Expertise
and insight
for the future

htw saar

Sophia Lentz

Development of a method to analyse the 3D printing potential of operating materials in the medium engine assembly

Metropolia University of Applied Sciences &

htw saar University of Applied Sciences

Double Degree Programme

Bachelor of Engineering

Industrial Management

Bachelor's Thesis

Supervisors: Prof. Dr. Udo Venitz; Antonia Meiritz, M. Sc.

18 May 2020

Abstract

More and more companies and industries use additive manufacturing to test and produce parts. However, not all parts are suited to be manufactured additively. In combination with the growing application scope, suitable parts have to be identified quickly and without much effort. The goal of this thesis is to develop a method that allows companies to make quick and justified decisions regarding the suitability of operating materials for additive manufacturing. Additionally, a priority number is calculated. This allows the ranking of the proposals and therefore a prioritisation of the implementation. The decision about the suitability for additive manufacturing is based on exclusion criteria that regard the manufacturability and technical restrictions of additive manufacturing. Further, some priority criteria are defined that are quantified and result in the priority number. The decision is made mainly automatically, with just a few aspects that have to assessed manually by an additive manufacturing expert.

The development of the method is based on a literature research of already existing methods as well as the processes at Rolls-Royce Power Systems (RRPS). The requirements of RRPS and the specific application scope of operating materials result in a method that is customised to the usage at RRPS. It does however present a good groundwork for an adaption to other application cases besides operating materials. The overall structure can stay unchanged and the criteria and data adapted to the needs of another usage.

Keywords: Additive Manufacturing, 3D printing, Part identification for 3D printing, Prioritisation

.

I Table of content

II List of figures

III List of tables

IV List of abbreviations

3D	3-Dimensional
8D	8 Disciplines
AHP	Analytic Hierarchy Process
AM	Additive Manufacturing
BJ	Binder Jetting
CAD	Computer Aided Design
FDM	Fused Deposition Modelling
FMEA	Failure Mode and Effects Analysis
GB	Glass Beads
HR	High Reusability
MJF	Multi Jet Fusion
MS	Microsoft
PJ	Photopolymer Jetting
RPN	Risk Priority Number
RRPS	Rolls-Royce Power Systems AG
SLA	Stereolithography
SLS	Selective Laser Sintering
STL	Stereolithography, here: Standard Triangle Language
VBA	Visual Basic for Applications

V List of symbols

Symbol	Meaning	Unit
F_{tu}	Tensile Strength	$\frac{N}{mm^2}$
g	weight force	$\frac{m}{s^2}$
i	line index of a matrix	-
k	column index of a matrix	-
MPa	Mega pascal	$\frac{N}{mm^2}$
N	Newton	$\frac{kg \times m}{s^2}$
n	number of rows in a matrix	-

1 Introduction

Additive manufacturing, also called 3-Dimensional (3D) printing, is a technology that was not used in an industrial context for quite some time. Just in the past 10 years, the potential it offers for production and development was realised and explored. The sales of polymer material were constantly growing in recent years (cf. Wohlers 2019). There are great opportunities in the findings made since the development in 1983 and the application scope broadens constantly. Medicine or the aerospace industry are just examples (cf. Gebhardt, Kessler and Thurn 2019, p. 107,121). In 2018, almost half of the companies in the engineering industry have used 3D printed parts and components (Gebhardt 2018). The main materials used are polymers as well as metal. Throughout the companies, the application scopes vary. The majority uses 3D printing for prototyping, while the others concentrate on spare parts, tools, or batch production (cf. Gebhardt 2018). Whether batch production makes sense for a company depends highly on the product and the number needed. While additive manufacturing is economic for small production numbers, conventional technologies are often more cost efficient when a larger number needs to be produced (cf. Paulsen 2019). At the same time, the introduction of 3D printing as new technology requires some strategic changes in a company (cf. Mellor, Hao and Zhang 2014, p. 196). To start implementing 3D printing in the prototyping allows gaining experience through vivid and functioning objects before actually introducing a larger scale production. The Rolls-Royce Power Systems AG (RRPS) has also purchased a 3D printer, used by different departments throughout the company.

RRPS, with its core brand MTU, is part of the Rolls-Royce plc. Their products range from diesel and gas engines to generator sets and complete propulsion systems. The engine solutions are used e.g. for yachts, construction and industrial vehicles, rail and military vehicles or the gas and oil industry (cf. Rolls-Royce Power Systems AG 2020).

While the engines produced by RRPS are large engines in the overall view, they are differentiated internally. The series 2000 and 4000 are considered as medium engines, whereas series 8000 engines are viewed as large. In 2019, 6580 engines were delivered by RRPS, a large share produced in Friedrichshafen, Germany (cf. Rolls-Royce Holdings plc 2020). According to the Made-in-Country-Index, products manufactured in Germany are associated with a high quality and high security standards all over the world (cf. Hamke, Striapunina and Staffa 2017). In combination with the fact that RRPS engines are often used for yachts or similar, the expectations of the customers regarding the quality are high. Ideally, during the assembly no errors at all happen. However, as that is hard to achieve, errors are being prevented as well as possible. Operating materials are one possibility to avoid errors from happening. They are one of the main application cases of the internal 3D printer at RRPS.

1.1 Motivation

An internal additive manufacturing of operating materials has many potentials for RRPS and offers new possibilities regarding the characteristics of parts. Some of the most often named potentials are reduction of weight, integration of functions and realisation of more complex geometries (cf. Leutenecker-Twelsiek 2019, p.83). At RRPS, the 3D printer is also a possibility to reduce the procurement time, as no external company has to be engaged. While additive manufacturing offers great chances, at the same time not all parts are suited to be 3D printed. The manufacturability depends highly on the material used and the characteristics of the part in question. The decision about the manufacturability is now made by an additive manufacturing expert (AM expert). It does however not follow a defined process and is not reproducible. A file that is accessible, displays the decision process and informs about following steps offers transparency about the process. This also reduces the complexity of the decision process. Lastly, the capacity of the printer is restricted. The main reason for this restriction is the limited space of the build unit. As several different departments use the printer, conflicts about the priority of parts can arise.

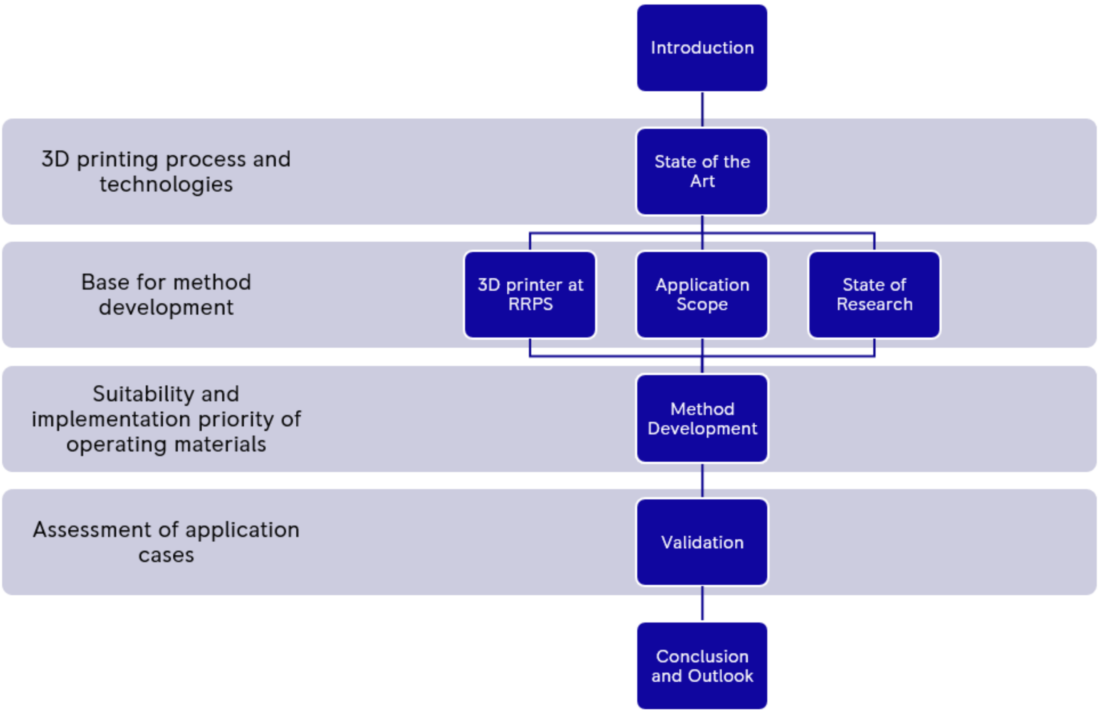
Out of the suitability of parts for 3D printing and the restricted capacity results the need for a solution that can determine the suitability of operating materials for additive manufacturing and at the same time objectively judge the urgency of the case.

1.2 Focus and goal

The aim is to develop a method that enables the employees to make quick and justified decisions about the implementation of operating materials using 3D printing. Most decisions should be made automatically, reducing the effort of the employees to a minimum. While some parts are going to be excluded, the ones that are suited for 3D printing are rated with a priority number and are ranked accordingly. This thesis is done in collaboration with the process optimisation team, who solve quality issues in the assembly. Therefore, the topic is restricted to the scope of operating materials. For other application scopes different information would have to be collected. The result of this thesis is customised to operating materials and the usage by the process optimisation team at RRPS.

1.3 Workflow

Figure 1 Workflow



Source: own work

The thesis is structured into five main chapters. After the introduction, the state of the art is presented. This includes the relevant theoretical information regarding additive manufacturing. The general process of 3D printing is explained and several additive manufacturing technologies are compared to each other. Once the reader has a good overview of the technology, the 3D printer that is used at RRPS is introduced. Its properties and application scopes are explained and the scope regarding operating materials presented in more detail. These information are based on facts provided by the manufacturer of the printer and internal knowledge.

Once all necessary background is given, in the third chapter existing methods to identify parts for additive manufacturing are illustrated. Different approaches are presented and reviewed. The findings form the basis for the development of the method for RRPS. This method, that analyses the 3D printing potential of operating materials, is a key part of this thesis. While some aspects of the development are based on the existing methods, others are adapted to the specific needs of RRPS and base on internal processes.

After the development, in chapter five, the developed method is validated by entering and assessing several application cases. A total of six cases are rated by the method, regarding the suitability for additive manufacturing and the urgency. The results are then compared to the manual assessment of an AM expert. Additionally, the applicability for the employees is tested.

Lastly, a conclusion of the results and an outlook about additional possibilities that can be included in future are given.

2 State of the Art

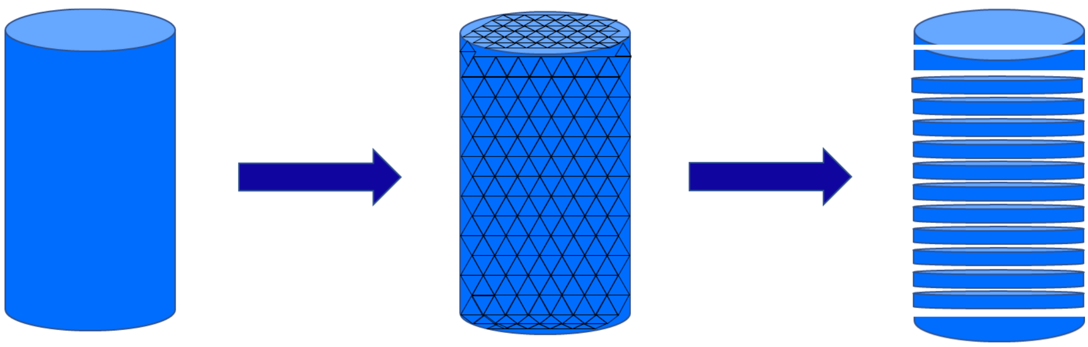
2.1 General information about 3D printing

In the production, three different manufacturing processes can be distinguished. They are stated by Gebhardt (2016) and Bühler, Schlaich and Sinner (2019) as (1) subtractive manufacturing, (2) formative manufacturing and (3) additive manufacturing. In (1), the material volume is reduced, like drilling, slicing, or milling. (2) refers to processes like forging or deep drawing, where the material volume stays the same during the process. Lastly, (3) includes processes where the volume increases through the adding of material, e.g. welding and soldering. As in 3D printing, layers are added on top of each other to build the final part, it is also allocated to additive production processes (cf. Gebhardt 2016, p. 1-2; Bühler, Schlaich and Sinner 2019, p. 58). Additive manufacturing is a standardised term referring to 3D printing and the two expressions are used as synonyms in this paper.

The first 3D printing process was invented in 1983 by Charles Hull, who is generally viewed as founder of additive manufacturing (cf. Bodden 2018, p. 10). Since this invention, the technology has developed a great deal and is now used in different industries like medical and aerospace, but also consumer goods (cf. Stratasys Ltd. 2020b).

Even though there are several technologies in 3D printing which are explained in chapter 2.2, the overall process is the same for all of them. Gibson, Rosen and Stucker (2015) and Irsa and Besendorfer (2019) provide a good overview of the steps. First, an object in a CAD (Computer Aided Design) software is designed. This CAD file is then converted to an STL file, which displays the object with triangles. The size of those triangles defines the precision of the object. As round objects are also divided into triangles, they should be very small to resemble the shape in the best way possible. However, the smaller those triangles are the more of them are needed and the bigger the file gets. This results in a high processing power needed. In a third step, the object is sliced into thin layers, using the triangles as orientation. In the later printing process, the layers are based on those virtual slices, which include information like the area where the part is to be build. Steps one to three are visualised in figure 2. Once the slices are determined, the information is sent to the printer. The printing process is automated and the next step is the post processing treatment. This depends on the technology that is used for printing and can include the removal of support structures, treatments to reach mechanical properties or simply cleaning the part from left over material (cf. Gibson Rosen and Stucker 2015, p. 4-6; Irsa and Besendorfer 2019, p. 118).

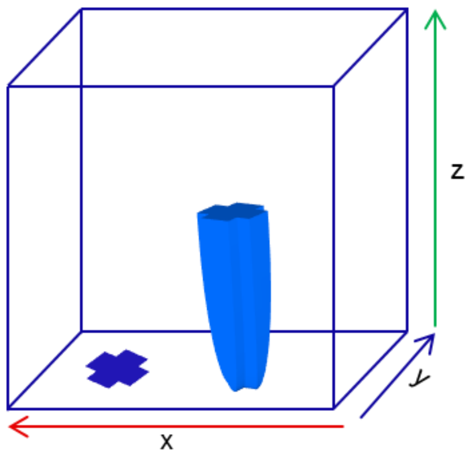
Figure 2 Pre-Processing files



Source: own work based on Campbell et al. 2011, p. 3

In additive manufacturing, instead of just the x-axis and the y-axis, which define the dimensions of e.g. a sheet of paper and are used in a traditional office printer, a z-axis is added. This resembles the third dimension, which is reached through stacking layers on top of each other. The difference is shown in figure 3, where the 2-dimensional object is displayed on the left and the same object on the right with the added third dimension.

Figure 3 Build unit with a 2D and 3D object



Source: own work

The box in which the objects are shown represents the build unit of the printer, in which the 3D parts are printed. This space is limited, depending on the size of the printer and as a result, the dimensions of parts that can be printed as one are restricted. For larger parts, it is necessary to split them into several parts and assemble them once the printing process is done.

Three main application areas are defined for 3D printing. They are explained by Gebhardt, Kessler and Thurn (2019). (1) Rapid prototyping refers to the fast manufacturing of test parts and prototypes. Rapid prototyping can be split in two areas: solid imaging and functional prototyping. The latter is used to identify lacks in function, the first to judge the design and proportions (cf. Gebhardt, Kessler and Thurn 2019, p. 7-12). In the beginning of additive manufacturing, 3D Printing was generally known as rapid prototyping, however, since the scope of application has widened, the two terms cannot be used as synonyms anymore (cf. Irsa and Besendorfer 2019, p. 120). In (2) Rapid tooling, tools or tool inserts are produced. They have the same properties as traditionally manufactured tools. Generally, only parts of the tools are produced, which are assembled later (cf. Gebhardt, Kessler and Thurn 2019, p. 14). Lastly, (3) rapid manufacturing refers to the production of a final product. Gebhardt, Kessler and Thurn (2019) define final product as follows*:* "A part generated by *additive manufacturing (AM)* will be designated as (final) product if it shows all properties and functions which have been determined during the development process of the product." (Gebhardt, Kessler and Thurn 2019, p. 11). The application at RRPS cannot be determined easily. Even though a final part is produced, operating materials are not part of the product that is manufactured and sold by RRPS. On the other hand, they show all required characteristics after the printing process. Due to the latter fact, the author classifies the use at RRPS as rapid manufacturing, though other opinions are just as reasonable.

2.2 Additive manufacturing technologies

Several 3D printing technologies have been developed over the years, using different materials and having various ways of stacking the layers on top of each other to build the 3D object. Some processes are powder based, whereas others are using liquids or wire-like structures. The most common materials used are metals, ceramics, polymers, sand and wax, as can be seen in table 1.

Table 1 Technology overview

Technology	Metal	Sand	Ceramic	Polymers	Wax
Fused Deposition Modeling				x	
Multi Jet Modelling				x	x
Stereolithography				x	
Selective Laser Sintering	x	x	x	x	

	Metal	Sand	Ceramic	Polymers	Wax
Binder Jetting	x		x	x	
Selective Laser Melting	x				
Electronic Beam Melting	x				

Sources: Fastermann 2012, p. 117-124; Feldmann and Pumpe 2016, p. 6; Gebhardt, Kessler and Thurn 2019, p. 36 – 55; Zeyn 2017, p. 37 – 38

Besides the technologies shown, there are far more, which however use similar processes and are therefore not regarded here.

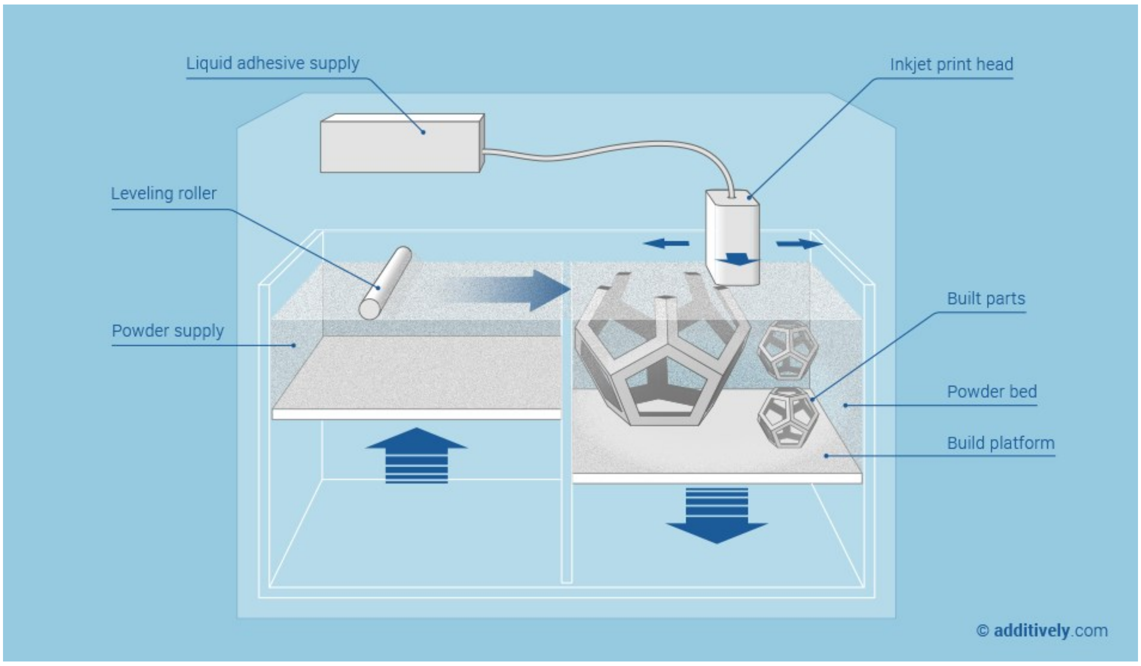
Additive manufacturing technologies can reach different levels of accuracy, differ from each other in the need of time for one layer and vary in the layer thickness that can be achieved. In the following chapters, the main technologies using polymers as a material and their distinctions will be shown. The author is aware of the fact that there are more processes using other materials. Regardless of that, since RRPS is owning a printer which is using polymers, those other processes are not further regarded in this work.

2.2.1 Binder Jetting

Binder Jetting (BJ) was in the beginning also called 3D-Printing (cf. Gibson, Rosen and Stucker 2015, p. 205). As that is commonly used to describe the general topic of additive manufacturing, BJ is going to be used in this paper, to avoid misunderstandings.

The concept of BJ is inspired by the traditional way of two-dimensional printing and is basically just adding a third axis to the process. As can be seen in figure 4, binder jetting printers consist of three main parts. The first component is the powder supply, where the powder that is used is stored. This powder is applied to the build platform by a levelling roller and the binding material is added to the defined spots on the powder by the inkjet print head (part 2). The powder layer is very thin, commonly around 100µm (cf. Gibson, Rosen and Stucker 2015, p. 213). However, there are of course also thinner or thicker layers, depending on the material and the diameter of the powder and values are ranging between 50µm and 280µm. (cf. Gibson, Rosen and Stucker 2015, p. 213). The smaller the layer thickness, the better the quality of the printed part, as the single layers cannot be seen and the surface quality is enhanced. After the layer is heated up and fused together, the build platform (part three) moves down exactly the depth of one layer and the next layer of powder is applied. This process is repeated until all objects are fused together and all layers are applied (cf. Gibson, Rosen and Stucker 2015, p. 205-206). Once the building process is finished, the objects are taken out and the post processing starts, consisting of cooling down and removing any powder that has not been used (cf. Gebhardt, Kessler and Thurn 2019, p. 55).

Figure 4 Binder Jetting Process

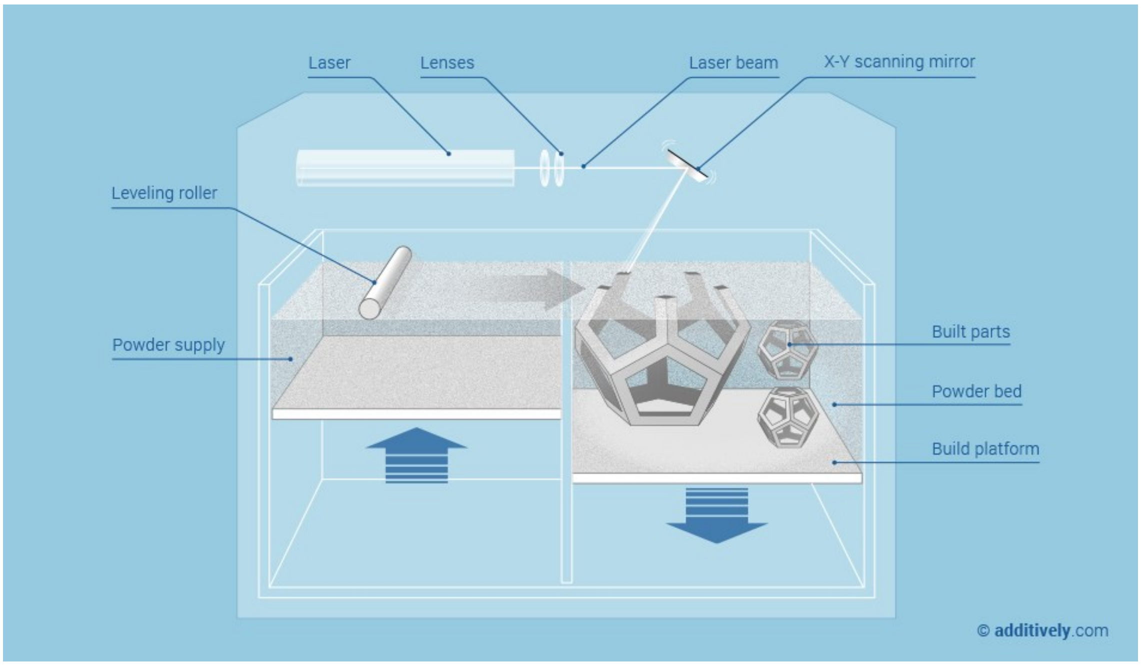


Source: Additively AG, 2018a

2.2.2 Selective Laser Sintering

The process of Selective Laser Sintering (SLS) (cf. figure 5) is quite similar to binder jetting. The printer also consists of a powder supply unit and the building platform, with a levelling roller which applies the powder. The main difference is the technique of binding the powder together as, in contrast to binder jetting, a laser is being used. The laser is melting the powder. These melted parts are fusing together when cooling down. Like this, the object is built layer for layer, with the build unit moving down after each one. Generally, a CO_2-Laser which is turned on and off at the right times by a computer and exactly positioned through mirrors, is used (cf. Schmid 2015, p. 10). The layer thickness of SLS is typically around 100µm (cf. Schmid 2015, p. 10).

Figure 5 Selective Laser Sintering Process

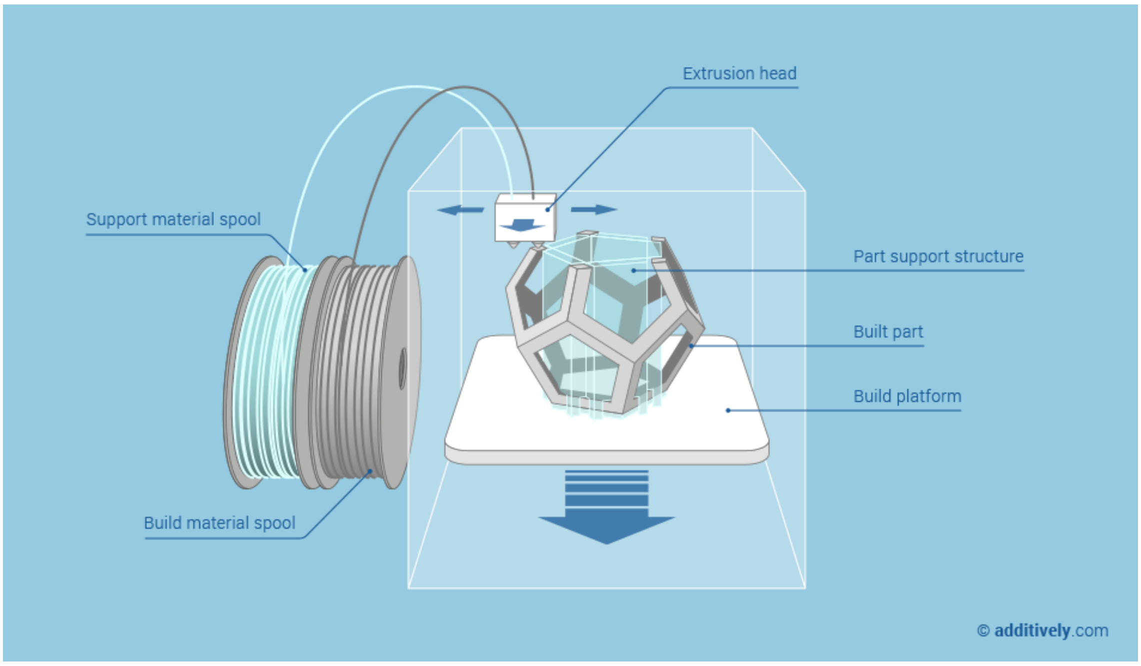


Source: Additively AG 2018b

2.2.3 Fused Deposition Modeling

Fused Deposition Modeling (cf. figure 6) is the first developed fused layer modelling technique, protected by the Stratasys Company. Due to the copyrighted name, other names like Fused Filament Fabrication or Fused Layer Modeling are used as well. Instead of working with powder, FDM uses melted plastic to apply the layers. A plastic cord is wrapped on a coil and connected to an extruder head with a nozzle. In this extruder head, the plastic is melted and pressed through a nozzle to be applied to the print bed to build the layers of the object. As there is nothing else in the build platform but the layers of the plastic, support material is needed for cavities and to keep overhanging material in place. This support material is simultaneously to the plastic applied by a different extruder and is usually a different plastic. After each applied layer, the platform is moved down one layer-thickness. (cf. Gebhardt, Kessler and Thurn 2019, p. 50-52). According to Stratasys, FDM reaches a layer thickness between 127µm and 330µm and an accuracy of 100µm - 200µm, depending on the printer that is being used (cf. Stratasys Ltd. 2020d).

Figure 6 Fused Deposition Modeling Process

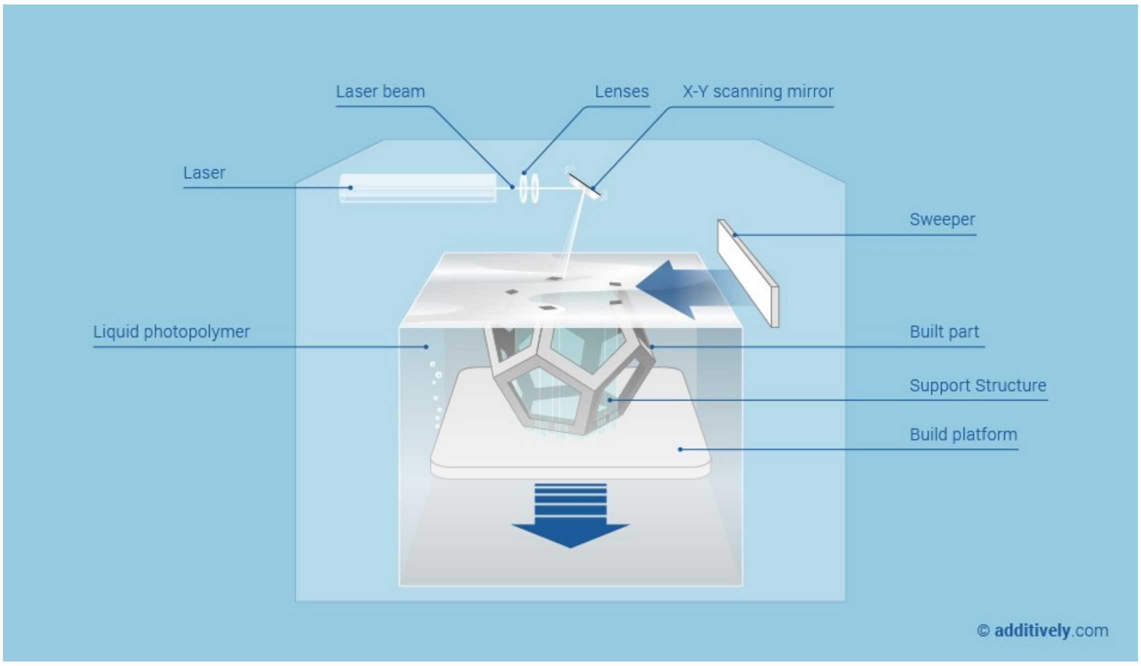


Source: Additively AG 2018c

2.2.4 Stereolithography

In the Stereolithography (SLA) process (cf. figure 7) a photopolymer, commonly resin, is polymerised by an UV Laser. The machine consists of an UV laser, most often a mirror, and the build space. This build space is filled with the liquid build material and has a moveable platform that can be lowered vertically, like in the other processes presented. The laser is being directed by the computer, based on an STL file and reflected onto the resin by a mirror. The material that is hit by the laser beam hardens as a reaction and the structure of the object is build layer by layer. As in FDM, a support structure is needed since there cannot be any floating parts. This support structure consists of the same material as the object itself and needs to be removed later. The removal leaves marks on the surface, so the printing object should be positioned accordingly (cf. Gebhardt, Kessler and Thurn 2019, p. 37-39). In SLA, the layers have a thickness of 10µm to 50µm, relatively low compared to the other processes presented in this work (cf. Zeyn 2017, p. 38).

Figure 7 Stereolithography Process

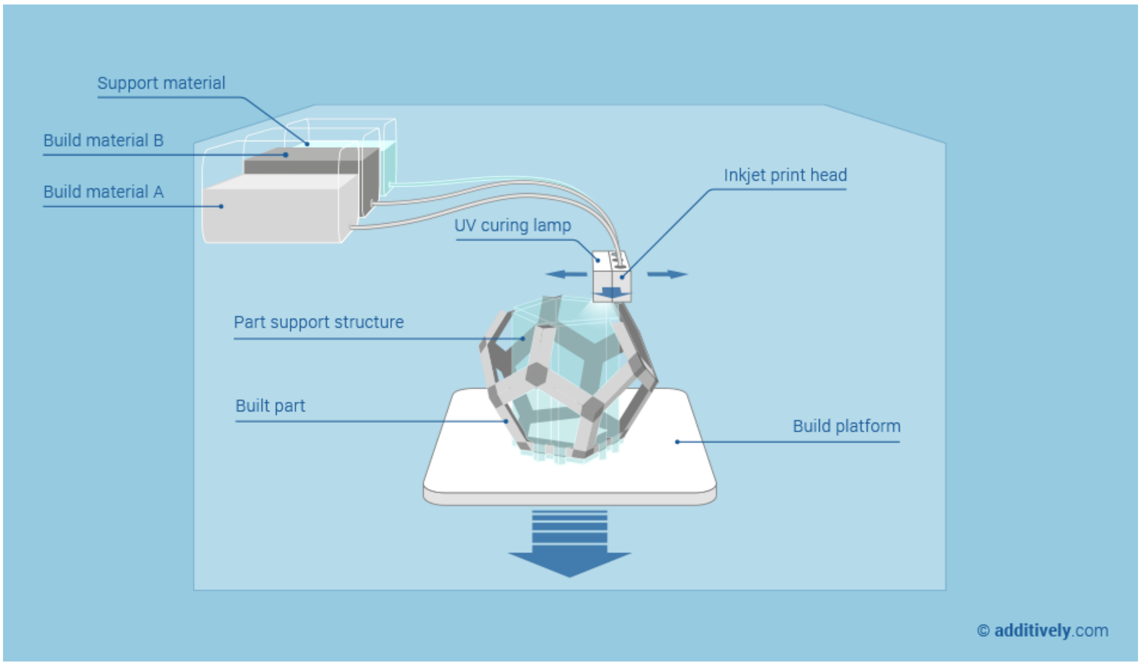


Source: Additively AG 2018d

2.2.5 Photopolymer Jetting

As the name indicates, photopolymer jetting (PJ) (cf. figure 8) also uses photopolymer as material, but different than in SLA, a print head places the liquid polymer onto the build platform. In the same structure as the print head is also the UV lamp included which immediately cures the applied liquid. Because of the liquid state of the polymer, support material is needed but can be chosen freely. Therefore, a material that is easy to remove without leaving marks on the object can be selected. After each layer is hardened, the platform moves down a bit to make space for the next layer (cf. Irsa and Besendorfer 2019, p.129-130). Different colours can be realised through the use of several print heads with different materials of various colours and therefore offers more flexibility in the realisation of new objects (cf. Gebhardt, Gessler and Thurn, 2019, p. 39-41). PJ also has the smallest layer thickness with 14μm to 16μm and as a result can reach a high accuracy (cf. Gebhardt, Gessler and Thurn, 2019 p. 39; Zeyn 2017, p. 63).

Figure 8 Photopolymer Jetting Process



Source: Additively AG 2018e

2.2.6 Comparison of the technologies

As mentioned in chapter 2.2, the technologies differ from each other in view of the properties and technical specifications. To give the reader a better understanding of the differences in those specifications, they are displayed in table 2. The values are based on the currently offered industrial products by the leading 3D printing companies.

Table 2 Technical specifications of the technologies

	Layer Thickness	Accuracy	Post processing	Speed
Multi Jet Fusion (based on BJ) HP Jet Fusion 4200	80 µm	± 200µm hollow parts <100mm ± 0,2% hollow parts >100mm	Removal of loose powder	38mm/h
SLS EOS P770	60 - 180 µm	-	Removal of loose power	32 mm/h
FDM Stratasys Fortus 450MC	127 µm – 330 µm	+/- 127µm	Removal of support struc-tures needed	Depending on the geometry and printing mode

	Layer Thickness	Accuracy	Post processing	Speed
SLA 3D Systems ProX 950	50 µm – 150 µm	-	Removal of support structured needed	-
PJ Stratasys Objet 500	14 µm - 16 µm	<100mm: ± 100µm >100mm: ±200µm	Removal of support structures needed	7mm/h

Sources: HP Development Company, L.P. 2020d; Stratasys Ltd. 2020a, 2020c; EOS GmbH 2020; 3D Systems Inc. 2016; Gebhardt, Kessler and Thurn 2019

HP has developed a technology called multi jet fusion (MJF). It is based on BJ and used at RRPS. Therefore, those specifications are displayed in table 2. The exact differences will be explained in chapter 2.3.1. PJ reaches the lowest layer thickness, but at the same time is the slowest of the presented technologies. In the aspect of accuracy, FDM reaches the best values out of the available data. The removal of support structures that is required for the FDM, STL and PJ processes can leave marks on the part, which can cause problems regarding the surface quality. To avoid those marks, a treatment that removes those marks is needed. The decision for a technology depends largely on the application area it is used for.

2.3 HP printer at RRPS

At RRPS, a HP Jet Fusion 4200 printer is being used (cf. figure 9). The printer consists of a build unit, in which the powder is placed, a processing station (right) and the printer (left) itself.

To start a print job, the build unit has to be filled with the powder. This is an automated process and happens in the processing station, which the material cartridges are enclosed to. As soon as the build unit is filled with powder, it can be inserted to the printer and the printing process can be started. Once the process is finished, the build unit is inserted to the processing station for cooling down and to remove the powder that has not been used (cf. HP Development Company, L.P. 2020f). Up to 80% of the left-over powder can be reused for the next printing job (cf. HP Development Company, L.P. 2020c). One of the advantages of the printer is the separate printer and processing station. As there are also two build units that can be used, the printer could be in use non-stop: printing one job while the other build unit is cooling down (cf. HP Development Company, L.P. 2020f).

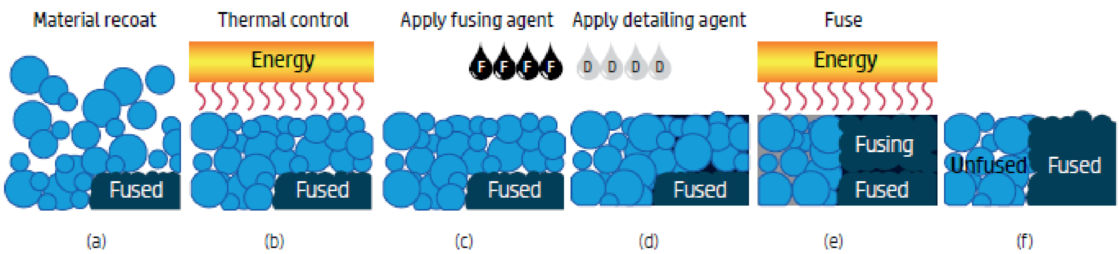
Figure 9 HP Jet Fusion 4200

Source: HP Development Company, L.P. 2020g

2.3.1 Multi jet fusion printing process

The general process of printing and post-processing was described in the last chapters. Now the printing process of the MJF technology is explained (cf. figure 10). The basic concept has already been shown in chapter 2.2.1 and will be explained in more detail in the following based on the information provided by HP (2018b).

Figure 10 HP Multi Jet Fusion printing process



Source: HP Development Cpmapny, L.P. 2018b

In step (a), a new layer of powder is applied to the already fused layer underneath and heated up to the right processing temperature (b). Due to the preheating, a stable powder temperature is ensured. As soon as the right temperature is reached, the fusing agent is applied (c), which is the binding material and bonds the powder. The detailing agent of step (d) is needed for reducing or amplifying the fusing. In this case, it is used to ensure that the object has sharp and smooth edges. After everything is applied to the layer of powder, it is fused together by heating up (e). This process is repeated until the part is finished. In the last step (f) the structure of fused and unfused powder can be seen (cf. HP Development Company, L.P. 2018b).

Though the MJF technology is similar to binder jetting, it is not quite the same. For once, besides the fusing agent a detailing agent is used. This enhances the detail of the edges and ensures a high level of surface quality (cf. HP Development Company, L.P. 2018b). MJF also reaches a better layer thickness. The standard layer thickness of BJ is 100µm - 150 µm, in comparison to 80µm reached by the Jet Fusion 4200 (cf. Gibson, Rosen and Stucker 2015, p. 213; cf. table 2). Though some BJ processes can reach a better layer thickness, in that case they also take a longer time. However, one of the main advantages of MJF is the reduced need for post processing. BJ parts need to be treated with sintering or resin infiltration to reach the required properties (cf. Gebhardt, Kessler and Thurn 2019, p. 53). In contrast, the only post processing needed for parts printed with MJF is the removal of loose powder with a blasting machine (cf. HP Development Company, L.P. 2020f).

The specifications of the HP Jet Fusion 4200 have already been used in table 2 and are displayed in more detail in table 3.

Table 3 HP Jet Fusion 4200 specifications

Characteristic	Specifications
Effective building volume	380 x 284 x 380 mm^3
Building speed	Up to 4115 cm^3 / hour
Layer thickness	80µm
Job processing resolution	600 dpi
Print resolution	1200 dpi
Printer dimensions	2210 x 1200 x 1448 mm
Power consumption	9 to 11 kW
Printing time at a 100% full build unit	11,5hrs (fast print) to 16,5hrs (balanced mode)
Cooling time at a 100% full build unit	31hrs to 46hrs, 10hrs with an integrated fast cooling

Sources: HP Development Company, L.P. 2020d, 2020e, 2018a

2.3.2 Material for the HP Jet Fusion 4200

HP (2020c) offers three different materials for the HP Jet Fusion 4200. The powder that is used for printing at RRPS is called “HP 3D High Reusability (HR) PA 12” and is ideal for constructions that should be watertight and are in touch with oils and greases, as it is often the case at RRPS. Another material, that is also used, though not as often is “HP 3D HR PA 12 Glass Beads (GB)”. It is nearly the same as the one mentioned before but has a 40% share of glass beads and offers a high shape retention. The third material that is used is “HP 3D HR PA 11”, which offers impact resistance and ductility as well as an enhanced elongation at break. With those characteristics, it is best suitable for objects using springs or need to have moveable parts (cf. HP Development Company L.P. 2020c). Some of the main mechanical properties of the thermoplastics are shown in table 4.

Table 4 Material characteristics

Measure variable	HP 3D HR PA 12	HP 3D HR PA 12 GB	HP 3D HR PA 11
Tensile strength	50 MPa	30 MPa	52 MPa
Tensile modulus	1700 MPa	2600 MPa	1700 MPa
Elongation at break	17%	9%	25 %-36 %
Heat deflection temperature	175°C at 0,45 MPa 95°C at 1,82 MPa	170°C at 0,45 MPa 110°C at 1,82 MPa	185°C at 0,45 MPa 54°C at 1,82 MPa
Density of parts	1,01 g/cm^3	1,3 g/cm^3	1,05 g/cm^3

Sources: HP Development Company, L.P. 2020a, 2020b, 2020h

Especially the mechanical properties like tensile strength, tensile modulus etc. depend on the direction that is regarded, e.g. ZX, ZY, XY. In table 4, the lowest values are stated, as otherwise it would be too confusing to read.

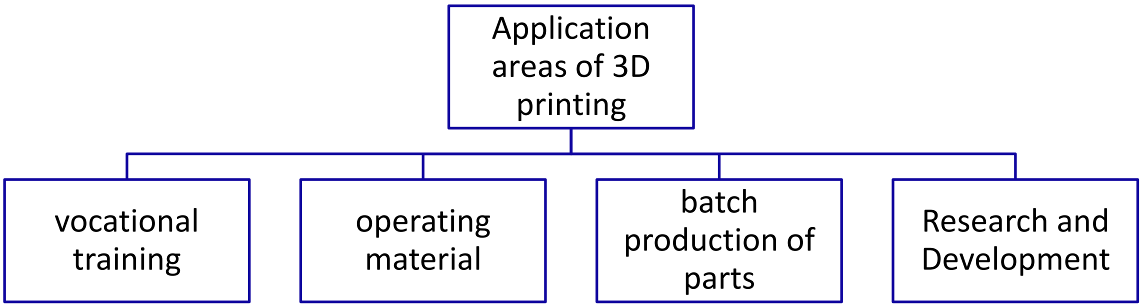
2.3.3 Selection criteria of RRPS

RRPS has specific requirements regarding the properties of the final 3D part and the printer itself. As mentioned in the previous section, the operating parts should be watertight and resistant against oils and greases, which is from high importance. Furthermore, the mechanical properties that can be reached using one of the three materials provided by HP meet the demand of the company. They offer a high variety and can be used depending on the current needs and therefore provide a high flexibility. However, not only the mechanical properties have convinced but also the printing time. A 100% full build unit can be printed within 21,5hrs, including the cooling time (cf. table 3). At the point of purchase, this was up to ten times faster than comparable FDM and SLS technologies (cf. HP Development Company L.P. 2016). Another aspect was the reusability of the powder, both in economic and environmental aspects. The HP Jet Fusion 4200 is perfectly suitable for a non-expensive production of small batch sizes. At the same time, it is the best option for a larger number of parts due to the faster printing process. The system has about half the cost-per-part than comparable FDM and SLS technologies at that time (cf. HP Development Company L.P. 2016). It offers a complete package to optimize the workflow (cf. HP Development Company L.P. 2019). At the point of buying, this was the solution with the best characteristics and technological features for a reasonable cost (cf. HP Development Company L.P. 2016). An employee added that the quality of parts exceeds comparable SLM and FDM printers by far. She sees a high potential in the MJF technology, which is still a relatively new approach in additive manufacturing (Riedel 2020).

2.4 Application areas of 3D printing at RRPS

2.4.1 Overview of application scopes

Figure 11 Application areas of 3D printing at RRPS



Source: Riedel 2020

The 3D printer is used in four different areas at RRPS (cf. figure 11). The vocational training is one of the first areas it was applied to. The apprentices learn how to use a 3D printer, including the design of parts, the arrangement of parts in the build unit to get an optimal result and post-processing. During the post-processing, left-over powder has to be removed from the printed parts and returned to the storage if it is still good to use. Otherwise it is disposed. However, there is still a treatment with a blasting machine needed to remove all powder. Besides the vocational training, the suitability of the printer for a batch production of engine components is being tested. The suitability largely depends on the mechanical properties reached by the material. Further possible application areas are part of the Research and Development. This includes the consideration of a purchase of a second printer or even a metal 3D printer (Riedel 2020). In this paper, only the scope for operating materials is considered, which is explained in 2.4.2.

2.4.2 Application scope of operating materials

The method is mainly used by the process optimisation team in the assembly environment. Their tasks include the analysation of problems caused by the assembly, the definition of error elimination measures and the optimisation of the assembly in terms of the process.

The employees use several different quality methods to ensure the quality during assembly. Most commonly, 8 Discipline (8D) Reports are used. The report defines eight steps that help to define and introduce counter measures (cf. Lennings et al. 2019, p. 7-8). Those are

1. Team
2. Problem description
3. Emergency measure
4. Error cause
5. Planned measures
6. Introduced measures
7. Avoidance of a repetition of the error
8. Verification

Additionally, some head data like engine type, engine ID and the detection location are included.

The possible counter measures are based on the TOP-principle (cf. Schwarz 2016, p. 127):

- Technical measures
- Organisational measures
- Personal measures

It is a principle defined in the work safety and taken over for the error and problem avoidance by RRPS. While a personal measure would be talking to an employee and pointing out the mistake, organisational measures are e.g. an additional point ticked by an employee in a checklist or installation instructions. A technical measure would be the introduction of an operating material.

2.4.3 Definition of operating material

Operating materials includes jigs and fixtures and refers to equipment needed to manufacture the end product. It is not part of the final products and remains at the company. Jigs and fixtures hold, support und locate the workpiece and jigs additionally guide it into the correct position (cf. Venkataraman 2015, p. 1.4-1.5). Some operating materials have no fix place but are part of the engine during the assembly process, e.g. to protect components from getting scratches.

2.4.4 Suitability of 3D printing for operating materials

The need of operating materials results out of several issues. For once, it can be used as a measure to avoid errors before they occur. Further, already known errors can be prevented from happening and be eliminated. Sometimes, operating materials are used to increase the work safety, e.g. when covering sharp edges.

Additive manufacturing offers great potential for the production of operating materials and there are several issues that can be improved by using 3D printing. Usually, the procurement process for new equipment takes some time, as the workload is quite high. The time between the first occurrence of a need and the arrival of a prototype can be drastically reduced by using the internal 3D printer. Depending on the urgency, a testing part can be constructed and produced within a few days. Once the part is properly introduced, replenishment can be printed quickly when necessary. There is no dependence on suppliers and the internal printing orders can be adjusted to the importance of the case. Especially severe errors require fast measures. For those so-called emergency measures a long waiting time must be avoided and with additive manufacturing, the possible measures that can be taken quickly are increased significantly.

Other benefits that can be achieved are a weight reduction resulting in a better handling for employees. With a density of 1,01 $^{g}/_{cm^3}$ (cf. table 4), the parts are less than half the weight of aluminium, which has a density of 2,7 $^{g}/_{cm^3}$ and only $\frac{1}{7}$ of iron parts, that have 7,86 $^{g}/_{cm^3}$. More complex structures are possible with additive manufacturing due to the layer-wise building and therefore an improvement of functions can be achieved, e.g. through a re-design of a part (cf. Gebhardt, Kessler and Thurn, p. 139).

Some ideas for operating materials might not have been feasible because of technical restrictions. An internal production of operating materials can also be more economic for the company, depending on the technical requirements and the volume of the jig or fixture and the number of items needed (cf. 3.2.1).

Collecting experience in 3D printing now can result in a future advantage. As batch production with 3D printing is being considered as well at the moment, the implementation of additive manufactured operating materials to support the assembly can be a good groundwork for a fast and reliable introduction of new application scopes.

It is important to note that not all operating materials are suited for additive manufacturing. There are many factors to be considered for this decision, resulting in a high workload for the responsible employee. Further, as pointed out before, not all operating materials have the same urgency. While some need to be implemented as soon as possible, others can wait as they have no significant improvement to offer. Currently, there is an MS Excel sheet in which the proposals are collected. However, there is no prioritisation included in that list and some required and useful information is not queried. Also, no process of how to work off the proposals is defined. These issues result in the need for a new solution.

3 Identification of suitable parts for additive manufacturing

3.1 State of Research

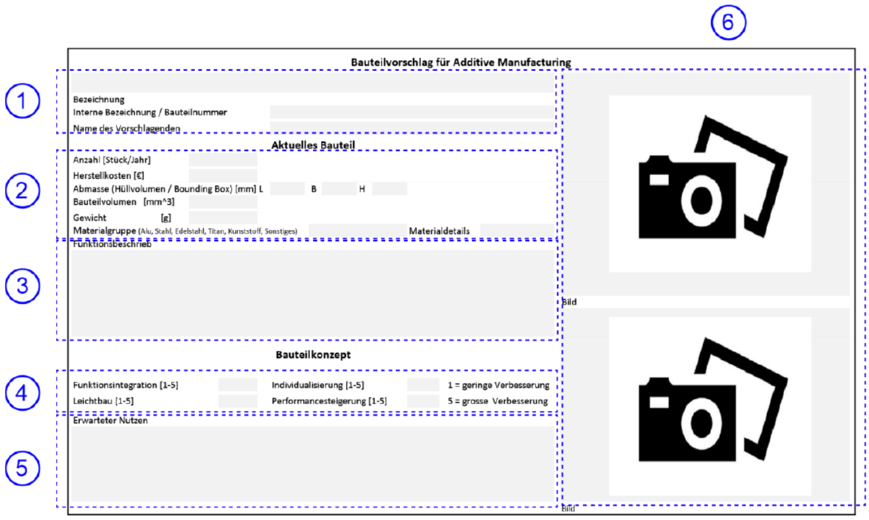
For this new solution, the goal is to develop a method in which all important criteria are rated and a priority can be determined. Like this, a decision for additive manufacturing can be justified. In literature, there are two approaches to develop such a method. Leutenecker-Twelsiek (2019) has developed a bottom-up system, in comparison to Knofius, van der Heijden and Zijm (2016), who have elaborated a top-down system. In the following, the two approaches are being reviewed.

3.1.1 Bottom-up system

In his dissertation, Dr. Leutenecker-Twelsiek is writing about identifying and designing parts for additive manufacturing and, in chapter 5, develops an assessment matrix in which parts are being evaluated regarding their suitability for additive manufacturing.

He proposes to start with a documentation sheet in which the main characteristics of a part are written. Those include in the first section (1) the name of the part, (2) the part number and (3) the name of the submitter. In section two, properties of the part are asked. These include economic aspects like (1) the number of parts per year and (2) the manufacturing costs and are complemented by the (3) dimensions, (4) volume, (5) mass and (6) material of the part. The function is described in section three. One of the most important sections is section four, in which the expected benefit is stated. Leutenecker-Twelsiek has defined four improvement potentials, namely (1) integration of functions, (2) individualisation, (3) lightweight production and (4) improvement of performance. Those topics are rated on a scale from 1-5, where 1 means small improvement and 5 big improvement. The gained benefit can be described in detail in section five. Lastly, in section six, a picture can be included. The documentation sheet is shown in figure 12.

Figure 12 Documentation sheet for part characteristics



Source: Leutenecker-Twelsiek 2019, p. 97

All of this data is transferred to an evaluation matrix split into three parts: component data, evaluation of experts and cost estimation. While in the section of the component data all information stated above are included, the experts assess the part on four criteria: (1) technological feasibility, (2) post processing work, (3) customer benefit and (4) benefit for the company. Comparable to the improvement points, these criteria are also assessed and weighted on a scale from 0 – 5, which is explained in more detail in the work of Leutenecker-Twelsiek. For the cost estimation, the cost for one replica is multiplied by the percentage of weight saved (cf. Leutenecker-Twelsiek 2019, p. 79-102).

This approach can be described as a personal based identification. The possible parts are identified by persons, which offers the possibility to include not only quantifiable improvements, but also qualitative cases. Moreover, not only existing parts are reviewed and assessed but additive manufacturing can be taken into consideration when producing a new part. The company should have some 3D printing experience to be able to identify parts that really bring a benefit and are suited for additive manufacturing (cf. Leutenecker-Twelsiek 2019, p. 80).

The approach elaborated by Leutenecker-Twelsiek includes some aspects that are of use for RRPS, especially the clustering of the needed information into component data, key figures and improvement potential. However, some functions that are important are not included, which is why the method is not suitable for the case. On the one hand, there are several points that need to be added in the general data that is collected in the documentation sheet. Considering that the potential of operating parts often comes with errors detected, the number of problem-solving methods like 8D reports needs to be known for a better follow-up. The affected product types and whether it is a repeated error is also good to know. What is even more important is the ranking. The method is missing a prioritisation with which the printing order can be determined, e.g. based on number of errors, safety risks or cost saving.

3.1.2 Top-down system

Knofius, van der Heijden and Zijm (2016) have developed a top-down approach to “identify promising spare parts from a large assortment” (Knofius, van der Heijden and Zijm 2016, p. 7). In the first step, the assortment is selected, as not all parts are being viewed at once, and spare part attributes are defined. Those attributes are company specific and can include (1) the demand rate in parts per month, (2) remaining usage period in months, (3) manufacturing / order costs in euros, (4) number of supply options in numbers etc. The properties of these attributes are assigned to improvement potentials, namely (1) reduce manufacturing / order costs, (2) reduce direct part usage costs, (3) improve supply chain responsiveness, (4) reduce effect of supply disruption etc. Furthermore, the improvement potential is allocated to company goals (cf. table 5). The technology constraints of additive manufacturing are defined as Go/No-Go criteria, like material type or part size. All this data should be retrievable of databases and therefore be filled in automatically or without much effort for the employee.

Table 5 Allocation of attributes to improvements

	Company goal 1		Company goal 2		Company goal 3	
Attributes	Improve-ment 1	Improve-ment 2	Improve-ment 3	Improve-ment 4	Improve-ment 5	Improve-ment 6
1						
2						
3						

Source: Knofius, van der Heijden and Zijm 2016

In order to weight the spare part attributes, the company goals are given a score (1 – 3) and the attributes are pairwise compared using the analytic hierarchy process, resulting in an importance measure. Scores are given to the attributes in a range from 0 – 1, which result out of the normalisation of the value ranges like months or euros. They are multiplied with the importance measure, resulting in a weighted score. To identify the overall score, the scores of technology constraints are multiplied with each other, the scores of attributes are summed up and both of these results are multiplied again. As the technology constraints have a score of either 1 or 0, the result will be zero when there is a technology constraint (No Go-attribute) (cf. table 6) (Knofius, van der Heijden, Zijm 2016, p. 8-14).

Table 6 Score calculation for parts

	Weight (resulting out of the AHP)	Score (resulting out of normalised values)	Weighted score (weight x score)	Result (0 = no implementation, 0<x<1 implementation)
Attribute 1	15%	0,4	0,06	(0,06 + 0,225 + 0,04) x (1 x 0) = 0
Attribute 2	45%	0,5	0,225	
Attribute 3	40%	0,1	0,04	
Technology constraint A	-	1	1	
Technology constraint B	-	0	0	

Source: Knofius, van der Heijden and Zijm 2016

While Leutenecker-Twelsieks approach is personal based, this one is computer-based. The information is retrieved from databases and the criteria and improvement potentials are quantifiable. A decision is made based on a reduction of costs or enhancement of responsiveness and no personal assessment of benefits like integration of functions is included. (cf. Leutenecker-Twelsiek 2019, p. 79)

The top-down approach includes an importance measurement, resulting in a more detailed ranking of parts that Leutenecker-Twelsieks approach is missing. It does however not include improved functionalities that are possible with additive manufacturing, as it would be inefficient to evaluate those aspects. Those functionalities are improvement of functions, a better performance or lightweight production. The enhancements are from great importance for RRPS; therefore the approach is not suited.

3.1.3 Further approaches

The two introduced theories agree on one methodology consisting of three steps: analyse, identify and rate. This approach is also supported by Burkhart and Aurich (2017) as well as Lindemann et al. (2014).

Lindemann et al. (2014) have also developed a bottom-up system called trade-off methodology matrix. The case is judged by non-AM experts regarding e.g. complexity, manufacturability, size and design improvements based on a scale from 1-5. Out of these, a ranking is created, of which the top three cases are assessed by AM experts (cf. Lindemann et al. 2014). The process optimisation team at RRPS however wants to judge all possible operating materials. Additionally, the criteria that have to be judged by non-AM experts require some knowledge about 3D printing. A submitter often does not know which design improvements are possible or has a different perspective on how complex a part is.

Burkhardt and Aurich (2017) judge the limits, compromises and restrictions of the current technology used and at the same time the potentials of additive manufacturing and the characteristics like the function. The characteristic approach includes topics like products, processes and the material. Lastly, target criteria are defined on the base of the previously found improvement potentials. They can include the costs, the quality or the reliability of the part. These criteria are then rated regarding each production technology (cf. Burkhardt and Aurich 2017). In this approach, each part has to be assessed regarding improvement potentials which are not defined specifically. The effort is not practicable for RRPS.

3.1.4 Additional criteria

Each developed system considers different criteria to be important and follows different rating systems. This can well be seen in the top-down and bottom-up approach. Yet there are also criteria regarded as mandatory, that occur in every method. The usage of main criteria in different approaches is displayed in table 7.

Table 7 Mandatory selection criteria by current literature

Part properties	Leutenecker-Twelsiek	Knofius et al.	Burkhart/Aurich	Lindemann et al.
Costs	X	X	X	X
Dimensions	X	X	X	X
Weight	X		X	X
Material	X	X	X	X
Number of items needed	X	X		X
Improvement Potential	**Leutenecker-Twelsiek**	**Knofius et al.**	**Burkhart/Aurich**	**Lindemann et al.**
Integration of functions	X		X	X
weight saving	X		X	X
complexity	X		X	X

Sources: Leutenecker-Twelsiek 2019, p. 83, 97-98; Knofius, van der Heijden and Zijm. 2016, p. 8 and 10; Burkhart and Aurich 2017; p. 38-39; Lindemann et al. 2014, p. 219-221

As can be seen, the properties that are often regarded to identify parts for additive manufacturing are (1) the dimensions, (2) the manufacturing costs, (3) the weight, (4) the material and lastly (5) the number needed. Especially the material needs to be suited for the function of the part, which is why a description of functions should also be included. After the general possibility of manufacturing with 3D printing was regarded, the improvement potential needs to be judged to justify the change of production type. Possible improvements that have been mentioned in three of the four papers are (1) integration of functions, (2) weight saving and (3) performance improvement. The approach of Knofius, van der Heijden and Zijm (2016) regards other benefits, as it is computer based. (1) Integration of functions is achieved when a part includes the functions of several other parts into one, which simplifies the effort during the assembly. (2) Weight saving is self-explanatory and (3) performance improvement refers to the optimal design for the function of a part, to use it in the best way possible without any losses. Performance improvement also often includes a more complex design.

While these data about part properties and improvement potentials might work perfectly well for other companies, only some of them are suited for RRPS. Therefore, a ranking method that includes all relevant data was developed. The development and the reasons why some criteria were not chosen is explained in section 3.2

3.2 Development of the method at RRPS

RRPS has specific requirements regarding the method. A main aspect is the applicability and practicability for employees. First of all, the data input should not take long. Further, the data situation and the knowledge of the submitter have to be considered during the development of the criteria. Not all information is known in detail to all employees, especially as they are no AM experts. Moreover, the effort to collect all data is often not justified by the importance and influence of it. As a result, the method concentrates on few, but important criteria that lead to a reliable outcome.

The outcome exists of three areas, (1) a decision whether the operating material is suited for additive manufacturing, (2) which proposal should be implemented first and (3) how the proposal is processed internally. For an assessment of the suitability, three exclusion criteria were defined. The ranking which indicates the order of implementation is based on three priority criteria.

3.2.1 Exclusion criteria

Not every proposal is suited for additive manufacturing, with many and more criteria that can lead to an exclusion of the case.

The first defined exclusion criterion is questioned as “Is the operating material exposed to a heat >95°C?” The most often used material for printing are HP 3D HR PA 12 and HP 3D HR PA 12 GB, which have been presented in section 2.3.2. The comparison of the heat deflection temperature has shown that the lowest temperature at which a deflection is caused is 95°C at a pressure of 1,82 MPa. For the third possible material, this limit is even lower at 54°C (cf. table 4). However, as it is not used frequently, it is left unattended in this paper. The heat deflection temperature is included in the method as there are operating materials that are exposed to a great heat and it is easy to judge for the submitter.

For the second exclusion criteria, it is asked “Is an accuracy <0,5mm required?”. It may be that an operating material needs a very high accuracy to be suitable for the use case. That could be a tight fit that is necessary, with little moving range or the requirement of an exact positioning. The HP Jet Fusion 4200 can only reach a certain quality, depending on the size of the part. In table 8, the reached accuracy by the printer and tolerances of conventional technologies based on DIN ISO 2768-1 are displayed to show the differences in the values that can be reached. DIN ISO 2768-1 refers to subtractive manufacturing processes, one of the main alternatives to additive manufacturing.

Table 8 Accuracy of 3D printing and subtractive processes

Size in mm	Accuracy in mm			
	HP	Conventional manufacturing		
		Fine	Middle	Coarse
50	0,2	0,15	0,3	0,8
100	0,2	0,2	0,5	1,2
150	0,3	0,2	0,5	1,2
200	0,4	0,2	0,5	1,2
250	0,5	0,2	0,5	1,2
300	0,6	0,2	0,5	1,2
350	0,7	0,2	0,5	1,2
400	0,8	0,2	0,5	1,2

Source: HP Development Company, L.P. 2020d, DIN ISO 2768-1

As it can be seen, the accuracy of subtractive processes remains the same for nominal dimensions of 100mm to up to 400mm, whereas the HP Jet Fusion 4200 has increasing values at an increasing part size.

The accuracy limit of 0,5mm is set for various reasons. For once, it is fairly easy assessable. Half a millimetre is easier to judge without measuring than $2/5$ or other uneven numbers. Furthermore, it is about the middle of accuracies reached. Even though larger parts with larger tolerances may be printed, that does not happen regularly and requires some other measures to be taken, like placement in the printer. The majority of parts is around a size range of 250 mm and 0,5 mm is a medium value applicable to each case.

The last criterion that can lead to an immediate exclusion is the size, as the space inside the printer is limited (cf. figure 3). It is asked as "does the part fit into 380 x 284 x 380 mm?". The printing space of the HP Jet Fusion 4200 is restricted to 380 x 284 x 380 mm and therefore the parts that are intended for 3D printing have to fit into these dimensions. With a sloping positioning, bigger parts can be realized. However, like that, fewer parts can fit into the printer, leading to a worse parts-per-printing-job ratio and increasing the processing time. The before mentioned accuracy is better at the centre of the unit and gradually worsens the closer the part is placed to the edges. For big objects, that results in a very high accuracy in the middle and an, in comparison, low one at the edges.

As those differences can lead to problems during the usage, a desired solution for the long-term is to find a way to split parts that are too large into several smaller parts. There are currently some tests running to find an applicable way to put those pieces together that works in any case. Possible techniques are plug connections or gluing the separate parts together. Once a suitable solution is found, the criterion of the part size can be removed from the method as it then does not constitute an exclusion criterion anymore. Nevertheless, until this is the case, the criterion is from high importance.

As mentioned before, there are many and more criteria that can lead to exclusion. In this method, it is restricted to the three outlined criteria to reduce the amount of data that has to be filled in and to solely query factors that actually matter for RRPS. However, during the development of the method, the mechanical properties that can be reached by the material (cf. table 4) have also been considered to be an exclusion criterion. Especially in the engine assembly, components tend to be very heavy and a high load on operating materials is no rarity. The lowest limit is defined by the material HP 3D HR PA 12 GB, with a maximum tensile strength (F_{tu}) of 30 MPa. The actual mass that can be loaded on the material can then be calculated. To reach the mass per mm^2, the F_{tu} is divided by the weight force (g). As one cm^2 contains 100 mm^2, the first result is the multiplied by 100 to get the mass per cm^2.

$$\frac{F_{tu}}{g} = \frac{30\frac{N}{mm^2}}{9{,}81\ \frac{m}{s^2}} = 3{,}058\frac{kg}{mm^2} = 305{,}8\frac{kg}{cm^2} \quad (1)$$

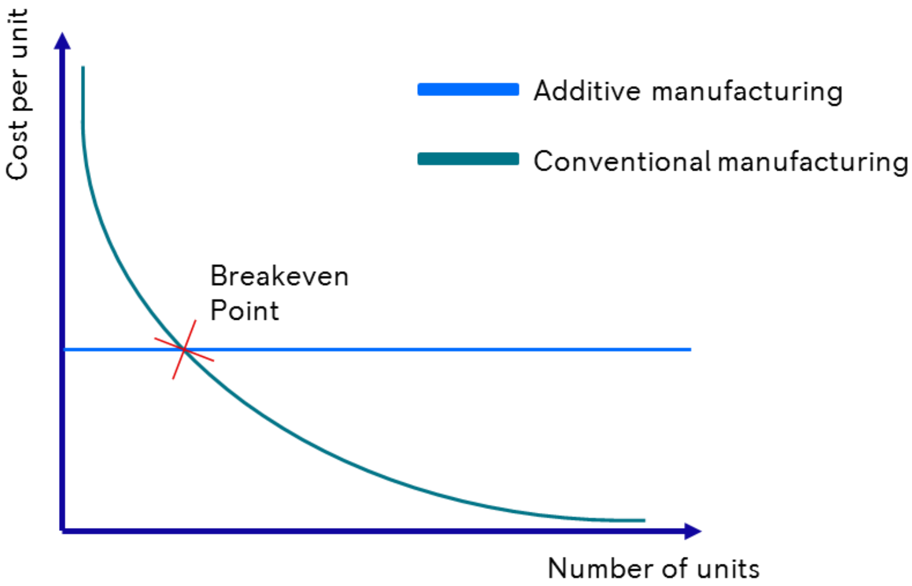
A maximum load of roughly 300 $^{kg}/_{cm^2}$ is considered to be high enough to not be a significant factor that can lead to an immediate exclusion of the part. The operating materials are used during the manual assembly and are handled by the employees without additional equipment. However, as soon as a part is used as a tool and the load is a torque, high amounts can be reached very quickly. In such a case, the AM expert has to reconsider the properties of the proposed part and may be required to take some exact measures to identify if an implementation is possible.

Another criterion that is often considered to be an exclusion factor is the impermeability towards oils and water. It has not been further regarded as especially the HP 3D HR PA 12 is completely watertight and does not react to oils and greases (cf. 2.3.2).

Lastly, the surface quality was considered. For operating materials, the focus is rather on functionality than surface quality and in the cases that have already been implemented, there were no special requirements towards the surface. Therefore, this factor is not included in the developed method.

Besides the direct exclusion criteria, there is also one indirect criterion defined. That is the needed number for a sufficient supply without any shortages during the normal work routine.

Figure 13 Cost comparison of additive vs. conventional manufacturing



Source: own work based on Attaran 2017

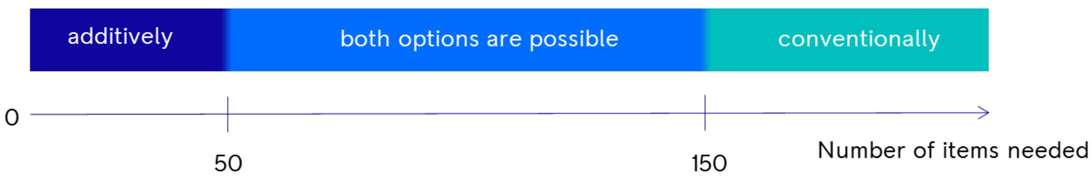
As shown in Figure 13, the costs per part for producing parts with additive manufacturing are the same, no matter how high the number is. In comparison, conventional manufacturing technologies like milling or forging have decreasing costs per part the larger the produced number gets. They are therefore mostly used for mass production. There is however no fix breakeven point that clearly defines the most economic manufacturing technology for all cases. An important factor that has to be considered in this decision is the complexity of the part. 3D printing offers the possibility to manufacture far more complex parts than conventionally possible. A high number of complex parts is therefore better suited for additive manufacturing, whereas solid block structures have no need of being 3D printed and might just as well be milled or forged. Moreover, the costs highly depend on the volume, which determines the amount of material that is needed to build the part.

As the position of the breakeven point depends on the complexity, the volume and the size of the part, an average was defined in the method based on Paulsen (2019). He has analysed the costs of different manufacturing ways of three parts that differ in size and shape. It has to be noted that in that analysis the amortised price per unit is regarded. While for a small part like a potentiometer knob, the MJF technology is the most economical way to produce to up to 2048 parts, a typical medium sized part like a drone leg hits the break-even point at 256. Up to there, 3D printing technologies are the best choice. A large part like a junction housing can be economically produced with additive manufacturing only up to a number of 32, when CNC machining starts to be the better choice. The analysis shows clearly that the size plays an important role in the costs per part (cf. Paulsen 2019).

Another basis on which a recommendation about the way of manufacturing is done in the method are previous implemented parts. At RRPS, out of 32 parts in the current 3D printing workflow, only three exceed 50 required units.

As a result of the analysis of Paulsen (2019) and the experience in the company, a scale with three gradations was defined in the developed method. Parts which require less than 50 items are recommended to be produced additively. Between 50 and 150, both 3D printing and conventional technologies are possible and over 150, a conventional production is advised (cf. figure 14). 150 were set as an upper limit for 3D printing based on the average of 32 for a large part and 256 for a medium sized part. The exact average of 144 was rounded up to 150 to have an even number.

Figure 14 Suggested implementation technology based on the number needed



Source: own work

The three presented exclusion criteria lead to the decision whether it is possible to produce the part using the printer at RRPS or if it can be excluded at once. The question asked is “Is the operating material, based on the exclusion criteria, suitable for 3D printing?”. To get a “yes”, there are three requirements:

1. The part is not exposed to a heat >95°C
2. The part is not required to have a high accuracy of <0,5mm
3. The part fits into the printer which is 380 x 284 x 380 mm

To avoid unclear answers or statements like “it depends on” on this topic, the questions are so formulated that they can be answered with “yes” or “no”. The submitter can only enter one of those two possibilities through a drop-down menu. For the third criterion, a third option is available, namely “uncertain”, as the final shape and size of a part can be hard to judge. Only when the first two criteria are answered with “no” and the last with “yes”, the part is suited for additive manufacturing. If the size is uncertain no decision about the suitability can be made and it is stated that the measures have to be checked. As soon as one requirement is not fulfilled, the part is excluded and not further considered.

After the general suitability of the part for additive manufacturing is determined, the suggested way of implementation based on the number needed is output (cf. figure 14).

The suggestion made with a formula is then verified by an additive manufacturing expert. They decide if it is possible to manufacture the operating material conventionally. For this decision, they consider the complexity of the part, the requirements of the solution and how the part shall be used. Only after this manual decision is made, a final decision if the part is produced additively is possible. For this, the recommendation based on the number of items needed and the producibility using conventional technology are considered. Table 9 shows in which cases 3D printing is the way to go and when a conventional technology should be chosen.

Table 9 3D printing decision criteria

Suggested implementation based on the number needed	Producibility (decided by AM expert)	Resulting production technology
≤ 50 items → Additive	Additive	Additive
	Conventional	Additive
50 < x ≤ 150 → Both	Additive	Additive
	Conventional	Conventional
>150 items → Conventional	Additive	Additive
	Conventional	Conventional

Source: own work

The decision cannot be made when the measures of the part still have to be checked or it has not yet been decided whether it is possible to produce the item conventionally. In such cases, "decision still pending" will be stated in the according field. Further, if an exclusion criterion is not fulfilled, there is no decision for 3D printing as well.

3.2.2 Priority criteria

Once a decision about the implementation with 3D printing has been made, a prioritisation of the proposals is needed to set the best implementation order. This can be difficult to determine by hand. To take off some workload from the AM expert, a priority number is calculated by the method based on three criteria.

In the application within the process optimisation team, measures for error elimination and error prevention are the main use of operating materials. The properties of an error are therefore from high importance for the urgency of a case. Other cases are proposals that are regarding the work safety. Therefore, it is not possible to refer to problems as error, as not every problem is an error.

A problem can be described with two aspects. First, the problem frequency has to be determined, divided in three possibilities:

- one-time occurrence
- a repeated occurrence
- no occurrence yet

A query of how many assembly mistakes exactly have led to the need was decided to be unpractical. Due to the high-quality standards expected and set by RRPS, even an one-time failure should not happen again and an error occurring twice or more needs to be avoided by all means. Ten times the same mistake is already considered to be an immense amount. The same is true for any other problems. If one employee gets injured, the cause for that should be eliminated as soon as possible to avoid more injuries. The three different types of problem frequency are one indicator for the priority of the case.

Once this is determined, the problem severity is judged. Generally, that is dependent on the time that is needed to fix the error and on the costs it has caused. However, the exact amounts of these are not generally known among the employees. Besides time and costs, the security of the employees is part of the seriousness of a mistake. As soon as an employee is injured or at risk to be injured, the severity reaches a very high level. Yet, the occupational safety is even harder to quantify than time and cost. As a result, the severity has to be assessed otherwise.

At RRPS, there is a closed-loop quality control defined, with five loops indicated by different colours. All errors detected in the assembly line or at the quality gate at the end of each assembly line are in quality loop one and two. They are indicated with the colour white. The third quality loop includes errors detected during the test runs and the last quality gate before dispatch and is marked with yellow. Lastly, quality loops four and five with the colour red are errors detected by customers. From the first to the last quality loop, the severity is increasing. The later a failure is detected, the worse for RRPS, as the reputation can suffer and money is lost for the repair of the error. Within the classification in the closed quality loops, it is further divided into low, intermediate and high. These are based on a failure mode and effects analysis (FMEA). During a FMEA, the severity of an event, the probability of an event occurring and the detection probability of the event are rated with 1, 3, 5, 7 and 10. The severity of an event as part of the FMEA has to be distinguished from the problem severity defined as part of the method. The underlying criteria of how to judge the factors can be seen in appendix A (p. 68) (table 21).

The risk priority number (RPN) is calculated as follows:

$$severity \times probability\ of\ occuring \times detection\ probability \qquad 2$$

The error is classified as “light” if the RPN is lower than 46. Between 46 and 125, it is a “medium” error and above 125 it is considered as “serious”. This division results in nine stages of error severity, ranging from “light white” to “serious red”. For the sake of completeness, if it is a preventive measure that is not based on an existing problem, that option is also included in the method. This classification of the error severity is also used by the employees at RRPS when filling in an 8D Report (cf. 2.4.3). Therefore, it was decided to be the best choice in the method as well. While the FMEA risk assessment in combination with the closed loop quality control is a great way to assess the severity of assembly errors, work safety issues cannot be rated on this scale. It was therefore decided to include "work safety issue" additionally to the before defined classifications. Like that is ensured that the severity can be judged even if it is no error.

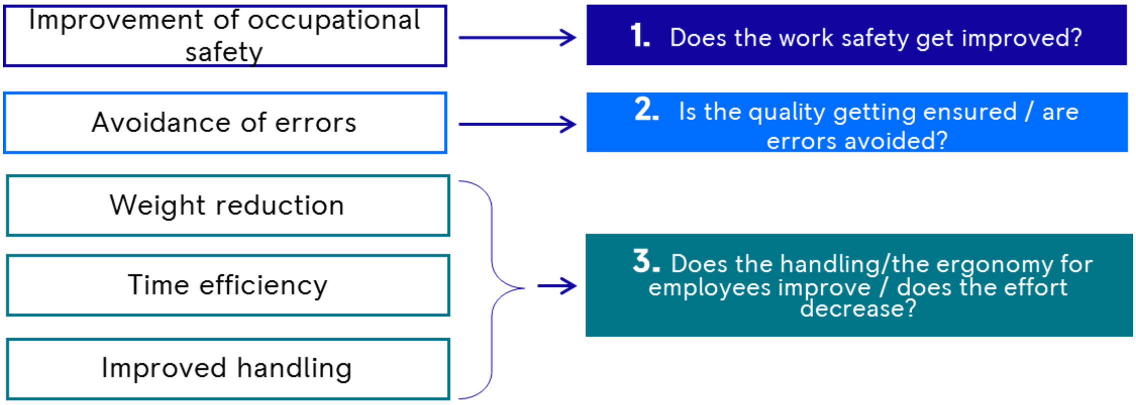
The combination of frequency and severity are very important factors for the urgency. An error classified as "red" almost always requires some kind of emergency measures and has to be a top priority in the implementation, whereas solely preventive measures can be postponed in favour of more urgent cases.

A specific question if the proposal is an emergency measure would ease the identification of top priority cases. However, an emergency measure is defined by the frequency and severity. The higher the severity is, the more important is it to introduce counter measures. Further, emergency measures always have to have the highest priority. Once the submitters notice that, it will result in each proposal to be an emergency measure to increase the chance of a fast implementation. As that is not an applicable solution, the option of an emergency measure was dismissed.

Besides the severity and frequency, the improvements achieved by introducing an operating material are part of the priority number. Additive manufacturing offers quite a few possible improvements. In the reviewed literature, an (1) integration of functions, (2) more complexity and a (3) weight reduction are seen as the most important improvements (cf. 3.1.3). However, there are other advancements that can be reached. Operating materials at RRPS used during the assembly process should help to (4) avoid errors or to (5) improve the handling for the employees. Moreover, the occupational safety is a high priority and an operating material that can help to (6) avoid work accidents brings a high improvement. Besides that, operating materials can (7) reduce the expenditure of time. Especially the masking of parts before an engine gets painted can take a lot of time for components that are not easily accessible or have a complicated structure. A cover for such parts reduces the effort of masking as only the edges between the cover and the part have to get protected instead of the whole unit. The last considered benefit was the (8) cost reduction. As stated in 3.2.1, additive manufacturing is especially for small numbers often more cost effective. To lower expenses is a goal of many companies and often one of the most regarded factors in a decision (cf. 3.1).

Now, there are eight possible improvements mentioned above. A method querying that many things is almost certainly overwhelming for the submitter of a proposal. As Leutenecker-Twelsiek (2019) stated on the base of Newell and Simon (1972) and Berti (2010), a human brain can only process about seven pieces of information at the same time. When there are other processes happening at the same time, the brain capacity is even less than seven and ranges around three to five (cf. Newell and Simon 1972; Berti 2010; Leutenecker-Twelsiek 2019). For reasons of clarity and applicability, it has therefore been decided to cluster the improvements into three main areas. The allocation and the three resulting improvement fields are displayed in figure 15.

Figure 15 Clustering of possible improvements

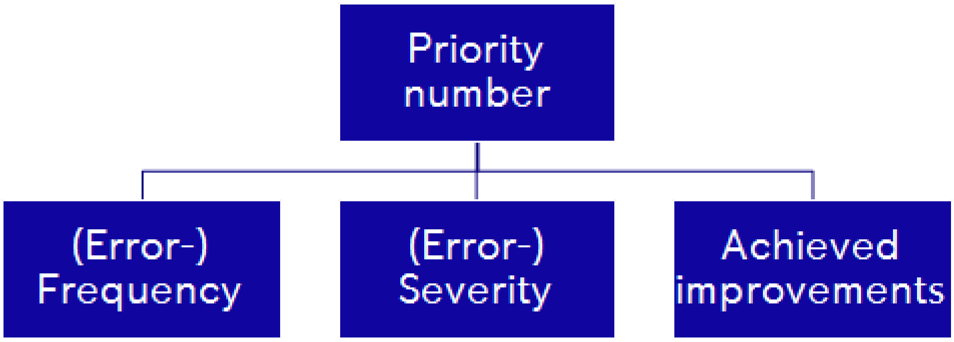


Source: own work

In the developed method, an increased work safety, an ensured quality and an improved handling for the employees have been defined as possible improvements that can be reached when using a 3D printer to produce an operating material. Integration of functions and an enhanced complexity have been dismissed during the development process. They are hard to judge for non-specialists of the topic of additive manufacturing. Furthermore, which functions are suited for integration and how complex the part can be designed can often only be seen during the designing process and is hard to determine beforehand. The cost reduction was not included as to give a verifiable answer about the exact amount is not easy. The exact volume can just as the complexity not be determined beforehand and also for conventional technologies, the costs can vary. However, as the decision about the best manufacturing technology is made based on the number needed, the cost is indirectly included in the decision (cf. 3.2.1). Besides those content-related reasons, it is also important that all required information can be displayed on one page without scrolling. A large number of criteria would simply not allow this, resulting in an impractical method.

Out of the presented criteria, a priority number is calculated. The weighting of the criteria is based on the analytical hierarchy process (AHP). The AHP consists of several steps. In the first step, a main goal and the criteria to reach that goal are defined (cf. Ronniger 2019). The goal in this case would be to prioritise the implementation of a proposal based on the criteria stated above (cf. figure 16).

Figure 16 Main goal of the AHP and criteria to reach it



Source: own work

Once the hierarchy is defined, the criteria are pairwise compared. This is done with the use of a matrix, in which it is determined whether the lines are more important than the columns. The scale defined by Saaty and Vargas (2012, p. 6) ranges from 1-9:

1 = equal importance

3 = moderate importance

5 = strong importance

7 = very strong importance

9 = extreme importance

The values 2, 4, 6 and 8 are considered as interim values (cf. Saaty and Vargas 2012, p.6). This scale results in a matrix displayed as table 10.

Table 10 Pairwise comparisons of the criteria

	(Error-) Frequency	(Error-) Severity	Achieved improvements
(Error-) Frequency	1	1/3	1/3
(Error-) Severity	3	1	1
Achieved improvements	3	1	1

Source: based on Saaty and Vargas 2012

In the blue coloured cells, the values of the comparisons are entered.

While the frequency should be considered, as it does make a difference whether it is a repeated problem or a preventive measure, the severity is considered to be of higher importance. It has a higher influence on the processing and urgency of the error than the frequency. However, it is not considered as a strong importance as the difference is not that high.

The achieved improvements are also deemed to be of a higher importance for the priority than the frequency. No matter how often an error has occurred, there has to be an improvement achieved to justify the introduction of an operating material. Especially a better occupational safety has to have a high impact on the priority number and should be weighted higher than the frequency.

Not only work safety issues but also emergency measures require a large number. As emergency measures at the same time have a high severity, the achieved improvements and the error severity are considered to be of the same importance.

In the diagonal, indicated in grey in table 10, all values are “1” as the criteria are compared with themselves. In the spaces indicated in red, the reciprocal of the determined values based on the scale are entered (cf. Saaty and Vargas 2012, p.6).

When all criteria have been compared to each other, the weighting is determined. In the first step, the matrix has to be squared. This is done based on formula 3. Each field is defined by a column index (k) and a line index (i). To square it, each field in the row is multiplied with a field in the column and the results are added up.

$$a_{k,i}^2 = \sum_{j=1}^{n} a_{ji} \times a_{kj} \qquad 3$$

n number of rows in the matrix

The same number of rows and columns is a condition to be able to square a matrix. In this case, that is three, resulting in n = 3. The result of the first squaring is shown in table 11.

Table 11 Squared pairwise comparisons

	(Error-) Frequency	(Error-) Severity	Achieved improvements
(Error-) Frequency	3	1,5	1,5
(Error-) Severity	9	3	3
Achieved improvements	9	3	3

Source: own work

Then, the eigenvector is calculated by building the sums of each row and the sum of all the row sums. By dividing the line sum by the total sum, the value gets normalized. The result is the value with which the criteria are weighted.

Table 12 Calculation of the weighting

				Row sums	Eigenvector
(Error-) Frequency	3	1,5	1,5	5	5/35 = 0,14
(Error-) Severity	9	3	3	15	15/35 = 0,43
Achieved improvements	9	3	3	15	15/35 = 0,43
	Column sums			5 + 15 + 15 = 35	0,14 + 0,43 + 0,43 = 1

Source: own work

As it can be seen in table 12, the frequency is weighted with 0,14, the severity with 0,43 and the achieved benefits with 0,43 as well. This results in formula 4 for the calculation of the priority number. It is multiplied with 100 to reach a scale from 0 – 100.

$$(0{,}14 \times x_f + 0{,}43 \times x_s + 0{,}43 \times x_i) \times 100 \qquad 4$$

x_f (Error-) Frequency

x_s (Error-) Severity

x_i Achieved improvements

The criteria are qualitative criteria, so a scale that defines how to assess them quantitatively has to be determined. The values are shown in table 13.

Table 13 Quantification of the priority criteria

<table>
<tr><th>(Error-) Severity</th><th>Rating</th><th>(Error-) Frequency</th><th>Rating</th><th>Achieved improvements</th><th>Rating</th></tr>
<tr><td>preventive measure</td><td>0</td><td rowspan="3">No occurrence yet</td><td rowspan="3">0</td><td>Improvement of handling</td><td>0,1</td></tr>
<tr><td>light white</td><td>0,1</td><td rowspan="2">Error avoidance</td><td rowspan="2">0,25</td></tr>
<tr><td>medium white</td><td>0,2</td></tr>
<tr><td>serious white</td><td>0,3</td><td rowspan="4">One-time failure</td><td rowspan="4">0,5</td><td>Improvement of handling + error avoidance</td><td>0,4</td></tr>
<tr><td>light yellow</td><td>0,4</td><td rowspan="2">Improved work safety</td><td rowspan="2">0,55</td></tr>
<tr><td>medium yellow</td><td>0,5</td></tr>
<tr><td>serious yellow</td><td>0,6</td><td rowspan="2">Improved work safety + improvement of handling</td><td rowspan="2">0,7</td></tr>
<tr><td>light red</td><td>0,7</td><td rowspan="4">Repeated error</td><td rowspan="4">1</td></tr>
<tr><td>medium red</td><td>0,8</td><td rowspan="2">Improved work safety + error avoidance</td><td rowspan="2">0,85</td></tr>
<tr><td>serious red</td><td>0,9</td></tr>
<tr><td>Work safety</td><td>1</td><td>Improved work safety + error avoidance + improvement of handling</td><td>1</td></tr>
</table>

Source: own work

The severity has nine different specifications, ranging from light white to a serious red error. Additionally, a preventive measure can be chosen. As in that case was no problem yet, it is rated with zero. Between those specifications, the gradation steps are even. A medium white severity is more important than a light white the same way a light red severity is more important than a serious yellow. This allows to define a scale from 0 to 1, on which 0,1 represents a preventive measure and 0,9 a serious red error. Some problems are work safety issues. The submitter must be able to choose that from the severity scale as well as work safety cannot be rated on the closed loop quality control. Work safety issues are always very important and are therefore rated with 1 (cf. table 13).

The scale for the error severity was taken as base for the rating of the other two priority criteria. The order of the characteristics of the error frequency from low to high is

1. No occurrence yet

2. One-time occurrence
3. Repeated occurrence

This results in the preventive measures to have the lowest rating and the repeated errors to have the highest. With the error severity as base, the characteristics have also to be rated on a scale from 0 to 1. Measures that base on potential problems are rated with zero as they have not occurred previously. One-time occurrences are quantified with 0,5 and repeated occurrences with 1. To reach these values, the ratings were standardised to the basic scale (cf. Appendix B, p. 69).

Lastly, the achieved benefits are assessed. Out of the three possibilities, seven combinations are possible (cf. table 13). The assessment values are also standardised to a scale from 0,1 to 1 (cf. Appendix B, p. 69), resulting in the rating shown in table 13. In this case, the scale starts with one, as an improvement rated with zero contradicts the nature of improvements.

The priority number ranges from 0 to 100. The result resembles the percentage of priority and the importance can be seen at one glance.

Once the priority number of a proposal is determined, it has to be classified as a high, medium or low urgency. Three gradation steps have been defined as follows:

0 - 33: low urgency

>33 - 66: medium urgency

>66 - 100: high urgency

Additionally, if the work safety is improved, the case is also considered as high, independently of the priority number reached by the other criteria.

Besides the factors needed to reach a decision about the manufacturability and the priority, general information and data about the operating material is needed. These are presented in 3.2.3.

3.2.3 Further information and data

The additional data are needed for several purposes. They build the base for the further implementation process. To introduce an operating material, an application has to be filed, requiring several data about the case. Additionally, the designer gets information about the use and requirements.

The first important information is the date on which the proposal is done. That allows keeping track of how long it takes from the first idea for an operating material to the final design and implementation.

Also, a contact person is queried as the development of a new proposal is done in close collaboration with the submitter to ensure that the developed solution meets all requirements.

A key information is whether it is a new operating material or if there is already working equipment that should be improved. This distinction is made as for existing material several documents and information like technical drawings, material number (ID), manufacturing costs, the needed amount and the size and volume are already available. Considering that new operating materials have to be designed and applied for, the whole procurement process is way easier for improvements of existing operating equipment.

The material number in the case of existing operating materials and the designation are from importance as well. The name is already an indicator for the application and the shape of the part and can be used for a quick and easy identification. Through the material number, technical drawings and other information can be easily found.

At RRPS, there are several different engine series, naturally located at different parts throughout the company premises. Therefore, information about which series needs the operating material gives information about which employees need to be informed about a change and indicates who else has information about this idea and can be contacted about it.

Within the engine series, not all engines are the same. They differ from each other in size and build. Not every operating material is used for each engine type. During the assembly, employees need to know when to use which operating material and have to prepare all required parts beforehand, which is why the information is queried in the method.

Most operating equipment is used together with an engine component. It does not suffice to have the operating material readily prepared. The right place at the engine has to be known as well for a correct application. Common instances at RRPS are covers for open pipes during the assembly process. Those constitute a risk of dirt or small parts like screws falling inside, which can be prevented by having a lid. The condition for the solution to function is that the employee knows on which pipe to use the operating material.

Each engine is assembled at different stations along an assembly line. For some series, there are several lines the engines have to go along. Besides those lines, there is also the area where components are pre-assembled, the final assembly after the test runs and the paint department. The place of usage could be any station at any line or in some of the upstream or downstream departments. This information is needed for a correct placement of newly printed operating materials, without much questioning.

Besides these documentation data, the cause for an improvement or new material is important. As the main application of the method will be within the process optimisation, this cause is often some kind of problem during the assembly process. This might be errors occurring or employees struggling with current fixtures. Furthermore, whenever the safety of the employees is at risk, an operating material can reduce that risk. Whenever an error occurs, there are tracking numbers created for a follow-up. If one of those numbers is available, it should be included in the problem description, as more information can be gathered through them. With a detailed description of the issue, the urgency of an operating material can be judged additionally to the automated ranking that is created (cf. 3.2.2).

The cause of the need for an operating material has to be solved somehow. The solution the submitter has in mind is to be described, as it helps the AM expert to judge the manufacturability using 3D printing. A general statement along the lines of “solution for the problem” does not serve. Rather, a detailed description of the required solution should be formulated to support the design of the part and the understanding of the requirements regarding shape and targeted purpose of the operating material.

3.2.4 Structure of the developed method

Out of the data that are needed for the design and the criteria that are defined for the exclusion and the priority number, the method was designed. It was decided that Microsoft (MS) Excel is the most practicable solution, as it offers the possibility to include formulas. Also, the employees using the method are using MS Excel on a daily basis and are confident with its handling. The method is divided into five sections:

1. Information on the operating material
2. Problem description
3. Information on the solution
4. Main improvements
5. Decision and current state

Sections one to four are to be filled in by the submitter of a proposal. The fifth section includes mostly automatically filled in parts and just a few aspects that have to be decided manually.

The developed method starts with the information on the operating material (cf. figure 17). Like that, the base for the further processes and the design is given right at the beginning. During the development, it was important to keep the order of the information in mind. Before the name of the operating material is asked, it has to be stated whether it is an improvement or new equipment. Equally, the affected series should be queried before the affected component, going from the overall view to the smaller picture.

Figure 17 Part 1 - Information on the operating material

Information on the operating material						
Date	Contact person	New operating material / improvement of an operating material	Name of the operating material, ID if available	Affected series / engine types	Affected component (Name + ID)	Place of use (line/station)

Source: own work

Once all the information on the operating material is entered, the problem is described and classified by the frequency and severity (cf. 3.2.2, figure 18). This allows having all information needed about the problem bundled in one section.

Figure 18 Part 2 - Problem description

Problem description		
Problem description, Q-notification number, 8D report (if available)	(Error-) Frequency	(Error-) Severity

Source: own work

The suggested solution and the required properties are entered next (cf. figure 19). When thinking of the solution, the usage of the operating material is already being considered. Therefore, the exclusion criteria are queried in section as well. Further, the number of items needed is included. Like that, all the properties and information regarding the solution can be seen at one glance.

Figure 19 Part 3 - Information on the solution

Information on the solution				
Exclusion criteria				
Proposed solution	Is the material exposed to a heat >95°C?	Is an accuracy < 0,5mm required?	Does the part fit into 380 x 284 x 380 mm?	Number of items needed

Source: own work

In the last part that is to be filled in by the submitter, the main improvements have to be stated (cf. figure 20). They are formulated as yes/no questions to enable a simple and structured entering of information.

Figure 20 Part 4 - Main improvements

Main improvements		
Does the work safety get improved?	Is the quality getting ensured / are errors avoided?	Does the handling / the ergonomy for employees improve / does the effort decrease?

Source: own work

Based on the four previous sections and the exclusion and priority criteria, the decision about the manufacturability and the priority is made. The arrangement of the section can be seen in figure 21.

Figure 21 Part 5 – Manufacturability, urgency and current state

Decision and current state								
Is the operating material, based on the exclusion criteria, suitable for 3D printing?	Suggested implementation based on the number needed	Is it possible to manufacture the operating material conventionally? (Decided by AM expert)	Decision for additive manufacturing?	Priority number	Urgency	Comment regarding the implementation	Suggested way of implementation	Current state of implementation

Source: own work

First, the general suitability for 3D printing is assessed, explained in detail in 3.2.1. Then, the priority number and urgency are calculated, stated in 3.2.2.

After the assessment of the case, a comment regarding the implementation can be made. No matter how high the priority number is and how urgent a case may be, sometimes there are some facts that lead to an exclusion of the proposal even though all criteria of the method are fulfilled. One example is an operating material used for an engine type that is not to be continued in the future. Such information often just appears after doing a more detailed inquiry about the use and specific requirements. Other examples are information about why the proposal is postponed in favour of other cases or dates of meetings and their results.

Depending on the urgency, a suggested way of implementation is output in the method. The general way for a new operating material is to apply for it. For that, an operating material application has to be filed and submitted to the department by which it is processed. There, an identification number is assigned to the operating material and it is officially introduced. While this is the default way of implementation for each operating material, proposals with a high priority number and urgency require emergency measures. Such cases are transferred to the 3D printing workflow of the process optimisation team and printed as soon as possible. Only after this prototype is produced, an operating material application is filed and the material number is defined. For cases with a medium priority both options are possible. Here, a manual decision has to be made based on the information about the problem description and a personal estimation of the urgency.

Lastly, the current state of implementation is stated. There are several options to choose from in a drop-down menu:

- Waiting list
- Postponed
- Transferred to workflow
- Application for operating material filed
- Exclusion

Cases on the waiting list are not yet implemented but the process will soon be started by either transferring to the workflow or applying for it. Reasons for a postponement of cases could be one-time failures that do not have a high severity. The method as a whole is displayed in appendix C (p.70).

When all information is entered and the priority number and urgency is determined, all the proposals are sorted. The sorting of the proposals is done in two steps. The overall order and the one within the sorting criteria are shown in table 14.

Table 14 Sorting criteria

Sorting criteria	Ranking
1. Urgency	1.1 High
	1.2 Medium
	1.3 Low
2. Priority Number	2.1 Descending high to low

Source: own work

First, the cases are sorted according to their urgency. Issues with a high urgency are at the top and a low urgency at the bottom. They are then sorted by the priority number from high to low. This results in an order from high to low urgency and within that from high to low priority number.

4 Validation of the method

To ensure that the developed method is applicable and user-friendly and at the same time provides reasonable results it needs to be validated. For the validation, three approaches were meant to be pursued. Those are (1) collection of proposals in the process optimisation team, (2) proposals of the masking and paint department and (3) proposals of the employees at the assembly line. While the applicability has to be validated, the excel-file is not meant to be accessed by all employees at RRPS. One problem would be the saving space and the access for all users, as not each employee is allowed to each drive and folder. Even more important is however that changes by unauthorised persons must be avoided. Further, only credible suggestions should be made. They should base on previous errors or bring significant improvements. With too many people, inputs can get out of hand quickly, resulting a complex and confusing list of proposals. Therefore, the file is only made accessible for members of the process optimisation team. They are working with the current solution and will also work with the new method in future.

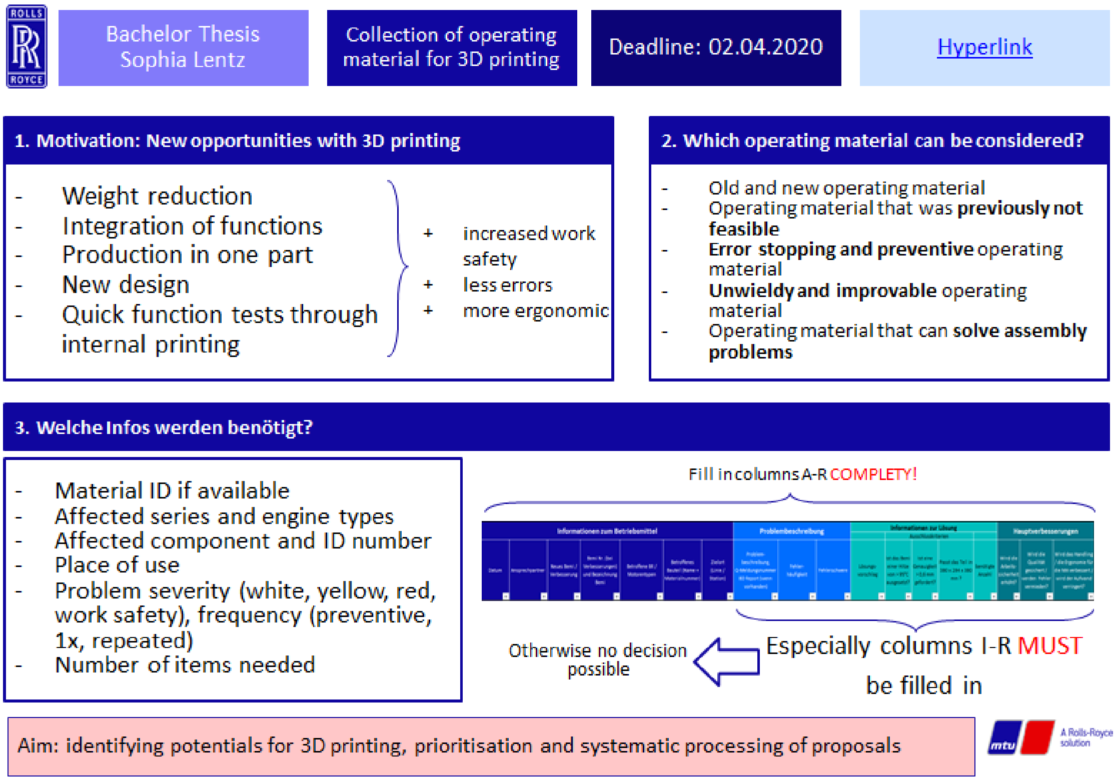
The normal process of making suggestions has to be distinguished from the approach in this thesis. Usually, all proposals are entered by the process optimisation team. They are approached by the masking and paint department or assembly when a need for new operating materials occurs. In the context of the validation, there is an one-time collection of suggestions by other departments done. This allows to introduce the topic of additive manufacturing and to raise awareness for the possibility of 3D printing for operating materials.

4.1 Approaches to the proposal collection

4.1.1 Process optimisation team

The main source of proposals was the process optimisation team. As their tasks include error elimination measures, they have a good knowledge of repeated errors and which problems can be avoided by using operating materials. To introduce the topic to them, an One-Pager was designed in MS PowerPoint (cf. figure 22).

Figure 22 One-Pager presentation for the process optimisation team



Source: own work

This was presented in the weekly team-meeting, so all team members could be informed at once and to answer any questions right away. Starting with a brief explanation of the topic and the motivation, the chances additive manufacturing offers and the resulting benefits especially in the assembly were pointed out. Then, the eligible operating materials were discussed. Besides new ideas for error avoiding or problem solving, existing equipment that has improvement potential and previously not feasible proposals can be included. As the method queries some information that has to be looked up, those are also displayed so they can be seen at one glance and missing parts can be identified quickly. Lastly, the layout of the method is shown, so the employees know what to expect. It is important that the columns are filled in entirely. Even one missing piece of information, especially in the section of problem description, information on the solution and main improvements, means that no decision can be made. This results in the proposal staying at the bottom of the priority list, which should be avoided in everyone's interest. The aim of the method, to identify potentials for 3D printing, prioritisation and the systematic processing of proposals, is summarised at the end of the One-Pager. During a time of three weeks, the team got the opportunity to enter all proposals into the method.

4.1.2 Masking and paint department

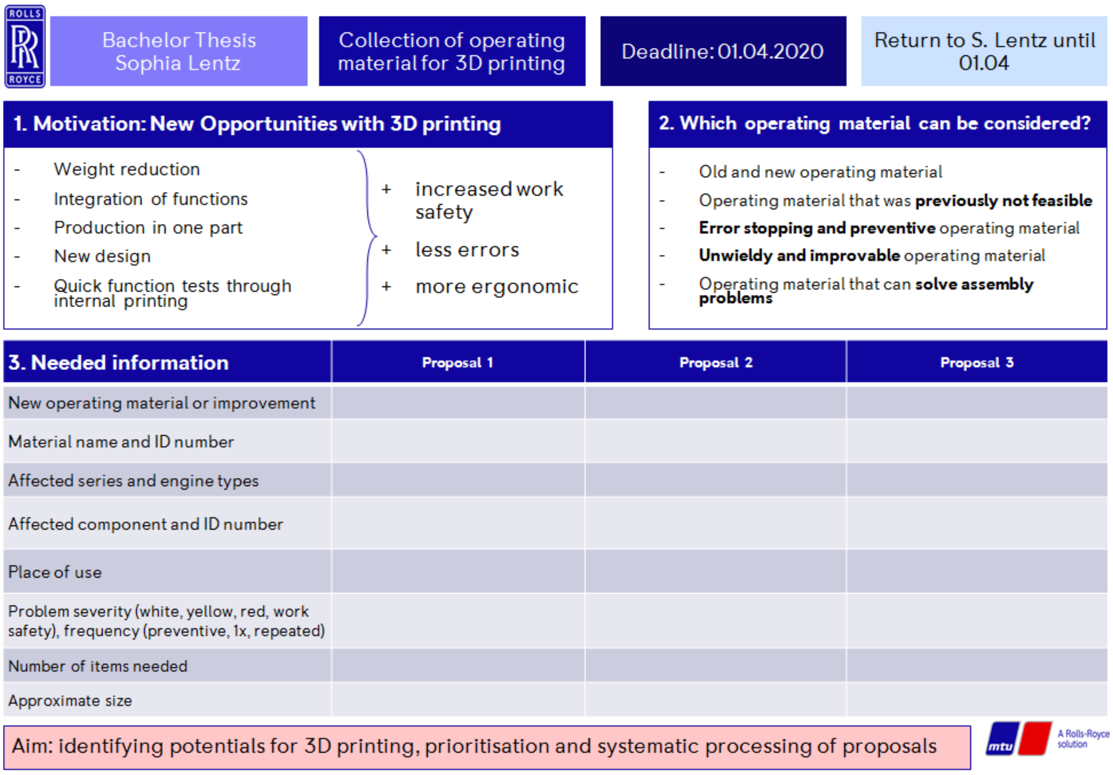
The second approach that was followed was to talk to the employees of the masking and paint department. Especially during the masking of parts that should not be painted, 3D printed parts can be beneficial. For complex parts, the masking is made significantly easier by having covers for the part, resulting in a time reduction and a better handling for the employees. Even a small gap can lead to varnish or paint spray on the component, which should be avoided by all means. Some parts have already been implemented with the aim to be used during the masking in the past. Therefore, the responsible employee for masking and painting has some experience in the possibilities of additive manufacturing. In the last few weeks, several issues have occurred, leading to some new proposals. As the access to the file is restricted, a meeting was arranged with the responsible employee to collect and talk through the suggestions. The proposals were then entered into the method together.

4.1.3 Assembly line

The employees at the assembly line are the ones who know best where improvement is needed, which errors occur often and how the handling and ergonomy for the workers can be improved. Due to the special situation during the SARS-CoV-2 outbreak and the measures taken by RRPS, a meeting with the Hanchos of the assembly line was not possible. Hancho is a Japanese term that translates to team leader. It was first introduced by the Toyota Production System (cf. Monden 2011, p. 421). Each Hancho is responsible for one section of the assembly and their tasks include the support during disruptions of the assembly process and continuous process improvement (cf. Jäns 2016, p. 120). Even though that approach could not be followed, the planned procedure will be explained.

The first step would be to contact the master of the series about the topic and the process of collecting suggestions. Once he is informed, an One-Pager would be distributed to functional managers and Hanchos. Figure 23 shows a first draft of this One-Pager.

Figure 23 One-Pager presentation for the assembly line


Bachelor Thesis Sophia Lentz

Collection of operating material for 3D printing

Deadline: 01.04.2020

Return to S. Lentz until 01.04

1. Motivation: New Opportunities with 3D printing

- Weight reduction
- Integration of functions
- Production in one part
- New design
- Quick function tests through internal printing

+ increased work safety
+ less errors
+ more ergonomic

2. Which operating material can be considered?

- Old and new operating material
- Operating material that was **previously not feasible**
- **Error stopping and preventive** operating material
- **Unwieldy and improvable** operating material
- Operating material that can **solve assembly problems**

3. Needed information	Proposal 1	Proposal 2	Proposal 3
New operating material or improvement			
Material name and ID number			
Affected series and engine types			
Affected component and ID number			
Place of use			
Problem severity (white, yellow, red, work safety), frequency (preventive, 1x, repeated)			
Number of items needed			
Approximate size			

Aim: identifying potentials for 3D printing, prioritisation and systematic processing of proposals

Source: own work

As can be seen, the top half of the One-Pager is the same as in the previously presented one for the process optimisation team (cf. 4.1.1). Only the bottom half is designed differently. As the employees in the assembly have only restricted access to a computer, a table for the proposal collection was designed. This DIN A 4 page would be distributed to the staff, providing them with an easy way to enter all information at once. The time frame would be about two weeks, with a reminder after one week. At the end of the deadline or earlier if already finished, the One-Pager with the filled in table would be returned to the author. The proposals would then be discussed, as not all information is included in the table. Even though this approach was not possible, the collection of proposals of the Hanchos will be done at a later point when the measures against SARS-CoV-2 are loosend again.

4.2 Results of the proposal collection

All proposals were entered into the method, either by the process optimisation team or by the author in meetings with employees. The results of the collection will be discussed in this section. It has to be noted that the data of the proposals are generalised due to confidential reasons.

4.2.1 Proposal 1 – pipe cover

The first proposal is an improvement of an existing operating material. During the assembly, an open pipe is currently covered with a foam lid. This lid falls off very easily, resulting in a risk of dirt or small parts falling inside. However, no error has followed out of this problem yet. The suggested operating material is therefore a preventive measure. To avoid the falling off of the lid, a cover made with 3D printing that have a tight fit and are slightly clamping to the pipe is suggested.

There is no special heat exposal and even though a tight fit is required, the accuracy reached by the 3D printer is still sufficient in this case. The diameter of the pipe does not exceed the space the build unit offers. All exclusion criteria are therefore met and there are no technical restrictions that obstruct the use of additive manufacturing.

As the lids stay with the engines during the assembly line, until the risk of parts falling inside the pipe is eliminated, 140 parts, a quite high number, is needed to cover all engines.

The improvement of the operating material does not increase the work safety, but the quality is getting ensured and errors are avoided. The handling for employees will not improve significantly, so this benefit is not reached.

4.2.2 Proposal 2 – test pin

Another proposal regards a new operating material. The problem is a component that was installed the wrong way round, preventing the engine from spinning. The error has occurred before and is therefore classified as a repeated error. Further, it was detected by the customer and is indicated as red. From the identification number of the 8D Report, the report can be found and the RPN figured. The severity was assessed with seven, the occurrence with three and the detection with seven (cf. Appendix A, p. 68 (table 21)). This results in an RPN of 147 and a serious red error. To avoid the error in future, the solution proposal is to introduce an additive manufactured test pin with a mark that indicates the correct assembly.

The proposal meets all exclusion criteria. It is not exposed to a great heat, does not require a high accuracy and it does fit into the building space of the printer. Just two pieces are required for a full coverage of the need, as the test pins stay at one station and do not move through the assembly with the engine.

Out of the three main improvements, only the quality is getting ensured by avoiding errors. The operating material does not improve the work safety or the handling and ergonomy for the employees.

4.2.3 Proposal 3 - masking

The majority of proposals was made by the masking and paint department. As quite some time can be saved especially during the masking of parts, there is always some need for new operating material. The proposals are quite similar, only differing in shape and number of items needed. Therefore, only one of the proposals is presented in this work.

The chosen proposal is a new operating material, needed for a quite large part that takes up some time during the masking process. It is a preventive measure. During the masking, it is made sure that all parts are covered properly, despite the time needed. However, there is always the chance that errors occur and a time reduction enables the employees to cover more engines per day, resulting in a higher productivity. Therefore, the error frequency and severity are classified as preventive.

During the masking and painting, the engine is not exposed to a heat greater than 95°C and a press fit is not required as well. However, as the affected component is quite big, it is hard to judge whether the proposal fits into the build unit. Therefore, the question if the part fits into 380 x 284 x 380 mm was answered with “not clear”. To cover all engines, 40 parts are needed.

Two out of the three possible improvements are achieved by the operating material. The quality is getting ensured and the handling for the employees is improved by decreasing the effort during the process. The work safety is not improved by the proposal.

4.2.4 Proposal 4 – damage avoidance

There is a component that often causes problems, as it is damaged during the assembly process. This happens repeatedly and causes a necessary replacement of the component before it gets dispatched. The error is classified to have a light yellow severity.

The proposed solution is a cover that is put on the component right at the beginning of the process. The exclusion criteria are all met, as the component is not exposed to great heat, it does not need a high accuracy and it also fits into the printer.

By the solution, the quality is getting ensured, but the work safety is not improved and the handling for the employees does not get enhanced either.

4.2.5 Proposal 5 – wrong assembly

Proposal number five is based on the wrong assembly of a component. Even though a technical drawing exists, the employees frequently have to fix the component at the next station. As it always gets detected very early, the error severity is judged as light white, while the frequency is entered as repeated error.

The operating material would stay with the engine. During the process, it will get exposed to a het higher than 95°C. A high accuracy is not required and the size does not exceed the build unit. For a complete coverage of all engines, 30 items are needed.

While the work safety is not improved by the operating material, errors are avoided and the assembly effort for the employees decreases. Thus, two out of the three main improvements are achieved.

4.2.6 Proposal 6 – work safety

The last proposal is a work safety issue. Employees have repeatedly hurt themselves at the sharp edges of a holder. The error severity is judged as a preventive measure, as it cannot be judged on a scale from light white to serious red (cf. 3.2.2). To avoid future injuries, a 3D printed cover for the sharp edges is suggested. The exclusion criteria are all fulfilled, as the holder is not exposed to a heat of more than 95°C, it does not require a high accuracy and it fits into 380 x 284 x 380mm. The series where the operating material is needed has a quite small number of engines per day. Therefore, only 12 items are needed, even though it is circulation material.

All three of the main improvements are fulfilled. Besides the work safety that is ensured, the handling for the employees improves. They do not have to be extra careful when working with the holder anymore and can concentrate on their actual task. Additionally, the quality is getting ensured for the same reason.

4.3 Assessment of the results

The result of the prioritisation should represent a decision and sorting that can be understood and justified by the AM expert. As sections one to four of the method are filled in by the submitter, the assessment of the results is concentrating on section five (cf. 3.2.4). The decisions that are checked are the following:

- Suitability for 3D printing based on the exclusion criteria
- Decision for additive manufacturing
    - Suggested implementation based on the number needed
- Priority Number and Urgency
- Suggested way of implementation

4.3.1 Assessment of proposal 1 – pipe cover

The first proposal that was made is regarding the coverage of a pipe. Based on the information entered by the submitter, the following decisions should be reached.

As all exclusion criteria are met, the part is, in principle, suited for additive manufacturing. However, this does not mean that the design can start right away. In total, 140 items are needed. Based on the scale defined in 3.2.1, the method should give back that both additive and conventional manufacturing technologies are possible. The final decision about the production technology is made by the AM expert. An offer about the production of new covers out of foam has shown that there is no cost advantage when using 3D printing. Additionally, the part should slightly clamp to the pipe, which is difficult to realise with additive manufacturing. As a conventional production is possible, the decision should be against additive manufacturing, leading to an exclusion of the part. This decision is supported by the quite high number needed.

Even though it is expected that the part will be excluded by the method, a priority number is still calculated. No error has occurred yet, so the improvement will be a preventive measure. Accordingly, the frequency and severity are judged as preventive. With error avoidance being the only improvement that is reached, the priority number is expected to be quite low. Consequently, the urgency should be low too, which would correspond to the assessment by the AM expert. A low urgency should then result in a suggested implementation via an operating material application. As the proposal is expected to be excluded anyway, the suggested way of implementation should not be stated.

As can be seen in table 15, the actual result is matching the expected. Based on the data entered by the submitter, the method comes to the same decision as the AM expert.

Table 15 Proposal 1 - expected vs. actual result

	Expected result	Actual result
Suitability for 3D printing	Yes	Yes
Suggest implementation based on the number needed	Both are possible	Both are possible
Decision for 3D printing?	No	No
Priority number and urgency	Low priority number and urgency	Low priority number and urgency
Suggested way of implementation	Exclusion	Exclusion

Source: own work

4.3.2 Assessment of proposal 2 – test pin

The next submitted part was a test pin to ensure the correct assembly of a component. Based on the fact that the exclusion criteria are all fulfilled, the method should declare the part as suitable for additive manufacturing. For a full coverage, only two items are needed. As additive manufacturing is almost always the most economic decision for small numbers, this should be the suggested implementation. Based on the design, it is also possible to produce the part using a conventional technology. However, the low number of needed parts should still result in a decision for additive manufacturing.

The problem on which the proposal is based is classified as a repeated, serious red error. At the same time, the quality is getting ensured but no other improvements are achieved. Nevertheless, as the severity of the error is the highest it can get, a high priority number and urgency is expected. Resulting out of this, the suggested way of implementation should be via the 3D printing workflow, to ensure a fast realisation. The expectations are largely met, except the priority number that represents a medium urgency and the resulting way of implementation (cf. table 16).

Table 16 Proposal 2 - expected vs. actual result

	Expected result	Actual result
Suitability for 3D printing	Yes	Yes
Suggest implementation based on the number needed	Additive manufacturing	Additive manufacturing
Decision for 3D printing?	Yes	Yes
Priority number and urgency	High priority number and urgency	Medium priority number and urgency
Suggested way of implementation	Implementation via work-flow	Manual decision about the way

Source: own work

4.3.3 Assessment of proposal 3 - masking

For proposal three, made by the masking department, the measures are not clear. Until they are checked, it is expected that no decision about the suitability of the case can be made by the method. If the part fits, it should be suited for additive manufacturing. As 40 units are needed, the suggested implementation is 3D printing as well. At the same time, the low complexity qualifies the operating material for a conventional production. The decision should still be for 3D printing, as at 40 items, it is expected to still be the most economic choice.

Though the proposal is a preventive measure, it still reaches two improvements. The priority number is therefore expected to be low or medium. If the urgency is low, the proposal is suggested to be implemented via an application for a new operating material. A medium urgency can be implemented via the 3D printing workflow, during which an application is filed as well. Table 17 shows that the results are matching the expectation.

Table 17 Proposal 3 - expected vs. actual result

	Expected	Actual
Suitability for 3D printing	Cannot be taken yet	Cannot be taken yet
Suggested implementation based on the number needed	Additive manufacturing	Additive manufacturing
Decision for 3D printing?	Depending on the measures	Depending on the measures
Priority number and urgency	Low to medium priority number and urgency	Low priority number and urgency
Suggested way of implementation	Depending on the urgency	Implementation via application for new operating material

Source: own work

4.3.4 Assessment of proposal 4 – damage avoidance

All exclusion criteria are fulfilled by proposal four, that is needed to protect a component from getting damaged. An exclusion based on one of them should therefore not happen. 15 items are needed for each engine type. For such a low number, additive manufacturing is usually the most economic choice. Additionally, from the technical point of view, a conventional manufacturing is not recommended. Metal would pose a risk of also damaging the component and something like foam could be too soft and not keep the shape well enough. Therefore, the decision should be for 3D printing.

A repeated error that is classified as light yellow and brings only one improvement should have medium to high urgency. The suggested way of implementation can then be both, via the workflow or an application. In table 18, the results are compared to each other.

Table 18 Proposal 4 - expected vs. actual result

	Expected result	Actual result
Suitability for 3D printing	Yes	Yes
Suggest implementation based on the number needed	Additive manufacturing	Additive manufacturing
Decision for 3D printing?	Yes	Yes
Priority number and urgency	Medium to high priority number and urgency	Medium priority number and urgency
Suggested way of implementation	Depending on the urgency	Manual decision about the way

Source: own work

4.3.5 Assessment of proposal 5 – wrong assembly

This proposal is exposed to a great heat. Therefore, it should be excluded based on exclusion criteria by the method. No further assessment is done.

Table 19 Proposal 5 - expected vs. actual result

	Expected result	Actual result
Suitability for 3D printing	No	No
Suggested way of implementation	Exclusion	Exclusion

Source: own work

4.3.6 Assessment of proposal 6 – work safety

Lastly, the work safety issue is assessed. In this case as well, all exclusion criteria are met. The method is therefore expected to declare the case as suited for 3D printing. As only 12 items are needed for a complete coverage, the suggested implementation should be additive manufacturing.

The part is a repeated error, with the severity judged as preventive measure. Additionally, all three possible improvements are achieved when implementing this proposal. The work safety improvement alone should result in a high urgency, no matter which priority number is reached. However, with three achieved benefits and a repeated error, the priority number is expected to be very high as well. The suggested way of implementation should then be via the 3D printing workflow.

For this proposal, expected and actual result are corresponding as well. In table 20, the results are compared.

Table 20 Proposal 6 - expected vs. actual result

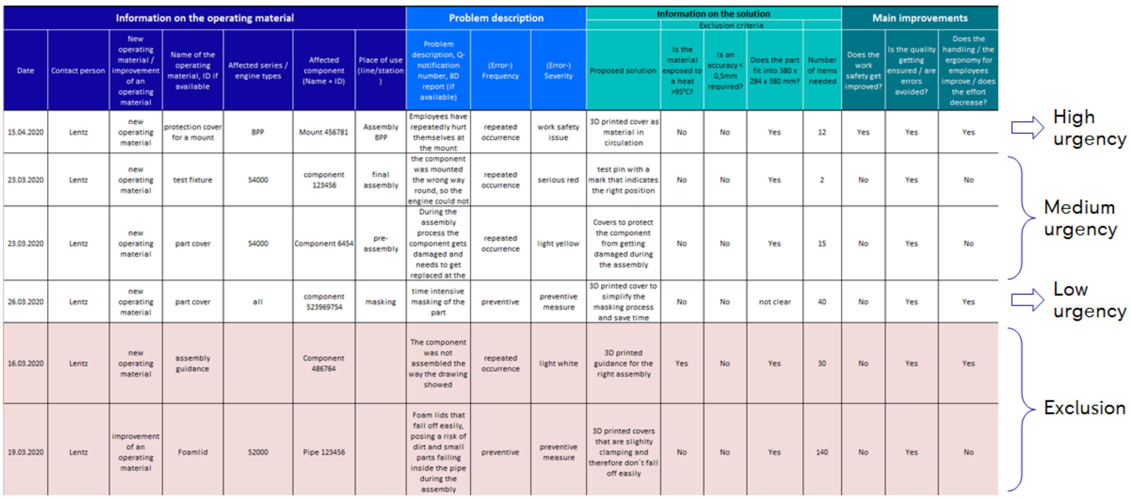
	Expected result	Actual result
Suitability for 3D printing	Yes	Yes
Suggest implementation based on the number needed	Additive manufacturing	Additive manufacturing
Decision for 3D printing?	Yes	Yes
Priority number and urgency	High priority number and urgency	High priority number and urgency
Suggested way of implementation	Implementation via workflow	Implementation via workflow

Source: own work

4.3.7 Assessment of the sorting

The final step of the validation is the assessment of the implementation order the method gives back. It results out of the sorting (cf. 3.2.4) and is shown in figure 24. The sorting can be seen in more detail in appendix C (p. 70).

Figure 24 Order of the proposals



Information on the operating material							Problem description			Information on the solution	Exclusion criteria				Main improvements		
Date	Contact person	New operating material / improvement of an operating material	Name of the operating material, ID if available	Affected series / engine types	Affected component (Name + ID)	Place of use (line/station)	Problem description, Q-notification number, 8D report (if available)	(Error-) Frequency	(Error-) Severity	Proposed solution	Is the material exposed to a heat >95°C?	Is an accuracy < 0,5mm required?	Does the part fit into 380 x 284 x 380 mm?	Number of items needed	Does the work safety get improved?	Is the quality getting ensured / are errors avoided?	Does the handling / the ergonomy for employees improve / does the effort decrease?
15.04.2020	Lentz	new operating material	protection cover for a mount	BPP	Mount 456781	Assembly BPP	Employees have repeatedly hurt themselves at the mount	repeated occurrence	work safety issue	3D printed cover as material in circulation	No	No	Yes	12	Yes	Yes	Yes
23.03.2020	Lentz	new operating material	test fixture	S4000	component 123456	final assembly	the component was mounted the wrong way round, so the engine could not	repeated occurrence	serious red	test pin with a mark that indicates the right position	No	No	Yes	2	No	Yes	No
23.03.2020	Lentz	new operating material	part cover	S4000	Component 6454	pre-assembly	During the assembly process the component gets damaged and needs to get replaced at the	repeated occurrence	light yellow	Covers to protect the component from getting damaged during the assembly	No	No	Yes	15	No	Yes	No
26.03.2020	Lentz	new operating material	part cover	all	component 523969754	masking	time intensive masking of the part	preventive	preventive measure	3D printed cover to simplify the masking process and save time	No	No	not clear	40	No	Yes	Yes
16.03.2020	Lentz	new operating material	assembly guidance		Component 486764		The component was not assembled the way the drawing showed	repeated occurrence	light white	3D printed guidance for the right assembly	Yes	No	Yes	30	No	Yes	Yes
19.03.2020	Lentz	improvement of an operating material	Foamlid	S2000	Pipe 123456		Foam lids that fall off easily, posing a risk of dirt and small parts falling inside the pipe during the assembly	preventive	preventive measure	3D printed covers that are slighlty clamping and therefore don´t fall off easily	No	No	Yes	140	No	Yes	No

Source: own work

The case that is deemed as the most important is the work safety issue (proposal 6) that achieves all three possible improvements. Right after, the test pin (proposal 2) is on the second place, followed by the proposal classified as light yellow (proposal 4). Then comes proposal 3 made by the masking and lastly, the two excluded proposals 1 (pipe cover) and 5 (wrong assembly). They are already highlighted red to indicate the exclusion.

This sorting was then compared to the judgement by the AM expert. They confirmed that it is a reasonable order that matches their assessment.

4.4 Changes made based on the validation

Overall, the outcome of the method matches a manual decision rather well. There is however one point that needs to be rethought. Proposal 6, the work safety issue, was rightly judged with a high urgency. However, proposal 2, the test pin, is a serious red error, meaning that it was detected by the customer. Additionally, it is a repeated problem. Such issues should be rated with a high urgency. The case was however rated with a medium urgency. As a result, the gradation steps of the scale regarding the urgency have to be adjusted. Before, each kind of urgency was represented by one third of the scale from 0 to 100 (cf. 3.2.2). This is now changed into the following:

- 0 – 30 low urgency
- >30 – 60 medium urgency
- >60 – 100 high urgency

Any priority number that is higher than 60 results in a high urgency for the case. To reach an equal size of the other two sections, the limit between a low and medium urgency is adjusted as well. With those adjustments, the classification of the priority is tailored to the cases that occur at RRPS.

5 Conclusion and Outlook

The main part of this thesis is the development of a method that allows RRPS to identify suitable operating materials for additive manufacturing and their implementation priority. With the theoretical background about different 3D printing processes and the HP Jet Fusion 4200 used at RRPS, the relevant criteria regarding technological restrictions could be identified. These exclusion criteria are (1) the heat an operating material is exposed to, (2) the accuracy that is required and (3) the size of the operating material. They are complemented by the number needed, which is an indicator for the manufacturing costs. Based on these criteria, a decision about the suitability of an operating material for 3D printing can be made.

Existing methods that help to determine the suitability of parts for additive manufacturing have laid the groundwork for possible improvements that can be achieved. In combination with the requirements of RRPS, the improvements of importance were identified. The possible improvements that can be achieved by an operating material are (1) an improved work safety, (2) quality assurance and error avoidance and (3) improvement of handling and ergonomy for employees. Additionally, the problem, out of which the need for an operating material occurs, is classified into problem frequency and severity. The combination of achieved improvements and problem classification results in a priority number that indicates the urgency of a case. With the analytic hierarchy process, a transparent and comprehensible development of this priority number was possible. The implementation priority and the resulting sorting of cases close a gap in the currently available literature. Additionally to the exclusion and priority criteria, some more information regarding operating materials are included in the method. They include information about the contact person, the place of use, affected engines and components, identification numbers etc. These information are the base for further processing and the design of the part.

The information and criteria were developed according to the requirements of the process optimisation team at RRPS and the application scope of operating material. For other applications or companies, it is likely that some aspects have to be changed, e.g. different exclusion criteria or other information.

Lastly, the method could be validated with some application cases and has proven its applicability and accuracy.

There are still some improvement potentials in the developed method. While the entering of the needed information into the next free row in the excel sheet is a perfectly suitable way, there is an easier solution. The best way would be an input screen that automatically opens when selecting the first cell of a row. In that screen, mandatory information has to be filled in before finishing. At the same time, the required information is displayed in a more transparent way. The input mask can be realised with visual basic for applications (VBA) programming. The needed effort would however exceed the scope of this thesis.

Another potential is an automated sorting of the proposals. This could happen whenever the file is opened. It would enable the AM expert to see the priority and state of implementation at one glance without having to manually sort the data.

A last suggestion for a possible improvement is a connection to the following steps of the process. This includes forwarding to the application for an operating material through a hyperlink. Further, some of the information that is required for the method is also needed in the 3D printing workflow of the process optimisation team. An automated takeover of these into the workflow when the case is transmitted would save the employees some time and prevent errors caused by the copying. It was refrained from the inclusion in this thesis as it is likely that some VBA programming is needed.

These are just some of the possibilities for further development of the method. Nevertheless, the developed method supports the decision making regarding the 3D printing of operating materials at the process optimisation team. The workload for the AM expert is reduced, so they can concentrate on other important tasks. For the process optimisation team, the developed method simplifies the process of introducing an additive manufactured operating material. It will support RRPS in gaining experience in the topic of 3D printing and enable the further introduction in the scope of operating materials.

VI List of references

3D Systems Inc. (2016). Online Source. Available at: https://www.methodsmachine.com/assets/prox-950_20160621_WEB.pdf (accessed on 12.05.2020).

Additively AG (2018a). Online Source. Binder Jetting (BJ). Available at: https://www.additively.com/en/learn-about/binder-jetting (accessed on 09.12.2019).

Additively AG (2018b). Online Source. Laser Sintering (LS). Available at: https://www.additively.com/en/learn-about/laser-sintering (accessed at 09.12.2019).

Additively AG (2018c). Online Source. Fused Deposition Modeling (FDM). Available at: https://www.additively.com/en/learn-about/fused-deposition-modeling (accessed on 09.12.2019).

Additively AG (2018d). Stereolithography (SL). Available at: https://www.additively.com/en/learn-about/stereolithography (accessed on 09.12.2019).

Additively AG (2018e). Photopolymer Jetting (PJ). Available at: https://www.additively.com/en/learn-about/photopolymer-jetting (accessed 09.12.2019).

Attaran, M. (2017). Additive Manufacturing: The Most Promising Technology to Alter the Supply Chain and Logistics. Journal of Service Science and Management 10 (03), 189–206. https://doi.org/10.4236/jssm.2017.103017.

Berti, S. (2010). Vergangenheit, Gegenwart und Zukunft eines theoretischen Konstrukts. In: Psychologische Rundschau 61 (1), S. 3-9. DOI:

10.1026/0033-3042/a000004.

Bodden, V. (2018). 3-D printers. Minneapolis, Minnesota, Checkerboard Library.

Bühler, P. / Schlaich, P. / Sinner, D. (2019). Produktdesign. Konzeption – Entwurf – Technologie. Berlin, Heidelberg, Springer Vieweg Berlin, Heidelberg.

Burkhart, M. / Aurich, J. C. (2017). Bauteilidentifikation in der additiven Fertigung. In: Zeitschrift für wirtschaftlichen Fabrikbetrieb 112. Carl Hanser Verlag, München.

Campbell T. / Williams C. / Ivanova O. / Garrett B. (2011). Could 3D printing change the world? Technologies, Potential and Implications of Additive Manufacturing. Atlantic Council, Strategic Foresight Report 2011. (accessed on 03.02.2020).

DIN ISO 2768-1:1991-06. Allgemeintoleranzen; Toleranzen für Längen- und Winkelmaße ohne einzelne Toleranzeintragung.

EOS GmbH (2020). Online Source. Available at: https://www.eos.info/de/additive-fertigung/3d-druck-kunststoffe/eos-polymer-systeme/eos-p-770 (accessed on 10.05.2020).

Fastermann, P. (2012). 3D-Druck/Rapid Prototyping. Eine Zukunftstechnologie - Kompakt Erklärt. Berlin, Heidelberg, Springer-Verlag Berlin Heidelberg.

Feldmann, C. / Pumpe, A. (2016). 3D-Druck - Verfahrensauswahl und Wirtschaftlichkeit. Entscheidungsunterstützung für Unternehmen. Wiesbaden, Springer Gabler.

Gebhardt, A. (2016). Additive Fertigungsverfahren. Additive Manufacturing und 3D-Drucken für Prototyping - Tooling - Produktion. 5. Edn. München, Hanser.

Gebhardt, A. / Kessler, J. /Thurn, L. (2019). 3D Printing - Understanding Additive Manufacturing. 2. Edn. München, Carl Hanser Verlag.

Gebhardt, R. (2018). Online Source. 3D Druck setzt sich im Maschinenbau durch. Available at: https://www.vdma.org/v2viewer/-/v2article/render/26469625 (accessed on 21.04.2020).

Gibson, I. / Rosen, D. / Stucker, B. (2015). Additive Manufacturing Technologies. New York, NY, Springer New York.

Hamke, A. / Striapunina, K. / Staffa, V. (2017). Made-in-Country-Index. Statista. available at: https://de.statista.com/page/Made-In-Country-Index . (accessed on 04.05.2020).

HP Development Company, L. P. (2020a). Online Source. HP 3D High Reusability PA 12. Available at: https://static1.sw-cdn.net/files/cms/materials/data-sheets/HP%20Data%20sheet.pdf (accessed on 28.04.2020).

HP Development Company, L. P. (2020b). Online Source. HP 3D High Reusability PA 11. Available at: https://cimquest-inc.com/resource-center/HP/Materials/HP-PA11-Datasheet.pdf (accessed on 28.04.2020).

HP Development Company, L. P. (2020c). Online Source. HP 3D printing materials. Available at: https://www8.hp.com/h20195/v2/getpdf.aspx/4AA7-1533ENA.pdf (accessed on 28.04.2020).

HP Development Company, L. P. (2020d). Online Source. HP Jet Fusion 4200 3D Printing Solution. Available at: https://www8.hp.com/h20195/v2/GetDocument.aspx?docname=4AA6-4892ENA (accessed on 28.04.2020).

HP Development Company, L. P. (2020e). Online Source. Specifications to help you choose. Available at: https://www8.hp.com/h20195/v2/GetDocument.aspx?docname=4AA7-4999ENA (accessed on 28.04.2020).

HP Development Company, L. P. (2020f). Online Source. Reinventing 3D Printing. See how the HP Jet Fusion 3D printing solution unlocks the full potential of 3D printing. Available at: https://www8.hp.com/h20195/v2/GetDocument.aspx?docname=4AA6-6446ENW (accessed on 28.04.2020).

HP Development Company, L.P. (2020g). Online Source. Available at: https://www8.hp.com/us/en/printers/3d-printers/products/multi-jet-fusion-4200.html?jumpid=hpr_r1002_usen_link4 (accessed on 12.12.2019).

HP Development Company, L.P. (2020h). Online Source. Available at: https://h20195.www2.hp.com/V2/getpdf.aspx/4AA7-7085ENW.pdf . (Accessed on 13.05.2020)

HP Development Company, L.P. (2016). Online Source. HP Delivers World´s First Production-Ready 3D Printing System. Available at: https://press.ext.hp.com/us/en/press-releases/2016/hp-delivers-worlds-first-production-ready-3d-printing-system.html#.Vz8x3PkrKUk (accessed on 29.04.2020)

HP Development Company, L. P. (2018a). Online Source. HP Jet Fusion 3D 3200, 4200, 4210 Drucklösung Benutzerhandbuch. Available at: http://h10032.www1.hp.com/ctg/Manual/c05448928 (accessed on 28.04.2020).

HP Development Company, L. P. (2018b). Online Source. HP Multi Jet Fusion Technology. A disruptive 3D printing technology for a new era of manufacturing. Technical White Paper. Available at: https://enable.hp.com/us-en-3dprint-wp-technical (accessed on 28.04.2020).

Irsa, W. / Besendorfer, K. (2019). 3-D-Druck. in: Sabrina Romina Sorko/Wolfram Irsa (ed.). Interaktive Lehre des Ingenieursstudiums. Berlin, Heidelberg, Springer Berlin Heidelberg, 117–144.

Jäns, I. (2016). Erfolgreiche Gruppenarbeit. Konzepte, Instrumente, Erfahrungen. Gabler Verlag.

Knofius, N. / van der Heijden, M. C. / Zijm, W. H. M. (2016). Selecting parts for additive manufacturing in service logistics. University of Twente. https://doi.org/10.1108/JMTM-02-2016-0025.

Lennings, F. / Bart, H. / Nübel, H. / Wette, O. (2019). Abläufe verbessern - Betriebserfolg garantieren. Berlin, Heidelberg, Springer Berlin Heidelberg.

Leutenecker-Twelsiek, B. (2019). Additive Fertigung in der industriellen Serienproduktion: Bauteilidentifikation und Gestaltung. Doctoral Thesis. https://doi.org/10.3929/ethz-b-000347164.

Lindemann, C. / Reiher, T. / Jahnke, U. / Koch, R. (2015). Towards a sustainable and economic selection of part candidates for additive manufacturing. Rapid Prototyping Journal 21 (2), 216–227. https://doi.org/10.1108/RPJ-12-2014-0179.

Mellor, S. / Hao, L. / Zhang, D. (2014). Additive manufacturing: A framework for implementation. International Journal of Production Economics 149, 194–201. https://doi.org/10.1016/j.ijpe.2013.07.008.

Monden, Y. (2011). Toyota Production System. An Integrated Approach to Just-In-Time. Productivity Press.

MTU Friedrichshafen GmbH (2013). Kriterienkatalog RPZ. Internal document.

Newell, A. / Simon, H.A. (1972). Human Problem Solving. Englewood Cliffs. N.J. Prentice Hall.

Paulsen, Greg (2019). Online Source. What is the 3D Printing vs Injection Molding Cost-per-Unit Breakeven? Available at: https://www.xometry.com/blog/3d-printing-vs-injection-molding-breakeven. (accessed on 18.03.2020).

Riedel, C. (2020). Application scope and decision criteria of RRPS. Oral interview.

Rolls-Royce Holdings plc (2020). Online Source. 2019 Annual Report. Available at: https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/annual-report/2019/2019-full-annual-report.pdf (accessed on 10.05.2020).

Rolls-Royce Power Systems AG (2020). Online Source. Available at: https://www.mtu-solutions.com/eu/en/applications.html (accessed on 10.05.2020).

Ronniger, Curt Ullrich (2019). Online Source. Analytischer Hierarchieprozess. Available at: http://www.versuchsmethoden.de/AHP.pdf (accessed on 24.03.2020).

Saaty, T. L. / Vargas, L. G. (2012). Models, Methods, Concepts & Applications of the Analytic Hierarchy Process. Dordrecht, Springer US.

Schmid, M. (2015). Additive Fertigung mit selektivem Lasersintern (SLS). Prozess- und Werkstoffüberblick. Wiesbaden, Springer Vieweg.

Schwarz R. (2016). Grundzüge der Sicherheitstechnik. In: Sachkunde im Bewachungsgewerbe (IHK). Wiesbaden, Springer Gabler.

Stratasys Ltd. (2020a). Online Source. Available at: https://www.stratasys.com/3d-printers/fortus-380mc-450mc. (accessed on 27.04.2020).

Stratasys Ltd. (2020b). Online Source. Available at: https://www.stratasys.com/3d-printing-industries (accessed on 29.04.2020).

Stratasys Ltd. (2020c). Online Source. Available at: https://www.stratasys.com/de/3d-printers/objet-350-500-connex3 (accessed on 12.05.2020)

Stratasys Ltd. (2020d). Online Source. Available at: https://www.stratasys.com/3d-printers (accessed on 12.05.2020).

Venkataraman, K. (2015). Design of Jigs, Fixtures and Press Tools. Chichester, West Sussex/London, John Wiley and Sons; Athena Academic Ltd.

Wohlers, T. T. (2019). Wohlers Report 2019. 3D printing and additive manufacturing state of the industry. Fort Collins, Colorado, Wohlers Associates.

Zeyn, H. (2017). Industrialisierung der Additiven Fertigung. Digitalisierte Prozesskette - von der Entwicklung bis zum einsetzbaren Artikel Industrie 4.0. Berlin, Wien, Zürich, Beuth Verlag, VDE Verlag.

Appendix A

FMEA Risk Assessment

Table 21 FMEA risk assessment

	Severity (as part of the FMEA analysis)	Probability of occurring	Detection probability
1	**Minor** no impact on function or production process, very low relevance for the customer, very low correction effort regarding costs	**Improbable** very rare occurrence, technical avoidance measures introduced, proven concept, low complexity	**Certain** the error gets detected certainly during the process, implemented a technical error check
3	**Low** function and production process are lightly impacted, low relevance for customer, low correction effort	**Low** error is repeated few unconnected times, organisational specified technical measures, proven concept with small changes, low complexity	**High** error gets detected; technical measures are implemented
5	**Intermediate** function and production are available only restricted, relevance for customer is moderate, medium correction efforts	**Intermediate** occasional occurrence, detailed organisational avoidance, proven concept with changes, manageable complexity	**Intermediate** error can get detected; organisational error checking measures are implemented
7	**High** failure of function, danger of light injuries, serious affection of production process, high correction effort	**High** repeated error, organisational or personal avoidance, mainly new concept, high complexity	**Low** error is hard to detect; organisational or personal error checking is implemented
10	**Significant** total failure of function, danger of serious injuries, very severe affection of production, high relevance for the customer and very high correction effort	**Very high** systematic, regular occurrence, no avoidance measures, new concept without experience, high complexity	**Improbable** error is hard to detect; no error checking measures are taken

Source: MTU Friedrichshafen GmbH 2013

Appendix B

Standardisation of the (Error-) Frequency

The quantification of the three forms of the frequency has to be made according to the basic scale from 0,1 to 1. They are first rated with 0,1, 0,2 and 0,3. These values are then standardised to the basic scale. The calculation can be seen in formula 5.

$$\frac{(x-0{,}1)}{0{,}2} \qquad 5$$

x corresponds to the number defined beforehand, either 0,1, 0,2 or 0,3. Of x, the minimum value is subtracted, resulting in $(x-0{,}1)$. This is then divided by the difference between the maximum and the minimum value. In this case, it is $0{,}3-0{,}1=0{,}2$. The results are then:

- 0 preventive measure
- 0,5 one-time occurrence
- 1 repeated occurrence

Standardisation of the achieved improvements

The same has to be done for the quantification of the achieved improvements. There are seven combination possibilities, first defined from 0,1 to 0,7. They are standardised to a scale from 0,1 to 1 with formula 6.

$$0{,}1+\frac{(x-0{,}1)}{0{,}6}\times 0{,}9 \qquad 6$$

(x-0,1) has the same definition as before. There is an 0,1 added before the fraction, as the basic scale starts with 0,1 instead of 0. The division by 0,6 results out of the difference of the maximum value 0,7 and the minimum value 0,1. Finally, the fraction is multiplied with 0,9, resulting out of the span from 0,1 - 1 of the final scale.

- 0,1 Improvement of Handling
- 0,25 Error Avoidance
- 0,4 Improvement of handling + error avoidance
- 0,55 Improved work safety
- 0,7 Improved work safety + improvement of handling
- 0,85 Improved work safety + error avoidance
- 1 Improved work safety + error avoidance + improvement of handling

Appendix C

Whole Method

Continued on page 71

Information on the operating material						
Date	Contact person	New operating material / improvement of an operating material	Name of the operating material, ID if available	Affected series / engine types	Affected component (Name + ID)	Place of use (line/station)
15.04.2020	Lentz	new operating material	work saftey, protection cover for a mount	BPP	Mount 456781	Assembly BPP
23.03.2020	Lentz	new operating material	test pin	S4000	component 123456	final assembly
23.03.2020	Lentz	new operating material	damage avoidance part cover	S4000	Component 6454	pre-assembly
26.03.2020	Lentz	new operating material	masking part cover	all	component 523969754	masking
16.03.2020	Lentz	new operating material	assembly guidance (wrong assembly)		Component 486764	
19.03.2020	Lentz	improvement of an operating material	Pipe cover	S2000	Pipe 123456	

	Problem description		
Date	Problem description, Q-notification number, 8D report (if available)	(Error-) Frequency	(Error-) Severity
15.04.2020	Employees have repeatedly hurt themselves at the mount	repeated occurrence	work safety issue
23.03.2020	the component was mounted the wrong way round, so the engine could not	repeated occurrence	serious red
23.03.2020	During the assembly process the component gets damaged and needs to get replaced at the	repeated occurrence	light yellow
26.03.2020	time intensive masking of the part	preventive	preventive measure
16.03.2020	The component was not assembled the way the drawing showed	repeated occurrence	light white
19.03.2020	Foam lids that fall off easily, posing a risk of dirt and small parts falling inside the pipe during the assembly	preventive	preventive measure

	Information on the solution					Main improvements		
		Exclusion criteria						
Date	Proposed solution	Is the material exposed to a heat >95°C?	Is an accuracy < 0,5mm required?	Does the part fit into 380 x 284 x 380 mm?	Number of items needed	Does the work safety get improved?	Is the quality getting ensured / are errors avoided?	Does the handling / the ergonomy for employees improve / does the effort decrease?
15.04.2020	3D printed cover as material in circulation	No	No	Yes	12	Yes	Yes	Yes
23.03.2020	test pin with a mark that indicates the right position	No	No	Yes	2	No	Yes	No
23.03.2020	Covers to protect the component from getting damaged during the assembly	No	No	Yes	15	No	Yes	No
26.03.2020	3D printed cover to simplify the masking process and save time	No	No	not clear	40	No	Yes	Yes
16.03.2020	3D printed guidance for the right assembly	Yes	No	Yes	30	No	Yes	Yes
19.03.2020	3D printed covers that are slighlty clamping and therefore don´t fall off easily	No	No	Yes	140	No	Yes	No

Decision and current state								
Is the operating material, based on the exclusion criteria, suitable for 3D printing?	Suggested implementation based on the number needed	Is it possible to manufacture the operating material conventionally? (Decided by AM expert)	Decision for additive manufacturing?	Priority number	Urgency	Comment regarding the implementation	Suggested way of implementation	Current state of implementation
Yes	additive	Yes	Yes	100	High		Implementation via Workflow TMPO	Waiting list
Yes	additive	Yes	Yes	63,45	Medium		Implementation suggested, manual decision about the way	Waiting list
Yes	additive	No	Yes	41,95	Medium		Implementation suggested, manual decision about the way	Waiting list
Check measures!	additive	Yes	Decision still pending	17,2	low			Waiting list
No	additive	Yes	No	35,5	Exclusion		Exclusion based on exclusion criteria	Exclusion
Yes	both possible	Yes	No	10,75	Exclusion	Excluded as new parts milled out of foam seem to be the better choice	Exclusion due to manufacturability	Exclusion

Continued from page 70

wirtschafts
wissenschaften
htw saar

Erklärung

Ich versichere, dass ich die Bachelor-Thesis selbstständig verfasst habe und keine anderen als die angegebenen Hilfsmittel benutzt wurden. Diese Arbeit oder eine Arbeit mit gleichem oder ähnlichem Thema wurde nicht bereits an anderer Stelle vorgelegt.

Da die vorliegende Arbeit allerdings im Rahmen eines laufenden Doppelabschluss-Programms entstand, wird sie hiermit gleichzeitig und erstmalig an beteiligten Hochschulen vorgelegt.

Die/der betreuende Dozentin/Dozent erhält die Arbeit zusätzlich in einer elektronischen Form, die eine Plagiatüberprüfung ermöglicht. Ich bin damit einverstanden, dass die Arbeit mit Plagiarismus-Software überprüft wird. Ich weiß, dass bei der Überprüfung die Arbeit möglicherweise der Plagiarismus- Software hinzugefügt wird.

Saarbrücken, den ____________________

____

Unterschrift

wirtschafts
wissenschaften
htw saar

Declaration

I hereby declare that I have authored this Bachelor-Thesis independently and that I have not used other than the declared sources and resources. The presented work has not yet been submitted in the same or a similar form.

However, the thesis was written within the framework of an ongoing double degree programme. It is hereby presented simultaneously and for the first time at the participating universities.

Additionally, the supervisor will receive the thesis in electronic form that allows plagiarism checks. I agree that the work may be checked with plagiarism software. I am aware that the work may be added to the plagiarism software during the review.

Saarbrücken, ______________________

____

Signature