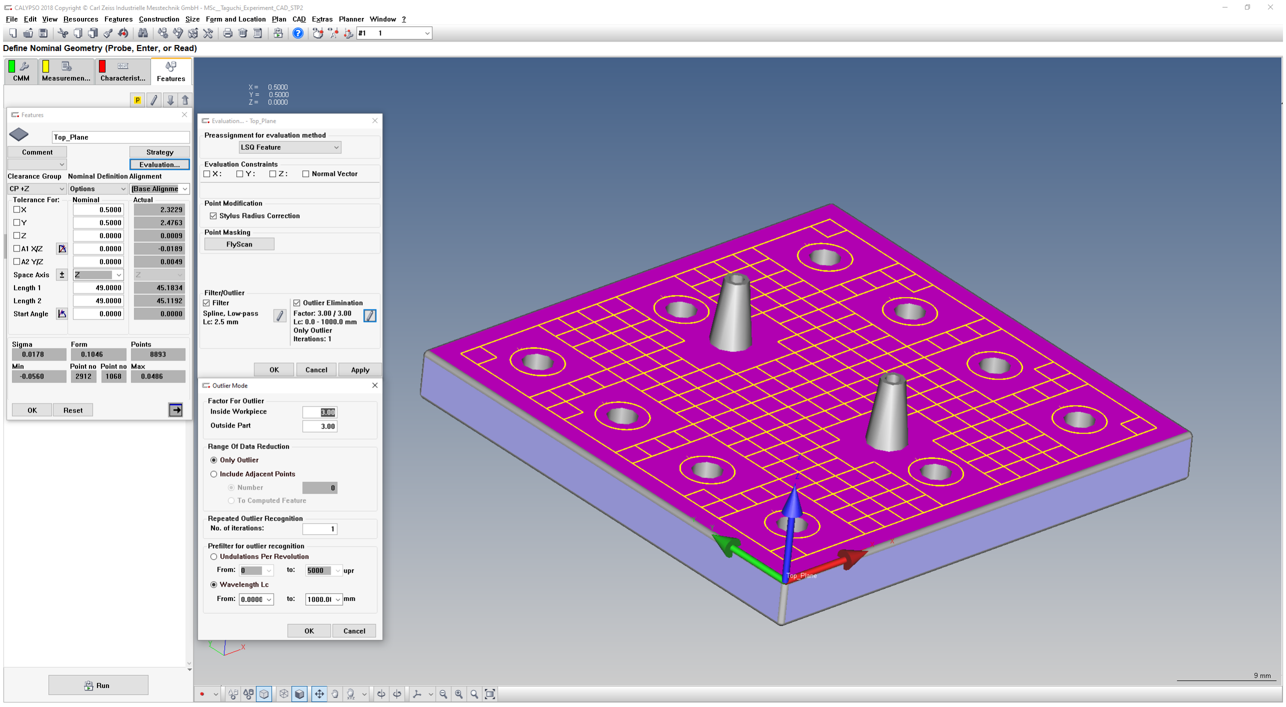


Figure 15: Measurement plan

The measurement plan was set up together with Arnt Espen Melhus from Carl Zeiss AS in Oslo. With the aid of Team Viewer, Melhus ensured that the measurement plan was sufficient in relation to the tolerances needed with respect to the size of the specimens and surface roughness.

A filter and outlier elimination was introduced to the points results. The filter was added as a ”Spline, Low Pass” with a wavelength of Lc of 2.5mm. The Spline filter method follows the ISO 16610-22. The outlier elimination was set to a factor of: 3.00/3.00 with 1 iteration. The filter and outlier elimination helps reducing ”spikes” in the flatness results and corrects if there was any bumps on the surface.

The tolerance for both the flatness and straightness was set to 0.100 mm. As the tolerance is only used as a reference and does not imply any if the part is successful or not. The flatness tolerance is set by creating a fictional layer 0.05 mm above the actual surface of the CAD model and a layer 0.05 mm below the actual surface. This creates a 0.100 mm tolerance gap.

The results recorded for flatness are the deviation from the lowest recorded point to the highest recorded point. The recorded results were taken with the filter and outlier elimination implied.

In figure 16 is the clamping setup utilized for the CMM. A custom made clamping mechanism was 3D printed to ensure both accuracy and repeatability in the measurements of the specimens. The solution not only allows for precise positioning, but also guarantees consistent results across multiple measurements.

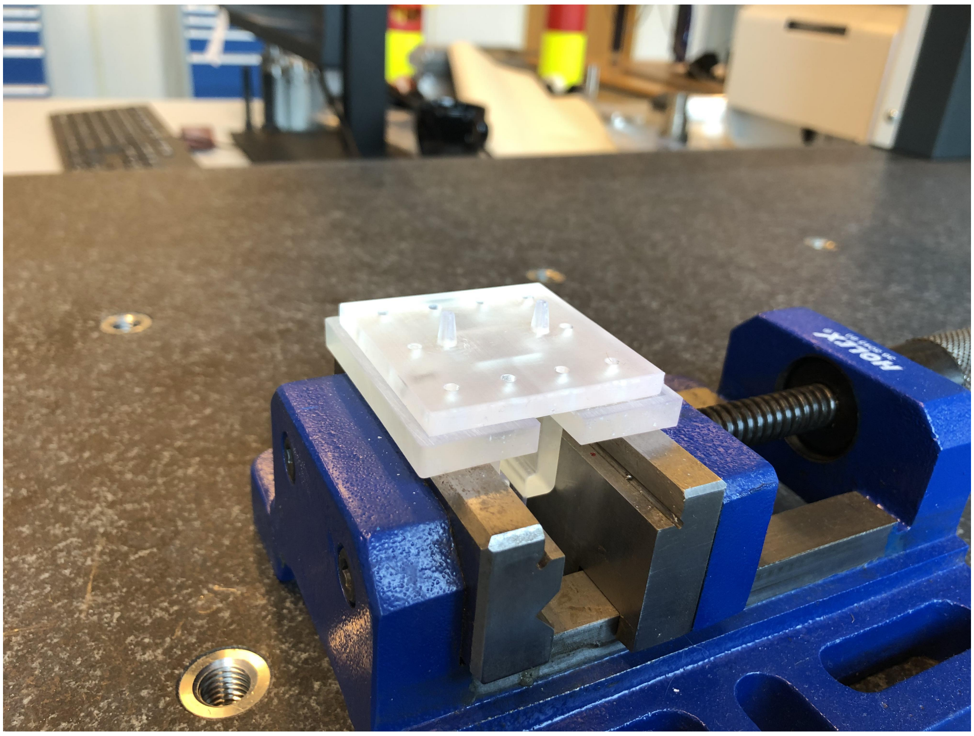


Figure 16: CMM clamping method

3.2.6 *Minitab Data Analysis Tool*

Minitab analysis tool was used to evaluate the data obtained for the experiment. The Taguchi experimental design was created, analyzed, and predicted within the software. The Taguchi setup is a robust method that can be evaluated in Minitab. The identification of the most significant factors affecting the response variable, and their optimal levels. The software generated regression analysis, general linear ANOVA and graphs to visually evaluate the data.

A regression analysis was created, which helped identify the relationships between the input variables and the output response. This analysis was used to determine the equation that described the relationship between the variables.

General linear ANOVA analysis is generated to analyze the variance in the data. the method is used to model the relationship between a continuous response variable and one or more categorical predictor variables.

In the Minitab software graphs were created to visually evaluate the data and identify any trends or patterns in the data.

3.3 Potential Sources of Error

It is important to consider the potential sources of error that could affect the accuracy and precision of the results in the study. Three main categories can be classified as potential sources of error; human error, mechanical errors and material variability. Human error can occur due to incorrect print settings, post-processing or a mix up of the test specimens. Mechanical error can arise from wear and tear of the equipment along the way, which can alter the production of the parts. Material variability can result from differences in resin used to create the parts. Additionally, the measurement plan used to collect the data may not be accurate enough or may have filters that can affect the results. Finally, a typo or misreading of results can also lead to erroneous results.

4 Results

4.1 Test Experiments

In the search of the ”vital few” factors of the process, the Pareto analysis became too time consuming to conduct. The many factors in the process quickly revealed that the Pareto analysis was not the correct tool in the search for the important factors. Though in the process of trying to conduct the experiments relative to the analysis set up, together with literature review in the research process simultaneously, the important factors and levels were found.

4.1.1 *Testing the 3D Printing Process*

As stated above the Pareto analysis on its own was difficult to work with in finding the vital few factors. By trail and error in different test specimens, the impact of different parameters quickly surfaced.

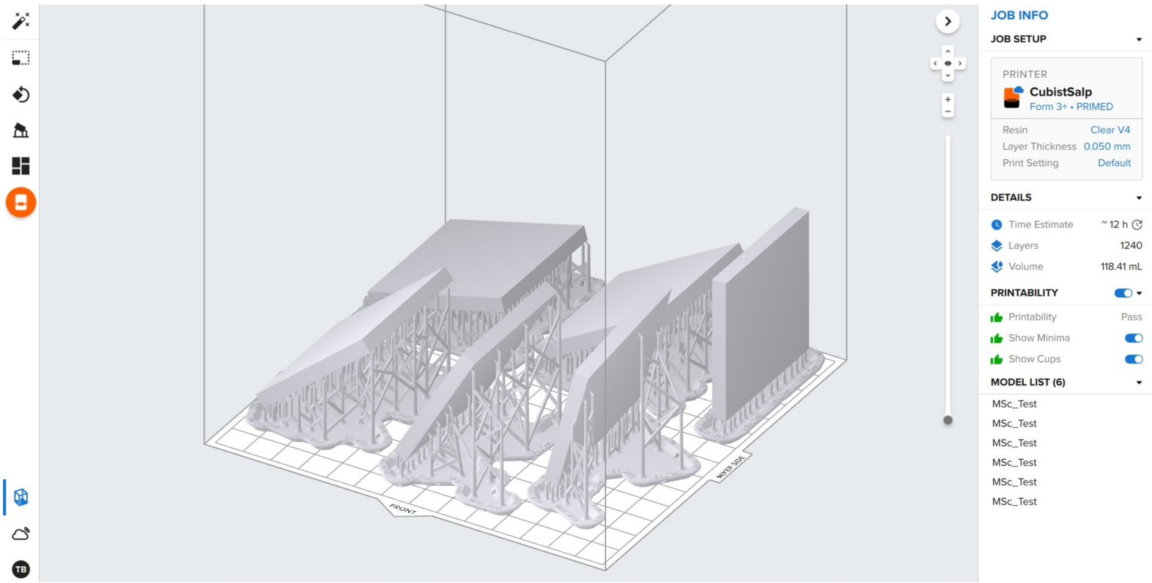


Figure 17: Testing print orientation

Figure 17 shows the PreForm slicer setup as different print orientations were tested.

The post-process was evaluated on the basis of the literature survey done on how the Clear resin behaved relative to the UV curing light. The UV curing chamber quickly highlighted some flaws in its design. In figure 18 the UV lights at the bottom of the chamber had only a source of light on one side. As the plate in the chamber supporting the part spins around, the light from the bottom will not be captured by the part enough to get an even UV cure.

Figure 18: UV Curing chamber internal

To prevent an uneven UV curing from the start, a support platform for the experiment specimens was created. Furthermore, the support structure created in the 3D printer was removed before UV curing to not hinder the UV light reaching the part. In figure 19 the support platform is shown. The method significantly minimized distortion in the parts before conducting the Taguchi experiment.

Figure 19: UV Cure support platform

4.1.2 *The Vital Few Factors and Levels*

The following are the factors chosen for the experiments and research carried out in the first stage of the thesis. The explanation indicates why the factor and level were chosen.

Print Orientation: Print Orientation was chosen because the orientation of the layers can significantly affect the cured resin's total surface area and the support structure's generation relative to the orientation, which impacts the part's surface finish.

The chosen orientations of printing based on experiments and research:

- 20 Degrees - Recommended orientation by Formlabs. Parts has to be inclined, if not internal holes will keep resin inside and get clogged up.

- 45 Degrees - Trivial incline to test.
- 90 Degrees - Minimizing the surface area of the platform. Chosen to see the effect of minimizing support creation relative to orientation.

Layer Thickness: Layer Thickness was selected as a factor because the beam essentially cures the part layer by layer in the 3D printer. Therefore, more layers should equal a more cured model straight from the 3D printer. To test this factor, three different thicknesses were chosen.

- 0.025 mm
- 0.050 mm
- 0.100 mm

UV Curing Time: UV Curing Time was chosen because research indicates that it is the most influential parameter in the mechanical strength of the models. By Formlabs, higher curing time yields higher ultimate tensile strength. However, lower degrees of cure should yield lower distortion for printed models.

- 5 min - By research, lower degree of cure should yield lower distortion for printed models.
- 15 min - The recommended curing time provided by Formlabs for the specific resin.
- 30 min - The specified curing time for fully post-cured models for the specific resin.

UV Curing Temperature: The UV cure temperature was chosen because it is an essential factor in the cure process.

- 40°C - The recommended UV curing temperature according to Formlabs Services to prevent distortion in models regarding the ClearV4 resin.
- 60°C - The recommended UV curing temperature in Formlabs guidelines.
- 80°C - Checking the influence of a higher temperature related to UV curing.

For the other parameters kept constant, see subsection 3.2.3.

4.2 3D Printing of Taguchi Experiments

The Taguchi experiment specimens were 3D printed according to the set-up of the L9 Taguchi matrix.

All experiments were printed, washed and cured according to the setup explained throughout section 3. In figure 20 experiment 1 is done 3D printing.

Figure 20: Experiment 1 from the Taguchi experiment setup

There were no known errors made in the 3D printing process and the curing of the experiment specimens.

4.3 CMM - Flatness Results

The data collected follow the method explained in Section 3.2.5. In Table 8 the data collected from the flatness measurement are shown.

Table 8: Flatness results - Taguchi experimentation

	Results deviation [mm]			
Experiment	**I**	**II**	**III**	**Average Deviation Results [mm]**
1	0,292	0,364	0,329	0,3283
2	0,242	0,237	0,236	0,2383
3	0,097	0,103	0,091	0,0970
4	0,748	0,760	0,800	0,7693
5	0,167	0,156	0,202	0,1750
6	0,111	0,108	0,092	0,1037
7	0,802	0,636	0,673	0,7037
8	0,403	0,392	0,33	0,3750
9	0,108	0,119	0,097	0,1080

The results from table 8 executed on the CMM once for each specimen. In regards of the results measured there are no visual ”outs” regarding the I, II, and III for each experiment. This is an assurance that the 3D printing and process done has been kept constant. The measurements could have been done multiple times for each specimen, but should not be necessary. The number of point on the surface of the flatness measurement according to Arnt Espen at Zeiss was absolutely sufficient.

The measurements were exported from excel to Minitab for further Taguchi evaluation.

4.4 Taguchi Data Evaluation - Minitab

This section presents the evaluation of the Taguchi experiment by Minitab. The results from the CMM distortion measurement have been calculated to Signal-to-Noise ratio, as shown in table 9. The table clearly indicates that the model calculation is correct as the highest SNR is achieved by the lowest overall mean.

Table 9: Taguchi Evaluation Results

	Result Deviation [mm]			**Signal-To-Noise**	**Mean [mm]**
Experiment	**I**	**II**	**III**	**SNR1**	**MEAN1**
1	0,292	0,364	0,329	9,639023225	0,328333333
2	0,242	0,237	0,236	12,45577759	0,238333333
3	0,097	0,103	0,091	20,25350166	0,097
4	0,748	0,760	0,800	2,274084103	0,769333333
5	0,167	0,156	0,202	15,08502902	0,175
6	0,111	0,108	0,092	19,65919937	0,103666667
7	0,802	0,636	0,673	3,008479197	0,703666667
8	0,403	0,392	0,330	8,48759916	0,375
9	0,108	0,119	0,097	19,30159305	0,108

4.4.1 *Response Tables - Signal to Noise Ratios and Means*

The response table for SNR in table 10 summarizes the results of the Taguchi experiment. The SNR is a ratio of the mean signal to the variation of the noise, and it is an indicator of the performance quality. In any characteristic method of Taguchi, the highest SNR value for a given factor-level combination indicates the best possible performance, the flattest surface. The rank order of the factors based on their influence are as followed; print orientation, UV curing temperature, layer thickness, and UV curing time. Based on the results in the table, the combination of factors of recommended levels to achieve the best performance is the one that yields the highest SNR values for each factor.

Table 10: Response table for signal to noise ratios

Response Table for Signal to Noise Ratios (Smaller is better)				
	Layer Thickness	Print Orientation	UV Curing Time	UV Curing Temperature
1	14,116	4,974	12,595	14,675
2	12,339	12,009	11,344	11,708
3	10,266	19,738	12,782	10,338
Delta	3,85	14,764	1,439	4,337
Rank	**3**	**1**	**4**	**2**

The response table for the means in Table 11 provides a summary of the average flatness of the printed parts for each combination of factor levels. From the table it can be observed that the most influential factor is print orientation, following the same pattern as in the table 10. It is important to note that the mean is not the only factor to consider when evaluating the performance of the parts. The SNR analysis provides a more comprehensive evaluation of the factors' effects on the response. However, the means can provide useful insights into the expected performance of the printed parts under certain conditions.

Table 11: Response Table for Means

Response Table for Means (Smaller is better)				
	Layer Thickness	Print Orientation	UV Curing Time	UV Curing Temperature
1	0,2212	0,6004	0,269	0,2038
2	0,3493	0,2628	0,3719	0,3486
3	0,3956	0,1029	0,3252	0,4138
Delta	0,1743	0,4976	0,1029	0,21
Rank	**3**	**1**	**4**	**2**

The main effect plot for SN ratios in figure 21, provides a visual representation of the effect of each factor on the response. From the plot, it is clear that print orientation and UV curing temperature have the most significant impact on the response, as they have a wider spread.

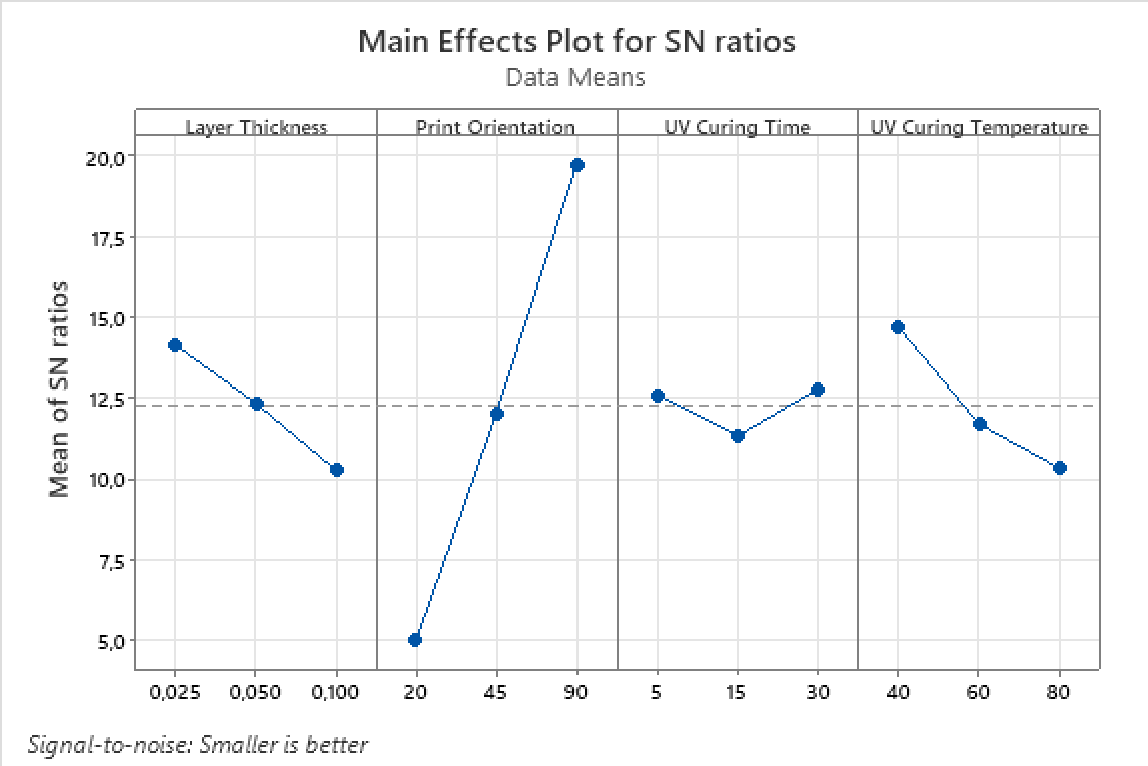


Figure 21: Main effects plot for SN ratios

The main effects plot for means in figure 22 is a visual representation of the impact of each factor on the average response. The plot shows that the print orientation has the most significant impact on the response, as it is the largest difference between the high and low level. Overall, the main effects plot for means confirms the findings from the response table for means, indicating that print orientation is the most important factor to consider in optimizing response.

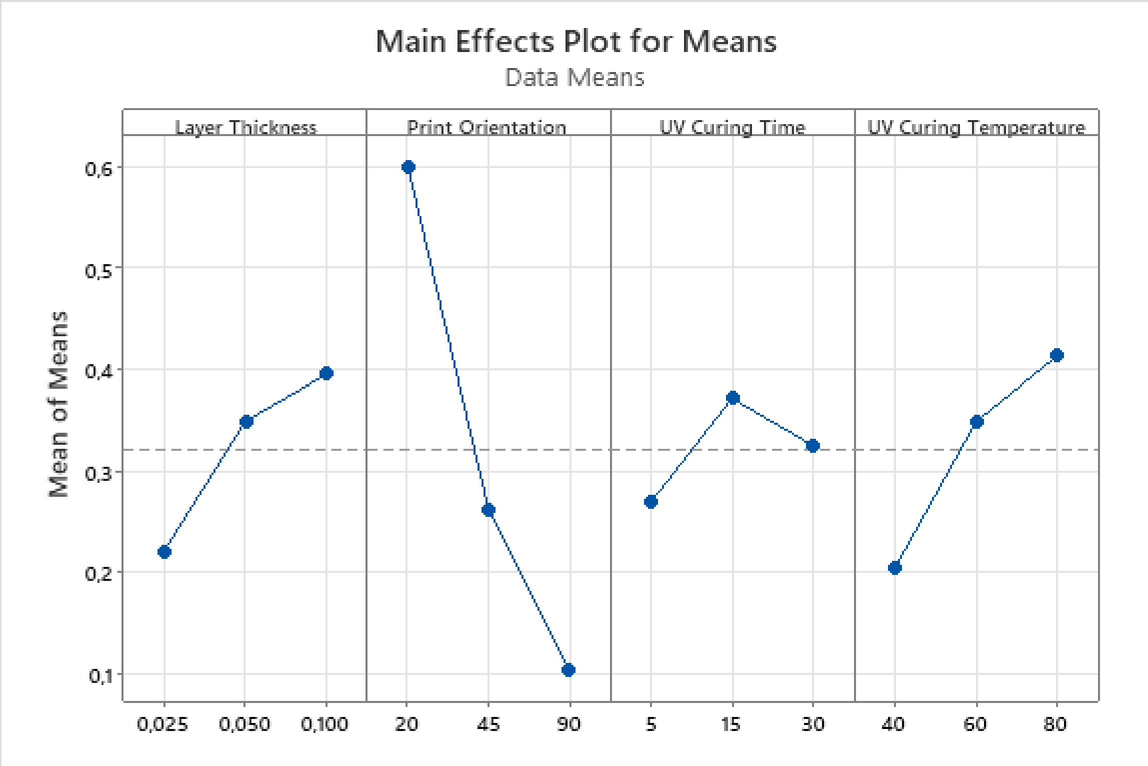


Figure 22: Main effects plot for means

4.4.2 *Regression Analysis*

$$\begin{aligned} MEAN1 = & 0,198 + 2,12 LayerThickness \\ & - 0,00668 PrintOrientation \\ & + 0,00183 UVCuringTime \\ & + 0,00525 UVCuringTemperature \end{aligned} \tag{4}$$

The equation 4 represents the regression model for predicting the mean response ”MEAN1”, in other words the flatness. Based on the four factors; layer thickness, print orientation, UV curing time and UV curing temperature. The coefficiants in the equation represent the estimated effect of each factor on the mean response. The coefficient for print orientation is negative which indicate that increasing this factor is related with a decrease in the mean response. In contrast to the other factors, where the coefficients are positive, indicating increasing the factor is relative to an increase in the mean response.

Table 12: Coefficients

Coefficients					
Term	**Coef**	**SE Coef**	**T-Value**	**P-Value**	**VIF**
Constant	0,198	0,223	0,89	0,425	
Layer Thickness	2,12	1,47	1,45	0,221	1
Print Orientation	-0,00668	0,00158	-4,24	0,013	1
UV Curing Time	0,00183	0,00445	0,41	0,703	1
UV Curing Temperature	0,00525	0,0028	1,88	0,134	1

The table of coefficients in table 12 show the estimated coefficients for each predictor variable in the model. Along with other information as the standard error of each coefficient, T-value, P-value and VIF (Variance Inflation Factor).

Based on the coefficients table, the constant term has a coefficient of 0.198 with a standard error of 0.223, indicating that the intercept is not statistically significant. Among the predictors, only print orientation was found to be statistically significant, with a negative coefficient of -0.00668 and a low P-value of 0.013. The VIF values for all predictors are below 5, indicating that there are no issue with multicollinearity, as already known due to linearity of Taguchi. Layer thickness, UV curing time and UV curing temperature are not statistically significant predictors, as indicated by their high P-values. Overall the results suggest that print orientation is the most important predictor of the dependent variable, while the others have limited effect.

Table 13: Regression analysis of variance

Analysis of Variance						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percent
Regression	4	0,446129	0,111532	5,93	0,056	86 %
Layer Thickness	1	0,039491	0,039491	2,1	0,221	8 %
Print Orientation	1	0,337321	0,337321	17,94	0,013	65 %
UV Curing Time	1	0,003167	0,003167	0,17	0,703	1 %
UV Curing Temperature	1	0,06615	0,06615	3,52	0,134	13 %
Error	4	0,075197	0,018799			14 %
Total	8	0,521325				100 %

The table 13 is the Analysis of variance for the regression model. In this table, each source of variation is listed along with its degree of freedom (DF), adjusted sum of squares (Adj SS), Adjusted mean square (Adj MS), F-Value, P-Value and percent contribution.

The first row Regression, represent the overall significance of the regression model, which has 4 degrees of freedom. The F-value of 5.93 and the P-value of 0.056 indicate that the model is marginally significant. A P-value less than 0.050 is generally considered statistically significant. Since the P-value for the regression is close to 0.050 means that the model may still be significant at higher significant levels. This indicates it is worthwhile to investigate the model further.

The individual predictors show that print orientation has a statistically significant impact on the response with an F-value of 17.94 and a low P-value of 0.013, indicating that the print orientation significantly contributes to the variability in the response.

On the other hand, layer thickness and UV curing temperature have higher P-values of 0.221 and 0.134, respectively, indicating that their effect on the response is not statistically significant. The UV curing time has the lowest impact on the response variability, with an F-value of 0.17

and high P-value of 0.703. The error row indicate the unexplained variation in the response, and it contributes 14% to the total variation in the response. The contribution percentage is calculated by taking the percentage of the individual Adjusted SS divided by the total Adjusted SS. The ANOVA table provides valuable information on the significant predictors and their contribution to the response variability, which can help further optimizing the 3D printing process.

Table 14: Model summary

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
0,13711	85,58 %	71,15 %	24,52 %

The table 14 is showing the summary of the regression model. The first value, S, represents the standard error of the estimate, which is a variability of the data points around the fitted regression line. The smaller the S value, the better fit of the model to the data.

The next values, R-sq, R-sq(adj) and R-sq(pred), are measures of how good the fit the data to the model. R-sq is the coefficient of determination and represents the proportion of determination and represents the proportion of the variation in the dependent variable that is explained by the independent variables in the model. In other words, the R-sq at 85.58% means that the 85.58% of the variability in the dependent variable is explained by the independent variables.

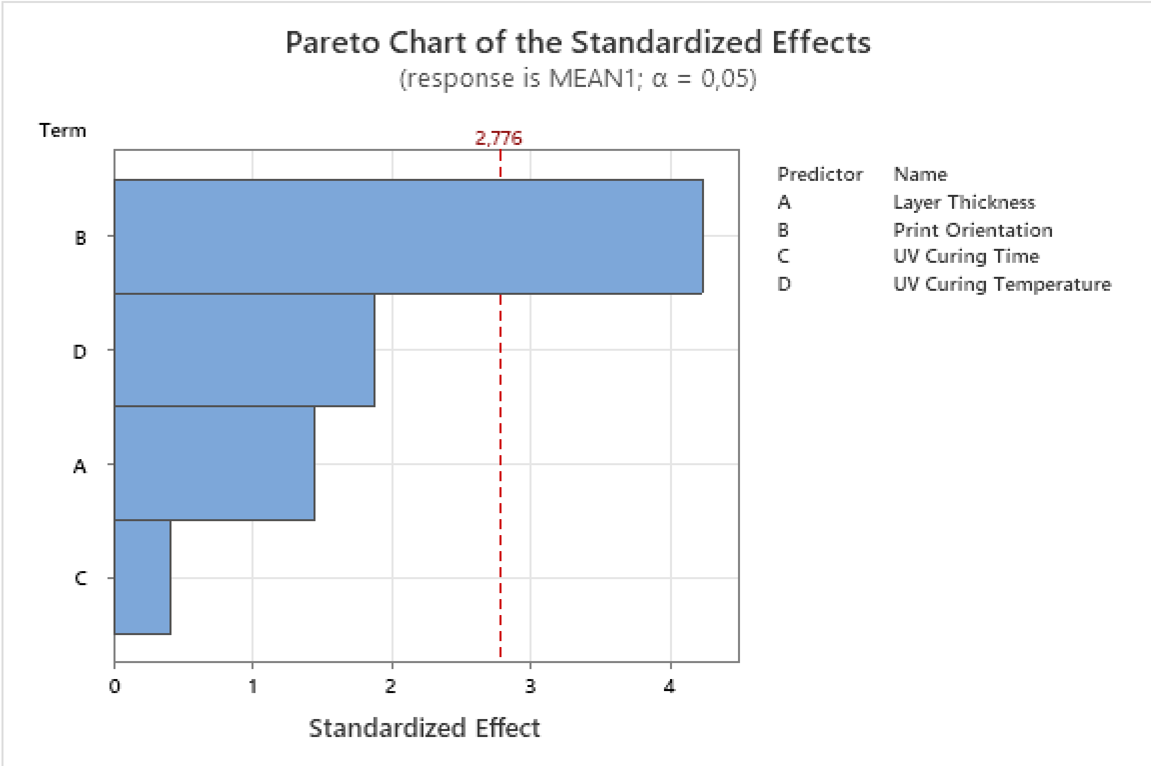


Figure 23: Pareto chart of the standardized effects

The pareto chart of the standardized effects in figure 23 display the relative size of the factors in descending order of importance. As stated from results above, the print orientation appears to be the most important factor.

The dotted line at 2.776 of standardized effect is the standard deviation away from mean, which corresponds to the significance level of 0.050 (α =0.005). Any predictor standardized effect value above this threshold is considered to have a statistically effect on the response variable.

As the other predictors; A, C and D are below the threshold of 2.776, they may still have some effect on the response variable. It is therefore important to not only rely on the Pareto chart as it is important to consider all predictors of the model.

4.4.3 *Prediction of Taguchi Results*

Based on the Taguchi results the other 81 combinations of factors can be predicted. Creating this helps finding clear trends between the response and the predictor variable. All predicted experiment values can be found in the appendix B.

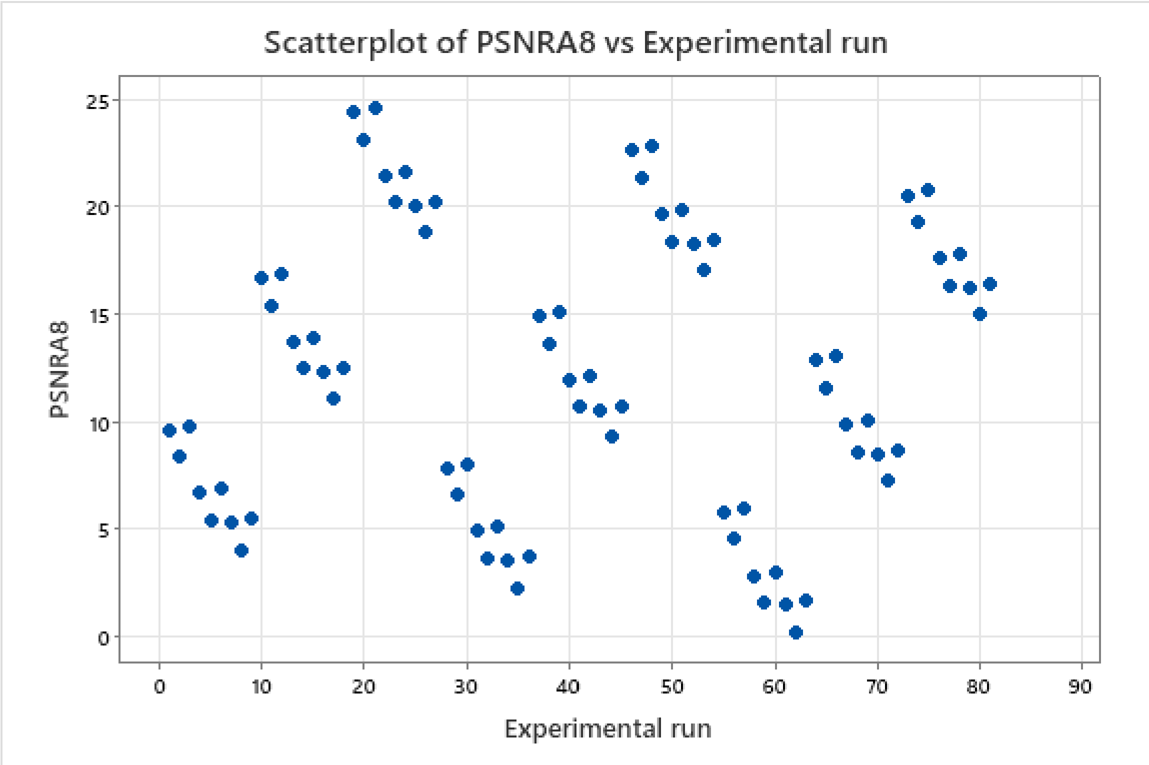


Figure 24: Scatterplot of predicted SNR vs experimental run

In figure 24 the predicted SNR values are plotted against the experimental run. The trends follow the print orientation levels of 20°, 45° and 90°. This highlight the importance of the print orientation factor relative to the other factors.

4.4.4 *Optimum Combination of Factors*

Based on the results from the Taguchi evaluation and predicted values the combination of factors for maximizing the SNR for the 3D printed parts can be identified. In the predicted values the predicted experimental run 19 and 21 had the highest SNR of 24.40325907 and 24.59032178, respectively. In the prediction of MEAN1 (flatness) run 19 predicted a value of

-0.16922222 versus run 21 with a predicted value of -0.113. As the SNR value was as close as it were the predicted value of experiment 19 was lower. Using the ”Smaller-the-Better” model, the conclusion was made to proceed with the experimental run 19 as it had the lowest predicted value for MEAN1 while also having a high predicted SNR value.

Table 15: Optimum Predicted Parameters

Predicted values from Taguchi evaluation						
Experimental Run	**Layer Thickness**	**Print Orientation**	**UV Curing Temperature**	**UV Curing Time**	**PSNRA8**	**PMEAN8**
19	0,025	90	40	5	24,40325907	-0,169222222

The optimum combination of factors for maximizing the SNR and minimizing the MEAN for the 3D printed parts are shown in table 15. The results indicate that the optimum combination of factors maximizing the SNR and achieving good flatness of the printed parts involves using a thin layer thickness, printing vertically at 90°, and using a relatively low UV curing temperature and time.

4.4.5 *Validation of Optimum Factor Combination*

A validation run for the predicted optimum factor combination was executed. It is important to validate the predicted values to ensure that the prediction corresponds to the actual results. The following section presents the results from the validation experiment, it follows the exact same execution from methodology as the other experiments.

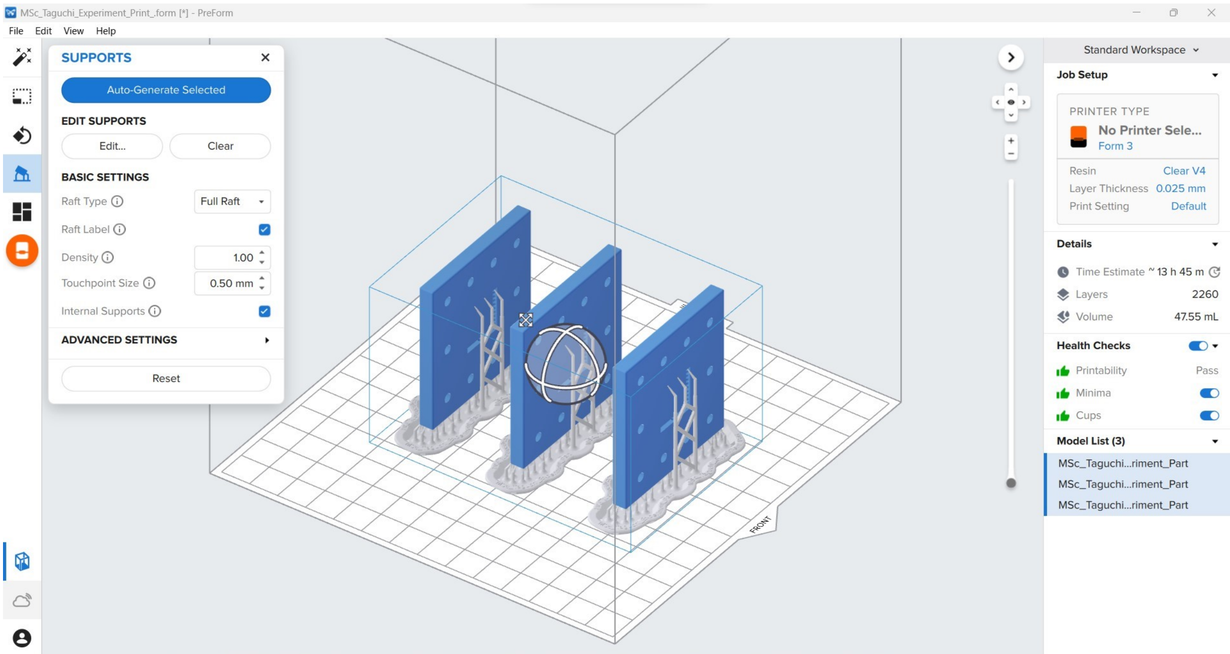


Figure 25: Optimum factor combination run in PreForm slicer

The setup for the print is illustrated in figure 25.

Table 16: Flatness results of optimum factor combination

	Results deviation [mm]			
Test Run	**I**	**II**	**III**	**Average Deviation Results [mm]**
19	0,101	0,090	0,097	0,0960

In table 16 the flatness results from the CMM is presented. The results show that the predicted value of -0.16922222 is not met. The 3D printed part does not bend the opposite direction due to the predicted value being negative. Although, the average result does result in the flattest surface of all the experiments done.

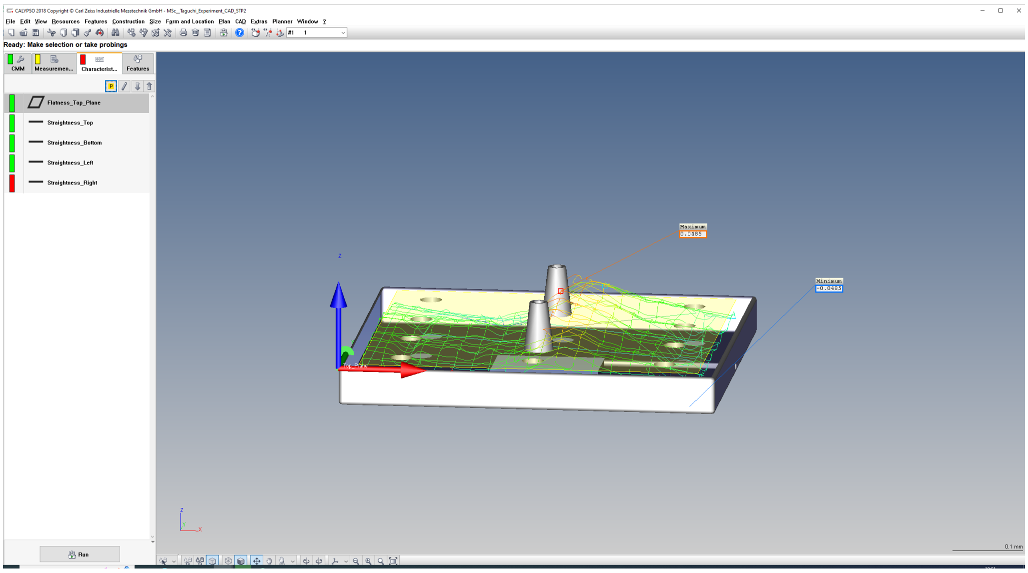


Figure 26: Flatness of surface of validation run on optimum factors in Calypso CMM software

The flatness of the surface is plotted in the Calypso software relative to the CAD in figure 26. With the highest point being in between the two pins on the model. It is important to state that the curve representation with its peak to the right in the figure, is the side located down to the build platform. This make the right side of the part with the most ”hang-time” in the 3D printing process. It is possible that this can make not fully cured resin to seep down due to gravity creating an uneven surface.

5 Financial Overview

This section provides a brief financial overview. The focus has been on the costs associated with material consumption and, in the future, the considerations for mass production.

5.1 Material Consumption Costs

The thesis involved only the Clear V4 for experimentation and fabrication of test specimens. It has been recorded the amount of material consumption, it becomes possible to estimate the overall costs involved in the thesis. The financial focus has been on the usage of material. The costs of equipment used are not estimated.

The total usage of Clear V4 resin was 1L. As a 1L tank of resin costs $ 149.00 to this date (Formlabs, 2023b).

5.2 Mass Production Costs

This thesis does not directly cover aspects of mass production. As the part is 50% than the original part, it is difficult to estimate. If the part used in this thesis were to be produced in large quantities, a larger more comprehensive setup would have to be created. In such a setup, the following should be considered; Material and equipment costs, material procurement, workforce, overhead expenses, quality assurance and testing, packaging and distribution.

In conclusion, the brief financial overview mainly highlight the material consumption. If applicable, the consideration of mass production must undergo a more comprehensive understanding of the financial implications.

6 Environmental accounts

As almost everything we do and make has an impact on the environment it is important to recognize the impact of our actions and creations. This section provides an overview of the potential environmental impact associated with the project, as well as the measures taken to reduce it.

6.1 Resource Consumption

The development of the study required various resources, including computing power and raw materials. The thesis use of computing power was not at a significant high. Regarding materials, efforts were made to manage usage. As 3D printing already minimizes waste material in model fabrication, the only management is to not print unnecessary 3D models.

The total consumption of material resources was limited to about 1 L of Clear V4 resin.

6.2 Energy Consumption

Energy consumption was not recorded throughout the thesis. It is important to state that the methods used, such as Taguchi, are an energy efficient practice to optimize processes and products.

6.3 Recycling Measures

Proper recycling guidelines and regulations were followed. To ensure environmentally friendly disposal of materials and components.

6.4 Environmental Benefits

As the main goal of the thesis is to optimize the parameters in additive manufacturing, the benefit is a more efficient process. This results in less waste products and less energy consumption in the creation of parts not applicable to its intended use.

In conclusion, efforts was made to minimize the environmental impact of this project. As there may be areas of improvement, the impact of the thesis on the environment is not significant.

7 Discussion

The use of the Taguchi method in the study was instrumental in navigating the complex multiparameter process of resin-based 3D printing. The findings indicate the sensitivity of the process in adjustment of the parameters and their significant effect on the result of flatness on the 3D printed specimens.

The results indicate that the print orientation had the highest impact on the SNR and flatness of the surface. A vertical orientation of 90 ° provided the best results. These findings are in line with the established literature on the subject, which identifies the model's orientation within the slicer program and 3D printer as one of the most influential parameters for successful 3D printing. However, inconsistency may arise in the auto-generated orientation of 3D models within the slicer program when setting up a new model for 3D printing, potentially contributing to pre-process variations.

Another significant finding was the impact of the UV curing process. The results indicate that a lower UV curing temperature and time could yield a better SNR and a flatter surface. This is a contradiction to the higher temperature, and longer curing times lead to better mechanical properties. However, the geometry of the 3D printed part with a lower UV curing time and temperature will be closer to the original CAD model. This aligns with the existing literature on the subject, which suggests that a lower degree of cure will result in less residual stress and distortion in the printed part.

Nevertheless, the existing literature also suggests that factors such as the degree of cure, UV light exposure, and the translucency of the resin play a role in the curing depth relative to UV exposure time. These factors are vital because differences in geometry and thickness around the part can create uneven mechanical properties and lead to distortion. The results may vary with different geometries and resins, and the potential trade-off between mechanical properties and geometric accuracy may need further investigation.

Although previous studies have examined the influence of shrinkage related to the photocure from liquid to solid, as Zhang et al. (2021) found that reducing the DoC during printing could reduce the residual stress and distortion of the printed parts. This study adds to the existing literature by investigating the impact of print orientation and layer thickness with additional UV curing in a chamber on the geometric accuracy of printed parts.

Possible sources of error in this study include variations in material properties, machine calibration, and measurement techniques. Effort was made to keep the process constant and minimize these sources of error, but they could still have influenced the results to some extent. As previous literature states by Baumgarner and Piovesan (2021), the uncured and post-cured Clear V4 resin differ from the ultimate tensile strength stated by Formlabs, this adds to the possible differences that could affect the results. Future studies could focus on improving accuracy, conducting more precise machine calibration, and exploring other measurement techniques. In addition, exploring the usage of newer improved 3D printing machinery and UV curing chamber. It is important to recognize the potential variations in measurement accuracy, and the use of filters on the results could have influenced the final results.

It is important to acknowledge the certain limitations of the study. The study focused only on a specific printing technology and material. The results may not be generalized to other 3D printing methods or materials. Together with the limitation in Taguchi, a linear method limited to only a selected range of four parameters with three different levels. A larger set of parameters could provide better more comprehensive understanding.

In summary, while unaware of any errors made, it is recognizable that not all of the complexities in 3D printing has been solved. Despite the limitations, our study contributes significantly to the understanding of the factors that influence the flatness of specific 3D printed parts. One remaining detail is the mechanical properties of parts cured for shorter durations and at lower temperatures than those recommended by Formlabs.

Future studies could examine the implications of the work that is not yet addressed. Ultimately, the findings serve as a foundation for further exploration in the field of resin 3D printing. The results can potentially enhance the quality and applicability of 3D printed parts in various industries, a key objective in this study.

8 Conclusion

In conclusion, the thesis has successfully achieved its goals of optimizing the multiparameter process of resin-based 3D printing to minimize distortion while maintaining optimal structural and mechanical performance of 3D printed parts. The research scope was clearly defined, and the goals were effectively addressed throughout the study.

The key findings of this thesis highlight the importance of printing orientation, layer thickness, UV curing temperature, and UV curing time in achieving desired outcomes. Print orientation, particularly a vertical setting of 90°, was found to have the highest influence on both the SNR and the flatness of the printed parts. The lower temperature and UV curing time were also shown to contribute to a better SNR and surface flatness. These results provide valuable insights for optimizing the 3D printing process and improving the quality of printed parts.

The relevance of this work lies in its potential to enhance the quality and applicability of 3D printed parts in various industries. By understanding the influential factors and their effects, manufacturers and researches can make informed decisions to achieve the desired balance between geometric accuracy and mechanical properties in 3D printed parts. This thesis contributes to the existing knowledge in the field of resin 3D printing and provides a foundation for further exploration and advancements.

In light of the different experiments and their findings, the following reflections emerge:
Print orientation: The effect of this parameter on the quality of the printed parts was substantial, revealing the necessity of carefully considering orientation in any 3D printing process.

Layer thickness, UV curing temperature and time: While these parameters had less dramatic effect, they nonetheless contributed to the final quality, indicating that a comprehensive approach to parameter optimization must consider these aspects as well.

Taguchi method: The effectiveness of this method for optimization was proven, indicating its potential for wider application within the field of additive manufacturing.

My understanding of the various parameters involved has transformed my perspective on the intricacies of 3D printing. The prominent role of orientation in the pre-process phase of additive manufacturing underscores its significance. This realization has brought into focus the importance of the ”auto-generate” print orientation and support structure feature within the slicing software. The implications are clear: this ’auto-generate’ function can directly influence the overall quality of the final printed part. Therefore, a deep understanding of print orientation becomes crucial. This newfound insight makes it evident that the process is not merely a push-button operation, but delicate craft that requires mastery over various interlinked factors.

Overall, this thesis not only expands out understanding of the factors influencing the quality of resin-based 3D printed parts, but also provides practical insights and recommendations for optimizing the printing process by Taguchi method. It is hoped that the findings presented in this thesis will inspire further research and advancements in the field, ultimately contributing to the growth and development of additive manufacturing technologies.

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formlabs

General Purpose Resins

Materials for High Resolution Models and Rapid Prototyping

High Detail. For demanding applications, our carefully-engineered resins capture the finest features in your model.

Strong and Precise. Our resins create accurate and robust parts, ideal for rapid prototyping, functional testing and product development.

Smooth Surface Finish. Perfectly smooth right out of the printer, parts printed on the Formlabs stereolithography printers have the polish and finish of a final product.

V4 Clear FLGPCL04	V4 Grey FLGPGR04	V2 Draft FLDRGR02	V1 Grey Pro FLPRGR01
V4 White LGPWH04	V4 Black FLGPBL04	V4 Color FLGPCB01	* May not be available in all regions

Prepared 04 . 09 . 2016

Rev. 01 04 . 09 . 2016

MATERIAL PROPERTIES DATA

Standard Resins

The following material properties are comparable for Clear Resin, White Resin, Grey Resin, Black Resin, and Color Kit.

	METRIC [1]		IMPERIAL [1]		METHOD
	Green [2]	Post-Cured [3]	Green [2]	Post-Cured [3]	
Tensile Properties					
Ultimate Tensile Strength	38 MPa	65 MPa	5510 psi	9380 psi	ASTM D638-14
Tensile Modulus	1.6 GPa	2.8 GPa	234 ksi	402 ksi	ASTM D638-14
Elongation at Break	12%	6%	12%	6%	ASTM D638-14
Flexural Properties					
Flexural Modulus	1.3 GPa	2.2 GPa	181 psi	320 psi	ASTM D 790-15
Impact Properties					
Notched Izod	16 J/m	25 J/m	0.3 ft-lbf/in	0.46 ft-lbf/in	ASTM D256-10
Thermal Properties					
Heat Deflection Temp. @ 1.8 MPa	43 °C	58 °C	109 °F	137 °F	ASTM D 648-16
Heat Deflection Temp. @ 0.45 MPa	50 °C	73 °C	121 °F	134 °F	ASTM D 648-16

[1] Material properties can vary with part geometry, print orientation, print settings, and temperature.

[2] Data was obtained from green parts, printed using Form 2, 100 µm, Clear settings, without additional treatments.

[3] Data was obtained from parts printed using Form 2, 100 µm, Clear settings and post-cured with 1.25 mW/cm^2 of 405 nm LED light for 60 minutes at 60 °C.

SOLVENT COMPATIBILITY

Percent weight gain over 24 hours for a printed and post-cured 1 x 1 x 1 cm cube immersed in respective solvent:

Solvent	24 hr weight gain, %	Solvent	24 hr weight gain, %
Acetic Acid 5%	< 1	Mineral oil (Light)	< 1
Acetone	Sample cracked	Mineral oil (Heavy)	< 1
Bleach ~5% NaOCl	< 1	Salt Water (3.5% NaCl)	< 1
Butyl Acetate	< 1	Skydrol 5	1
Diesel Fuel	< 1	Sodium Hydroxide solution (0.025% PH 10)	< 1
Diethyl glycol Monomethyl Ether	1.7	Strong Acid (HCl conc)	Distorted
Hydraulic Oil	< 1	Water	< 1
Hydrogen peroxide (3%)	< 1	Xylene	< 1
Isooctane (aka gasoline)	< 1		
Isopropyl Alcohol	< 1		

Predicted values from Taguchi evaluation

Experimental Run	Layer Thickness	Print Orientation	UV Curing Temperature	UV Curing Time	PSNRA8	PMEAN8
1	0,025	20	40	5	9,639023225	0,328333333
2	0,025	20	40	15	8,387567552	0,431222222
3	0,025	20	40	30	9,82608593	0,384555556
4	0,025	20	60	5	6,671626847	0,473111111
5	0,025	20	60	15	5,420171174	0,576
6	0,025	20	60	30	6,858689552	0,529333333
7	0,025	20	80	5	5,3022031	0,538333333
8	0,025	20	80	15	4,050747427	0,641222222
9	0,025	20	80	30	5,489265805	0,594555556
10	0,025	45	40	5	16,67462964	-0,009333333
11	0,025	45	40	15	15,42317397	0,093555556
12	0,025	45	40	30	16,86169235	0,046888889
13	0,025	45	60	5	13,70723326	0,135444444
14	0,025	45	60	15	12,45577759	0,238333333
15	0,025	45	60	30	13,89429597	0,191666667
16	0,025	45	80	5	12,33780952	0,200666667
17	0,025	45	80	15	11,08635384	0,303555556
18	0,025	45	80	30	12,52487222	0,256888889
19	**0,025**	**90**	**40**	**5**	**24,40325907**	**-0,169222222**
20	0,025	90	40	15	23,1518034	-0,066333333
21	0,025	90	40	30	24,59032178	-0,113
22	0,025	90	60	5	21,4358627	-0,024444444
23	0,025	90	60	15	20,18440702	0,078444444
24	0,025	90	60	30	21,6229254	0,031777778
25	0,025	90	80	5	20,06643895	0,040777778
26	0,025	90	80	15	18,81498328	0,143666667
27	0,025	90	80	30	20,25350166	0,097
28	0,05	20	40	5	7,8623599	0,456444444
29	0,05	20	40	15	6,610904228	0,559333333
30	0,05	20	40	30	8,049422606	0,512666667
31	0,05	20	60	5	4,894963523	0,601222222
32	0,05	20	60	15	3,64350785	0,704111111
33	0,05	20	60	30	5,082026228	0,657444444
34	0,05	20	80	5	3,525539776	0,666444444
35	0,05	20	80	15	2,274084103	0,769333333
36	0,05	20	80	30	3,712602481	0,722666667
37	0,05	45	40	5	14,89796632	0,118777778
38	0,05	45	40	15	13,64651064	0,221666667
39	0,05	45	40	30	15,08502902	0,175
40	0,05	45	60	5	11,93056994	0,263555556
41	0,05	45	60	15	10,67911427	0,366444444
42	0,05	45	60	30	12,11763264	0,319777778
43	0,05	45	80	5	10,56114619	0,328777778
44	0,05	45	80	15	9,309690519	0,431666667
45	0,05	45	80	30	10,7482089	0,385
46	0,05	90	40	5	22,62659575	-0,041111111
47	0,05	90	40	15	21,37514008	0,061777778

48	0,05	90	40	30	22,81365846	0,015111111
49	0,05	90	60	5	19,65919937	0,103666667
50	0,05	90	60	15	18,4077437	0,206555556
51	0,05	90	60	30	19,84626208	0,159888889
52	0,05	90	80	5	18,28977563	0,168888889
53	0,05	90	80	15	17,03831995	0,271777778
54	0,05	90	80	30	18,47683833	0,225111111
55	0,1	20	40	5	5,788812869	0,502666667
56	0,1	20	40	15	4,537357197	0,605555556
57	0,1	20	40	30	5,975875575	0,558888889
58	0,1	20	60	5	2,821416492	0,647444444
59	0,1	20	60	15	1,569960819	0,750333333
60	0,1	20	60	30	3,008479197	0,703666667
61	0,1	20	80	5	1,451992745	0,712666667
62	0,1	20	80	15	0,200537072	0,815555556
63	0,1	20	80	30	1,63905545	0,768888889
64	0,1	45	40	5	12,82441928	0,165
65	0,1	45	40	15	11,57296361	0,267888889
66	0,1	45	40	30	13,01148199	0,221222222
67	0,1	45	60	5	9,857022907	0,309777778
68	0,1	45	60	15	8,605567234	0,412666667
69	0,1	45	60	30	10,04408561	0,366
70	0,1	45	80	5	8,48759916	0,375
71	0,1	45	80	15	7,236143488	0,477888889
72	0,1	45	80	30	8,674661865	0,431222222
73	0,1	90	40	5	20,55304872	0,005111111
74	0,1	90	40	15	19,30159305	0,108
75	0,1	90	40	30	20,74011143	0,061333333
76	0,1	90	60	5	17,58565234	0,149888889
77	0,1	90	60	15	16,33419667	0,252777778
78	0,1	90	60	30	17,77271505	0,206111111
79	0,1	90	80	5	16,2162286	0,215111111
80	0,1	90	80	15	14,96477292	0,318
81	0,1	90	80	30	16,4032913	0,271333333

Safety Data Sheet

according to Regulation (EC) No. 1907/2006 (REACH)

Revision date: 23.02.2021	*Version: 7.2*	*Print date: 23.02.2021*

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1 Product identifier

Trade name/designation:	2-Propanol GPR RECTAPUR®
Product No.:	20839
CAS No.:	67-63-0
Index No.:	603-117-00-0
REACH No.:	01-2119457558-25-XXXX
Other means of identification:	2-Hydroxy propane, Dimethyl carbinol, IPA, Isopropanol, Isopropyl alcohol

1.2 Relevant identified uses of the substance or mixture and uses advised against

Relevant identified uses:	General chemical reagent

1.3 Details of the supplier of the safety data sheet

United Kingdom

VWR International Ltd.

Street	Hunter Boulevard, Magna Park
Postal code/City	Lutterworth, LE17 4XN
Telephone	0800 22 33 44
Telefax:	01455 55 85 86
E-mail (competent person)	SDS@vwr.com

1.4 Emergency phone number

Telephone	+44 (0) 1270 502894 (CareChem24)

SECTION 2: Hazard identification

2.1 Classification of the substance or mixture

2.1.1 Classification according to Regulation (EC) No 1272/2008 [CLP]

Hazard classes and hazard categories	Hazard statements
Flammable liquid, category 2	H225
Eye irritation, category 2	H319
Specific target organ toxicity (single exposure), category 3, narcotic effect	H336

2.2 Label elements

2.2.1 Labelling according to Regulation (EC) No. 1272/2008 [CLP]

Hazard pictograms

Signal word: Danger

Hazard statements	
H225	Highly flammable liquid and vapour.
H319	Causes serious eye irritation.
H336	May cause drowsiness or dizziness.

Precautionary statements	
P210	Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking.
P280	Wear protective gloves/protective clothing/eye protection/face protection.
P305+P351+P338	IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.

2.3 Other hazards

This substance does not meet the PBT/vPvB criteria of REACH, Annex XIII.

SECTION 3: Composition / information on ingredients

3.1 Substances

Substance name	2-Propanol
Molecular formula	$(CH_3)_2CHOH$
Molecular weight	60.1 g/mol
CAS No.	67-63-0
REACH registration No.	01-2119457558-25-XXXX
Index No.	603-117-00-0

SECTION 4: First aid measures

4.1 General information

IF exposed or if you feel unwell: Call a POISON CENTRE or doctor/physician. If unconscious but breathing normally, place in recovery position and seek medical advice. Never give anything by mouth to an unconscious person or a person with cramps. Change contaminated, saturated clothing. Do not leave affected person unattended.

After inhalation

Call a POISON CENTRE/doctor. Remove casualty to fresh air and keep warm and at rest. If breathing is irregular or stopped, administer artificial respiration.

In case of skin contact

After contact with skin, wash immediately with plenty of water and soap. Remove contaminated, saturated clothing immediately. In case of skin reactions, consult a physician.

After eye contact

In case of contact with eyes flush immediately with plenty of flowing water for 10 to 15 minutes holding eyelids apart and consult an ophthalmologist. Protect uninjured eye. Remove contact lenses, if present and easy to do. Continue rinsing.

In case of ingestion

If accidentally swallowed rinse the mouth with plenty of water (only if the person is conscious) and obtain immediate medical attention. Do NOT induce vomiting. Give nothing to eat or drink.

Self-protection of the first aider

First aider: Pay attention to self-protection!

4.2 Most important symptoms and effects, both acute and delayed

no data available

4.3 Indication of any immediate medical attention and special treatment needed

no data available

SECTION 5: Firefighting measures

5.1 Extinguishing media

Suitable extinguishing media

Water spray
ABC-powder

Carbon dioxide (CO_2)
Nitrogen

Extinguishing media which must not be used for safety reasons
no restriction

5.2 Special hazards arising from the substance or mixture

In case of fire may be liberated:
Carbon monoxide
Carbon dioxide (CO_2)

5.3 Advice for firefighters

DO NOT fight fire when fire reaches explosives.
Special protective equipment for firefighters
Wear a self-contained breathing apparatus and chemical protective clothing.

Additional information

Do not allow run-off from fire-fighting to enter drains or water courses.
Do not inhale explosion and combustion gases.
Use caution when applying carbon dioxide in confined spaces. Carbon dioxide can displace oxygen.
Use water spray jet to protect personnel and to cool endangered containers.
In case of fire: Evacuate area.

SECTION 6: Accidental release measures

6.1 Personal precautions, protective equipment and emergency procedures

In case of major fire and large quantities: Remove persons to safety.

6.2 Environmental precautions

Discharge into the environment must be avoided.

6.3 Methods and material for containment and cleaning up

Spilled product must never be returned to the original container for recycling. Collect in closed and suitable containers for disposal.

6.4 Additional information

Clear spills immediately.

SECTION 7: Handling and storage

7.1 Precautions for safe handling

Avoid:
Inhalation
Avoid contact with eyes and skin.
Use extractor hood (laboratory).
If handled uncovered, arrangements with local exhaust ventilation have to be used.
If local exhaust ventilation is not possible or not sufficient, the entire working area must be ventilated by technical means.
Keep away from sources of ignition - No smoking.
Usual measures for fire prevention.
Take precautionary measures against static discharges.

7.2 Conditions for safe storage, including any incompatibilities

Recommended storage temperature: 15-25°C

Storage class: 3

Keep container tightly closed and in a well-ventilated place. Keep/Store away from combustible materials.

7.3 Specific end use(s)

Apart from the uses mentioned in section 1.2 no other specific uses are stipulated.

SECTION 8: Exposure controls/personal protection

8.1 Control parameters

Does not contain substances above concentration limits fixing an occupational exposure limit.

8.2 Exposure controls

8.2.1 Appropriate engineering controls

Technical measures and the application of suitable work processes have priority over personal protection equipment. If handled uncovered, arrangements with local exhaust ventilation have to be used.

8.2.2 Personal protection equipment

Wear suitable protective clothing. When handling with chemical substances, protective clothing with CE-labels including the four control digits must be worn.

Eye/face protection

Eye glasses with side protection DIN-/EN-Norms: DIN EN 166

Recommendation: VWR 111-0432

Skin protection

When handling with chemical substances, protective gloves must be worn with the CE-label including the four control digits. Recommended glove articles DIN-/EN-Norms EN ISO 374 In the case of wanting to use the gloves again, clean them before taking off and air them well.

By short-term hand contact

Suitable material:	Butyl caoutchouc (butyl rubber)/FKM (fluoro rubber)
Thickness of the glove material:	0,70 mm
Breakthrough time::	> 480 min
Recommended glove articles:	VWR 112-3819

By long-term hand contact

Suitable material:	Butyl caoutchouc (butyl rubber)/FKM (fluoro rubber)
Thickness of the glove material:	0,70 mm
Breakthrough time::	> 480 min
Recommended glove articles:	VWR 112-3819

Respiratory protection

Respiratory protection necessary at: aerosol or mist formation

Suitable respiratory protection apparatus:	Full-/half-/quarter-face masks (DIN EN 136/140)
Recommendation:	VWR 111-0206
Suitable material:	ABEK2P3
Recommendation:	VWR 111-0059

Additional information

Wash hands before breaks and after work. Avoid contact with eyes and skin. When using do not eat, drink or smoke. Provide eye shower and label its location conspicuously.

8.2.3 *Environmental exposure controls*

no data available

SECTION 9: Physical and chemical properties

9.1 Information on basic physical and chemical properties

(a) Appearance	
Physical state:	liquid
Colour:	colourless
(b) Odour:	no data available
(c) Odour threshold:	no data available

Safety relevant basic data

(d) pH:	no data available
(e) Melting point/freezing point:	-89 °C
(f) Initial boiling point and boiling range:	82 °C (1013 hPa)
(g) Flash point:	12 °C
(h) Evaporation rate:	no data available
(i) Flammability (solid, gas):	Highly flammable liquid and vapour.
(j) Flammability or explosive limits	
Lower explosion limit:	2.3 % (v/v)
Upper explosion limit:	12.7 % (v/v)
(k) Vapour pressure:	43 hPa (20 °C)
(l) Vapour density:	2.07 (20 °C)
(m) Relative density:	0.786 g/cm³ (20 °C)
(n) Solubility(ies)	
Water solubility:	soluble (20 °C)
Soluble (g/L) in Ethanol:	no data available
(o) Partition coefficient: n-octanol/water:	0.05 (20 °C)
(p) Auto-ignition temperature:	425 °C (DIN 51794)
(q) Decomposition temperature:	no data available
(r) Viscosity	
Kinematic viscosity:	no data available
Dynamic viscosity:	2.2 mPa*s (20 °C)
(s) Explosive properties:	not applicable
(t) Oxidising properties:	not applicable

9.2 Other information

Bulk density:	no data available
Refraction index:	0.3852 (589 nm; 20 °C)
Dissociation constant:	no data available
Surface tension:	no data available
Henry's Law Constant:	no data available

SECTION 10: Stability and reactivity

10.1 Reactivity

no data available

10.2 Chemical stability

The product is chemically stable under standard ambient conditions (room temperature).

10.3 Possibility of hazardous reactions

no data available

10.4 Conditions to avoid

no data available

10.5 Incompatible materials

no data available

10.6 Hazardous decomposition products

no data available

10.7 Additional information

no data available

SECTION 11: Toxicological information

11.1 Information on toxicological effects

Acute effects

Acute oral toxicity:

LD50: > 5045 mg/kg - Rat - (RTECS)

LDLo: > 3570 mg/kg - Human - (RTECS)

Acute dermal toxicity:

LD50: > 12800 mg/kg - Rabbit - (RTECS)

Acute inhalation toxicity:

LC50: 72600 mg/m3 - Rat - (Japan GHS Basis for Classification Data)

Irritant and corrosive effects

Primary irritation to the skin:

not applicable

Irritation to eyes:

Causes serious eye irritation.

Irritation to respiratory tract:

not applicable

Respiratory or skin sensitisation

In case of skin contact: not sensitising

After inhalation: not sensitising

STOT-single exposure

May cause drowsiness or dizziness.

STOT-repeated exposure

not applicable

CMR effects (carcinogenicity, mutagenicity and toxicity for reproduction)

Carcinogenicity

No indication of human carcinogenicity.

Germ cell mutagenicity

No indications of human germ cell mutagenicity exist.

Reproductive toxicity

No indications of human reproductive toxicity exist.

Aspiration hazard

not applicable

Other adverse effects

no data available

Additional information

no data available

SECTION 12: Ecological information

12.1 Ecotoxicity

Fish toxicity:

LC50: 9640 mg/l (96 h) - Brooke, L.T., D.J. Call, D.L. Geiger, and C.E. Northcott 1984. Acute Toxicities of Organic Chemicals to Fathead Minnows (Pimephales promelas), Vol. 1. Center for Lake Superior Environmental Stud., Univ.of Wisconsin-Superior, Superior, WI :414

Daphnia toxicity:

LC50: 1400 mg/l (48 h) - Blackman, R.A.A. 1974. Toxicity of Oil-Sinking Agents. Mar.Pollut.Bull. 5:116-118

Algae toxicity:
no data available

Bacteria toxicity:
no data available

12.2 Persistence and degradability
no data available

12.3 Bioaccumulative potential
Partition coefficient: n-octanol/water: 0.05 (20 °C)

12.4 Mobility in soil:
no data available

12.5 Results of PBT/vPvB assessment
This substance does not meet the PBT/vPvB criteria of REACH, Annex XIII.

12.6 Other adverse effects
no data available

SECTION 13: Disposal considerations

13.1 Waste treatment methods

Appropriate disposal / Product
Dispose according to local legislation. Consult the appropriate local waste disposal expert about waste disposal.

Waste code product: 070104

Appropriate disposal / Package
Dispose according to local legislation. Handle contaminated packages in the same way as the substance itself.

Additional information
no data available

SECTION 14: Transport information

Land transport (ADR/RID)

14.1	UN-No.:	1219
14.2	Proper Shipping Name:	ISOPROPANOL
14.3	Class(es):	3
	Classification code:	F1
	Hazard label(s):	3
14.4	Packing group:	II
14.5	Environmental hazards:	No
14.6	Special precautions for user:	
	Hazard identification number (Kemler No.):	33
	tunnel restriction code:	D/E (Passage forbidden through tunnels of category D when carried in bulk or in tanks. Passage forbidden through tunnels of category E.)

Sea transport (IMDG)

14.1	UN-No.:	1219
14.2	Proper Shipping Name:	ISOPROPANOL
14.3	Class(es):	3
	Classification code:	
	Hazard label(s):	3
14.4	Packing group:	II
14.5	Environmental hazards:	No
	Marine pollutant:	No
14.6	Special precautions for user:	
	Segregation group:	-
	EmS-No.	F-E S-D

14.7 Transport in bulk according to Annex II of MARPOL 73/78 and the IBC Code
not relevant

Air transport (ICAO-TI / IATA-DGR)

14.1	UN-No.:	1219
14.2	Proper Shipping Name:	ISOPROPANOL
14.3	Class(es):	3
	Classification code:	
	Hazard label(s):	3
14.4	Packing group:	II
14.5	Special precautions for user:	

SECTION 15: Regulatory information

15.1 Safety, health and environmental regulations/legislation specific for the substance or mixture

EU legislation

- Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC (Text with EEA relevance)
- Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (Text with EEA relevance)
- Commission Regulation (EU) No 453/2010 of 20 May 2010 amending Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (Text with EEA relevance)
- Commission Regulation (EU) 2015/830 of 28 May 2015 amending Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

National regulations

-

Water hazard class: slightly hazardous to water

15.2 Chemical Safety Assessment

For this substance a chemical safety assessment has not been carried out.

SECTION 16: Other information

Abbreviations and acronyms

ACGIH - American Conference of Governmental Industrial Hygiensts
ADR - European Agreement concerning the International Carriage of Dangerous Goods by Road
AGS - Committee on Hazardous Substances (Ausschuss für Gefahrstoffe)
CLP - Regulation on Classification, Labelling and Packaging of Substances and Mixtures
DFG - German Research Foundation (Deutsche Forschungsgemeinschaft)
DNEL - Derived No Effect Level
Gestis - Information system on hazardous substances of the German Social Accident Insurance (Gefahrstoffinformationssystem der Deutschen Gesetzlichen Unfallversicherung)
IATA-DGR - International Air Transport Association-Dangerous Goods Regulations
ICAO-TI - International Civil Aviation Organization-Technical Instructions
IMDG - International Maritime Code for Dangerous Goods
KOSHA - Korea Occupational Safety and Health Agency
LTV - Long Term Value
NIOSH - National Institute for Occupational Safety and Health
OSHA - Occupational Safety & Health Administration
PBT - Persistent, Bioaccumulative and Toxic
PNEC - Predicted No Effect Concentration
RID - Regulation concerning the International Carriage of Dangerous Goods by Rail
STV - Short Term Value
SVHC - Substances of Very High Concern
vPvB - very Persistent, very Bioaccumulative

Training advice: Provide adequate information, instruction and training for operators.

Additional information

Indication of changes	none

The above information describes exclusively the safety requirements of the product and is based on our present-day knowledge. The information is intended to give you advice about the safe handling of the product named in this safety data sheet, for storage, processing, transport and disposal. The information cannot be transferred to other products. In the case of mixing the product with other products or in the case of processing, the information on this safety data sheet is not necessarily valid for the new made-up material.

From:	"Jan-Tore Jakobsen" <jan-tore.jakobsen@uis.no>
To:	"Tiedemann Bratten" <tiedemannb@hotmail.com>
Date:	2/8/2023 5:50:11 AM
Subject:	VS: clear [ref:_00Di0dMD6._5005d1pWJEp:ref]

Fra: Jan-Tore Jakobsen
Sendt: tirsdag 10. januar 2023 13:50
Til: Chandima Ratnayake Mudiyanselage <chandima.ratnayake@uis.no>
Emne: VS: clear [ref:_00Di0dMD6._5005d1pWJEp:ref]

Fra: support@formlabs.com <support@formlabs.com>
Sendt: fredag 2. september 2022 15:58
Til: Jan-Tore Jakobsen <jan-tore.jakobsen@uis.no>
Emne: clear [ref:_00Di0dMD6._5005d1pWJEp:ref]

Good afternoon,

Thank you for reaching out to Formlabs Services. My name is Barbi. I will help you today.

I am very sorry to see this happened to your model.

I would like to kindly ask you a few questions.

1. Have you cured the model on supports? If not please make sure you do it that way.
2. If curing on supports did not help we usually reduce the recommended temperatures by 20 C degrees.

I am sharing some tricks.:

When post-curing prints with the Form Cure or Form Cure L, follow Formlabs best practices to help parts achieve their optimal mechanical properties.

- Dry parts before post-curing to maintain the machine in good working condition.
- Preheat the prints while the machine preheats to the target temperature.
- Consider part size and geometry when post-curing to safely and effectively post-cure prints.

If there is solvent on the surfaces of a print when it is placed in the machine, the solvent evaporates and condenses on the inner surfaces of the machine. This can cause clouding on reflective surfaces.

The printed part must be in the machine while it heats. If the part is not placed in the machine until preheating is complete, it may crack.

Consider part size and the geometry of each print when selecting a post-cure cycle. Modify the post-curing process for parts that are large, long, or thick, have dense support structures, or have thin features. I am attaching the article as well.

A successful 3D print starts with a well-designed model. Please, follow our best practices to optimize designs and reduce failures. I have another article .

Please, let me know how it goes or if you have any further questions. I am here to assist you.

I am looking forward to hearing from you.

Kind Regards,

Barbi Bacsa
Formlabs Services

Register for our upcoming Formlabs Remote Service Sessions .

Join now for free training at Formlabs University .

Manage your prints and get print status notifications on Formlabs Dashboard . Register today!

Your case number is: 00674333
Files relevant to this case can be uploaded via this link .
Formlabs GmbH - Funkhaus Berlin - Nalepastr 18 12459 Berlin - HRB 166201 B - DE299521578 - Managing Directors: Luke Winston, Stefan Holländer

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