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# Optimization of batching and the effect on overall production time with the fused deposition modeling additive manufacturing

Master's thesis in industrial management
School of technology and innovation

Vaasa 2022

**UNIVERSITY OF VAASA**
**Master's thesis in industrial management**
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**Topic of the thesis:** Optimization of batching and the effect on overall production time with the fused deposition modeling additive manufacturing
**Degree:** Master of business administration
**Major Subject:** Industrial management
**Supervisor:** Rayko Toshev
**Year of graduation:** 2022 **Pages:** 69

**ABSTRACT:**
In this thesis, we will look at the batching of production and production scheduling in Fused deposition modeling (FDM) system. Literature about FDM technology, manufacturing execution systems, and production scheduling is found for the literature review.

This literature review will be then followed by an analysis done with software for fused deposition modeling (FDM) printers. Different sizes of printed parts are used for the software to learn about nesting, batching, and material and time approximation. After this, scheduling software is used to schedule production.

The research questions answered in the thesis are how can the nesting of models in fused deposition modeling 3D printer be optimized and how can the work scheduling for Fused deposition modeling 3D printers be improved.

The results from the analysis show that the most time saved comes from setting up and post-processing the products. As the material usage differences are minimal, the nesting of as many of the same parts as possible in an orientation where support is minimized showed the best result.

For the production scheduling results, the same products should be scheduled to be printed at the same time, and also in the scheduling, the results are similar and the nesting of as many as possible products is favored.

The conclusion is that the nesting of products in additive manufacturing (AM) production is that orientation is the most important factor in saving time and material. When orientation is done most efficiently in single products, the support is minimized in the products.

Work schedules should be done in a way where simple products are printed in bigger batches. Also, products with more than one part should be printed subsequently or in the same batches, so that the post-processing and the finishing of those products can be done most efficiently, and the products can be sent to the customer as soon as possible.

**KEYWORDS:** Additive manufacturing, Production management, work scheduling, Fused deposition modeling

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# 1 Introduction

Additive manufacturing (AM) has been growing in interest in recent years. This is because AM enables the production of complex products with reduced costs. Also, this technology allows low-volume production of customized parts to be viable, for example for Technobothnia laboratory which has low volume.

This thesis aims to find the characteristics that make effective production management for AM. First, we will look at literature about AM technology and the software around AM technologies. After AM literature, nesting and production schedule will be looked at. After the theoretical side of the thesis, there will be data gathering from slicing software CuraSlicer, where nesting of products is experimented. After the nesting analysis, production scheduling analysis will be done to find out data for scheduling these products analysed in previous analysis. The thesis will answer questions about production scheduling and batching of AM production. The master's thesis has been done at the University of Vaasa for the school of technology and innovation.

## 1.1 Objectives

The goal of this thesis is to find theoretical information about AM and make an experiment study that will answer the research questions. The objective is to analyse how the products can be nested in the Curaslicer software and how time and material can be saved in the nesting phase of the FDM printing. In the production scheduling analysis the nested products will be scheduled to see how the scheduling can be done.
The research questions will be answered in the conclusions chapter.

### 1.1.1 Field of science

The field of science will be production planning and production scheduling in the field of Fused deposition modeling (FDM). Industrial management is the general field of science.

### 1.1.2 Research questions

Below are the research questions that this thesis will answer.

- “How can the nesting of models in fused deposition modeling 3D printer be optimized?”

- “How can the work scheduling for Fused deposition modeling 3D printers be improved?”

## 1.2 Background information and limitations.

The Way we create products has been radically altered by AM. AM is a game-changer, from design to tooling to replacement parts. And its impact is only starting to be felt, as the machine’s speed and capacity have just passed a tipping point where the AM technology has become an efficient option. because of this, the impact can be seen in many industries. (Hilkene Cullen 2020).

The background for this thesis is that AM has been interesting to me for a while, and I got an opportunity from the University of Vaasa to get an experiment study for this topic and collect literature data and experiment on software for FDM. In the thesis, the limitations are that the FDM models are discussed, but the models discussed are limited to those which Thingiverse website has to offer as free models for the software. The software side is discussed, and open-source variants are also discussed. The scheduling part of the experiment does not include logistics after the initial production, as this thesis focuses on the production and AM technology.

## 1.3 Structure of the study

The structure of the study will be that literature will be reviewed about AM technology, AM software, MES software, scheduling methods, and 3D nesting.

After the literature review, there will be an analysis done that will start with slicing software CuraSlicer, where different parts will be nested and material and time needed will be calculated. After that, Octoprint software will be used as an MES and lastly, Production scheduling software will be used to schedule two different production simulations according to the data gathered before.

After the analysis, the conclusions chapter will conclude the results from the analysis and the whole thesis.

# 2 Literature review

In the literature review, we will look at AM technologies and different production planning, scheduling, and managing tools that can be used in the AM field. These are Manufacturing execution systems and enterprise resource planning systems. The difference in AM field for these systems are looked at in the chapters about the systems. The methods used in the data collection will be discussed in more detail in the methodology chapter.

## 2.1 Advantages, challenges, and Impact of additive manufacturing

With AM, the parts can be made on sight and for example, small parts can be printed at the place they are needed. (Babu & Goodridge, 2015). Even though AM has grown in interest, some challenges are universal for the systems which are discussed in chapter two. Here are some overall advantages and challenges by (Sushan Negi, Suresh Dhiman, and Rajesh Kumar Sharma, 2013). Listed in the chapters below.

## 2.2 Impact of additive manufacturing

One way in which AM changes the production of parts is the repair sector. AM makes it possible to fabricate replacement parts on-demand on sight, so only materials need to be transported. Of course, some parts are easier and more efficient to be purchased as traditionally manufactured, but for small replacement parts which are not crucial and can be manufactured on sight, AM will impact. One example of replacement parts that AM will widely impact are machines that need repairing, and the parts are not so readily available. Another example could be a location that is far away, and parts are not readily available. Repair section applications are many, and AM will certainly have an impact on it the further the technology is developed. (Hilkene Cullen 2020).

AM has an impact on the prototyping and development cycles of products and makes prototyping and design development more available as it is cheaper and faster to prototype and develop designs for products. (Hilkene Cullen 2020).

For example, the aerospace industry is interested in AM technologies as with this technology, as metal parts can be fabricated directly without any tools. Especially titanium parts have been interesting for aerospace industry applications. Article of Sushan Negi stated that there are some studies done, where benefits are listed for the impact of AM. overall, the product introduction lead time will be increased by 30% and up to 70% compared to previous lead times with normal manufacturing. Manufacturing costs for low-volume parts could be lowered by 30% to 35% (Sushan Negi et. al 2015).

AM has a huge impact on the supply chain side of manufacturing also, it is stated in the article The impact of AM in the aircraft spare parts supply chain: supply chain operation reference (scor) model-based analysis (Liu, Huang, Mokasdar, Zhou, & Hou, 2014) that overall, AM technology has an impact on reducing supply chain safety inventories and demonstrates aircraft spare part supply chain more efficient. However, to achieve impact on the supply chain, large investments must be made to AM technology.

## 2.3 Advantages and challenges of additive manufacturing

One of the big advantages of AM technologies is the reduced lead time which is directly impacting the normal components market. There is not so much material waste coming from AM, as the materials are usually fed into the system in the amounts needed. Some forms of AM technologies need support structures, but the material used will be less than from subtractive manufacturing. With these two advantages, also cost will be reduced overall.

When it comes to prototyping, the quality of prototyping has increased because of AM. It is easier to make prototypes and even metal prototypes can be made. Some assemblies which are wanted to make without screws, glue, are only available through AM. This makes complex geometry parts stronger when made with AM. With AM, snap-fit can be used to make parts without glue or screws.

AM systems do not need any tools in the manufacturing process, and only in post-processing, there may be a need for tools to cut off support structures from plastic parts. No molds are needed, and this will further increase the time and cost saved.

There are a lot of advantages when it comes to AM, but there are also issues that restrict the use of AM in certain areas. Major challenges can be seen in the surface finish, the strength of the materials, and systems cost. Here are some challenges that AM faces. (Varotsis Alkaios Bournias 2020).

Parts fabricated by AM systems may have different behavior when it comes to strength properties, compared to conventionally manufactured parts. An example of this is that the strength of AM part can be better in the direction of the layer compared to the anisomorthic properties. Also, the layer thickness is a challenge for AM. When layers are thin, the process takes more time. but the quality of parts finish can improve. The layers must be optimized, and it is one of the important factors which needs to be considered. (Varotsis Alkaios Bournias 2020).

Support structures used is also a challenge that AM faces. By optimizing the way, the parts are manufactured, the support structure needs can be minimized. Also, the way AM parts are fabricated layer by layer results in the “stair-stepping” phenomenon. This can be seen in the way that the curved surface of the parts is not so smooth in comparison to other manufacturing methods. Because of this, a lot of post-processing is needed. Post-processing also brings challenges to AM technologies, as polishing the surface will lengthen the manufacturing process and may be costly if there are certain post-processing machines needed. (Varotsis Alkaios Bournias 2020).

For AM to be effective, there need to be big investments in technology. Companies that already are in today's radically demanding market climate and using conventional manufacturing technologies, fail to recognize the potential of AM technologies and they lack the tools that would allow them to make decisions on these kinds of new investments. So, the challenge in the AM in already existing companies is the need for big investments and the lack of tools or commitment to changing the conventional manufacturing processes into AM processes. Surely AM cannot be used in every process or every part, but overall, the barrier is big for starting to move into AM processes. (Mojtaba Khorram Niaki & Nonino, 2017).

## 2.4 Additive manufacturing

In this chapter, we look at the basics of AM and effective production. We also discuss the AM as a technology. We discuss theory, as well as how AM technology has evolved, and look at different types of technology briefly. The most important technology for the thesis is the FDM technology, as it is the most common technology.

AM was called rapid prototyping in the early days of the technology in the mid-1980s. AM has come a long way since then, and nowadays it is used from printing little household items to more industrial-oriented manufacturing of certain products. AM can be divided into two parts. The first part is the digital side of the process, where the product is modeled in the software, and then the physical process with a 3D printer machine. (Sushan Negi et. al 2015).

There are different AM technologies. They can be classified into two major aspects. There are seven major types of AM processes that are listed in the ASTM published standards document, which are: Powder bed fusion, directed energy deposition, binder deposition, vat photopolymerization, material jetting, material extrusion, and sheet lamination. These are based on what kind of material they use, and what kind of deposition methods are used. in the following section, the basic process of AM is discussed. (ASTM International 2021).

## 2.5 Additive manufacturing process

In all AM technologies, the basic starting point is the same, 3D modeling with the computer software. With the software, the CAD (Computer-aided design) software model is made. This software is CAD, which is for example Solidworks and SketchUp (3D printing.com). This software uses STEP format, which is then converted into an STL file which is a standard input format file for usual AM systems. This type of file describes object/geometry with the triangulated surfaces using a coordinate system. STL file then needs to be imported into the software that pre-processes the file for the use of AM printer. In the preprocessing phase, the support structure is modeled, and the product model is sliced into layers that are of a certain thickness. G-code generation is how the part will be oriented in the machine and how the printing machine is pathing for each layer. G-code generator creates instructions for the machine. (Sushan Negi et. al 2015).

The AM machine is given this information through the software. With this information, the physical product is fabricated layer by layer with the printing machine. The layer thickness and pathing are processed by the software and the printer prints how it is commanded in the software. After all the layers are fabricated, it is time for post-processing. In post-processing, the part and un-needed support structure is removed, and the surface could be treated by removing the supports and cleaning or painting the piece. This improves the appearance of the part. (Sushan Negi, Suresh Dhiman, and Rajesh Kumar Sharma, 2013).

The STL file that is used in AM has been developed in 1987 by 3D systems for stereolithography apparatus. Since the development of this file type, it has become the standard for almost every AM system. STL file tesselates the surface and generates a large number of triangular facets to approximate the CAD model of the product. This means that when the model is produced in the software, the surface of the model is represented by small triangles. When the triangle number increases, the file size gets larger. The STL file has coordinates of three points, and the file has a list of x, y, and z coordinates which indicates where the triangles are in the file.

(Sushan Negi et. al 2015).

Below is a picture to perceive the triangulation of the product inside the software, where CAD model is converted into an STL file which has the triangulation in the object. (all3dp 2021).

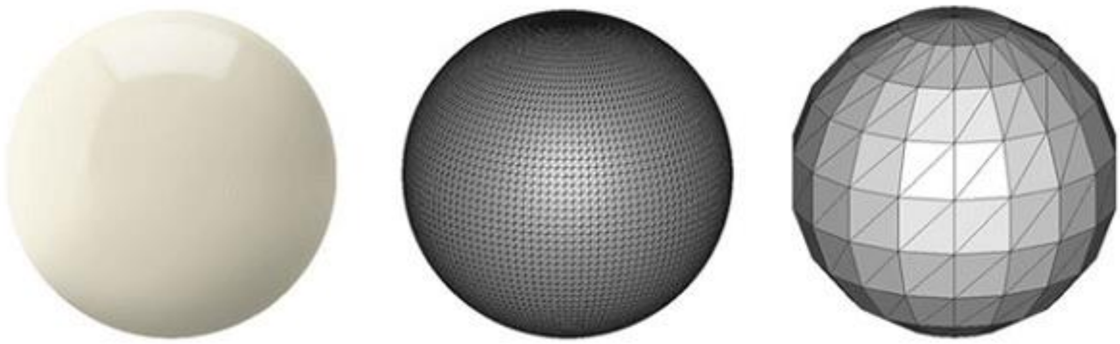

**Figure 1:** CAD model is converted into an STL file.

## 2.6 Fused Deposition Modeling

FDM is the technology of AM which is the most widely used AM technology. FDM system uses a thermoplastic filament which is used in the semi-molten form in the machine and it is extruded layer by layer from a nozzle tip which melts the filament into the layer of the platform. The nozzle tip uses the X, Y, and Z-axis to fabricate the filament on the layers. The platform is at a lower temperature than the molten filament, and this causes the filament to solidify on the platform. The filament will solidify on top of the other layers and this way the product is manufactured. The latest FDM machines can have two nozzles for two different filaments, one for the support structures and one for the filament which is used in the main part of the model. There are a lot of filaments that can be used in this kind of system, and the most notable are polylactic acid (PLA), Polyethylene terephthalate (PET), and acrylonitrile butadiene styrene (ABS) filaments. These filaments have different kinds of properties. (Sushan Negi et. al 2015).

Here is how the process works like. A spool of filament will be loaded into the printer. The nozzle is heated and as the temperature is desired, the filament will be fed to the head of the printer into the nozzle, where the filament will melt. This head with the nozzle is attached to a 3-axis system where it moves in X, Y, and Z directions in the machine. The melted filament is extruded from the nozzle in thin pieces and will be deposited in the platform in locations that are predetermined in the software before the physical printing. The filament will cool down to the place it is extruded. After one layer is printed, the extrusion head will move up or the platform will move down depending on the machine used, and another layer will be printed on top of the layer. This will be repeated until the model is fully finished. (Varotsis Alkaios Bournias 2020).

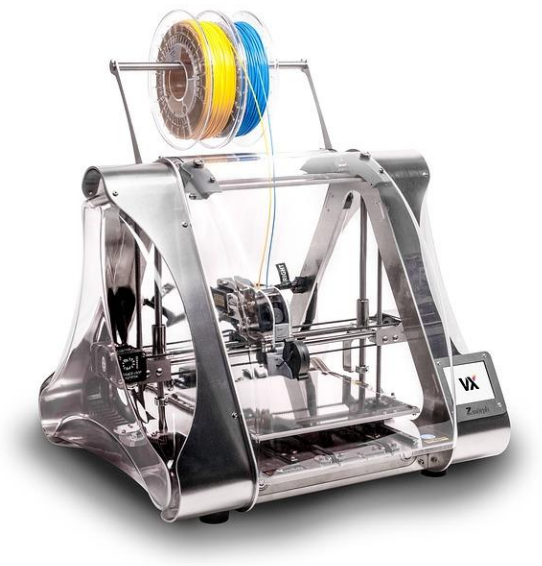

**Figure 2:** FDM machine (PixaBay 2020).

### 2.6.1 Problems

One of the problems of FDM printing is the warping effect. The cooling of the filament can be different for different sections of the model which is printed. This can lead to warping from the sharp corners, thin features, and large flat areas. Warping can be prevented by making more support structures or printing the model in a way that thin areas are in different positions and by monitoring the temperature more closely. Also, the filament materials which are used will affect the warping effect. (Varotsis Alkaios Bournias 2020).

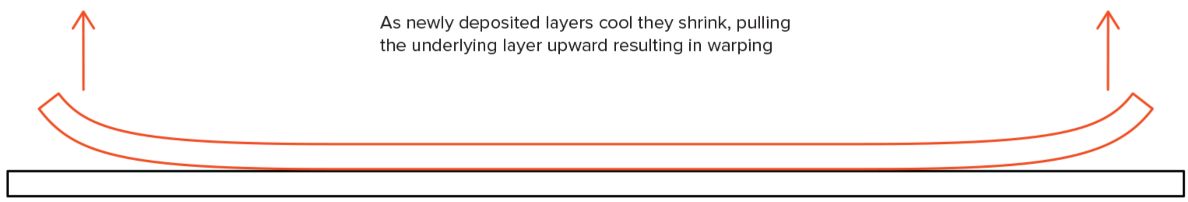


**Figure 3:** Warping effect of FDM printing (Varotsis Alkaios Bournias (2020).

Good layer adhesion is important for the FDM print to be successful. The new Molten filament layer must be pressed against the existing layer with enough pressure so that it is bonded well with the existing layer. The existing layer also melts a little bit when the molten filament is printed on top of it, and it bonds the layers together for them to be connected. If the layers are not intact enough, it will result in the part being not strong enough and the layers could not be intact, which results in a part that is not usable. (Varotsis Alkaios Bournias 2020).

The support structure for FDM printing is important. If there are overhanging structures in the print, support structures are necessary for the layer to be printed. Usually, this support structure will be of the same filament material as the other part of the model. There are also filament types that can be dissolved, and dissolvable filaments can be used in dual extrusion machines which will have two nozzles and where two different filaments can be used to make the support structures from the different filaments. (Varotsis Alkaios Bournias 2020).

FDM parts that do not need to be solid, the infill will be done for the part. The infill type and strength, as well as outer perimeter shell thickness, will determine the strength overall strength of the part. Infill and shell thickness will be determined in the software before starting the print, and the infill is usually the shape of rectangular, but there can also be a honeycomb structure or triangular structure. When using infill and not making a solid part, the material and the time needed will be reduced. The filling of the part can be determined by knowing where the part is used and how much strength the part is needed to have. Also, the need for using screws on the part which is printed will determine the amount of infill done, as the screw may not hold the part tight enough if the infill is minimal. (Varotsis Alkaios Bournias 2020).

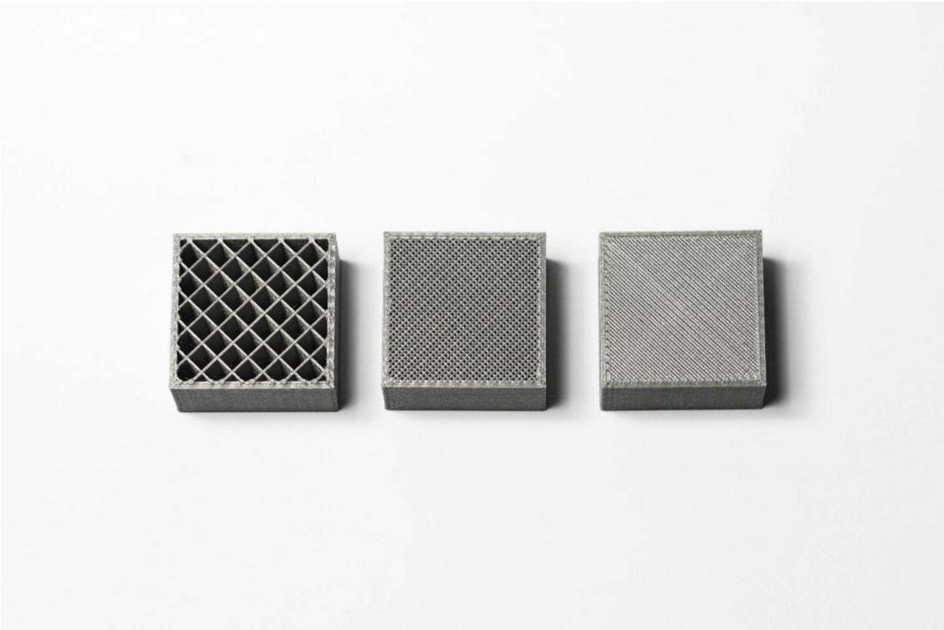

**Figure 4:** rectangular infill of the part (Varotsis Alkaios Bournias 2020).

FDM parts can be post-processed to have a good standard of finish. Post-processing methods that can be used are sanding with sandpaper, polishing, priming epoxy coating, or metal plating. This way, the part will have a high-quality finish which will be done for the needs of the part.

FDM technology advantages are that FDM is a very cost-effective way of producing prototypes and thermoplastic parts. Another advantage is that the lead time of FDM printing is short, and the technology is widely available. The last advantage here is the availability of different materials which have a lot of different usages. The disadvantages are that accuracy is not so polished in comparison to other AM technologies like SLS. FDM parts also have visible layers which need post-processing to make a quality finish for the looks of the parts. Also, the need for precise pressure and heat monitoring can be seen as a disadvantage. (Varotsis Alkaios Bournias 2020).

Overall FDM technology is a good way to make prototypes and different kinds of parts to be used for example in households, but it lacks the polish compared to some other

AM technologies and FDM printed parts are not recommended to use in mechanically critical parts.

## 2.7 Software of additive manufacturing

In the earlier chapters, we looked at different AM technologies and overall processes. In this chapter, we look at the software of AM systems more closely and find out about different software tools and overall software challenges. The software qualities are looked at more closely in the later chapter.

### 2.7.1 General software

AM software has general needs that are from start to finish the modeling, slicing, and the monitoring of the process of printing. In the software, the overall structure of the model is modeled, and the infill and support structures are modeled into the part which is going to be printed. In the production of the part, the software controls the manufacturing. There are also websites where people may download finished files for manufacturing, one website like this is www.thingiverse.com.

For AM systems, there are different software. Some are open-source and some are closed source. including ones that are used from start to finish. and then, there are different software tools for different tasks, including modeling, slicing, and the STL file downloading and converting. In the software, there can be plugins that are used for certain tasks, for example, Autodesk inventor which is used for simulation, visualization, and documentation. There is also open-source software that only is used for printing, and the modeling must be made in different software. One example of this is Octoprint. In Octoprint, the model is made in different software or downloaded from the internet, and then it is imported into the software which prints the part. (Häußge, 2020).

Here is a list of different software used in 3D modeling

- Autodesk 3D modeling, commercial.
- FREECAD 3D modeling, open-source.
- Sketchup 3D modeling, freemium and web-based.
- Octoprint 3D printer controller application, open-source.
- Cura 3D printer slicing application, open-source.

### 2.7.2 What makes a good software?

For the software to satisfy the needs of users, the software needs to have a good user interface. A good user interface makes sure the user experience using the software is fluid. There is a customer review article made about software qualities that are the most important. These software qualities are Ease of use, feature metrics, design, and support. Software qualities that are seen as best are feature metrics and ease of use. These two are rated the highest in customer reviews about software qualities and feature metrics being the number one rated quality trait. After these two comes in order design and then lastly support. From this article, we can conclude that feature metrics and ease of use are most important for software coming from the customers using the software. Without good features and ease of use, the software is lacking. (Munish Saini, Kuljit Kaur Chahal, Rohan Verma, Atarpuneet Singh 2019).

In AM situation, the software user experience is based on design and ease when everything can be done with ease from modeling to the end of the manufacturing.

For example, in Octoprint software, all the monitoring at the time of manufacturing can be done from the program itself. These include control and monitoring aspects like visualizing the current progress, temperature monitoring, and the choice of stopping, pausing, or starting the print from the program. These are the basic needs for good and fluid use of the software for an overall good software on 3D printing which is not on an industrial scale. (Häußge, 2020). On an industrial scale, there are more things to be considered, which are discussed in the later chapters.

The model design software where different kinds of computer-aided design (CAD) software is used, design software should be able to work in the purpose of AM needs. This means, that in the software the design can be designed in a way that it would be manufactured in a 3D printer. Conventional CAD, which is usually used in subtractive manufacturing, CAD describes the models differently than the 3D printing software. Software needs to consider the infill of the part, the layering of the model, and the need for support. Also, traditional CAD models are made solid, and in the case of AM, the models are needed to have different infill and hollow parts with "watertight" surfaces. If this is not done, the material needs for the manufactured part are huge. Some CAD models may not be able to model complex AM shapes. To achieve results CAD software for AM has been developed. (Wong Kenneth 2020).

One more feature, which makes software good is that the parts can be nested in the AM machine as efficiently as possible so that the machine can manufacture more parts with a single manufacturing cycle. Nesting is done in the different software packages, and the software package should be fast and clear on the nesting process. (Wiberg Anton, Persson Johan, Ölvander Johan 2019). For slicing software, which turns the model made by modeling software to G-code format, the features that make software easy and frictionless to use, the software must be quick on the translation of the model code, so that the user does not need to wait for a long time for the translation progress. As the software makes the path that the manufacturing machine follows, the pathing should be as effective as possible. Also, the options for the slicing should be easily accessible and distinct on what they do for the model.

As the slicing in the software affects the end products quality and the materials needed, as well as the time, is taken for the manufacturing, the software should have clear indicators for the slices of the model. Also, the support structures options should be in the software, to make the materials needed for the support as minimal as possible, and with the minimization of support structures, the quality of the produced model is also better. Sometimes, the amount of support structures needed comes down to trial and error, as new models are tried out and checked if the support structures hold all the weight of the model. Some slicing software can calculate geometric dimensions and tolerancing, and then create data about the model, and this way the model can be made better for long-term use and be more sustainable. This is a good feature for the software, but the software capable of that may be costly. (Wiberg Anton et. al 2019).

Here in figure five, the overall view of CuraSlicer slicing software is available. On the right are the options and the model is viewed at the center of the screen. All the changes made in the options can be directly seen on the model.

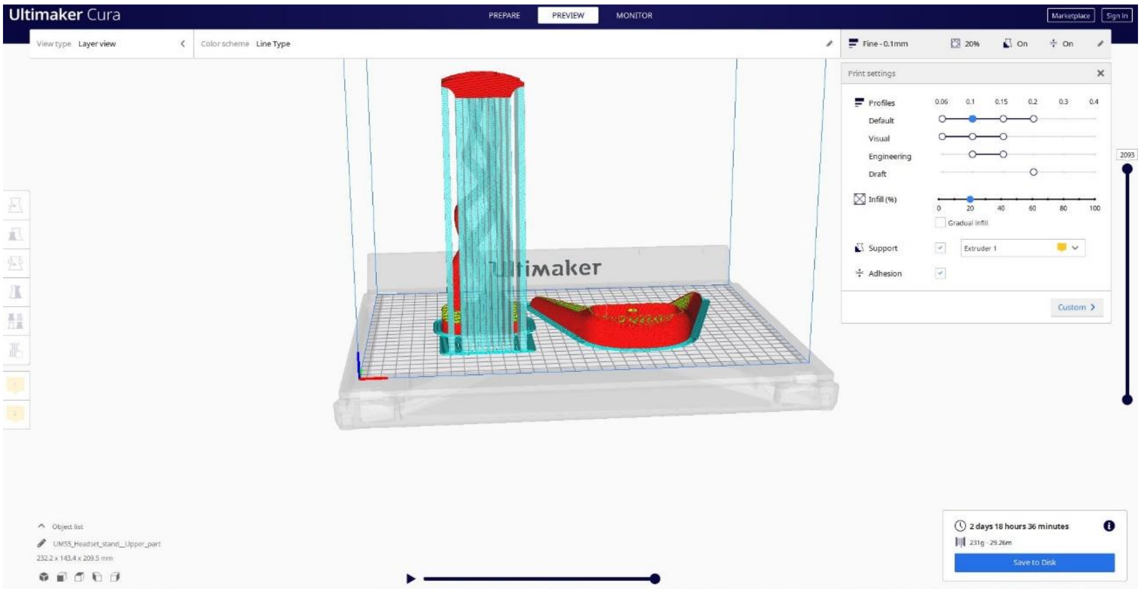


**Figure 5:** STL viewer in software Curaslicer.

Overall good software has easy-to-use of modeling. There are options for different filling percentages and printing orientations. Easiness of use comes also from the fact that the file is already formatted in the right file format, which makes the print is easy to start after all the modeling is done. When a part is modeled with this kind of software, the file is already in a format where the software slices the model into layers, and the inside of the model can be filled with infill structures. One of the software which is like this is Magics. It is a pre-processing and STL-file editor. Software like this is crucial for AM, as the model which is being generated can already be edited in the modeling phase of the process. Users can directly modify support structures, wall thickness and the infill, smooth surface, and delete points that are redundant in the AM process. (Vayre B, Vignat F, Villeneuve F. 2012).

## 2.8 Manufacturing execution systems

A manufacturing execution system (MES) is an information system that drives the effective execution of manufacturing operations. MES has been developed for the narrow gap between the floor of production plants and the office planning systems nowadays widely called enterprise resource planning systems (ERP). With current and accurate data, MES guides the activities that are needed for manufacturing to take place. MES system functions manage the production operations from the point of order until the point of delivery of the finished product. MES communicates critical information about activities done throughout the production across the organization and supply chain.
(B. Saenz de Ugarte, A. Artiba and R. Pellerin 2009).

Manufacturing Execution Systems (MES) has developed greatly from their beginning in the mid-1990s into more powerful and more integrated software applications as computing technologies have progressed. Their coverage of functionality has changed dramatically and can now include a standard and single framework to support most production execution processes from the release of the production order.
(B. Saenz de Ugarte et. al 2009).

MES as a system is in between Enterprise resource planning (ERP) system and the systems used to control tools and machines of production. Where ERP is used to control orders, purchasing, materials, and customer service, the MES system is used to schedule and execute processes of manufacturing according to information about orders and materials from the ERP system. For the management of production to be as fluid as possible, the information must flow through these systems seamlessly. When the information transfers through these systems as well as can be, the reliability and predictability will become better, and this leads to more scalable processes inside the company. (Systema 2019).

There are many shapes and sizes for MES applications. MES can be customized to the needs of certain company's needs or can be bought as a service as a complete package. There are different styles of installments for MES, some can be on the cloud, or some need to be installed into the computers. Even though there are differences between MES applications, the basic components are the same. (B. Saenz de Ugarte et. al 2009).

### 2.8.1 Manufacturing execution system components

In this chapter, we look at the different components which MES has and what the functions are. Even though different components can be categorized, not every component is needed, and some companies may decide to not use all of them.

MES can answer core questions about manufacturing:

- How to produce?
- What can be produced?
- When and what should be produced?
- When and what was produced?

Systema has combined some core components which MES manages and implement, to answer these questions about the manufacturing inside the company.

The first component is the *Enumerated steps*. Step in MES is a work-in-progress value-added operation that produces completed sealable products when sequentially linked with other steps in the sequence of production. These steps are mostly numerically enumerated, but alphanumeric conventions may be allowed by some MESs. (Systema 2019).

The above steps are placed in sequence resulting in a defined process flow that is also reusable. MES applications are great at managing process flows regardless of if they are short processes with very few steps or long process flows that are chained together if the manufacturing process is long and complex. This component is called *Process flow control.* (Systema 2019).

*Product definition* is the next component that can be defined. The product can be defined in the MSE by a single process flow or a series of many different process flows that are chained together to result in a product. Definition of product can also contain metadata about the classification of the product. MES defines products in low product mix and high product mix, as the basic context of product definition is the same on both of them. (Systema 2019).

What MES is doing is with the programmed steps is that it is to assign the right equipment to finish the step. This is called the *equipment assignment* component. In MESs, there may also be tracking of the product into certain work that the tools or machines are making on the product. This tracking can be used to polish the quality when the production of the product is optimized. (Systema 2019).

When production is ongoing, sometimes the process work in progress must be stopped or paused to collect data or investigate if there is a quality concern. MES can stop the processing ongoing and there can be optimization of current products according to the data gathered or even research and development for a new product. This *control* can be either real-time or future pauses on process flows can be determined beforehand. (Systema 2019).

MES logs the state of processes and identifies the availability of equipment on the processing. Each step where processing is completed will produce the next sentence in the process flow story, which ultimately leads to the complete product. The “genealogy” of the product can be studied and reviewed for quality improvement or another usage after the product has been shipped. (Systema 2019).

All these components come together as data points to support regulatory compliance requirements for the product. Components can be tracked and controlled during the processing of products and metrics can be gathered throughout the process for optimization and further polish of the whole process flows. The most important aspect of MES is data processing, and for the core components to provide data, the data must be processed quickly and the managing of data for the processing activities must be effective. Data must be in right place at the right time and be precise, for the process to flow smoothly. For this, the transactional database can be used to extract or store data. This will enhance the speed at which the data is handled. When the data is not used in immediate processes, it can be stored in a data warehouse where it can be used at a later time on upgrading process flows or researching possible new product types in the research and development section of the company. (B. Saenz de Ugarte et. al 2009).

These core components are the key to the functionalities which the MES must be able to do. These functionalities are processes such as scheduling and quality control, and there are also cross functions which are for example resource management and traceability. (B. Saenz de Ugarte et. al 2009).

- *Operational scheduling* is the timing of activities for optimized performance in the production plant, which is based on capacities and resources.
- *Resource allocation and the status* is guiding what materials should be used and tracking the materials used already.
- *Dispatching production units* is giving commands to order parts or materials to begin the next step or a process.
- *Document control* is managing and distributing information on processing products, orders and gathering statements about work and conditions.

- *Product tracking* tracks the product at the process flow, and it is used to make a full history of the product from parts to finished and shipped product.
- *Performance analysis* is comparing measured results in the plant to the simulated process, goals set by the company, or metrics that the customer has wanted.
- *Tracking the labor* is also one of MES functions, and labor during a shift can be tracked and the work patterns can be traced to be able to improve and manage labor.
- *Maintenance management* function gathers data about maintenances needed and maintenance is planned inside MES, and this way the machinery and tools can be kept up.
- *Process management* keeps up with the process flow and directs the planned activities inside the manufacturing.
- *Quality management* is recording the quality of the product and tracking the production of the product from the quality standpoint. For example, different machinery quality can be traced and if the quality is not as it should be, one process in the process flow can be changed or calibrated to match the quality need.
- *Data collection* function collects and manages the data that other functions gather to be used for the activities that can be done with the data. It is also important that the data collection function is organizing the data correctly, so it is easy to manage and improve upon.

These functions are defined for multiple manufacturing environments and are standardized to fit a variety of manufacturing companies' processes. The emphasis on different functions will vary between different kinds of companies. For example, quality control is more emphasized in production line manufacturing companies compared to the need for performance analysis. Also, different management needs are set by companies own needs and the correct management goals can lead to competitive advantage, savings in material costs, and the reduction of lead time. Overall, MES brings out data about the manufacturing inside the company which is important for the overall performance of manufacturing processes inside the company. (B. Saenz de Ugarte et. al 2009).

### 2.8.2 MES in additive manufacturing

For AM, the needs of MES are the same as in traditional manufacturing. There are differences in the AM processes, and MES has to be able to work with AM needs. For example, the MES system must be able to handle different kinds of scheduling and for example, batching is a process that can turn out to shorten the process time, and with correct MES calculations and scheduling the batching process can be made more efficient. As in this thesis, we look at the improvements in batching of the 3D printer process, MES management process is important on the batching process. If MES handles the manufacturing scheduling and batching processes seamlessly, effective production will be the outcome of this. When manufacturing is scheduled with the intention of being as effective as can be, being able to batch as many parts on one print with a 3D printer machine as can be done is important. (Gianluca D'Antonio, Frédéric Segonds, Floriane Laverne, Joel Sauza-Bedolla, Paolo Chiabert 2017).

MES system will be managing processes and the quality of the production processes. MES system needs to be able to manage the quality of the AM process. For example, the warping effect on FDM printing is one quality that must be taken into consideration as it will affect the quality of the final product. Also, the infill of the FDM printer production is important, as efficient infill calculations will make the infill material needs to be minimal. One of the MES system need is also real-time corrections to the printing process. This is done by storing and analyzing the data stored inside the MES. As AM system production of certain parts is done over and over, information in MES can be used to better the production in real-time. Also, if there is for example too much warping or the produced part is defective, the production process can be stopped. After the production is stopped, the cause for the defect can be checked. This saves time and resources as the production can be stopped and restarted before the whole production is finished. (Gianluca D’Antonio et.al 2017).

## 2.9 Design for additive manufacturing

These AM needs are different for MES systems compared to traditional manufacturing. MES systems must be tailored for AM systems to effectively produce parts on a larger scale. MES systems will make AM more effective and will bring quality of life upgrades to the production.

In AM, traditional design for manufacturing (DFM) practice cannot be used to minimize manufacturing and eliminate production issues and costs. As the AM process has unique capabilities compared to traditional manufacturing, the DFM must be re-thought and include the capabilities of AM needs. New design tools are needed for the effective managing of AM systems. Product shapes, properties, efficient manufacturing processes as well as materials and lifecycle costs assessment. (B. Saenz de Ugarte et. al 2009).

Design for additive manufacturing (DFAM) is defined as tools and methods which are helping the design of the product and the process optimization. Some of the qualities that DFAM which traditional DFM does not have are for example on-demand AM, where the customer can customize the product in the digital catalog and send the file to the manufacturer. DFAM includes the shapes, different manufacturing processes, and life cycles of the produced products made by an AM system. (B. Saenz de Ugarte et. al 2009).

These DFAM qualities are needed for MES to be able to be used effectively with AM systems. One of the MES qualities we are looking at in this thesis is the batching of production inside FDM printers. With correct optimization with MES calculations, the time needed for production in bigger products that have more parts or bigger batches of products can be bettered significantly. Another area in which MES can improve is the work scheduling for AM. (B. Saenz de Ugarte et. al 2009).

To be able to integrate MES systems, it is important to have a comprehensive design for integration consideration when designing the integration. If no design is done, the shop-floor integration may be lacking. MES systems usually are integrated with ERP software like SAP. Nowadays, integrations between MES and ERP are common and essential concerns on this kind of integration is horizontal and vertical integration of the system. (B. Saenz de Ugarte et. al 2009).

## 2.10 ERP systems in additive manufacturing

The basics of MES were covered, and in this chapter, we look at ERP integrations with AM systems and performance metrics with which different AM can be integrated. To be able to get all the benefits from the system, an AM system should be also integrated with other systems like MES for an enterprise-wide information system where effective connectivity to the shop floor is essential. Every company can have different benefits from integrating systems with AM systems, but some common factors include visibility of processes, tracing and tracking capabilities all over the company, and lastly more responsive processes. In the article by B. Saenz De Ugarte et al. , these integrations can be divided into two categories according to the approach. These two categories are data integration (application programming interface API) and software integration.
(B. Saenz de Ugarte et. al 2009).

Whereas MES systems operate the production side of the manufacturing, ERP systems cover the planning and management of the production to be efficient and to be able to get the most out of the production in terms of capacity.

The most important things which ERP systems bring to production are efficiency and improved financial performance overall in every production-related field. With ERP systems the local actors in the production operations will get improved power over the tasks and the quality of the work is bettered. In the concept of AM, we are looking at the production planning and ERP will help the planning of different 3D prints, and the calculations for decision making are made easier with ERP-systems as the data will be collected and stored from production, and the user can get the data available for the decisions. ERP-systems also connect the different actors inside the companies which will help the data collection from various production functions, and the data collected will help the management and operation of other functions inside companies. Because of the connectivity, the communications are also enhanced, and people inside different functions know somewhat about the other function's actions. For ERP systems, the management of production must be also capable as without the management, the ERP-system benefits are not as good as they could be. For bigger companies, every core function in the organization should be understood and necessary changes which need to be made should be made before the ERP system is implemented. (Kim Sundtoft Hald et. al 2013).

ERP systems can be integrated with AM systems and here are some features from ERP systems that are useful for making AM more efficient. First of all, with ERP systems, the production can be planned to be efficient, and the downtime can be minimized. For example, the parts which take longer to produce can be left overnight so no supervision is needed on the printer. This can be done in the ERP systems by scheduling the production in the way that smaller parts are printed when the workforce is available to look after the printers and on weekends and during nights the bigger parts can be printed. (B. Saenz de Ugarte et. al 2009).

The materials used and are also ERP-system function which will help to manufacture as the data collected from materials used can be used to be able for the operators of AM machines to be in line with the materials which are used and this way the data about the material costs. When data about materials used is gathered, the ERP system can give data about what materials are needed if the materials have inventory in the ERP system.

For AM, before integrating the ERP system the core system which includes the printing system and the MES which as stated earlier guides the manufacturing process should be working and be working properly. This is, to ensure that the ERP system will have a fully positive effect on the manufacturing process.

Some ERP integrating mistakes can be that enterprises making the integration are tempted to align the needs with the functionalities of ERP-system and not align the ERP-system with the needs of the company. Because ERP systems are complex, the integration can seem difficult, and careful management of all ERP components, as well as the base system which is having the ERP system, is important. AM, MES, and other systems are specific, and the needs are specific, so the ERP systems may have difficulties supporting requests at the base level of the system without any modifications. (Bouzid Mohamed Ramzi, Kraiem Naoufel, Henda Ben Ghezala 2015).

In the paper ERP integration: A reuse-based approach, evaluation, and prospect (Bouzid Mohamed Ranzi et.al 2015). there are processes for ERP integration that will help in the integration of ERP systems. One such process is the process of matching. The differences and similarities are checked and mismatches can be modified or if this seems to be problematic, the mismatches can be accepted and the integration can continue. ERP functionalities can be adapted to organization needs with a customization process, and this is known as "Directed by business needs of the organization".

ERP integration will bring features for material management and efficiency, and with these features, the integration should be successful, and mistakes can be avoided. (Bouzid Mohamed Ramzi et.al 2015).

# 3 Production Scheduling

Scheduling may be defined as the allocation of resources over time to perform tasks. Production planning and scheduling are critical activities in every manufacturing company's administration and shop floor. In twenty-first-century manufacturing, customer requirements need to be met quickly and production lead times should be reduced. In addition to strategic decisions, production planning and scheduling are some of the biggest drivers to increase efficiency. (Lohmer Jacob, Lasch Rainer 2020).

Production planning is the first component of Production scheduling. It is a production procedure that guarantees you have enough raw materials, personnel, and resources to deliver completed goods on time. It's an important phase in production planning and management. (Lohmer Jacob, Lasch Rainer 2020).

Nowadays Manufacturer's profit sources have shifted from one-time transactions to continuous profit sources. Production scheduling, therefore, has challenges like scheduling must be flexible and the products are highly customized as the industry is moving towards servitization. Adaptation to different portfolios of products and reactive approach to scheduling is getting more important going forwards in manufacturing overall. When scheduling for AM it is crucial to adopt flexible scheduling methods as the products can be whatever the customer wants and are possible to produce with AM machine. (Parente Manuel, Figueira Goncalo, Amorim Pedro, Margues Alexandra 2020).

Routing is the second process, which is used to determine the path that product follows in the production. Routing is not as relevant for AM as it is for production in big factories with many steps in the manufacturing process.

Scheduling is the next step, where the time and date of the production operations are scheduled for the systems in use.

Dispatching comes next, and this is ordering the manufacturing or the job scheduled.

The execution phase is when the manufacturing is executed by the planned schedule. Staff members must work together to ensure that items are produced in the right order and delivered on time. A proper schedule execution would have the fewest amount of bottlenecks or late orders. (Planettogether 2021).

There are advanced scheduling systems for production scheduling, that are computer-based. With these scheduling systems, the algorithm formulates the production problem and will generate information about the best possible schedule as a solution for this problem.

## 3.1 Production, planning, and scheduling methods

Here are five different types of production and planning methods:

Job-based planning
Job-based planning means that one product is handled by a single worker or a group. Usually, the products are customized one-time products or large projects with many customized products together. Products can be manufactured from request and can be included in the manufacturing process at any time. (Planettogether 2021).

Batch method
The batch method is a term for production where groups of products are manufactured. this method allows products to be produced in batches and every batch can be changed. A batch can be one product or hundreds of products. (Planettogether 2021).

Flow method
In flow manufacturing, demand drives the manufacturing of products. Products flow continuously through the production line uninterrupted in collective operations. Exam-

ples of flow manufactured products are televisions and other household items. The flow method has the benefit of minimizing the work-in-process. (Planettogether 2021).

Mass production method

In the mass production method, large quantities of standardized products are produced. Mass-produced product examples are Different kinds of drinks, which can be produced in a mass quantity in a production line, in a quick manner. (Planettogether 2021).

Process manufacturing method

In process manufacturing, different kinds of chemicals, liquids, or gases are produced in a standardized sequence. This method is similar to flow and mass production, where the products are characterized by a flow of production, but the completed product is not one unit of the product, rather it is counted in units such as liters or kilograms. (Planettogether 2021).

There are scheduling problems that methods have been implemented to solve them. These methods use a different algorithm for the scheduling problem. The first method is efficient optimal methods. These methods generate an optimal schedule with scheduling criteria. The algorithm is used to solve problems optimally and efficiently. (McCarhy, B, Liu Jiyin 1993).

Another method is a heuristic method. This method is delivering an acceptable, but not necessarily the optimal solution to the problem presented. A heuristic method is a fast option for problem-solving. (McCarhy, B, Liu Jiyin 1993).

The last method is the enumeration method. Enumeration methods are used to solve combinatorial optimization problems. Combinatorial optimization problems are problems where decision variables are binary, expressing that an object is chosen or is not chosen. This leads to a lot of possible solutions with the difficulty of selecting and finding solutions that are more optimal than others. Real-world examples of such problems include the scheduling of machines in production planning. (McCarhy, B, Liu Jiyin 1993).

## 3.2 3D nesting

In this chapter, the nesting of models on FDM printing is reviewed from the literature. Raw material, width, length, height, volume, and filling percentage are all characteristics of a printed part, and orientation is the way how the model is set up on the printing surface.

Nesting is one of the production planning steps for AM manufacturing. Nesting is a term for the preparation of more than one model in the printing surface of AM machine. Nesting the models is an important part of the set-up process and with efficient nesting, material and cost savings can be achieved. It occurs before the manufacturing will be started. Differently shaped and sized models can be nested into the printing surface at the same time. (J. De Antón, J. Senovilla, J.M. González, F. Acebes, J. Pajares 2020).

Nesting and scheduling approaches are important for efficient process planning and production management in Am systems to boost production rate. Nesting methods are used to properly arrange objects in the building envelope of an AM machine when procuring a batch of the parts. The objectives of nesting problems are in general to maximize the number of pieces processed at the same time or reduce the build time and cost of a single AM machine printing process. Scheduling for AM is focusing on productivity by allocating the workloads of AM machines and sequencing this workload. (Oh Joseph, Witherell Paul, Lu Yan, Sprock Timothy 2020).

Nesting and scheduling procedures are examined separately in different planning phases in traditional production. Nesting methods used in process planning in AM, on the other hand, frequently incorporate scheduling considerations from production planning. During the nesting process, for example, emergency pieces (based on due dates) may be clustered together, influencing scheduling decisions. Nesting outcomes like the number of builds and volume of parts per build often will affect the builds and performance indicators of scheduling problems. Performance indicators are build time, material usage, and cost. (Oh Joseph et.al 2020).

# 4 Methodology

## 4.1 Workflow

The preparation and scoping for the experiment will be done with the literature review. After that, data from the experiment is researched and analysed. The results and con-slusions will validate the data and the conclusions will be used to report the data.

For the data gathering, simulating experimenting will be done using Curaslicer software and files found from the Thingiverse for products produced with FDM printers. Data from different files will be downloaded and data about the Time it takes to make the product, material needed, batching, infill, and support will be gathered to an excel and compared. This way we will see about the effect of effective nesting on the used time and the materials. The infill will also be discussed and experimented with about how much the infill percentage affects the overall time and material.

With experimentation, the research questions can be answered.

- “How can the nesting of models in Fused deposition modeling 3D printer be op-timized?”

Nesting calculations will be done in the software to see how much nesting affects the time it takes to make products. Different orientations will be looked at and calculated.

- “How can the work scheduling for Fused deposition modeling 3D printers be improved?”

The time it takes to make a product will be compared and scheduling will be experi-mented with in scheduling software. Different batches will be compared and data about how the AM production should be scheduled will be gathered.

## 4.2 Tools

Curaslicer software is used as the main tool of simulating FDM printing. It is free to use and accessible by downloading from internet to personal computer. Ultimaker S5 device will be used as a virtual machine for experimenting. Octoprint will be used as MES. Octoprint is web-based printing software. Octoprint was used for this because it is open-source and it can simulate the execution of printing with a virtual printer. Then, a production scheduling tool is used to schedule the prints which were nested in Cura Slicer. The production scheduling experiment is done with a job-based planning method.

The scheduling tool used was determined because of these factors: This tool is open-source and free to use. The functions will be enough for making the production of the scale for this experiment. The tool I found the best was Google calendar. even though there are open-source tools that are free-to-use, that has been praised in blogs and websites which compare scheduling tools, the calendar in these tools is a premium option. (Heikkinen Karri 2016).

# 5 Analysis and results

In the experiment, we want to find out about the optimization of batching and the effect on overall production time with the FDM printing. The files for these products are downloaded from the Thingiverse website, which has free files for 3D-printing products. Ultimaker Cura has a material cost calculator in the software, and for these parts, PLA material is used that costs 27,90 euros for a kilogram on an internet shop. The first product we will be looking for is an easy-to-print hanger that is completed without any moving parts and will be used for usual household usage.

## 5.1 Hanger product

Here is a picture of the hanger in Ultimaker software:

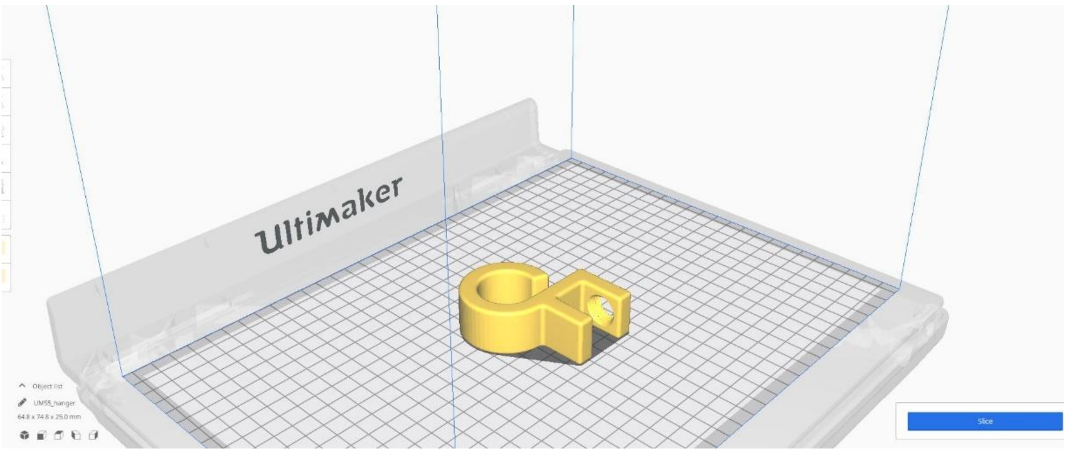


**Figure 6:** hanger in Ultimaker

This print is done with no support and with 20% infill which is the default infill in the Ultimaker software. This print is done with the default slicing option where layer height is 0,1 millimeters. This hanger will take 5 hours and 28 minutes to make on the Ulti-maker S5 and the needed material will be 26 grams of PLA material with only one product in the batch. One hanger cost 0,73 euros with this orientation. When two products are put in the printer, the difference in the material needed and the time is minimal. Up to 12 hanger products could be fit in the Ultimaker printing platform with the no support orientation. When this is done, the material needed and the time it takes to produce these products will be slightly less than what the one hanger needs and the real-time saving will come from heating up and set up. Heating time can be from five to ten minutes. (Thingiverse 2021).

Here is the excel table for the hanger times and material needed. No support means the orientation is like the first hanger picture, and the orientation with the need for support is when support is needed

| Product | Time | material need (grams) | batching | infill % | Support | cost | cost per part | layer |
|---|---|---|---|---|---|---|---|---|
| Hanger | 1:58:00 | 26 | 1 | 20 % | no | 0,73 € | 0,73 € | 0,2mm |
| hanger | 5:28:00 | 26 | 1 | 20 % | no | 0,73 € | 0,73 € | 0.1mm |
| hanger | 8:19:00 | 33 | 1 | 20 % | yes | 0,92 € | 0,92 € | 0.1mm |
| hanger | 15:16:48 | 53 | 2 | 20 % | no | 1,47 € | 0,74 € | 0.1mm |
| hanger | 16:54:00 | 66 | 2 | 20 % | yes | 1,85 € | 0,93 € | 0.1mm |
| hanger | 21:59 | 104 | 4 | 20 % | no | 2,80 € | 0,70 € | 0.1mm |
| hanger | 33:27:00 | 131 | 4 | 20 % | yes | 3,66 € | 0,92 € | 0.1mm |
| hanger | 65:17:00 | 309 | 12 | 20 % | no | 8,61 € | 0,72 € | 0.1mm |
| hanger | 99:28:00 | 393 | 12 | 20 % | yes | 10,96 € | 0,91 € | 0.1mm |

**Tableau 1:** Hanger product data.

When this Hanger model is printed in a different orientation, there is a need for support.

Here is a picture of how the hanger product is oriented on the platform:

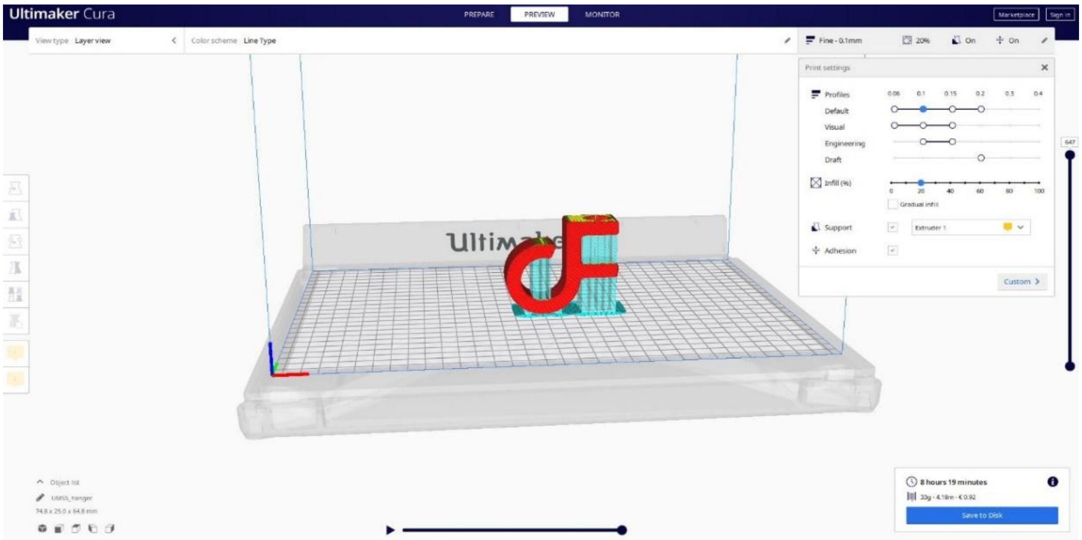


**Figure 7:** Hanger in an orientation where support is needed.

With this orientation, the hanger product takes 8 hours and 19 minutes to print. The material needed is 33 grams of PLA with 20% infill. Layer height is 0.1mm and the material costs 0,92euros.

There are different orientations for the hanger product that can be experimented with. Here is another orientation that needs support. It has the same material need of 33 grams of PLA with 20% infill and a layer height of 0.1mm as well as a cost of 0.92 euros. As can be seen from the material and time needed, there is very minimal difference in the orientation of the hanger product when support is needed. The hanger product was also experimented with the third option with support, and in that orientation, the conclusion is the same.

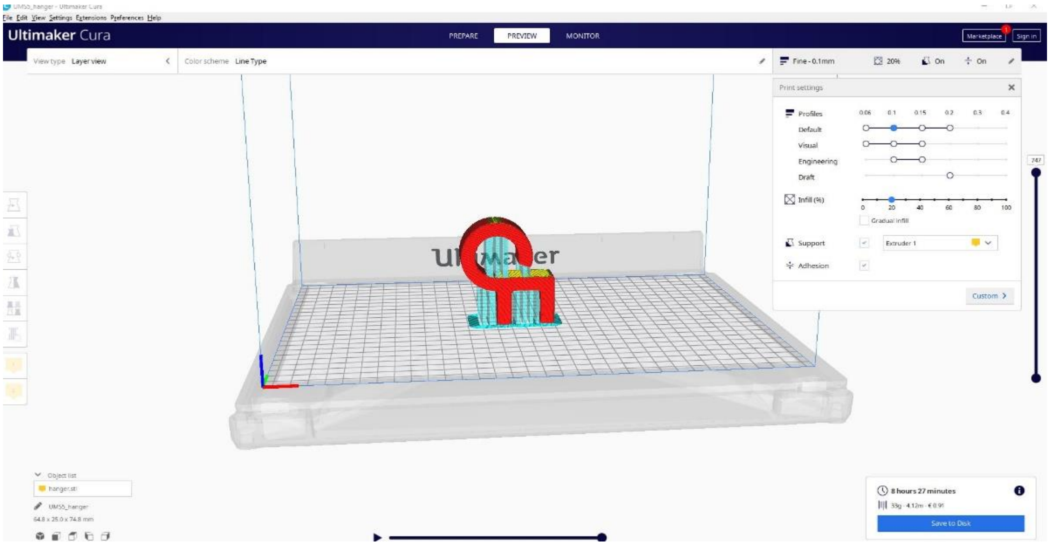


**Figure 8:** Hanger in another orientation with support.

The hanger can also be printed with a layer height of 0.2mm, and if printed like this, the hanger part will take 1 hour and 58 minutes to make, and it will use the same amount of material as the first print, which is 26grams of PLA. The quality of the product may not be as good as with the 0,1mm layer height, but this part can be printed faster. Compared to the 0,1mm layer height, the 0,2mm layer height on the hanger part will take 35% of the time it takes to print with 0,1mm.

The hanger product was printed with one layer only on the earlier prints. Next, the hanger is printed stacked on each other, with two layers and then a full stack of prints, as many as be fitted on the printing platform. In this print, the Curaslicer print arrangement option was used.

With two layers stacked on top of each other, 22 of the hanger products can be printed at the same time. The two-stack print will need five days, eight hours, and 23 minutes to complete. When printed this way, the material needed is 584grams of PLA with 20% infill and it cost 16,30 euros Here is a picture of the two layers of the model in print:

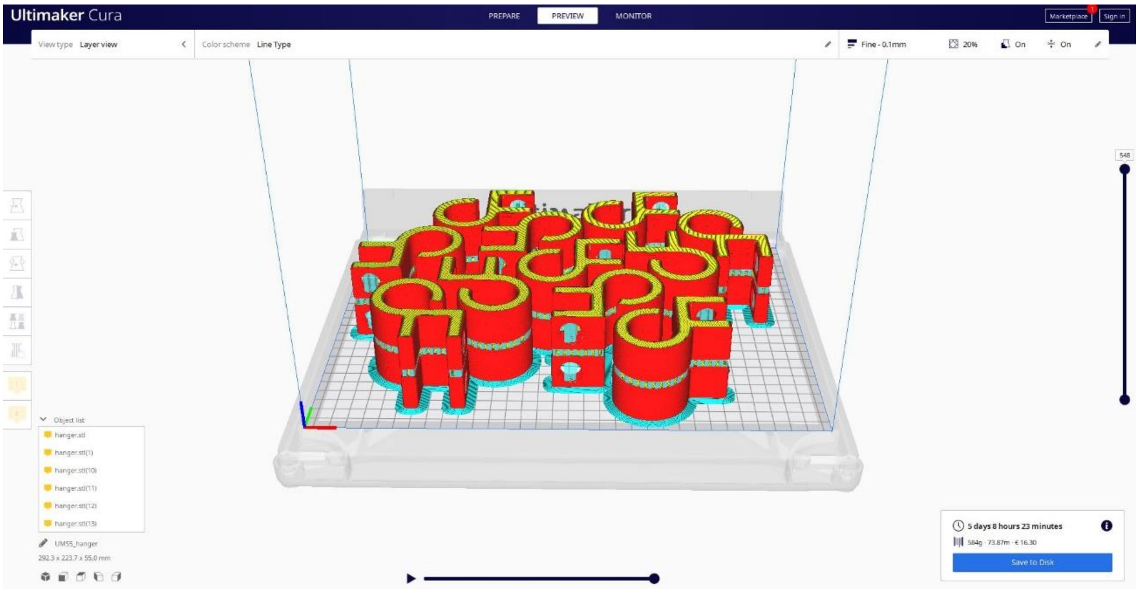


**Figure 9:** two-stack print of hanger product.

With the full stack, 110 of the hanger products can be printed at the same time and there will be ten of the hanger products stacked. There need to be support structures after every layer of the product, so in this case, the material need is more compared to only one layer of the product at a time. For the full-stack print, the slicing time was in hours, and this is a significant downside of the full-stack printing. The full stack of 110 hanger products takes 26 days, seven hours, and 48 minutes. It takes 2891grams of PLA with 20% infill and costs 80,66 euros. Full-stack printing is not a viable production method as the printer should be running for almost a month at a time and the slicing took five hours with a relatively new personal computer. If there is something wrong with the printing process, it will affect this kind of nesting more than smaller batches.

Here is the full stack print in Curaslicer:

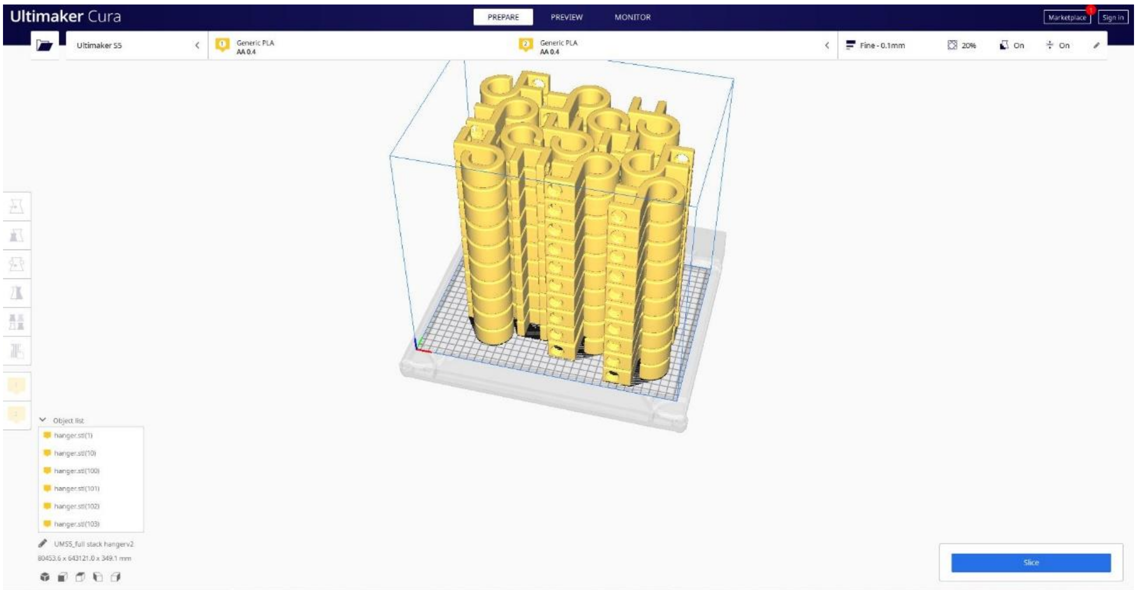


**Figure 10:** Full-stack of hanger products.

With no support orientation which is a more effective orientation for this part, the material need is 22% less compared to the orientation where support is needed. The real-time saving will come from the right orientation, setting up, and post-processing actions. In this case, the orientation of the part is more important than the batching optimization. In a real environment, the time saving will be even more with the right orientation than the approximation on the CuraSlicer, as the support needs to be removed from the part when printed with second orientation and more post-processing is needed for the places where the support structure is removed.

If the hangers can be left to be printed over the weekend, the hangers are finished after the weekend. With modern AM devices, the production can be monitored from a personal computer, and no need for physical presence is needed, but if something happens in the printing process, some checking may be needed.

## 5.2 Cable manager product

Another similar part in which we will be looking for data is part that can be used for cable management in household or office use. This part is bigger, and it can only be printed two at a time at most without support. In this orientation, the 20% infill is used with 0.1mm layer height and PLA material. Here is how the cable manager part looks:

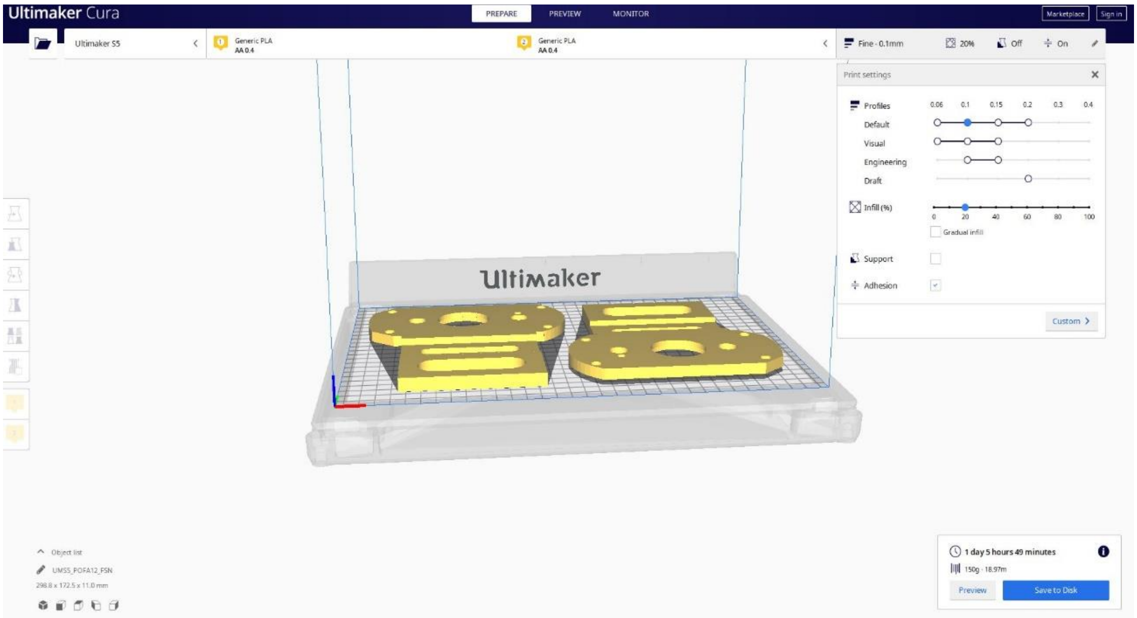


**Figure 11:** Cable management part in Ultimaker.

The cable manager part can be also set up with different orientations, where support is needed, but more of the same product can be printed at the same time.

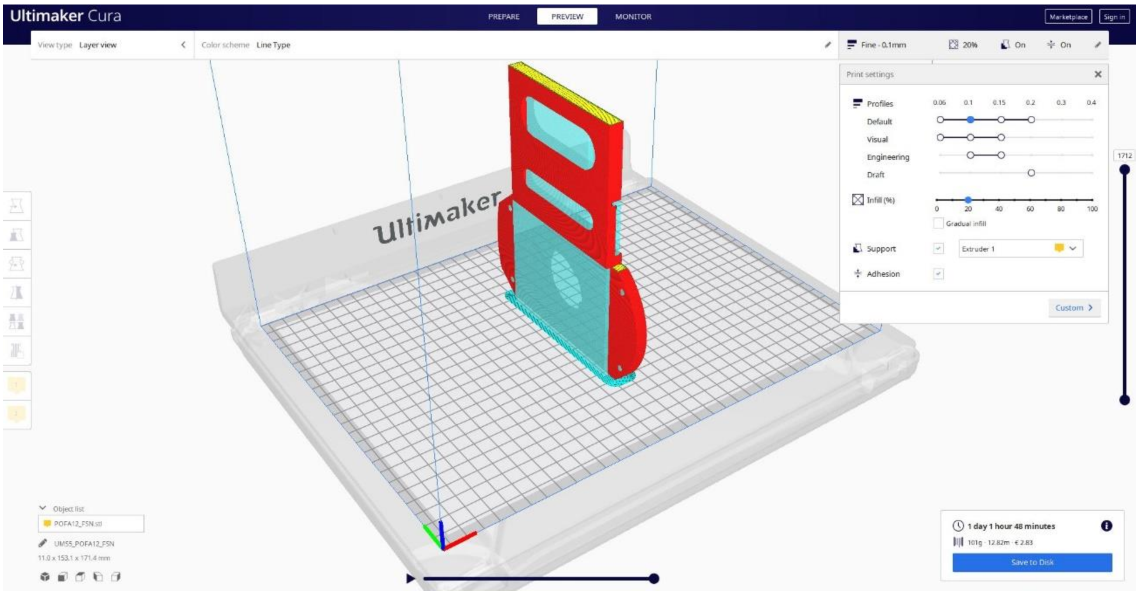


**Figure 12:** Cable management part in orientation with the need for support.

The adapter part needs 101 grams of material with this kind of orientation, which is 25% more than on the first orientation. The material is PLA, layer height 0.1mm and infill is 20%.

There is another orientation for this cable management part, that uses less material, but more space. This orientation uses 89 grams of PLA, it takes 22 hours and 25 minutes to make and it costs 2,49 euros. Layer height is the same as before, 0.1mm for the comparison between these two orientations. When printing only one product at a time, this orientation is cheaper and faster to produce than the first orientation that needed support. This orientation is orientation three in the excel table below and here is the orientation in the print preview window:

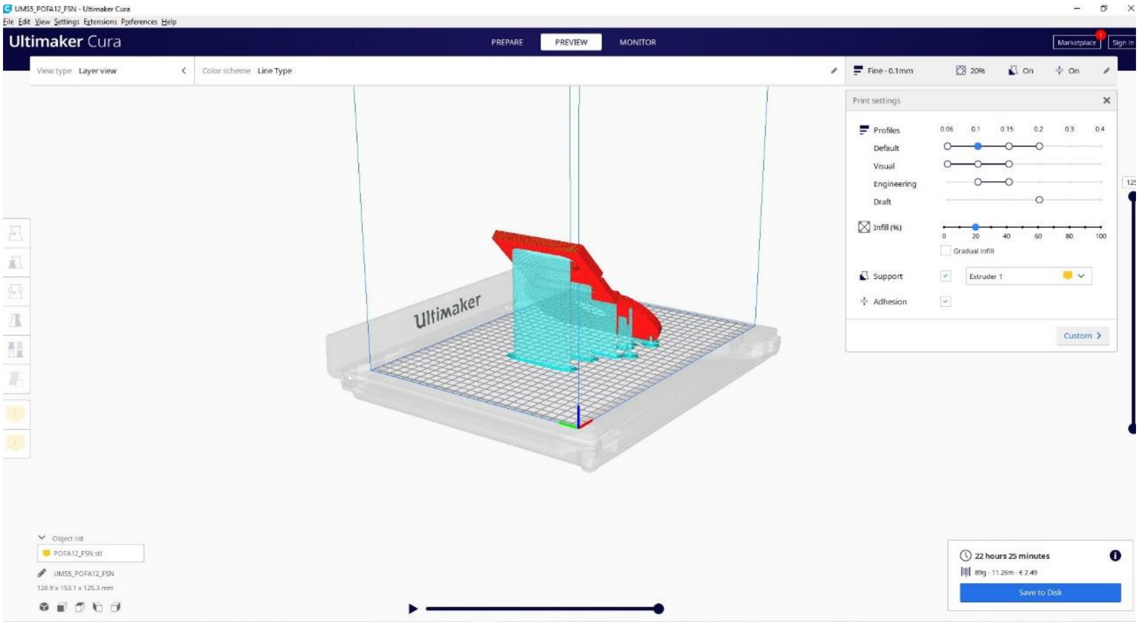


**Figure 13:** Cable management orientation three.

In the table below, we can see similar results to the hanger part, where the real-time saved is in setting up and post-processing. This shows that in these basic products that need no support and can be printed in one part, the scheduling for bigger batches is important and this will save time outside the initial printing process.

| Product | Time | material need (grams) | bat-ching | infill % | Sup por t | cost | cost per part | layer |
|---|---|---|---|---|---|---|---|---|
| cable manager | 14:52 | 75 | 1 | 20 % | no | 2,09 € | 2,09 € | 0,1mm |
| cable manager | 29:49:00 | 150 | 2 | 20 % | no | 4,19 € | 2,10 € | 0,1mm |
| cable manager | 5:27:00 | 72 | 1 | 20 % | no | 2,02 € | 2,02 € | 0,2mm |
| cable manager | 10:56:00 | 145 | 2 | 20 % | no | 4,03 € | 2,02 € | 0,2mm |
| cable manager orientation 2 | 25:48:00 | 101 | 1 | 20 % | yes | 2,83 € | 2,83 € | 0,1mm |
| cable manager | 52:01:00 | 202 | 2 | 20 % | yes | 5,64 € | 2,82 € | 0,1mm |
| cable manager | 78:18:00 | 304 | 3 | 20 % | yes | 8,47 € | 2,82 € | 0,1mm |
| cable manager | 104:12:00 | 404 | 4 | 20 % | yes | 11,26 € | 2,82 € | 0,1mm |
| cable manager | 7:26:00 | 100 | 1 | 20 % | yes | 2,79 € | 2,79 € | 0,2mm |
| cable manager orientation 3 | 22:25:00 | 89 | 1 | 20 % | yes | 2,49 € | 2,49 € | 0,1mm |

**Tableau 2:** Cable manager data.

In the table, there is a different orientation and different layer height. The layer height comparison states the same conclusion as in the hanger part, that the faster 0,2mm layer height takes only 35% of the time compared to 0,1mm layer height. In this part, the heating and cooling down and setup time will not make big difference, as this part does not fit on the printing platform as many times as the hanger part.

The time saved on the heating and cooling part can be approximated to 20 to 30minutes when comparing four-part batching to one-part batching. The heating and cooling down approximation are taken from a forum post from Printer users. (Ultimak-er Community 2014).

## 5.3 Headset stand product

For the next part, we will look at the headset stand product. There are two different versions of this product and in the second version, there are things that are more efficient for AM production. The first version is manufactured from two different sections, the lower part, and the upper part. Here is the picture from the sliced product with the supports showing with turquoise color. Here the headset stand is printed with both parts of the product in one print so that the stand can be put together after the print and there is no need for waiting for assembly. The infill is 20% material is PLA and layer height of 0.1mm.
(Thingiverse 2 2021).

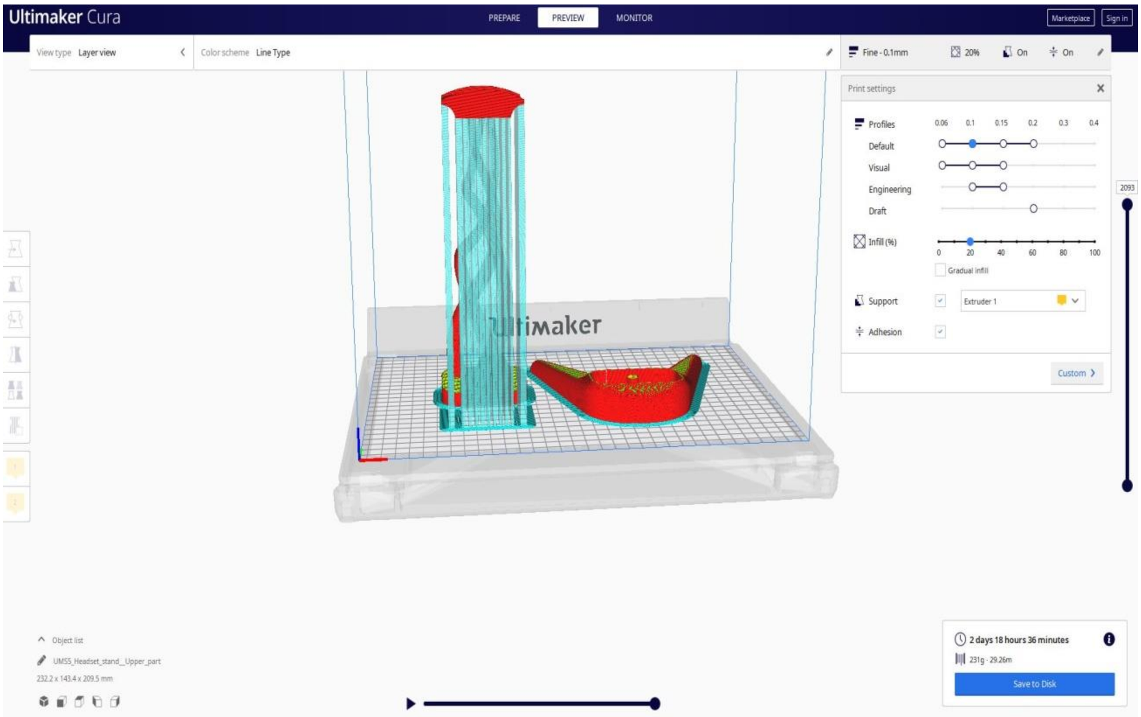


**Figure 14:** Stand version 1.

In the first version, there needs to be a screw which the stand will be put together after the printing. In the table below there are also batches with only the stand part and the lower part printed separately. The infill for this part is 20% infill and 0.1 mm PLA.

Here is the second version which is more efficient for AM production, and the support needed is minimized with the design of the upper part of the product which is V-shaped, and the support is not needed as much as the printing can be done on top of the structure.

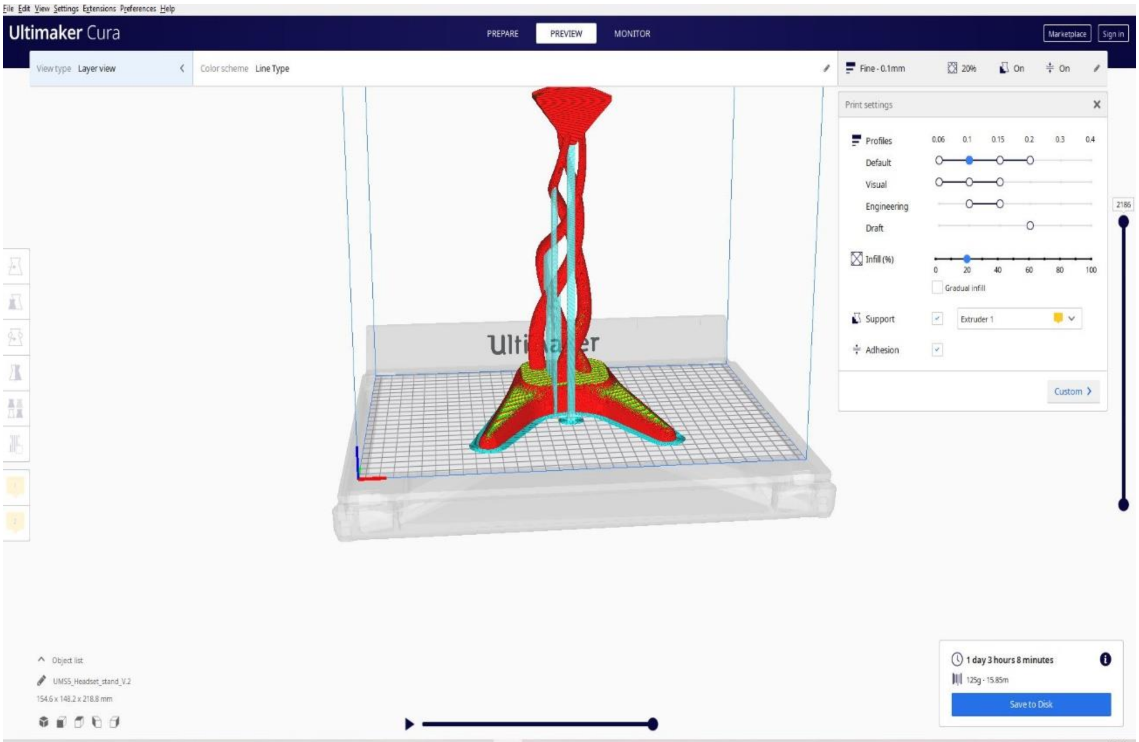


**Figure 15:** Stand version 2 efficient orientation.

This version of the stand will be produced in one part, and this will be better than the first version as there is no need for screws and this can save time from post-processing actions. The biggest thing which affects the material and time needed though is the design of the upper part and the need for no support. This will minimize the material needed from the support and will make the printing process take less time. The infill for this part is 20% infill and the material is PLA, with a layer height of 0.1 mm.

Here is the table for different versions, orientation, and batching of the headset product:

| Product | Time | material need (grams) | batching | in-fill % | Support | cost | cost per part | layer |
|---|---|---|---|---|---|---|---|---|
| Headset stand part 1 | 54:47:00 | 172 | 1 | 20 % | yes | 4,79 € | 4,79 € | 0,1 mm |
| Headset stand part 1 | 109:56:00 | 343 | 2 | 20 % | yes | 9,52 € | 4,76 € | 0,1 mm |
| Headset stand part 1 | 162:54:00 | 514 | 3 | 20 % | yes | 14,23 € | 4,74 € | 0,1 mm |
| headset stand part 2 | 11:58:00 | 61 | 1 | 20 % | no | 1,70 € | 1,70 € | 0,1 mm |
| headset stand part 2 | 24:07:00 | 123 | 2 | 20 % | no | 3,41 € | 1,71 € | 0,1 mm |
| headset stand v1 whole | 66:55:00 | 233 | 1 | 20 % | yes | 6,50 € | 6,50 € | 0,1 mm |
| headset stand v2 whole | 27:22:00 | 126 | 1 | 20 % | yes | 3,50 € | 3,50 € | 0,1 mm |
| headset stand v2 whole | 67:23:00 | 281 | 2 | 20 % | yes | 7,80 € | 3,90 € | 0,1 mm |
| headset stand v2 orientation 2 | 38:28:00 | 153 | 1 | 20 % | yes | 4,24 € | 4,24 € | 0,1 mm |
| Headset stand v2 orientation 3 | 51:17:00 | 186 | 1 | 20 % | yes | 5,18 € | 5,18 € | 0,1 mm |

**Tableau 3:** Headset product data.

Here we can see that the headset stand version two is cheaper and it takes less time to make than headset stand version one with two different parts. Even though there is orientation two which is different and can be done with version one and version two, which requires less support, version two still is more efficient to produce.

Orientation two looks like this and it uses an infill of 20% and the material is PLA and layer height is 0.1 mm:

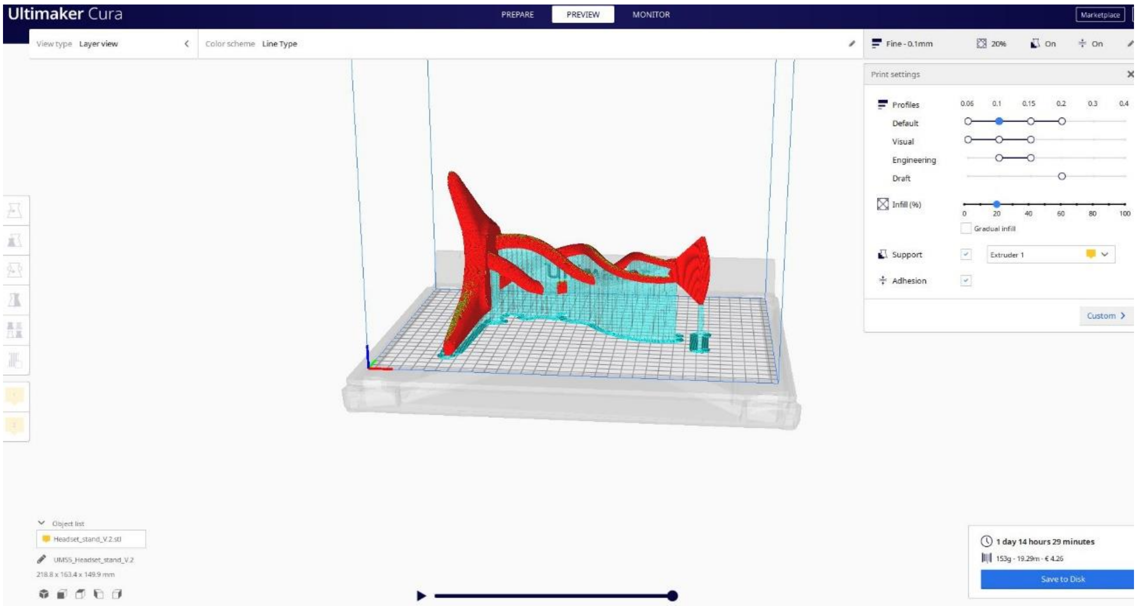


**Figure 16:** Different orientation for headset stand.

There is another orientation of headset v2 that is using a lot more material and time. This goes to show that orientation is important and this can save material and time costs. It is orientation three in the excel table above and this is how it looks like in the print preview:

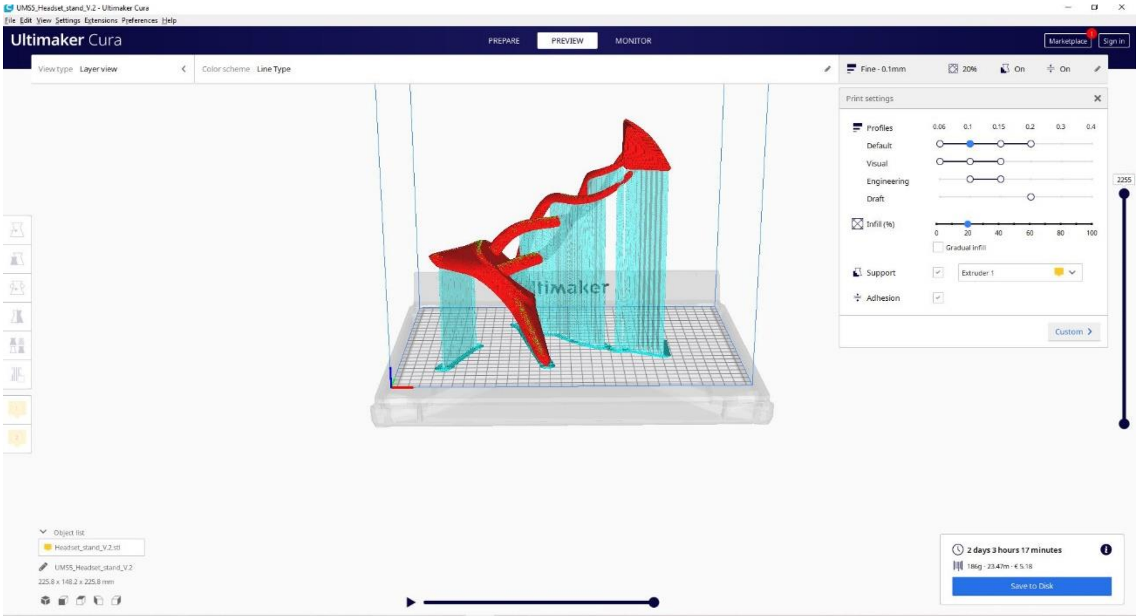


**Figure 2:** Orientation three of headset v2.

## 5.4 Octoprint

Octoprint was used after the slicing calculations to simulate the prints for each piece of product. The g-code from CuraSlicer was imported to Octoprint for printing. The importing was easy. The printing can be monitored in the octoprint. Octoprint shows the temperature of the printing bed and the printing process can be seen and controlled in real-time. The products were simulated with Octoprint and for the hanger product, the printing time in Octoprint matched the CuraSlicer printing time. Here is a picture of the hanger product in Octoprint.

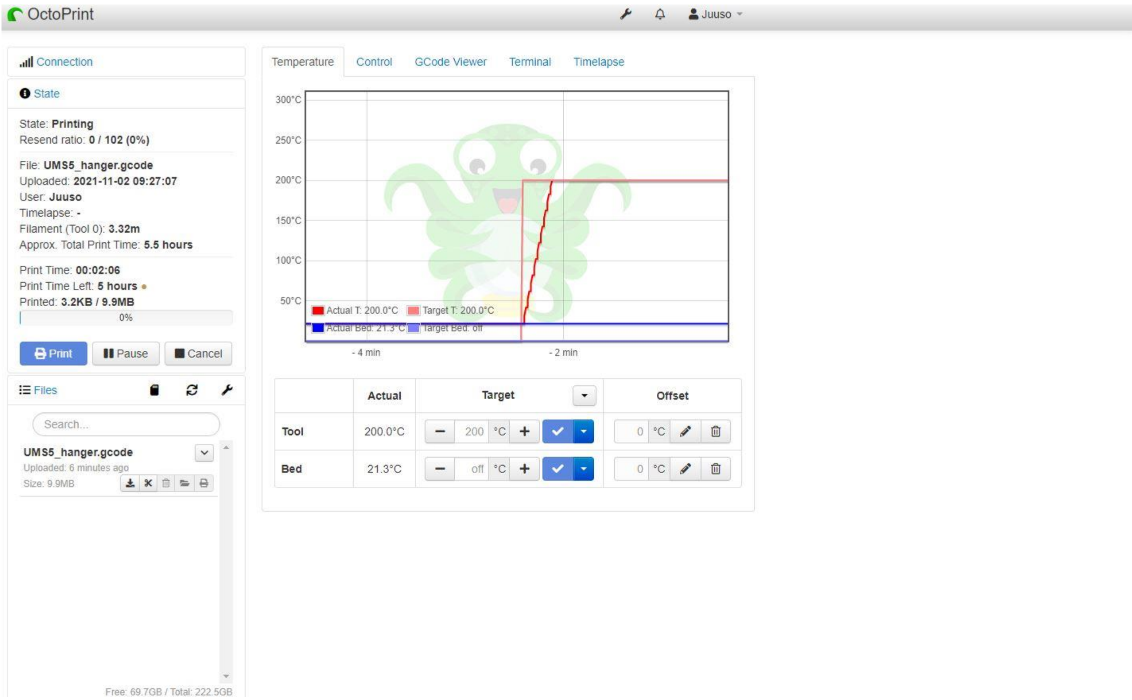


**Figure 18:** Hanger product in OctoPrint menu.

## 5.5 Production scheduling

In this section, the production of these models is experimented and they are scheduled in google calendar to find out what is the most important aspect of efficient scheduling.

The first experiment will be a simple schedule with four hanger products, a headset stand, and two cable manager products. These products need to be ready for the end of a week and there is one printer in use. It is assumed that the printer is working properly no interruptions will come, and the printer is printing overnight. The worker is working the 8-hour shift from 08:00 to 16:00.

Headset stand product takes 27 hours to print, hangers will take 22 hours and the cable manager takes 29 hours 49 minutes. The time taken is shown in below excel table. The nesting for these products was chosen according to the data gathered from CuraSlicer. This production schedule simulates the on-demand planning style.

| Product | nesting | time needed | post-processing | material need |
|---|---|---|---|---|
| Hanger | 4 | 22 | 30minutes | 104g |
| Cable manager | 2 | 29:49:00 | 30minutes | 150g |
| headset stand | 1 | 27:22:00 | 30minutes | 126g |

**Tableau 4:** Experiment one data.

The scheduling is started with a print of the hanger products to start post-processing actions on the second day when the hangers have been printed. After that, the headset is printed and the post-processing for the headset product is started. Lastly, the cable managers are printed.

In this scenario, the printer needs to be on all the time to be able to print these products on time. In this simple case, there is not much room for improvement, as the time it takes to make these products with one printer will be the same in every order of production. The most important scheduling factor here is that the two headset prints are done after the other so no additional set-up time is taken on the prints and the change-over is minimized. Also, there could be one more print to be fit for Friday as the products take four days to print. Here is the first calendar schedule:

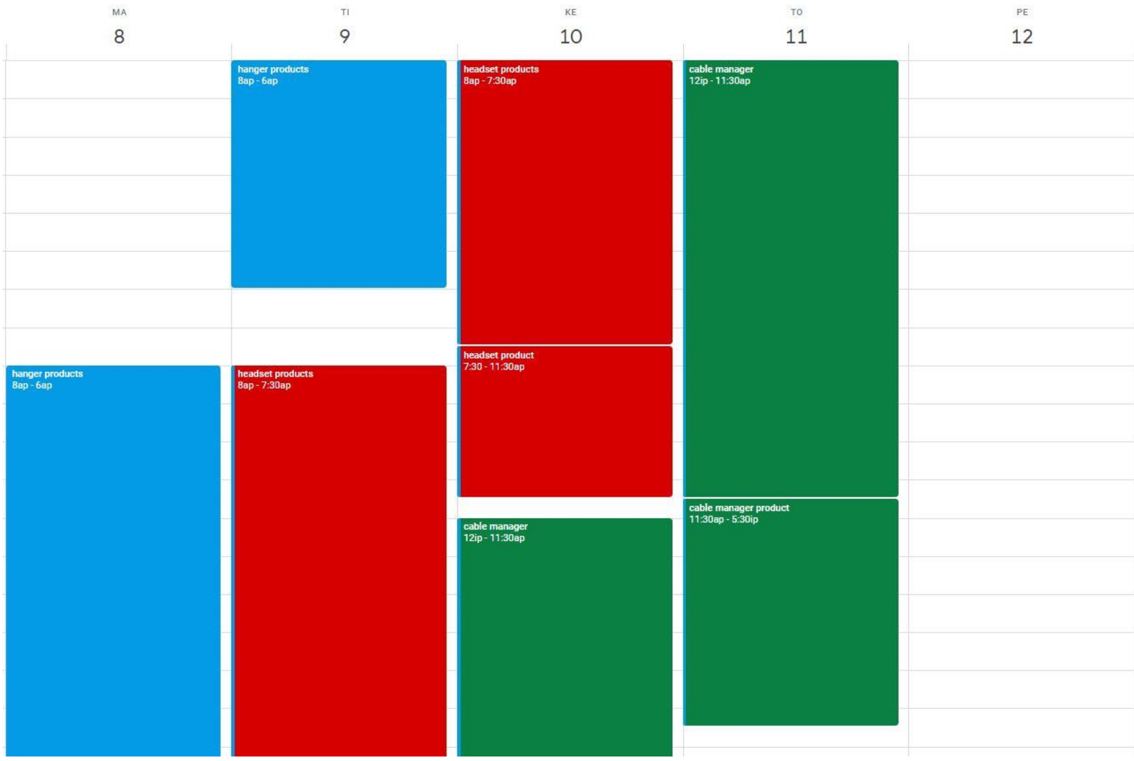


**Figure 3:** Schedule for the first experiment.

The next experiment we will be doing is with two machines and a longer production cycle. This experiment will be done by scheduling a longer production cycle and it is simulating batch method planning where a set number of products will be manufactured in batches.

If the batch is the same as above, four hangers, two cable managers, and one headset stand, the batch should be the same as above, but with two printers. This is because the most efficient nesting for these products and this batch is above-mentioned.

When a batch is bigger and in this case 12 hanger products, four cable managers, and two headset stands are printed, the scheduling changes. Here we have two printers simultaneously printing. Below is the product nesting table. The hanger products can be done in one print, and another printer, in this case, can print the hanger products when another printer will print other products.

| Product | nesting | time needed | post-processing | material need |
|---|---|---|---|---|
| Hanger | 12 | 65:17:00 | 30minutes | 309g |
| Cable manager | 2 | 29:49:00 | 30minutes | 150g |
| headset stand | 1 | 27:22:00 | 30minutes | 126g |

**Tableau 5:** Experiment two data.

The printer printing hanger product will print for three days to be able to finish 12 hangers at a time. after that, the headset can be printed with this printer. Another printer is started by printing two batches of cable managers, which takes three days to complete. After that, two headsets can be printed simultaneously with two printers, and this batch is printed. As in the first schedule, the post-processing is started and the other products are finished as the other products will begin printing. Here is an illustration of printer one printing. Blue color represents the Hanger product, red color is for the headset product and green is for the Cable manager. The printing is started at 8:00 and the print goes on overnight as the prints take more than 24 hours to complete at a time. Below are the schedules of both printers:


**Figure 20:** Printer one schedule.

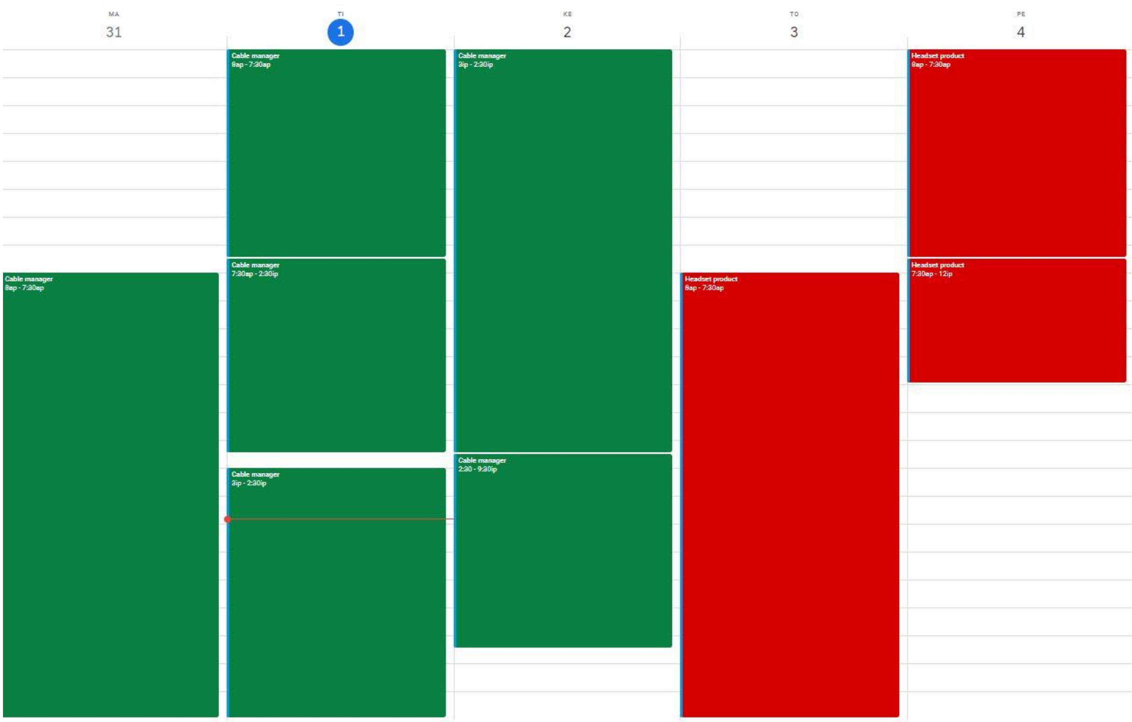


**Figure 21:** Printer two schedule.

# 6 Conclusions

## 6.1 Results

The conclusion according to the experimental study is that the part orientation is the most important aspect of efficient printing with an FDM machine. When a part is oriented correctly with the need for minimal support, there are considerable savings in the material and therefore the money it takes to produce products. When support is needed the orientation of the product had a significant change in the material need on the best orientations with one single product printed. This is easier to do with more simple products like the first product we looked at, which is the hanger product. On the simple hanger product, 22% less material was needed with the right orientation. On the hanger product, when heating up and cooling down is considered, it could take five to ten minutes per print according to forum posts from printer users on different FDM printers. (Ultimaker Community 2014).

When there are more parts to one product and no need to make so much of the same product, the batching scheduling will be different. In this case, the scheduling should be done in a way that the product can be printed as quickly as possible and if there is more than one part to the product, the product's parts should be printed at the same time so the product can be finished.

## 6.2 Research question answers

"How can the nesting of models in fused deposition modeling 3D printer be optimized?"

Based on the study, the nesting of models should be optimized in a way whereas the support should be minimized. The time for set-up and heating up and cooling down will be less when more parts are printed at the same time. This can be done in the software and there is an option for Curaslicer where it automates the orientation most effectively. When orienting most effectively, 22% of savings can be seen for the material.

For example, 12 hanger products could be printed at the same time, and compared to only printing one hanger, the warming up and cooling down saves over 60 minutes. Also, the traveling between different models in the printing area will be minimal, and this saves time as the nozzle does not need to travel without printing.

Depending on the size of the product and how many of the products can be nested in one print, the nesting should be done with one layer of prints. This will minimize the support and material need. Full-stack nesting is not a viable nesting option, as the time it takes to print a full-stack of the product like the hanger product takes close to a month, so the chance for something to go wrong in the printing process is more than when printing only 12 hanger products in a single layer. Also, support is needed in between the layers, so the material need and post-processing need are also more.

"How can the work scheduling for fused deposition modeling 3D printers be improved?"

Work schedules should be done in a way where simple products are printed in bigger batches. Also, products with more than one part should be printed subsequently or in the same batches, so that the post-processing and the finishing of those products can be done most efficiently, and the products can be sent to the customer as soon as possible. When bigger batches are done and many printers are used, the bigger batches effect is showing up in the time needed for overall printing. Bigger batches and nesting more at the same time is better here. Even though the printing process is more efficient when nesting more products in to one print, the time it takes to print may potentially lead to more problems in the print for example the machine stopping or filament failure and nozzle clogging. (Zhenseng Yang, Li Jin, Youruiling Yan, Uiming Mei 2018).

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# Appendix

## Appendix 1: Production schedule

Production
schedule.xlsx