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Analysis of additive manufacturing technology applied to valve housings for mobile machinery

BUCHHOLZ HYDRAULIK

Fachhochschule Kiel
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Non-disclosure Notice

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A **STRATASYS** COMPANY

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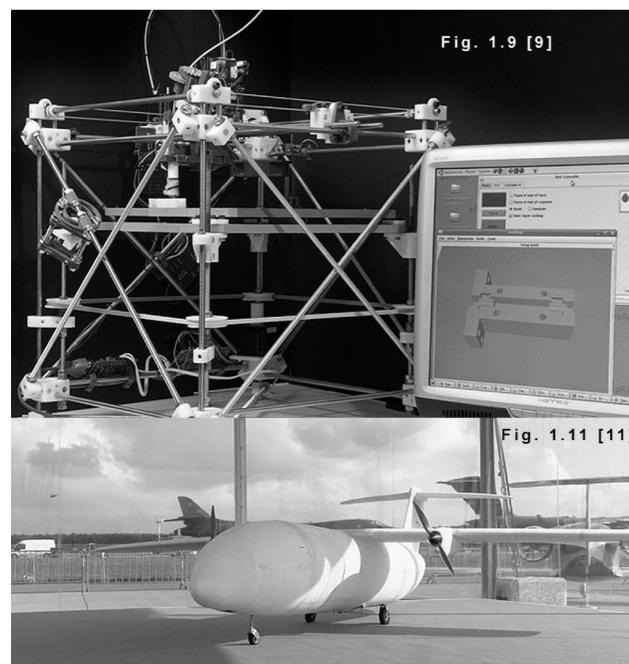
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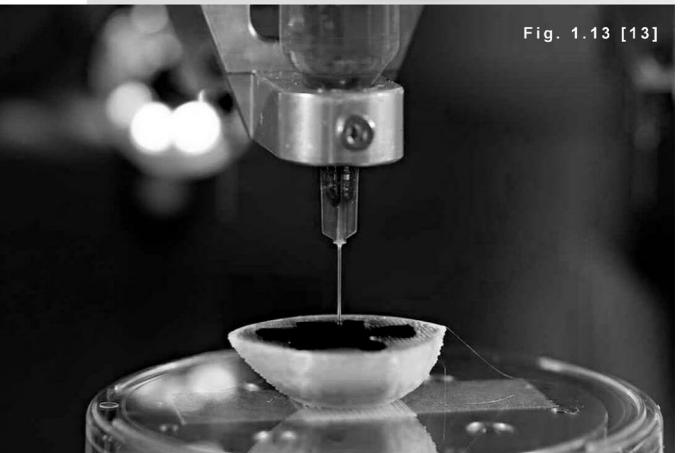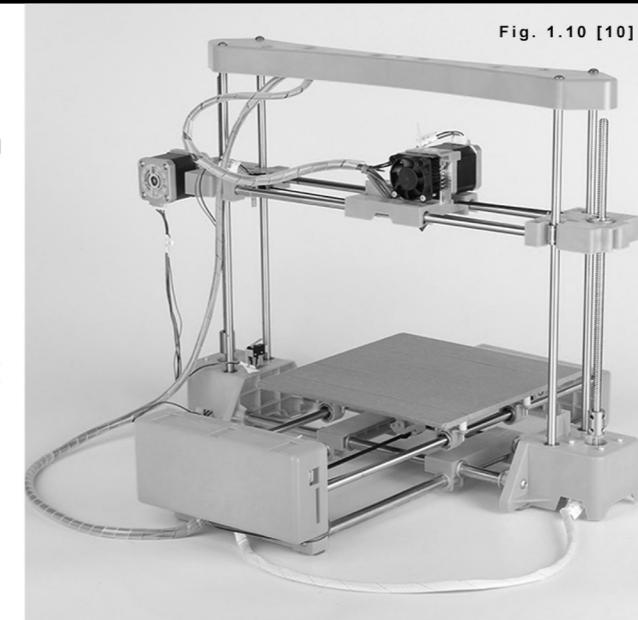
1.1 SYNOPSIS

Buchholz-Hydraulik is a company focused on the development and production of customized valves for mobile machinery. With view to new technologies, as additive manufacturing, they want to ensure state of the art products for their customers in the future.

The aim of the project is a feasibility study to change the current manufacturing to 3D- printing.

Firstly, the team can find a clear picture of the current market and the applications within the hydraulic market, then a large investigation comparing both methods. This contains an economy investigation, as well as a technological pre-study of the possibilities of post printing mechanical and machining.

The pre-study has been practiced designing and manufacturing a technology prototype, which is the most important step to present at the end the advantatges and constrains of the new method.

At the end, a conclusion to guide the company in a future is presented, specifying the restrictions and opportunities.

This report is exclusively for Buchholz Hydraulik and the responsible supervisor of the European Project Semester of the University of Applied Science in Kiel [1].

1.2 PREFACE

This project has been developed by an international team during the European Project Semester (EPS) at the University of Applied Science in Kiel. The team is composed of four students, who will be introduced in the following:

Adrián Lara Domínguez is 22 years old and from Spain. He is studying Mechanical Engineering at the Universitat Politècnica de València (UPV).

Aina Cladera Escalas is 21 years old and from Spain. She is studying Industrial Design and Product Development Engineering at the Universitat Politècnica de Catalunya (UPC).

Norman Beguin is 19 years old and from France. He is studying Mechanical Engineering at the University of Bethune.

Tariq Yasin is 27 years old and from Germany. He is studying International Sales and Purchasing Engineering at the University of Applied Science in Kiel.

In 1884 a little workshop foundation in Kiel started what would later be Buchholz Hydraulik. Even until today, this company is a mid-sized family business which is run by the owners' offspring.

Since the foundation in 1959 the objective has been on the development and production of customized valves for mobile hydraulics.

The company closely follows the development of the different projects, from designing the system to putting it into operation and optimizing it in the vehicle. Thanks to this the firm has established itself among one of the most important companies in terms of hydraulic solutions.

Every year, about 165.000 control valves are developed and produced, producing the last year a turnover of about 68million €.

Operating on three continents, the business responds to the challenges of a globalized world as a supplier to renowned manufacturers of industrial trucks and construction machinery, the automotive industry and the maritime industry [2].

Fig. 1.14 Buchholz Hydarulik manufacturing [14].

In a time of dynamic markets a rethink regarding production methods is needed. On one side there are the customers, who expect innovative and customized products with a high quality to an affordable price. On the other hand the companies are facing shorter life cycles, what leads to a shorter amortisation period of investments in machinery. Additive manufacturing, such as 3D-printing, has the potential to solve this issue. With additive manufacturing technology it is possible to produce a small batch of customized products [3].

On behalf of the company Buchholz Hydraulik GmbH, this report analyses if it is strategically expedient to invest in additive manufacturing technology. Conceivable is the usage of this technology for small batches of customized valve housings for the maritime sector.

Considering that, it is necessary to find a suitable production process, which can processes material, what meet the company's requirements. The requirements include, that the material resists the pressure of at least 320 bar and that it is undetectable. It is also very important, that the final product is easy to clean from inside (and stays clean), since pollution is the most common reason for destruction of valves. In addition, it is requested, that the printed valve housing is lighter than the current produced housing.

Beside these technical aspects, this report includes an analysis of the financial issue. Only if it is conceivable, that the implementation of an additive production technology is economical, it might going to be implemented.

1.5 REVIEW OF THE PROJECT ASSUMPTIONS AND RESULT OF THE PROBLEM ANALYSIS

With this project is pretended to investigate the new additive manufacturing technology to ascertain that it is possible that this method can be implemented and replace the current one more efficiently, reducing the weight of the product and improving the design, and economically, reducing the manufacture time and the material used.

The result, that is expected, is to find the appropriate material and additive manufacturing method, that meets all the specified characteristics, both design and economic. To achieve this, a study of the two methods will be carried out, both the current and the new one. Once the study is done, the possible design will be created using CAD programs, analyzing the mechanical characteristics by simulations, and ameliorating it using the simulation results. Then the plastic prototype will be created to show the design and size of the product. After having done all the technical part, will be prepared to make the comparison with the current method. And finally the conclusion of this project.

1.6 HISTORY OF THE PROJECT

The project began in the start of March 2018 with a visit to Buchholz Hydraulik. During this meeting the students were introduced to the company by Mr. Nissen (Head of Research & Development) and Mr. Arp (Head of Design). After a detailed description of the problem, the team was supposed to solve, Mr. Nissen showed the whole flow of materials in the company. The rest of the month the group attended different workshops at the university.

In the start of April, the students began with their project work by coming up with a schedule for the coming months and the first steps which are needed to be done. The members met almost daily in their team office and worked on their tasks. Furthermore, the group had regular team meetings with the supervisor, Prof. Dr. Hasenpath, once a week. Here the current state of the project was discussed and new to do´s were established.

On 23th of march the team members and the supervisor had another meeting with the company. During this meeting, the progress of the work was presented, questions to the company were asked, as well as a pair comparison for the pending Scoring Model was conducted.

After that, on the 7th of May the students were supposed to submit the midterm report of the project. Furthermore, the group had to present their results on 14th of May during a midterm presentation. In that presentation, the progress of the project as well as the planned next steps were shown. Hereafter, five weeks were left for the submission of the final paper. In order to meet the final submission date, the group worked daily on the different tasks. Among other things, a new design of the housing, a material comparison, as well as a cost comparison has been prepared. Also, the meeting with the supervisor was held weekly to ensure that the project was expedient. At the end, the final paper was submitted at the 18th of June, so that there was time to prepare the final presentation, which was planned for the 26th and 27th on June.

Fig. 2.1 Valve Housing

02 MAIN SEC-TION

2.1 DESIGN PROPOSAL
2.1.1 Current Design vs Proposal Designs

At this point of the report the design process followed for the adaptation of the current housing to the additive manufacturing technology will be showed. This way of manufacturing allows for more creative and personalized designs than the rest of the current technologies, due to this the company gave some guidelines to follow, which have been used for the design of the new housing. These requirements are: to obtain a greater lightness, a smaller or equal size than the current design, to eliminate the outflows of the lubrication pipes and to create curved cavities to create a more uniformly distributed pressure throughout the housing.

To start, from the plans that Buchholz provided the current 3D model of the housing was made, it can be seen in the images 2.2 and 2.3. As the first picture shows, the interior is composed of different interconnected cavities, among wich the main ducts, the lubrication lines and the holes not connected that correspond to the fixing holes.
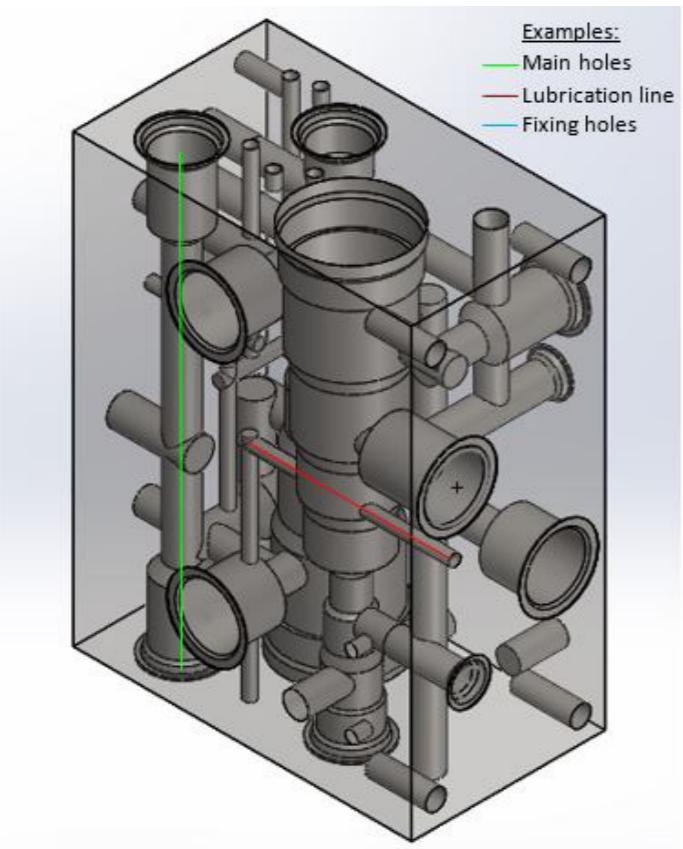
Fig. 2.2 Original design interior 1
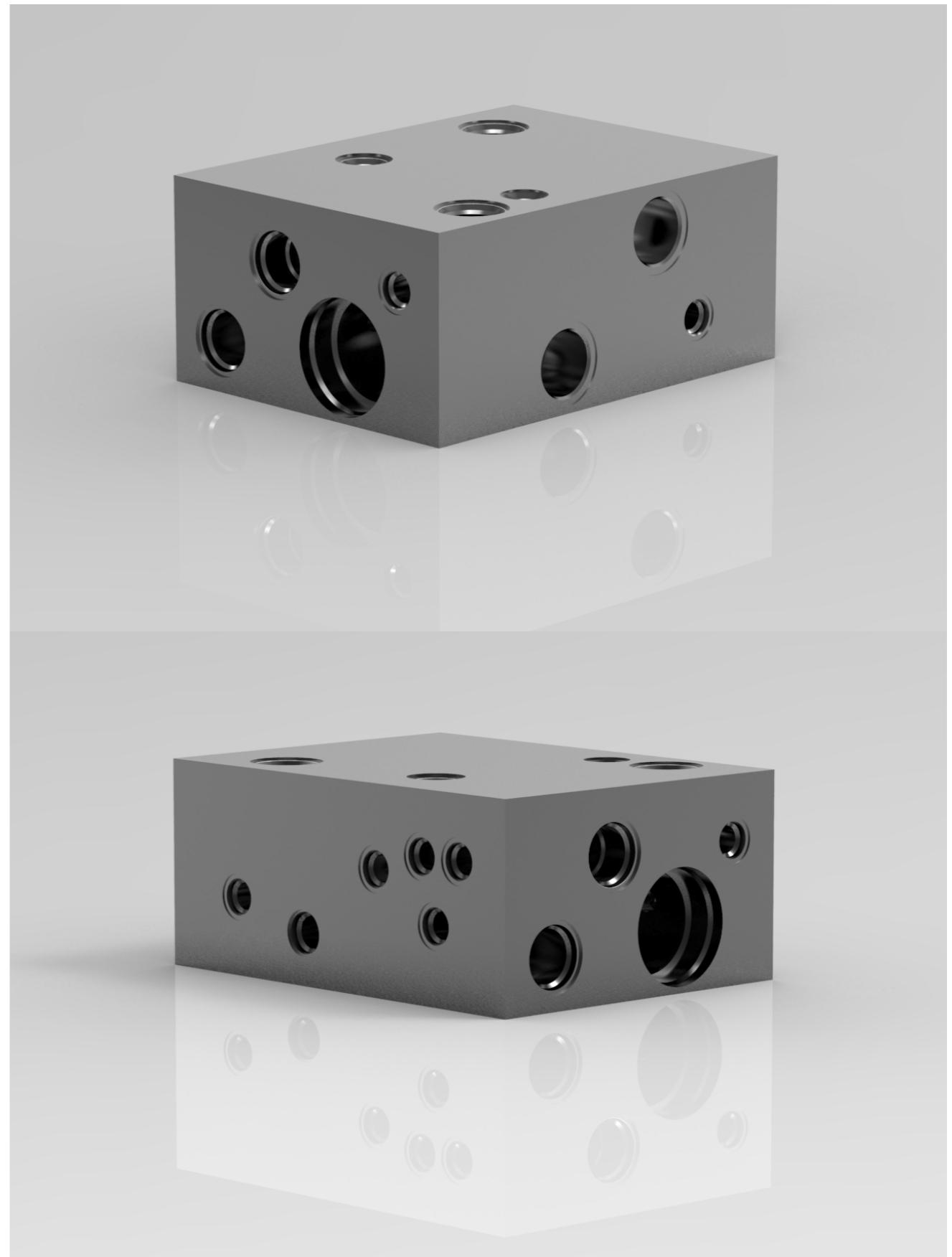
Fig. 2.3 Valve Housing 2.0 from outside

After having made the model of the part that is currently manufactured, it began the development of the functional design adapted to the new technology, the Design 2.0. The first step in the process was to eliminate the exit holes from the lubrication lines, the changes are shown in more detail in figure 2. 5.
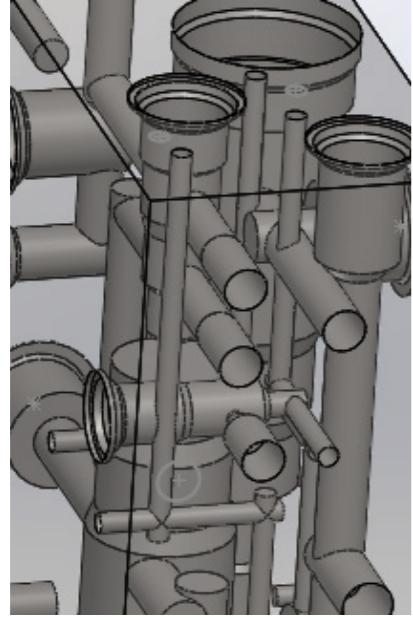
Fig. 2.4 Original design interior-2
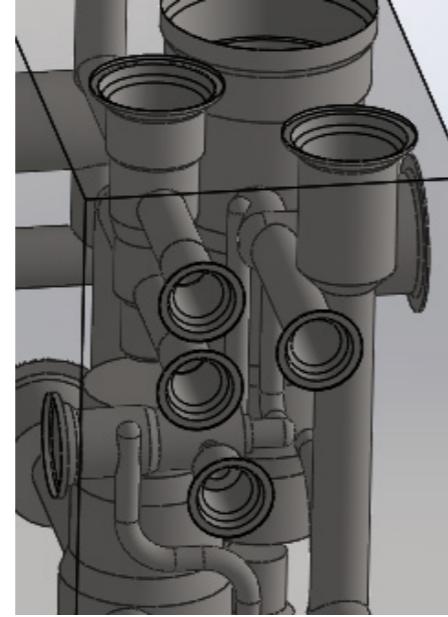
Fig. 2.5 Design 2.0 interior-1

The next process was to round off the blind spots inside the design, not only of the lubrication lines but of all the internal lines as it is one of the benefits of using this new technology. As you can see in the image 2. 7 the changes are noticeable and will make it easier for the pressure in the whole housing to be more stable.
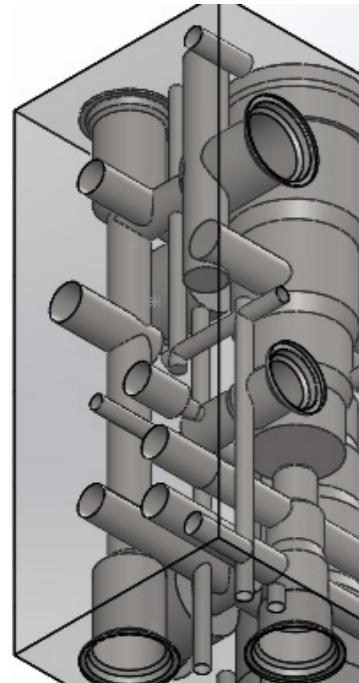
Fig. 2.6 Original design interior-3
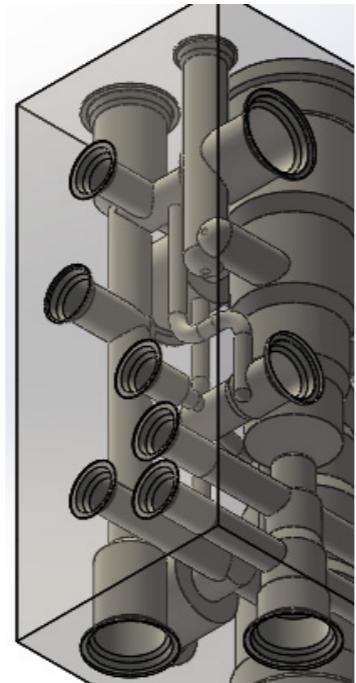
Fig. 2.7 Design 2.0 interior-2

Once these changes have been made, the final interior design of the housing adapted to the additive manufacturing technology can be seen in the images below.
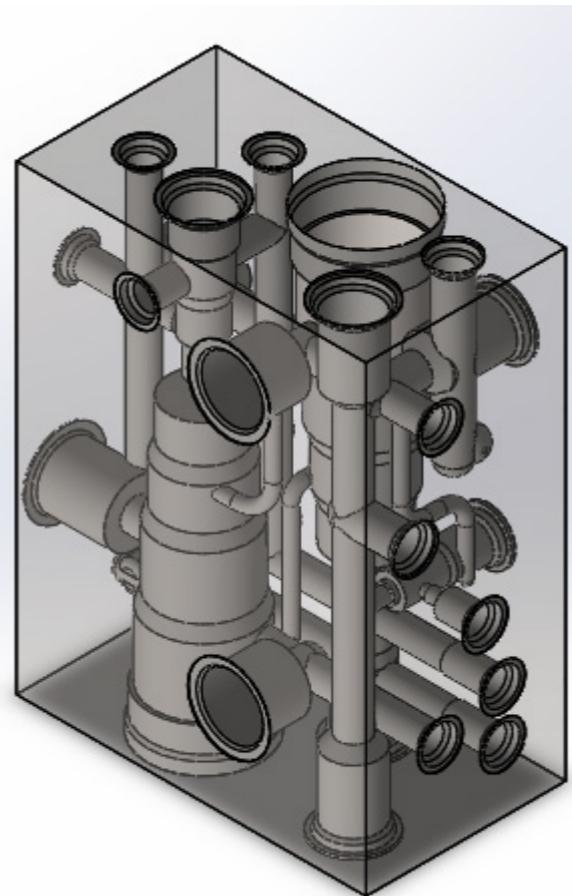
Fig. 2.8 Design 2.0 interior-3
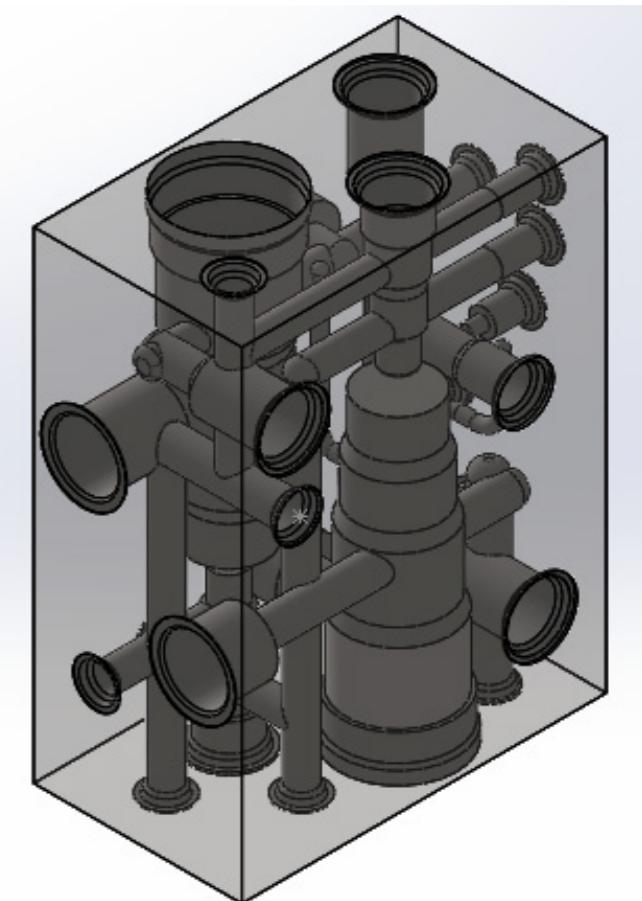
Fig. 2.9 Design 2.0 interior-4

After making the functional design, a design has been made that shows an alternative that is based on the flexibility of 3D technologies to create custom designs, the functionality of this new scheme is not checked, what is intended to show the amount of space that can be optimized using this method of manufacture, so the name of this design is fantasy, and can be seen along with the original layout in the figure 2. 10.
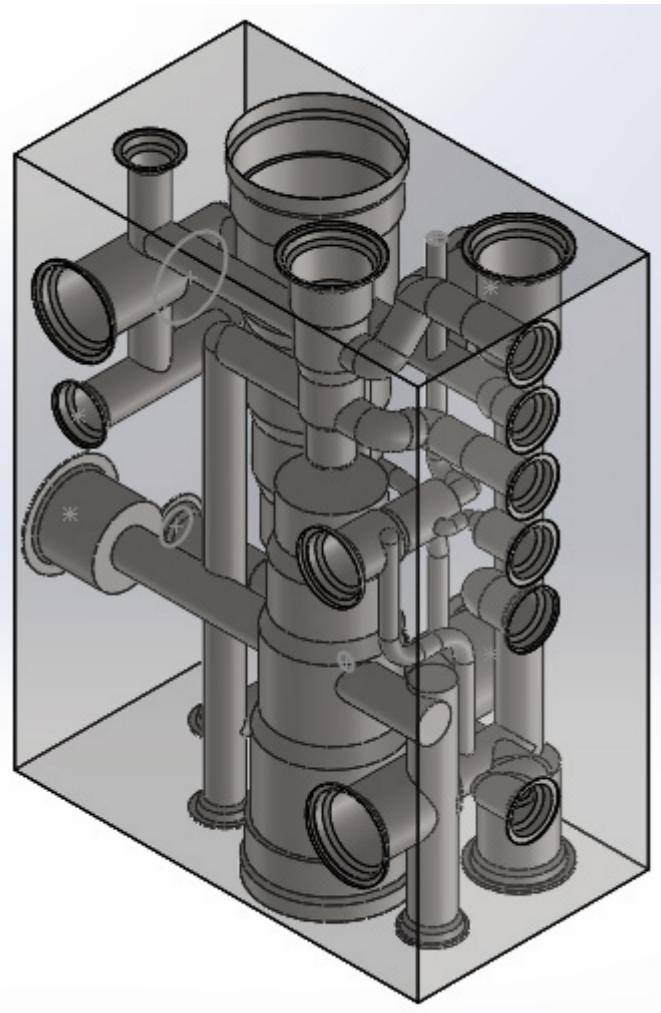
Fig. 2.10 Design 2.0 interior 5
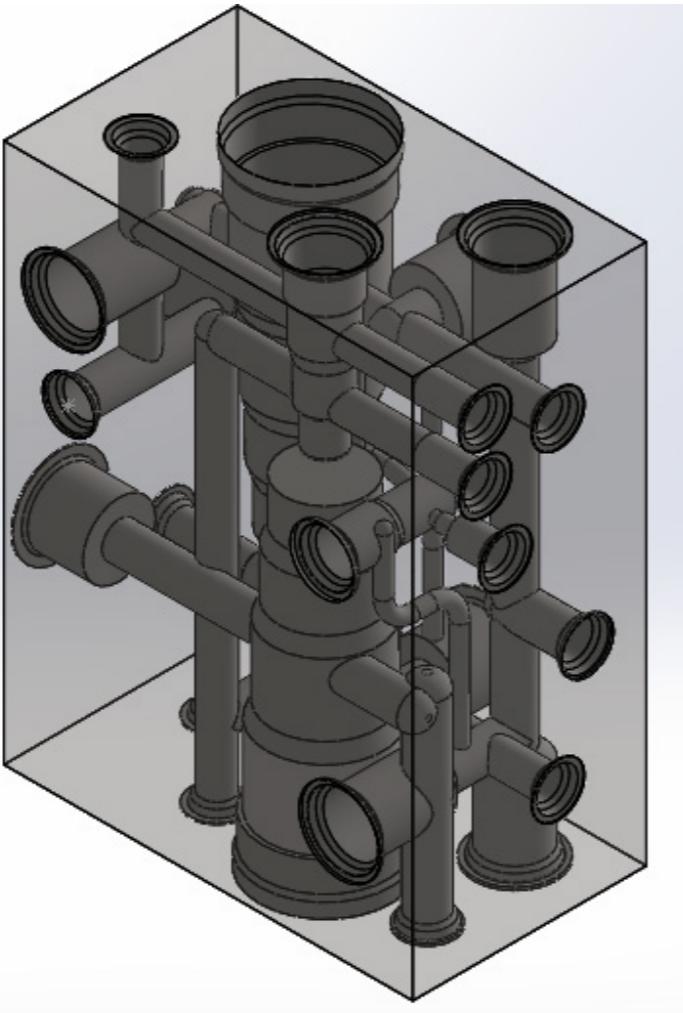
Fig. 2.11 Fantasy design interior

Fig. 2.12 Fantasy Design from outside

The changes are visible, all the entries on one side have been aligned using the curved ducts to connect them according to the initial distribution.

2.1.2 Shape Possibilities

Once the interior design of the valve housing had been changed, the aim was to reduce the weight of this one to a minimum, in order to do this it was thought two possible ways; the design and the material.

Firstly, with regard to design, it is proposed to reduce material, in an other words, to remove all the excess material from the housing that was initially only needed to be manufactured. As it can be seen from the images below, it is proposed two completely different exterior designs to demonstrate everything a 3D printer has to offer; the Design 3.0 and the Design 4.0.

In the figures 2.13 and 2.14 it is shown a design, which it has been called Design 3.0, since it is the third variation of the model. This model has the same interior changes as the Design 2.0, which it can be seen in the point 2.1.1. Apart from these changes, it has been also modified the exterior, for which it has been based on reducing the shape of all the sides without having to modify the central part where most of the holes are located. Once all the excess material from the sides has been reduced, it has been added the outholes that should be there. There remains a form like the one it is shown in the following images.

Fig. 2.13 Valve Housing: Design 3.0
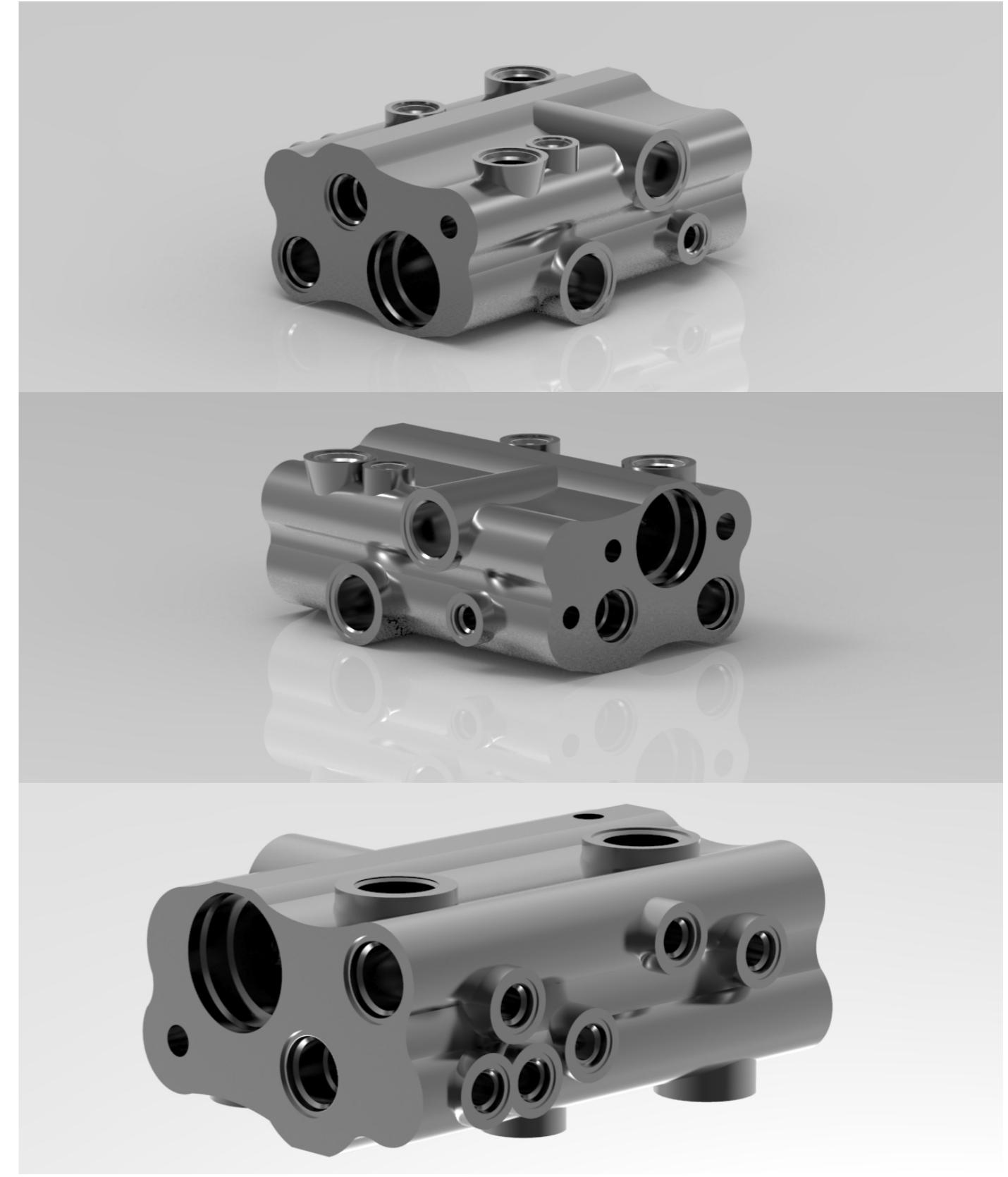
Fig. 2.14 Valve Housing: Design 3.0 from differents angles

It should be said that at the beginning the idea was to reduce the external shape as much as possible, adapting it to all the holes, always leaving the minimum thickness indicated by the 3D printer. Due to the design complexity that this meant and the lack of previous knowledge about which holes could be kept in position, move them or remove them, finally it has been designed this prototype so that it could be got a general idea of what can be printed currently with the additive manufacturing, maintaining its previous functionality that it has before being modified.

The next prototype is called Design 4.0, since it is the fourth variant, which it is shown in the following images. This design has been created taking as a base the Design 2.0, as the previous design already explained. In this model it has been not removed so much material, but enough to make it lighter, rounding the edges where there was unnecessary material. The purpose was to reduce material while also showing a prototype that was easier to clean than the previous one.

Fig. 2.15 Valve Housing: Design 4.0

Fig. 2.16 Valve Housing: Design 4.0 from differents angles

In conclusion, thanks to the additive manufacturing in metal, it is obtained some surface finishes, which must be polished after the printing, but instead it offers total freedom when it comes to design, which it has shown in the two previous prototypes. In addition, thanks to the reduction of material it creates a lower environmental impact and reduction of the cost of this, since it uses only the necessary material. Once the different options that can be printed have been shown, it has encouraged the company to study these designs and thanks to their greater knowledge of the product, they can reduce even more material and obtain a lower weight.

Finally, to reduce the weight it as been also considered the option of changing the manufacturing material for one with a lower density and therefore lighter. Always taking into account, which materials can be printed and which of them are meeting the initial requirements that Buchholz Hydraulik provided us. This point is explained in more detail in the point 2.3.1.

2.1.3 Weight Housing Comparison

Once the different designs proposed by the team have been introduced, both indoor and outdoor, a comparison of each design with different materials is shown in the following table. Always bearing in mind that the design must be compared with the same material, which have been chosen according to the Materials Comparison found in point 2. 3. 1. Thanks to this comparison, a better view can be obtained of the lightness that the final design could achieve. It is shown a density of 8 g/cm^3, which corresponds to the Stainless Steel 316L, and another of 4,42 g/cm^3, which corresponds to the Ti6Al4V.

	Volume	Weigth
Original	1578.4264 cm^3	11.2 kg

Table 2.1 Volume and Weight of the current valve housing

	Volume (cm³)	Weight with 8 g/cm³	Weight with 4,42 g/cm³
3.0	1208.2753	9.66 kg	5.33 kg
4.0	1483.9353	11.9 kg	6.56 kg
Fantasy	1483.9353	11.9 kg	6.56 kg

Table 2.2 Volume and Weight of the different designs and different materials

The Scoring Model is an instrument for a systematic decision making when non-financial aspects or financial and non-financial aspects need to be evaluated [4, p.278]. It is a commonly used method in different fields like business, technology and engineering [5, p.373]. Examples of application are the location selection [6, p.46] or the vendor selection [5, p.373].

To sum it up, the Scoring Model is particularly used when in a decision situation:

- an evaluation of financial aspects is not possible or insufficient.
- various of alternatives are comparable.
- a large number of influencing factors are need be considered [4, p.279]

Moreover, are the benefits of this model:

- decision situations are documented transparently.
- consequences of the different alternatives can be demonstrated.
- the risk of wrong decisions can be reduced [4, p.279].
- only when aspects are mentioned and discussed within the Scoring Model they are taken into consideration; opinions of the persons involved become clear [5, p.376].

Execution of the Scoring Model

Also, during this present project the Scoring Model is applied to the selection procedure of the suppliers for additive manufacturing system solutions.

There are different ways to execute a Scoring Model, so that in the following it will be focused on a four-step-execution according to Geisler [5, p.373 ff.].

The first step is to find criteria for evaluating the different suppliers. Important criteria for functions and technical requirements should be derived from the specification of requirements, if available. But also the supplier itself need to be evaluated. In case, that no specification of requirements exists, but also for finding criteria to evaluate the vendors, a brainstorming can be conducted. Criteria, that are found during this procedure need to "be structured hierarchically in target-tree [...] to ensure the catalogue of criteria is MECE: mutually exclusive

and collectively exhaustive." [5, p.374]. The requirement of "MECE" is not perfectly met in the Scoring Model conducted by the group (see also *Critic of the conducted Scoring Model* page 27). Table 2.3 shows the criteria found during the brainstorming, while table 2.4 shows them after being structured in a target- tree. For this, the criteria from the brainstorming are assigned to different groups (here: quality of the housing, costs, quality of the machine and provider) where they fit in.

Quality of the housing
Adherence to tolerances
Undetectable material
Weight of the housing
Design of the housing
Costs
Costs per housing
Time to produce one housing
One-off costs of the machine
Running costs of the machine
Quality of the machine
Flexibility of the machine
Reliability of the machine
Easy handling of the machine
Recycling of the material
Provider
Proximity of the material supplier
Proximity of the machine manufacturer
Cultural fit of the supplier/manufacturer

(Brainstorming list)
Undetectable material
Running costs of the machine
Reliability of the machine
Easy handling of the machine
Proximity of the machine manufacturer
Cultural fit of the supplier/manufacturer
Costs per housing
Adherence to tolerances
Design of the housing
Cultural fit of the supplier/manufacturer
Recycling of the material
Flexibility of the machine
One-off costs of the machine
Time to produce one housing
Weight of the housing

Table 2.3 Criteria after brainstorming [cf. 5]   *Table 2.4 Criteria in target-tree [cf. 5]*

The second step is about finding out, which criteria are more or less important than others. For that, the chosen criteria have to be weighed against each other by using, for instance, a pair comparison method. Table 2.5 shows the pair comparison table filled out by company Buchholz. The rules needed for that are the following: if the criterion in the row is "more im-portant" than the one in the column, it gets 2 points in the white cell and 0 points in the blue cell. If it is "less" important it gets 0 points in the white cell and 2 points in the blue cell. And if it is "equally important", it gets 1 point in the white cell and 1 point in the blue cell. At the end all points in a row have to be summed up. After that, the weighting of each criteria in its group (weighting group) can be calculated. For the total weighting of each criteria (across all groups) another step in needed: Either the participants involved have to divide 100% among the group criteria (here: quality of the housing, costs etc.), whereby high percentage means high importance. Or another pair comparison only across the group criteria can be conduc-ted, as it is shown in table 2.6.

After this, the total weighting of each criteria can be calculated.

	Adherence to tolerances	Undetectable material	Weight of the housing	Design of the housing	Costs per housing	Time to produce one housing	One-off costs of the machine	Running costs of the machine	Flexibility of the machine	Reliability of the machine	Easy handling of the machine	Recycling of the material	Proximity of the material supplier	Proximity of the machine manuf.	Cultural fit of the supplier/manuf.
Weighting total	7,6%	17,7%	16,4%	0,0%	6,1%	8,5%	2,4%	8,0%	9,3%	11,3%	7,4%	5,4%	0,0%	0,0%	0,0%
Weighting group	18,2%	42,4%	39,4%	0,0%	24,5%	34,0%	9,4%	32,1%	27,9%	33,8%	22,1%	16,2%	52,2%	30,4%	17,4%
Row total	12	28	26	0	13	18	5	17	19	23	15	11	12	7	4
Cultural fit of the supplier/manuf.	1	2	2	0	2	2	1	2	2	2	2	2	2	2	
Proximity of the machine manuf.	2	2	2	0	2	2	0	2	2	2	1	2	0		0
Proximity of the material supplier	0	2	2	0	1	0	0	2	2	2	1	0		0	0
Recycling of the material	2	2	2	0	1	1	0	1	2	2	2		1	1	0
Easy handling of the machine	1	2	2	0	1	1	0	2	2	2		0	0	0	0
Reliability of the machine	0	2	2	0	0	0	0	1	1		0	0	0	0	0
Flexibility of the machine	0	2	2	0	0	2	0	1		2	0	0	0	0	0
Running costs of the machine	1	2	2	0	1	2	0		1	1	0	1	0	0	0
One-off costs of the machine	0	2	2	0	2	2		2	2	2	2	2	2	2	1
Time to produce one housing	1	2	2	0	1		0	0	2	1	1	0	0	0	0
Costs per housing	2	2	2	0		1	0	1	2	2	1	1	1	0	0
Design of the housing	2	2	2		2	2	2	2	2	2	2	2	2	2	2
Weight of the housing	0	2		0	0	0	0	0	0	0	0	0	0	0	0
Undetectable material	0		0	0	0	0	0	0	0	0	0	0	0	0	0
Adherence to tolerances		2	2	0	0	1	1	2	2	1	0	2	0	1	1

Table 2.5 Pair comparison filled out by Buchholz [cf. 5]

Table 2.6 Pair comparison of group criteria filled out by Buchholz [cf. 5]

	Quality of the housing	Costs	Quality of the machine	Provider	Row total	Weighting
Quality of the housing		2	1	2	5	41,7%
Costs	0		1	2	3	25,0%
Quality of the machine	1	1		2	4	33,3%
Provider	0	0	0		0	0,0%

In the third step, a suitable scale for awarding points need to be established. For that, it is important that it is not too rough nor too detailed and that it does not have a middle value. Commonly used scales are "1-10" or "0-5", which is also used in the group´s conducted Scoring Model.

After that, points have to be awarded to each supplier for each criterion. It should be noted, that the points are supposed to "be given relatively rating the solutions against each other" [5, p.375].

The fourth and last step is the calculation of the score of each vendor: the points given to each criterion of each vendor have to be multiplied with the (total) weighting of the respective criterion, as it is shown in table 2.7. The result of this Scoring Model shows, that the company "SLM Solutions Group AG" with its machine "SLM 500" has the highest score and there it should be chosen. But it need to be considered, that not all criteria are evaluated, so that the significance is not very high.

Points 0-5 (0 = very bad ; 5 = very good)	Weighting	SLM 500 (SLM Solutions) Points	Score	M2 Cusing (Concept Laser) Points	Score	The EOSINT M280 (EOS) Points	Score	TruLAserCell 3000 (Trumpf) Points	Score	Arcam A2X (Arcam) Points	Score	M-Flex (ExOne) Points	Score	Ideal Points	Score
Quality of the housing (sum)	42%	-	0,00	-	0,00	-	0,00	-	0,00	-	0,00	-	0,00	-	2,08
Adherence to tolerances	8%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,38
Undetectable material	18%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,88
Weight of the housing	16%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,82
Design of the housing	0%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,00
Costs (sum)	25%	-	0,25	-	0,16	-	0,02	-	0,00	-	0,21	-	0,05	-	1,25
Costs per housing	6%	3	0,25	1	0,08	1	0,00	0	0,00		0,00		0,00	5	0,31
Time to produce one housing	8%	0	0,00	3	0,07	0	0,02	0	0,00		0,00		0,00	5	0,42
One-off costs of the machine	2%	0	0,00	0	0,00		0,00		0,00	2	0,05	2	0,05	5	0,12
Running costs of the machine	8%		0,00		0,00		0,00		0,00	2	0,16	0	0,00	5	0,40
Quality of the machine (sum)	33%	-	0,00	-	0,00	-	0,00	-	0,00	-	0,00	-	0,00	-	1,67
Flexibility of the machine	9%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,47
Reliability of the machine	11%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,56
Easy handling of the machine	7%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,37
Recycling of the material	5%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,27
Provider (sum)	0%	-	0,00	-	0,00	-	0,00	-	0,00	-	0,00	-	0,00	-	0,00
Proximity of the material supplier	0%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,00
Proximity of the machine manuf.	0%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,00
Cultural fit of the supplier/manuf.	0%		0,00		0,00		0,00		0,00		0,00		0,00	5	0,00
Quality of supplier (grand total)	100%	-	0,25	-	0,16	-	0,02	-	0,00	-	0,21	-	0,05	-	5,00
Percentage			5%		3%		0%		0%		4%		1%		100%

Table 2.7 Weighted Scoring Model filled out by the student group members [cf. 5]

The red-colored criteria are awarded with no points, since the group could not award any meaningful points to them because of different reasons. The different reasons and the Scoring System, to which the points were allocated are shown in table 2.8.

Criteria	Unit	very bad 0	1	2	3	4	very good 5	comment
Adherence to tolerances	-							Deleted - depends on the material, not on the machine
Undetectable material	-							Deleted - depends on the material, not on the machine
Weight of the housing	kg							Deleted - depends on the material and design
Design of the housing	-							Deleted - depends on the engineer
Costs per housing	€							Deleted - of lack of information
Time to produce one housing	cm³/h	< 20	20	50	100	500	>1000	build rate
One-off costs of the machine	€	> 1 mio.	630.000 - 1 mio.	400.000 - 630.000	250.000 - 400.000	160.000 - 250.000	0 - 160.000	
Running costs of the machine	€	>2		1-2		<1		inter gas consumption
Flexibility of the machine	-							Deleted - it is not specified
Reliability of the machine	-							Deleted - it is not specified
Easy handling of the machine	-							Deleted - it is not specified
Recycling of the material	-							Deleted - it is not specified
Proximity of the material supplier	km							Deleted - it is weighted with 0%
Proximity of the machine manufacturer	km							Deleted - it is weighted with 0%
Cultural fit of the supplier/manufacturer	-							Deleted - it is weighted with 0%

Table 2.8 Scoring System for allocation of points [cf. 7]

Possibilities to get information about criteria which are "not specified" is to gather offers from the different suppliers or to arrange supplier audits [cf. 8, p.208].

Since most of the listed criteria in this Scoring Model could not be evaluated, the students conducted another, smaller Scoring Model which is shown in the page 29.

General critic of the Scoring Model

The Scoring Model is often criticized as being "subjective" [5, p.376 and 9, p.54]. According to that, the selection and the weighting of the criteria, what is the basis of this instrument, is significantly dependent on nonobjective opinions. Consequently, also the result of the Scoring Model is influenced subjectively. However, to check how stable the outcome of the Model is, a "sensitive analysis" can be applied. For this analysis some of the values, given to the supplier, and some weightings of the criteria need to be changed. After that the impact on the result can be observed [5, p.376].

Another point of criticism is, that the execution of the Scoring Model is very complex and therefore expensive [9, p.54]. Among other things, this is because the conduct of this Model need several people to be involved. In addition, it can be time-consuming finding information for some criteria in order to award meaningful points to the different alternatives.

Critic of the conducted Scoring Model within this paper

The purpose of this paragraph is to point out, how the conducted Scoring Model during this paper can be optimized. For that, it will be focused on two different questions:

1. Is the specified catalogue of criteria in this paper "mutually exclusive and collectively exhaustive"?
2. Who should be involved in the decision making process within the Scoring Model?

The catalogue of criteria in this paper:

According to Geisler it is important, that the catalogue of criteria is "mutually exclusive and collectively exhaustive" [5, p.374]. This means, that every criterion of the catalogue needs to be disjunctive and that the catalogue as a whole needs to be complete.

During the conduct of the pair comparison with the company Buchholz, the student group realized, that the criterion "Recycling of the material" listed in the catalogue under the group criteria "Quality of the machine", is not really disjunctive. This is because the "Recycling of the material" describes, if the unused material in the building chamber during the production process, can be used afterwards again or not. This means, that the criterion "Recycling of the material" has an influence on the "costs per housing", which is why it is not a disjunctive criterion (see also table 2.9).

Quality of the housing
Adherence to tolerances
Undecetable material
Weight of the housing
Design of the housing
Costs
Costs per housing
Time to produce one housing
One-off costs of the machine
Running costs of the machine
Quality of the machine
Flexibility of the machine
Reliability of the machine
Easy handling of the machine
Recycling of the material
Provider
Proximity of the material supplier
Proximity of the machine manufacturer
Cultural fit of the supplier/manufacturer

Table 2.9 Non-disjunctive criterion [cf. 5]

Quality of the housing
Adherence to tolerances
Undetectable material
Weight of the housing
Costs
Costs per housing
Time to produce one housing
One-off costs of the machine
Running costs of the machine
Quality of the machine
Flexibility of the machine
Reliability of the machine
Easy handling of the machine
Supplier
Support
Stability and size
Reputation
Know-how in our industry
Cultural fit

Table 2.10 Optimized list of criteria [cf. 5]

Moreover, the students found some more criteria after conducting the pair comparison, what is an indicator, that the specified list of criteria is not complete. The criteria "stability and size", "reputation" and "know-how in our industry" should be added in the list under the group "Provider". Moreover, the two criteria "Proximity of the material supplier" and " Proximity of the machine manufacturer" should be replaced by the criterion "Support" [cf. 5, p.375]. In addition, the group name "Provider" should be replaced by the name "Supplier".

Furthermore, the criterion "Design of the housing" should be removed from the list, since it is independent of the supplier but rather from the CAD-model of the housing. Table 2.10 shows the optimized catalogue of criteria.

Persons involved in the decision making process within the Scoring Model:

The execution of the Scoring Model, from finding criteria in a brainstorming to awarding points to the different supplier, should be solely conducted by a group rather than by a single person. For that, it is important to involve responsible persons of all the concerned departments, in order to reduce the risk of wrong decision [8, p.208]. In the case of Buchholz Hydraulik this could be the department heads of research & development, design, quality, production and purchasing.

Second Scoring Model

Since the group was not able to allocate points to all the different criteria of the first Scoring Model (see also table 2.7 and 2.8), it has been decided during a meeting with the supervisor to conduct a second one (table 2.11 till table 2.12). In this Model, only criteria were chosen, for which it was possible to award points to them. The allocation of points was made according to the Scoring System in table 2.12.

	Build envelope	Beam focus diameter	Max. scan speed	Dimension of the machine	Build rate	Average inter gas consumption	One-off costs of the machine	Row total	Weighting total
Build envelope		1	2	2	0	1	2	8	19%
Beam focus diameter	1		2	2	0	2	2	9	21%
Max. scan speed	0	0		2	0	2	2	6	14%
Dimension of the machine	0	0	0		0	1	0	1	2%
Build rate	2	2	2	2		2	2	12	29%
Average inter gas consumption	1	0	0	1	0		1	3	7%
One-off costs of the machine	0	0	0	2	0	1		3	7%

Table 2.11 Second pair comparison [cf. 5]

The result of the second Scoring Model shows, that the company "SLM Solutions Group AG" have the highest score and therefore it should be chosen. But also here it need to be considered, that there are some other criteria need to be evaluated (for instance about the supplier itself) and that there were some information not given (red cells), so that the significance is not very high again.

In conclusion, it can be said that the Scoring Model is a very effective tool to sustain a systematic decision making process and to avoid decisions according to instinct. However, it is very time-consuming and needs a lot of information in order to get a meaningful outcome. The conducted Scoring Models by the student group may have a weak significance. But they give a good orientation, if the company Buchholz is planning to gather some more information about the different suppliers and wants to execute another Scoring Model.

2.2.2 Company Selected: SLM Solutions

One provider of metalbased additive manufacturing technology is the "SLM Solutions Group AG" which is located in Lübeck, Germany. SLM Solutions focuses on the development, assembly and sale of machines and inte-

Fig. 2.17 SLM Solutions logo [15]

grated system solutions in the field of selective laser melting (SLM®) [10].

The company offers three different Selective Laser Melting Machines, which are: SLM® 125, SLM® 280 2.0 and SLM® 500. They distinguishes in some functions and also in the size of the building envelope. Considering the dimensions of the valve housing 185 x 140 x 80 mm³ the building envelope of the SLM® 125 is too small, which is why in the following only the SLM® 280 2.0 and the SLM® 500 will be introduced [11].

Table 2.12 Second Scoring System [cf. 7]

Criteria	Unit	Points					
		very bad 0	1	2	3	4	very good 5
Build envelope	mm³	<200 x 200 x 250	200 x 200 x 250 - 250 x 250 x 300	250 x 250 x 300 - 300 x 300 x 350	300 x 300 x 350 - 350 x 350 x 400	350 x 350 x 400 - 400 x 400 x 450	>400 x 400 x 450
Beam focus diameter	-	unflexible			flexible		very flexible
Max. scan speed	m/s	<5	5-10	10-50	50-100	100-1000	>1000
Dimension of the machine	m²	>4		2-3		<2	
Build rate	cm³/h	<20	20-50	50-100	100-500	500-1000	>1000
Average inter gas consumption	l/min	>2		1-2		<1	
One-off costs of the machine	€	> 1 mio.	630.000 - 1 mio.	400.000 - 630.000	250.000 - 400.000	160.000 - 250.000	0 - 160.000

Table 2.13 Second Scoring Model [cf. 5]

Scoring model comparing the selective laser melting machines (SLM Solutions SLM 280 2.0, Concept M2 Concept Laser, EOS M280, TruLaserCell 3000 Trumpf, Arcam, Arcam XSA, ExOne M-Flex) against an Ideal. Each machine has a "Score" and "Points" column, evaluated on the criteria: Build envelope, Beam focus diameter, Max. scan speed, Dimension of the machine, Build rate, Average inter gas consumption and One-off costs of the machine. The overall weighting (Gewichtung) sums to 100%. The highlighted total score (Gesamtscore) for the SLM Solutions SLM 280 2.0 is 48% (highest), followed by Concept M2 with 38%, EOS M280 with 34%, Arcam XSA with 29%, Arcam with 13%, TruLaserCell 3000 with 11% and ExOne M-Flex with 11%; the Ideal column reaches 100%.

2.2.3 SLM Solutions Machines

SLM® 280 2.0

The SLM® 280 2.0, with its patented multi-beam technology, is convenient for series production and one-off production with individual parameters. It boasts a building envelope with the sizes 280 x 280 x 365 mm³ and is offered in different configurations (see also table 2.14.) [12].

Build envelope (L x W x H)	280 x 280 x 365 mm³ reduced by the substrate plate thickness ca. 25 mm
3D optics configuration, dual configuration: with switching unit	Single (1 x 400 W), Single (1 x 700 W), Twin (2 x 400 W), Twin (2 x 700 W), Dual (1 x 700 W and 1 x 1000 W) IPG fiber laser
Build rate	Up to 88 cm³ / h
Variable layer thickness	25 μm – 75 μm
Min. feature size	150 μm
Beam Focus diameter	80 μm – 150 μm
Max. scan speed	10 m/s
Average inert gas consumption in process	2,5 l/min (Argon)
Average inert gas consumption purging	70 l/min (Argon)
Size powder tank	40 l
E-Connection / power input	400 Volt 3NPE, 63 A, 50 / 60 Hz, 3,5 – 5,5 kW
Compressed air requirement / consumption	ISO 8573-1:2010 [1:4:1]: 50 l/min @ 6 bar
Dimensions (L x W x H)	2600 x 1200 x 2700 mm
Weight (without / incl. powder)	Approx. 1300 kg / approx. 1800 kg

Table 2.14 SLM® 280 2.0 – Machine configuration for all types of metal powders [12]

The whole production process is running under an inert gas atmosphere (Argon), just like all the Selective Laser Machines from the SLM Solutions Group AG. Moreover, is the SLM® 280 2.0 equipped with a 2+1 filter solution, what ought to lead to an increased filter lifetime and a low particle concentration during the production process.

In addition, the SLM Solutions Group AG offers two on-axis quality assurance system, which are optionally available for this machine. One system is the Melt Pool Monitoring (MPM). Its data can be used for an efficient developing and for evaluating the process parameters. It also enables to draw conclusions regarding irregularities during fusion, what is important for safetycritical parts.

The other quality assurance system is called Laser Power Monitoring (LPM) that continuously measures and documents the target and actual emitted laser output throughout the whole production process. With this function, it can be used as an early warning system to avoid machine downtime and also, thanks to the process documentation, it contributes to the quality assurance [12].

SLM® 500

The SLM® 500 is also equipped with the patented multi-beam technology and is designed for the series production of complex parts. It boasts a building envelope with the sizes 500 x 280 x 365 mm³ and is available in the configurations listed in table 2.15.

Because of the three time higher gas flow, the SLM® 500 produces parts with a higher density and surface quality.

Furthermore, this machine offers, as a basic feature, a Part Removal Station (PRS), where the build parts can be cleaned from excess powder. During this step, the next production process can be started, what makes the SLM® 500 optimally suited for the batch production.

The quality assurance systems MPM and LPM are also optionally available for this machine [13].

Build envelope (L x W x H)	500 x 280 x 365 mm³ reduced by the substrate plate thickness ca. 25 mm
3D optics configuration, dual configuration: with switching unit	Twin (2 x 400 W), Twin (2 x 700 W), Quad (4 x 400 W), Quad (4 x 700 W) IPG fiber laser
Build rate	Up to 171 cm³ / h
Variable layer thickness	20 µm – 75 µm
Min. feature size	150 µm
Beam Focus diameter	80 µm – 115 µm
Max. scan speed	10 m/s
Average inert gas consumption in process	5-7 l/min (Argon)
Average inert gas consumption purging	70 l/min (Argon)
Size powder tank	90 l
E-Connection / power input	400 Volt 3NPE, 64 A, 50 / 60 Hz, 8 – 10 kW
Compressed air requirement / consumption	ISO 8573-1:2010 [1:4:1]: 50 l/min @ 6 bar
Dimensions (L x W x H)	5200 x 2800 x 2700 mm3 (incl. PSV, PRS)
Weight (without / incl. powder)	Approx. 2400 kg / approx. 3100 kg

Table 2.15 SLM® 500 – Machine configuration for all types of metal powders [13]

2.2.4 SLM Solutions Materials

All of the following information about the different materials are taken from www.slm-solutions.com [14]. According to a statement during a meeting with Buchholz, aluminum-based alloys are not appropriate, due to the fact that the current cleaning method of the housings is not applicable to Al-alloys [28]. Still, one Al-alloy is introduced in the following, since the mechanical properties (e.g. $R_{p0,2}$) are comparable to the currently used material EN-GJS-400-15U and to ensure completeness. In addition, materials that exceed the needed mechanical requirements are introduced as well, because opportunities like material savings are possible.

Copper-based alloys:

CuSn10
The Bronze CuSn10 material is a copper-tin-alloy that boasts a high elongation and medium hardness. In addition, it is resistant to cavitation in sea water and a good corrosion resistance as well as good thermal conductivity. It is usually used for components and housings for devices in seawater environments.

Element / Material	Cu	Sn	Al	Fe	Mn	Ni	P	Pb	S	Sb	Si	Zn
Bronze CuSn10 10-45µm	Bal.	9.00 - 11.00	0.01	0.02	0.10	2.00	0.20	1.00	0.05	0.20	0.02	0.50

Table 2.16 Detailed chemical composition of CuSn10 (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	CuSn10[2,3]
Tensile strength	R_m [MPa]	495 ± 17
Offset yield stress	R_e [MPa]	373 ± 7
Break strain	A [%]	16 ± 4
Reduction area	Z [%]	16 ± 3
E-Modul	E [GPa]	116 ± 16
Hardness by Vickers	[HV10]	159 ± 1
Surface roughness	R_a [µm]	10 ± 2
Surface roughness	R_z [µm]	71 ± 13

Table 2.17 Mechanical properties of CuSn10 [14]

1 Layer thickness 30 µm - 2 Layer thickness 50 µm - 3 As build according to SLM

Solutions standards - 4 Heat treated - 5 Process conditions and parameters

Tool and stainless steel:

Invar 36®

This Fe-based alloy has a high nickel percentage and a low coefficient of thermal expansion below its Curie temperature of 280°C. It also has good mechanical properties at cryogenic temperatures and a low tendency to fatigue at low temperatures. It is usually used in the aerospace industry, for precision instruments as well as for valves in motors.

Element / Material	Fe	Ni	Cr	Mn	Si	C	Others	Total others
Fe-alloy Invar 36® 10-45µm	Bal.	35.00 - 37.00	0.50	0.50	0.50	0.10	0.20	0.50

Table 2.18 Detailed chemical composition of Invar 36® (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	Invar 36® [1,3]	Invar 36® [1,4]
Tensile strength	R_m [MPa]	487 ± 3	487 ± 3
Offset yield stress	$R_{p0,2}$ [MPa]	394 ± 2	386 ± 2
Break strain	A [%]	33 ± 1	32 ± 1
Reduction area	Z [%]	72 ± 3	71 ± 5
E-Modul	E [GPa]	125 ± 17	151 ± 13
Hardness by Vickers	[HV10]	149 ± 2	–
Surface roughness	R_a [µm]	13 ± 3	–
Surface roughness	R_z [µm]	82 ± 21	–

Table 2.19 Mechanical properties of Invar 36® [14]

Stainless steel 316L

The stainless steel 316L is an austenitic steel with high percentage of chromium. It is used in applications where a good corrosion resistance, a high strength under elevated temperatures and a high ductility is needed. Common application areas are aerospace and automotive as well as the food industry and maritime sector.

Element / Material	Fe	Cr	Ni	Mo	Si	Mn	C	N	P	S	O
316L (1.4404) 10-45µm	Bal.	16.00 - 18.00	10.00 - 14.00	2.00 - 3.00	1.00	2.00	0.030	0.10	0.045	0.030	0.10

Table 2.20 Detailed chemical composition of 316L (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	1.4404 / 316L[2,3]
Tensile strength	R_m [MPa]	633 ± 28
Offset yield stress	$R_{p0,2}$ [MPa]	519 ± 25
Break strain	A [%]	31 ± 6
Reduction area	Z [%]	49 ± 11
E-Modul	E [GPa]	184 ± 20
Hardness by Vickers	[HV10]	209 ± 2
Surface roughness	R_a [µm]	10 ± 2
Surface roughness	R_z [µm]	50 ± 12

Table 2.21 Mechanical properties of 316L [14]

Stainless steel 15-5PH

This stainless steel is a martensitic precipitation-hardening steel. It boasts a high strength and hardness and a moderate corrosion resistance. Typical application fields are aerospace industry, medical sector and the metalworking industries. This alloy is the ferrite-free version of 17-4PH (see also the next chapter, Stainless steel 17-4PH).

Element / Material	Fe	Cr	Ni	Cu	Nb + Ta	Si	Mn	C	N	P	S	O
15-5PH (1.4540) 10-45µm	Bal.	14.00 - 15.50	3.50 - 5.50	2.50 - 4.50	0.15 - 0.45	1.00	1.00	0.07	0.10	0.04	0.03	0.10

Table 2.22 Detailed chemical composition of 15-5PH (nominal),% [14]

1 Layer thickness 30 µm - 2 Layer thickness 50 µm - 3 As build according to SLM   Solutions standards - 4 Heat treated - 5 Process conditions and parameters

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Mechanical data[5]	Formula symbol and unit	1.4540 / 15-5PH[1,3]
Tensile strength	R_m [MPa]	1194 ± 28
Offset yield stress	$R_{p0,2}$ [MPa]	668 ± 29
Break strain	A [%]	14 ± 0
Reduction area	Z [%]	48 ± 1
E-Modul	E [GPa]	184 ± 23
Hardness by Vickers	[HV10]	353 ± 2
Surface roughness	R_a [µm]	10 ± 2
Surface roughness	R_z [µm]	62 ± 11

Table 2.23 Mechanical properties of 15-5PH [14]

Stainless steel 17-4PH

The stainless steel 17-4PH is also a martensitic precipitation-hardening steel. Its characteristics and application areas are the same like from the stainless steel 15-5PH (see also the previous chapter, Stainless steel 15-5PH).

Element / Material	Fe	Cr	Ni	Cu	Nb + Ta	Si	Mn	C	N	P	S	O
17-4PH (1.4542) 10-45µm	Bal.	15.00 - 17.50	3.00 - 5.00	3.00 - 5.00	0.15 - 0.45	1.00	1.00	0.07	0.10	0.04	0.03	0.10

Table 2.24 Detailed chemical composition of 17-4PH (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	1.4542 / 17-4PH[2,3]
Tensile strength	R_m [MPa]	832 ± 87
Offset yield stress	$R_{p0,2}$ [MPa]	572 ± 25
Break strain	A [%]	31 ± 3
Reduction area	Z [%]	55 ± 4
E-Modul	E [GPa]	155 ± 22

Table 2.25.a Mechanical properties of 17-4PH [14]

Mechanical data[5]	Formula symbol and unit	1.4542 / 17-4PH[2,3]
Hardness by Vickers	[HV10]	221 ± 4
Surface roughness	R_a [µm]	9 ± 2
Surface roughness	R_z [µm]	54 ± 15

Table 2.25.b Mechanical properties of 17-4PH [14]

Tool steel 1.2709

This maraging tool steel has a high percentage of alloyed nickel and some molybdenum. It is martensite hardenable and boasts a high toughness and tensile strength as well as good properties up to ca. 400°C. It is typically used for injection moldings and engineering parts in the automotive and aerospace industries.

Element / Material	Fe	Ni	Mo	Ti	Co	Al	Mn	C	P	S
1.2709 10-45µm	Bal.	18.00 - 19.00	4.70 - 5.20	0.50 - 0.80	8.50 - 9.50	0.05 - 0.15	0.10	0.03	0.01	0.01

Table 2.26 Detailed chemical composition of 1.2709 (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	1.2709[2,3]	1.2709[2,4]
Tensile strength	R_m [MPa]	1135 ± 29	1784 ±313
Offset yield stress	$R_{p0,2}$ [MPa]	987 ± 15	1920 ± 12
Break strain	A [%]	11 ± 1	3 ± 1
Reduction area	Z [%]	44 ± 2	10 ± 0
E-Modul	E [GPa]	113 ± 8	125 ± 5
Hardness by Vickers	[HV10]	373 ± 2	–
Surface roughness	R_a [µm]	9 ± 1	–
Surface roughness	R_z [µm]	67 ± 5	–

Table 2.27 Mechanical properties of 1.2709 [14]

1 Layer thickness 30 µm - **2** Layer thickness 50 µm - **3** As build according to SLM Solutions standards - **4** Heat treated - **5** Process conditions and parameters

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Tool steel H13

The tool steel 1.2344, also known as H13, is a chromium containing martensitic steel. It has a high tensile strength, a moderate corrosion resistance and it is resistant to thermal fatigue cracking. It is mostly used for injection moldings and tooling.

Element / Material	Fe	C	Cr	Mn	Mo	Ni + Cu	P	S	Si	V
H13 10-45µm	Bal.	0.32 - 0.45	4.75 - 5.50	0.20 - 0.60	1.10 - 1.75	0.75	0.03	0.03	0.80 - 1.25	0.80 - 1.20

Table 2.28 Detailed chemical composition of H13 (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	H13[2,3]	H13[2,4]
Tensile strength	R_m [MPa]	1525 ± 146	1888 ± 6
Offset yield stress	$R_{p0,2}$ [MPa]	1507	1655 ± 23
Break strain	A [%]	3	8 ± 1
Reduction area	Z [%]	3	15 ± 3
E-Modul	E [GPa]	217 ± 19	256 ± 38
Hardness by Vickers	[HV10]	–	–
Surface roughness	R_a [µm]	–	–
Surface roughness	R_z [µm]	–	–

Table 2.29 Mechanical properties of H13 [14]

Aluminum-based alloys:

AlSi10Mg

Under the offered Al-alloys of the SLM Solutions Group, there is one material, which is fulfilling the mechanical requirements and is comparable to the currently used material EN-GJS-400-15U:

The aluminum-based alloy AlSi10Mg is a widely used material in the additive manufacturing industry. It is commonly utilized for prototypes as well as functional parts that require good mechanical properties and low weight. Characteristics of this material are a very good corrosion resistance, good electrical conductivity, high dynamic tightness and a good thermal conductivity. Typical application areas are Aerospace, Automotive, Engineering and Heat exchangers.

Element / Material	Al	Si	Mg	Cu	Fe	Mn	Zn	Ti	Ni	Pb	Sn	Others	Total others
AlSi10Mg 20-63µm	Bal.	9.0 – 11.0	0.20 – 0.45	0.05	0.55	0.45	0.10	0.15	0.05	0.05	0.05	0.05	0.15

Table 2.30 Detailed chemical composition of AlSi10Mg (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	AlSi10Mg[2,3]
Tensile strength	R_m [MPa]	386 ± 42
Offset yield stress	$R_{p0,2}$ [MPa]	268 ± 8
Break strain	A [%]	6 ± 1
Reduction area	Z [%]	7 ± 1
E-Modul	E [GPa]	61 ± 9
Hardness by Vickers	[HV10]	122 ± 2
Surface roughness	R_a [µm]	8 ± 1
Surface roughness	R_z [µm]	63 ± 10

Table 2.31 Mechanical properties of AlSi10Mg [14]

Other offered Al-Alloys from the SLM Solutions Group AG are AlSi12, AlSi7Mg0.6 and AlSi9Cu3, which are not introduced as they are not fulfilling the mechanical properties needed by the company Buchholz.

1 Layer thickness 30 µm - 2 Layer thickness 50 µm - 3 As build according to SLM Solutions standards - 4 Heat treated - 5 Process conditions and parameters

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Nickel-based alloys:

HX

The nickel-based alloy HX has a high amount of chromium, molybedenum and iron. It is commonly used for applications with high temperature in corrosive environments in different industries. The main characteristics are a high strength, good ductility, excellent oxidation resistance at high temperatures and a high creep strength up to 850°C. Typical application fields are aerospace, energy, the chemical industry and turbine parts.

Element / Material	Ni	Cr	Co	Mo	Fe	W	C	Mn	P	S	Si
HX 10-45µm	Bal.	20.50 – 23.00	0.50 – 2.50	8.00 – 10.00	17.00 – 20.00	0.20 – 1.00	0.05 – 0.15	1.00	0.04	0.03	1.00

Table 2.32 Detailed chemical composition of HX (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	HX[1,3]
Tensile strength	R_m [MPa]	772 ± 24
Offset yield stress	$R_{p0,2}$ [MPa]	595 ± 28
Break strain	A [%]	20 ± 6
Reduction area	Z [%]	21 ± 7
E-Modul	E [GPa]	162 ± 11
Hardness by Vickers	[HV10]	248 ± 4
Surface roughness	R_a [µm]	9 ± 1
Surface roughness	R_z [µm]	60 ± 6

Table 2.33 Mechanical properties of HX [14]

IN625

The nickel-based alloy IN625 is a precipitation-hardenable material alloyed with chromium, molybedenum and niobium. Important characteristics are a high strength, good ductility, excellent creep-repute strength below 700°C and an excellent corrosion resistance. It is typically used for the construction of aircraft engines components with service temperatures below 650°C.

Element / Material	Ni	Cr	Co	Mo	Al	Fe	Ti	Nb	C	Mn	P	S	Si
IN625 10-45µm	Bal.	20.0 - 23.0	10.0	8.00 - 10.0	0.40	5.00	0.40	3.15 – 4.15	0.10	0.50	0.015	0.015	0.50

Table 2.34 Detailed chemical composition of IN625 (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	IN625[1,3]
Tensile strength	R_m [MPa]	961 ± 41
Offset yield stress	$R_{p0,2}$ [MPa]	707 ± 41
Break strain	A [%]	33 ± 2
Reduction area	Z [%]	51 ± 5
E-Modul	E [GPa]	182 ± 9
Hardness by Vickers	[HV10]	285 ± 3
Surface roughness	R_a [µm]	7 ± 2
Surface roughness	R_z [µm]	40 ± 10

Table 2.35 Mechanical properties of IN625 [14]

Other nickel-based alloys offered by SLM Solutions AG are IN718 and IN939, that have a slightly different chemical composition than the IN625. Details are specified under www.slm-solutions.com [14].

Titanium-based alloys:

Ti6Al4V (grade 23)

One Ti-alloy is Ti6Al4V ELI (grade 23), which is the high purity version of Ti6Al4V (grade 5), the most widely used titanium-based alloy in the world. It is suited for the aerospace industry, the automotive industry as well as biomedical applications. Its characteristics are a high strength, low density and good corrosion resistance.

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Element /Material	Ti	Al	V	Fe	C	N	O	H	Others	Total others
Ti6Al4V ELI (grade 23) 20-63µm	Bal.	5.50 - 6.50	3.50 - 4.50	0.25	0.08	0.03	0.13	0.0125	0.10	0.40

Table 2.36 Detailed chemical composition of Ti6Al4V ELI (grade 23) (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	Ti6Al4V[2,3]	Ti6Al4V[2,4]
Tensile strength	R_m [MPa]	1301 ± 18	1031 ± 5
Offset yield stress	$R_{p0,2}$ [MPa]	1158 ± 16	970 ± 6
Break strain	A [%]	3 ± 1	12 ± 1
Reduction area	Z [%]	5 ± 2	28 ± 7
E-Modul	E [GPa]	113 ± 9	118 ± 2
Hardness by Vickers	[HV10]	380 ± 8	−
Surface roughness	R_a [µm]	14 ± 1	−
Surface roughness	R_z [µm]	86 ± 11	−

Table 2.37 Mechanical properties of Ti6Al4V ELI (grade 23) [14]

Ti (grade 2)

The titanium alloy Ti (grade 2) is a pure titanium that is commonly used in different applications that require a high corrosion resistance, strength, ductility and low density.

Element /Material	Ti	Fe	C	N	O	H	Others	Total others
Ti (grade 2) 20-63µm	Bal.	0.30	0.08	0.03	0.25	0.015	0.10	0.40

Table 2.38 Detailed chemical composition of Ti (grade 2) (nominal),% [14]

Mechanical data[5]	Formula symbol and unit	Ti (grade 2)[1,3]
Tensile strength	R_m [MPa]	> 290
Offset yield stress	$R_{p0,2}$ [MPa]	> 180
Break strain	A [%]	> 20
Reduction area	Z [%]	−
E-Modul	E [GPa]	105
Hardness by Vickers	[HV10]	130 - 210
Surface roughness	R_a [µm]	−
Surface roughness	R_z [µm]	36 ± 4

Table 2.39 Mechanical properties of Ti (grade 2) [14]

Cobalt-based alloys:

CoCr28Mo6

This alloy is mix of cobalt, chromium and molybdenum. It boasts characteristics like resistance to heat, thermal fatigue and oxidation. Mostly it is used in the medical sector, aerospace industry and for turbine parts.

Element /Material	Co	Cr	Mo	W	Al	Si	Fe	Mn	Ti	Ni	C	B	N	P	S
CoCr28Mo6 10-45µm	Bal.	27 - 30	5.0 - 7.0	0.2	0.1	1.0	0.75	1.0	0.1	0.5	0.35	0.01	0.25	0.02	0.01

Table 2.40 Detailed chemical composition of CoCr28Mo6 (nominal),% [14]

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Mechanical data[5]	Formula symbol and unit	CoCr[1,3]	CoCr[2,3]
Tensile strength	R_m [MPa]	1101 ± 78	1039 ± 91
Offset yield stress	$R_{p0,2}$ [MPa]	720 ± 18	705 ± 73
Break strain	A [%]	10 ± 4	10 ± 4
Reduction area	Z [%]	11 ± 4	11 ± 3
E-Modul	E [GPa]	194 ± 9	191 ± 10
Hardness by Vickers	[HV10]	375 ± 2	372 ± 7
Surface roughness	R_a [µm]	10 ± 1	10 ± 2
Surface roughness	R_z [µm]	64 ± 6	65 ± 12

Table 2.41 Mechanical properties of CoCr28Mo6 [14]

2.3 COMPARISON
2.3.1 Material Comparison

Every 3D metal printing providers offer several materials which are adapted to their own machines. Not every company is providing the same, there is a wide range of materials. So, SLM-Solution has been chosen thanks to a lot of interesting powders. Some are ferromagnetic, and the others are non-ferromagnetic while special applications like submarines need to be non-detectable, hence using non-ferromagnetic ones.

First, the titanium alloy Ti-Al6-V4 has interesting properties and it is one of the lightest metals on the market, and moreover it is non-magnetic. Among all these materials, there are two types of stainless steel which correspond to the valves properties. First, the 316L Stainless Steel is a non-ferromagnetic metal, and secondly, the 17-4 Stainless Steel is a ferromagnetic metal. These two metals are alloys, so they have different properties and different percentages of elements which contribute to their magnetism. They seem interesting to be analyzed and compared to have an overview of a ferromagnetic and a non-ferromagnetic metal.

The stainless steel has a bigger density than the titanium but a smaller density than most of the materials provided. These metals should be compared with the current cast iron to show the advantages and constraints.

1 Layer thickness 30 µm - **2** Layer thickness 50 µm - **3** As build according to SLM Solutions standards - **4** Heat treated - **5** Process conditions and parameters

Materials	Ni-Alloys HX	Ni-Alloys IN 625	Ni-Alloys IN 718	Ni-Alloys IN 939	Ti-Alloys Ti6AL4V	Ti-Alloys Ti Grade 2
Characteristics	-High strength -Good ductility -Excellent oxidation resistance at high temperature -High creep strength up to 850°C	-High strength -Good ductility -Excellent creep-rupture strength below 700°C -Excellent corrosion resistance	-High strength -Good ductility -Mechanical properties up to 700 °C -Oxidation resistance	-High strength -Good ductility -High temperature mechanical properties -Corrosion resistance	-Good corrosion resistance -High specific strength -High cycle fatigue strength -High toughness	-Excellent biocompatibility -Excellent corrosion resistance to sea water -Good ductility --Moderate strength
Applications	Aerospace Energy Chemical industry Turbine parts	Aerospace Energy Chemical industry Turbine parts	Aerospace Energy Chemical industry Turbine parts	Aerospace Energy Chemical industry Turbine parts	Aerospace Automotive Medical Energy	Medical Aerospace Energy Chemical / Petrochemical Heat exchangers
Density	8.22	8.44	8.23	-	4.42	4.51
Magnetism (permeability = 1.0)	Considered but not completely (2.0)	Non (±1.0006)	Non (±1.0013)	-	Non (±10005)	Non (±10005)
Mechanical data	≥ current valve properties	≥ current valve properties	≥ current valve properties	≥ current valve properties	≥ current valve properties	Rm [MPa] > 290 $R_{p0,2}$ [MPa] > 180 A [%] > 20 1)

Materials	Co-Alloys CoCr-28Mo6	Stainless steel 316L	Stainless steel 17-4PH	Tool steel H13	Invar 36®	Cu-Alloys CuSn10
Characteristics	-Exceptional biocompatibility -Heat resistant -Resistance to thermal fatigue -Oxidation resistance	-Very good corrosion resistance -High strength under elevated temperatures -High ductility -Cost-effectiveness -Durable -no maintenance	-Precipitation hardenable -Excellent tensile strength -Moderate corrosion resistance -Durable -no maintenance	-High tensile strength -Moderate corrosion resistance -Resistant to thermal fatigue cracking	-Low coefficient of thermal expansion below 280°C -Excellent mechanical properties at cryogenic temperatures -Low tendency to fatigue at low temperatures	-Good mechanical properties -Resistance to cavitation in sea water -Good corrosion resistance -Good thermal conductivity
Applications	Medical Aerospace Energy Turbine parts	Aerospace /Automotive Surgical Instruments Food Industry Maritime	Aerospace Medical Chemical / Petrochemical Paper / Metalworking industries	Injection moulding Tooling	Aerospace Valves in motors Precision instruments	Maritime Heat exchangers
Density	8.4	8	7.75	7.75	8.05	8.78
Magnetism (permeability = 1.0)	Non	Considered Non- but not completely	Yes	Yes	Yes below 280°C	-
Mechanical data	≥ current valve properties	≥ current valve properties	≥ current valve properties	≥ current valve properties	≥ current valve properties	≥ current valve properties

Table 2.42 Some materials provided by SLM Solutions [15]

1) The second stainless steel (Ti Grade 2) has more or less the same than this one and a low density (4.51) too, but the mechanical data (Rm [MPa]: > 290, Rp0,2 [MPa]: > 180, A [%]: > 20) so it could be ls by SLM if the properties researched are corresponding.[15]

properties and applications provide by SLM is not precise interesting to have more detai-

☐ *Materials chosen for the comparison.*
☐ *Interesting properties.*
☐ *Problematic properties.*

Ti6AL4V Titanium alloys [16,17]

The Ti6AL4V is non-ferromagnetic titanium because of the aluminium (5.50-6.50%) and the vanadium which allow stabilize the alloy. A totally non-magnetic material has a relative magnetic permeability of 1 and the Ti6AL4 has permeability less than 1.01. The Ti6Al4V ELI in Grade 23 corresponds to the high purity version of Ti6Al4V Grade 5 which is the most used titanium alloy in the world.

Titanium	Balance
Carbon	0.08 %
Aluminium	5.50-6.50 %
Vanadium	3.50-4.50 %
Fe	0.25 %
Nitrogen	0.030 %
Hydrogen	0.0125 %
Oxygen	0.13 %
Others	0.10 %
Total Others	0.40 %

Table 2.43 Composition of Ti6AL4V from SLM

The Ti6AL4V is characterized by a high specific strength, high cycle fatigue strength, high toughness and good corrosion resistance. The Ti6AL4V is resistant to general corrosion but may be quickly attacked by special environments like hydrofluoric (HF), hydrochloric (HCl), sulfuric and phosphoric acids. Moreover, this Titanium has a low density (± 4.42) which is an important point. The titanium is one of the lighter metals on the market and a low weight is searched for the valve.

The Ti6AL4V could be used for several applications: automotive, aerospace, energy and sea water products.

Mechanical data[5]	Formula symbol and unit	Ti6Al4V[2,3]	Ti6Al4V[2,4]
Tensile strength	R_m [MPa]	1301 ± 18	1031 ± 5
Offset yield stress	$R_{p0,2}$ [MPa]	1158 ± 16	970 ± 6
Break strain	A [%]	3 ± 1	12 ± 1
Reduction area	Z [%]	5 ± 2	28 ± 7
E-Modul	E [GPa]	113 ± 9	118 ± 2
Hardness by Vickers	[HV10]	380 ± 8	–
Surface roughness	R_a [μm]	14 ± 1	–
Surface roughness	R_z [μm]	86 ± 11	–
Density	[g/cm³]	± 4.42	± 4.42

Table 2.44 Ti6AL4V mechanical properties

In conclusion, Titanium is a very light material with a density close to two times less large than the stainless steel and some of the material provided. This density is an important advantage for a valve that should be as light as possible. Its other mechanical properties and corrosion resistance makes it really interesting. The inconvenient is the price which is generally higher than the other metals, it could be three to four times more expensive than the stainless steel [18].

316L Stainless Steel [19,20,21,22,23]

The 316L Stainless Steel is generally considered as a non-ferromagnetic metal because it has a magnetic permeability close to 1 but it is not completely non-ferromagnetic. Austenitic structures are non-magnetic and an austenitic stainless steel should have a permeability of 1. A basic stainless steel is formed with a chromium addition (10.5%), has a ferritic structure and is magnetic. The 316L stainless steel is austenitic; it is composed of higher chromium (16-18%) and nickel. It is the nickel which modifies the physical structure of the steel, stabilizes the austenite, and makes it theoretically non-magnetic.

Fe	Balance
Carbon	0.030 %
Manganese	2.00 %
Phosphorus	0.045 %
Sulphur	0.030 %
Silicon	1.00 %
Chromium	16.00-18.00 %
Nickel	10.00-14.00 %
Molybdenum	2.00-3.00 %
Nitrogen	0.10 %
Oxygen	0.10 %

Table 2.45 Composition of 316L Stainless Steel from SLM Solutions

The 316L Stainless Steel is generally characterized by its possible post-processing, excellent mechanical properties, a high ductility, and high strength under elevated temperatures, corrosion resistance and cost-effectiveness. The addition of molybdenum (3%) makes it extremely corrosion-resistant, it can resist to corrosive attack by sodium, calcium brines, hypochlorite solutions and phosphoric acid.

This material is adapted for maritime, automotive and industrial applications, food and chemical plants, aerospace and turbine industry.

Mechanical data[5]	Formula symbol and unit	1.4404 / 316L[2,3]
Tensile strength	R_m [MPa]	633 ± 28
Offset yield stress	$R_{p0,2}$ [MPa]	519 ± 25
Break strain	A [%]	31 ± 6
Reduction area	Z [%]	49 ± 11
E-Modul	E [GPa]	184 ± 20
Hardness by Vickers	[HV10]	209 ± 2
Surface roughness	R_a [µm]	10 ± 2
Surface roughness	R_z [µm]	50 ± 12
Density	[g/cm³]	± 8.00

Table 2.46 316L Stainless Steel mechanical properties

17-4 stainless steel [24,25,26,27]

The 17-4 stainless steel is generally considered as a ferromagnetic metal because it has a magnetic permeability close to 95. It includes an addition of Chromium (15.00-17.50%), Nickel (3.00-5.00%) and Copper (3.00-5.00%) to make a martensitic metal. So, martensitic metals are detectable due to the nickel and the copper which make a very large permeability.

Fe	Balance.
Carbon	0.07 %
Manganese	1.00 %
Phosphorus	0.040 %
Sulphur	0.030 %
Silicon	1.00 %
Chromium	15.00-17.50 %
Nickel	3.00-5.00 %
Copper	3.00-5.00 %
Niobium + Tantalum	0.15-0.45 %
Oxygen	0.10 %

Table 2.47 Composition of 17-4 stainless steel from SLM Solutions

The 17-4 stainless steel is known for its exceptional mechanical properties and cost-effectiveness, resistance to abrasion, wear and moderate corrosion. Moreover it has an important hardness and tensile properties in heat treated condition.

It is really adapted to applications that require strength, hardness, reliability and also in acid and corrosion environments. The general applications of the 17-4 stainless steel are the aerospace applications, gas turbines, chemical processing equipment, oil and petroleum refining equipment, food processing equipment, the general metal working.

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Mechanical data[5]	Formula symbol and unit	1.4542 / 17-4PH[2,3]
Tensile strength	R_m [MPa]	832 ± 87
Offset yield stress	$R_{p0,2}$ [MPa]	572 ± 25
Break strain	A [%]	31 ± 3
Reduction area	Z [%]	55 ± 4
E-Modul	E [GPa]	155 ± 22
Hardness by Vickers	[HV10]	221 ± 4
Surface roughness	R_a [μm]	9 ± 2
Surface roughness	R_z [μm]	54 ± 15
Density	[g/cm³]	± 7.75

Table 2.48 17-4 stainless steel mechanical properties

Carbon	2.50-3.80 %
Manganese	0.20-0.50 %
Phosphorus	≤0,08 %
Sulphur	≤0,02 %
Silicon	0.50-2.50 %

Table 2.49 Composition of Cast Iron EN-GJS-400-15U

Tensile strength R_m [MPa]	400 ± 20
Elastic limit $R_{p0,2}$ [MPa]	250 ± 10
Elongation to the rupture	15 %

Table 2.50 Cast Iron EN-GJS-400-15U mechanical properties

Respect to the stainless steels, both materials are generally not expensive and easy to machine. They offer good material strength, good elasticity and corrosion resistance in all the environments. It is a material, which is very durable with few to zero maintenance. The difference is due to the magnetism and the corrosion resistance. The 17-4 PH stainless steel is magnetic and less corrosion-resistant than 316L stainless steel. The 316L stainless steel is lightly magnetic, but generally considered as non-magnetic and is possible to be found in non-magnetic versions with some manufacturers. Stainless steel is also an asset for the environment because it has a long durability and it is 100% recyclable. The stainless steel is considered as a cost effective metal but it is still five to seven times costlier than the cast iron [18].

Cast Iron EN-GJS-400-15U [28,29]:

This Cast Iron EN-GJS-400-15U offers an excellent machinability combined with good impact resistance. It is also generally known for its ductility, toughness and magnetic permeability. But there is also different a disadvantage with the cast iron, the shrinkage rate is large and can easily cause shrinkage defects.

Cast Iron EN-GJS-400-15U could be used to produce impact-resistant and shock-resistant parts. It is generally used in hydraulic and mechanic applications.

The Cast Iron EN-GJS-400-15U is a corrosion-resistant, reliable and durable material, but less than both stainless steels. It is generally used for shock resistant applications. The stainless steel offer excellent properties, an excellent corrosion resistance and is very durable, that is why it is more expensive than the Cast Iron. SLM provide two interesting stainless steels: one magnetic and one non-magnetic which could be used for special and adapted applications. The stainless steel is considered as a cost-effective material because its price remains affordable compared to the characteristics offered. However, these two materials are not light and have a high density compared to the lighter metals on the market. The valve needs to be as light as possible so it could be a constraint if the first goal is the weight. In this case, one is especially adapted for a prototype, desired as light as possible. The Titanium alloy Ti6AL4V has a weak density so it makes a very light material. Added to that, it has remarkable properties adapted for many situations and applications. Its mechanical properties and corrosion resistance make this material really interesting. The inconvenient is the price which is higher than the other metals and than the stainless steel.

To conclude on the materials, the Ti6AL4V seems the most appropriate material for this 3D printing valve application. The density of this one makes it the most interesting for a lighter housing with excellent properties, but without forgetting the huge price which could discourage some purchasers.

2.3.2 Costs Comparison

To find out if the implementation of a production process with additive manufacturing technology is economical, the expected costs are compared to the costs of the current production method. For that, the machine and material is chosen from SLM Solutions Group AG, since this supplier had the highest score in the Scoring Model. Moreover, it should to be mentioned, that the calculation of the current costs is based on information given from the company Buchholz, whereas the cost calculation of the new production method is based on another calculation accounting system which is derived from the "NPV Financial Calculation" from Geisler [30, p. 332 ff.].

Costs of current production method

Currently, Buchholz is using numerical control machines for the manufacturing of the housing. Regarding the current costs, the students were provided with following information:

Material costs (AMB II): 22 €/kg
Machine set up per unit: 235 min with 1,77 €/min
Machine run time per unit: 30min with 2,67 €/min

The production costs for one housing are therefore 742,45 € (see also table 2.51).

		Source
Material costs per unit [€/unit]	246,4	Source
Material costs [€/kg]	22	Internal information of Buchholz
Weight housing [kg]	11,2	CAD
Costs for machine set up [€/unit]	415,95	
Machine set up per unit [min]	235	Internal information of Buchholz
Costs per minute [€/min]	1,77	Internal information of Buchholz
Costs for machine run time [€/unit]	80,1	
Run time per unit [min]	30	Internal information of Buchholz
Costs per minute [€/min]	2,67	Internal information of Buchholz
Production costs per unit [€/unit]	742,45	
(current housing)		

Table 2.51 Current production costs per housing

Expected costs of a production process with additive manufacturing technology

The financial calculation for the new production method also includes, next to the expected variable costs per unit, the expected financial requirements per year (see table 2.53). For this, it is assumed that the machine "SLM 500" from the SLM Solutions Group AG has a useful life of 5 years. This is because it is expected that the additive manufacturing technology will develop a lot in the coming years, so that it can be assumed that after 5 years there will be machines which are significantly faster and better equipped than the current machines on the market [31,32,33].

In addition, the financial calculation includes a full cost calculation.

	A	B	C
1			Source
2	Machine run time per year [h]	1818	
3	Batch size [units]	150	Assumed value
4	Build rate [cm³/h]	171	Machine comparison
5	Volume housing [cm³]	2072	CAD

Table 2.52 Calculation of the machine run time per year

Table 2.53 Financial calculation of new production method

	2019	2020	2021	2022	2023	Factor	Notes	Source
Investments [€]	1.510.000	0	0	0	0		5 years useful life	Assumed value
3D-printer [€]	1.500.000						"SLM 500" from SLM Solutions Group AG	Assumed value
Installation [€]	2.000						Additional equipment, e.g. a table	[34] www.fabbaloo.com
Periphery [€]	1.000							Assumed value
Tools [€]	1.000							Assumed value
Trainings [€]	5.000							Assumed value
Integration of interfaces [€]	1.000							Assumed value
Operating costs per year [€]	270.804	276.786	282.883	289.095	294.925			
Material costs (Housing) [€]	267.750	273.105	278.567	284.138	289.821			
Batch size [units]	150	150	150	150	150			Assumed value
Material per unit kg]	11,9	11,9	11,9	11,9	11,9			CAD: [35] www.upmet.com
Material price [€]	150	153	156	159	162	2%	Material price increases by 2% every two years	Assumed value: [36] Phillips Corporation
Power [€]	2.554	2.681	2.815	2.956	3.104		"Stainless Steel 316L" from SLM Solutions	
Consumption [kW]	9	9	9	9	9			Machine comparison
Machine run time [h]	1.818	1.818	1.818	1.818	1.818			Assumed value
Fix [€]	100	105	110	116	122	5%	Price for power increases 5% per year	[37] www.energate-meessenger.de
Price [€/kWh]	0,15	0,16	0,17	0,17	0,18	5%	Price for power increases 5% per year	
Inert gas (only for Ti and Al) [€]	-	-	-	-	-			
Maintenance [€]	500	1.000	1.500	2.000	2.000	5%		Assumed value
Financial requirement [€]	1.780.804	276.786	282.883	289.095	294.925			
Variable unit costs [€/unit]	1.801	1.838	1.875	1.913	1.952			
Full costs per unit [€/unit]	3.905	3.945	3.986	4.027	4.066			
Operating costs [€]	270.804	276.786	282.883	289.095	294.925			
Depreciation [€]	300.000	300.000	300.000	300.000	300.000			
Calculative interests [€]	15000	15000	15000	15000	15000	5%		Assumed value

Explanation of the spreadsheet of the financial calculation

The spreadsheet of the financial calculation contains

1. Financial calculation (A1:F30)
2. The column "Factor" (G1:G30): with this factor the effect of an increasing price over the years for the respective position (e.g. material price) can be demonstrated.
3. The column "Notes" (H1:H30), that contains a small comment for the respective position.
4. The column "Source" (I1:I30), that shows from where the information of the respective row is coming from.

In the following, the content of the financial calculation will be explained more detailed:

(A3:A8) First, the investments for an implementing of a production process of additive manufacturing technology are listed. Beside the machine, there are other one-off costs need to be considered like installation, periphery, tools, trainings and integration of interfaces. The position "Integration of interfaces" contains the costs needed to integrate the new production process in the existing circumstances.

(A10) The operating costs are the sum of
    (A11) Material costs (Housing)
    (A15) Costs for power
    (A20) Costs for inert gas
    (A21) Costs for maintenance

(A23) The financial requirements are the sum of the investments (A2) and the operating costs (A10)

(A25) The variable unit costs are the variable costs divided by the batch size. The **variable costs** are:
    (A11) Material costs +
    (A15) Costs for power minus the fix power costs (A18) +
    (A20) Costs for inert gas

(A27) The full costs per unit are the full cost divided by the batch size. The full costs are:
    (A10) Operating costs +
    (A29) Depreciation +
    (A30) Calculative interests

The costs for inert gas are only occurring, when titanium or aluminium is processed. This is because, for those two materials Argon is needed that has to be purchased additionally. The processing of stainless steel needs only nitrogen, which is produced by the machine itself.

The full costs do not include any costs for the machine supervision, since it is assumed, that an already employed worker will be in charge for the supervision. So the costs for the worker would occur anyways and no extra costs would arise by implementing the new technology.

Furthermore, it need to be mentioned, that the full costs should be considered with caution, since they can give a distorted picture of the actual costs per unit [cf. 38 p.1ff.] . This becomes very clear, if the full costs per unit are compared with a batch size of "1" and a batch size of "150" (see table 2.54 and 2.55).

25	Variable unit costs [€/unit]	1.801	1.838	1.875	1.913	1.952
26						
27	Full costs per unit [€/unit]	3.905	3.945	3.986	4.027	4.066
28	Operating costs [€]	270.804	276.786	282.883	289.095	294.925
29	Depreciation [€]	300.000	300.000	300.000	300.000	300.000
30	Calculative interests [€]	15000	15000	15000	15000	15000

Table 2.54 Costs with batch size 150

25	Variable unit costs [€/unit]	1.801	1.838	1.875	1.913	1.952
26						
27	Full costs per unit [€/unit]	317.401	317.943	318.485	319.029	319.074
28	Operating costs [€]	2.401	2.943	3.485	4.029	4.074
29	Depreciation [€]	300.000	300.000	300.000	300.000	300.000
30	Calculative interests [€]	15000	15000	15000	15000	15000

Table 2.55 Costs with batch size 1

Due to the allocation of the fix costs, the depreciation of the machine and the calculative interests, the costs of one unit raises up to over 317.000 € assuming a batch size of "1". But in actual those are not costs that occur because of producing only one unit.

That is why, the variable unit costs are calculated, which show the actual costs per unit. As it can be seen in table 2.54 and table 2.55, the variable costs are not changing with a change of the batch size. The reason is, that no matter how many units are being produced - the material costs per unit and the power and inert gas needed per unit stay always the same.

Moreover, is the advantage of the executed financial calculation, that the cost drivers are broken down. With these information, it can be easily demonstrated how big the impact is, if the costs of one position (e.g. material price) are changing.

Conclusion

To sum up, it can be said that a production process with additive manufacturing technology is significantly higher compared to a production with numerical control machines. The reason for that is primary due to the high material costs. In addition, the machine run time for one unit is essentially higher compared to the traditional production process, what also leads to smaller possible batch sizes.

Nevertheless, it can be expected that in the coming years the additive manufacturing technology is going to develop a lot [31,32,33]. So, what might not seems to be economical today, can be economical in a few years.

03 CONCLU-SION

Fig. 3.1 Conclusion [16]

CONCLUSION

To talk about the conclusion of this project, but first the conclusions of each point have been talking. From the initial research on the two production methods, the team acquired a basic knowledge of 3D technology that was later used by each member to develop their own section.

The conclusion that can be obtained from the part of the materials is that titanium, Ti6AL4V, is the most appropriate in terms of the piece has a lower weight and meets the mechanical properties exceptionally, marking a great improvement over the current material, although it is true that titanium is more expensive than the actual material. Other option is stainless steel, which meets the mechanical and magnetic conditions established, it is cheaper, but the density is much higher.

As for the design, it has been observed that the changes provided by the flexibility and customization of the additive manufacturing technology can be very useful for the company if the current housings are adapted to this new technology, this would facilitate the reduction of weight, material used and even size of the pieces.

The cost comparison shows that currently the manufacturing process using numerical control machines is faster, cheaper and more efficient than the one possible with 3D printers, which could only achieve around 150 housings per year which does not meet the requirements of the company.

The conclusion is that additive manufacturing technology is a very interesting alternative that in the future may make a difference to current manufacturing technologies. But it is true that nowadays it is too expensive and too slow to be implemented as an alternative technology. Buchholz Hydraulik is urged to follow the progress of this technology and to consider the possibility of implementing it in their manufacturing processes in the future, when it will be more economical and efficient.
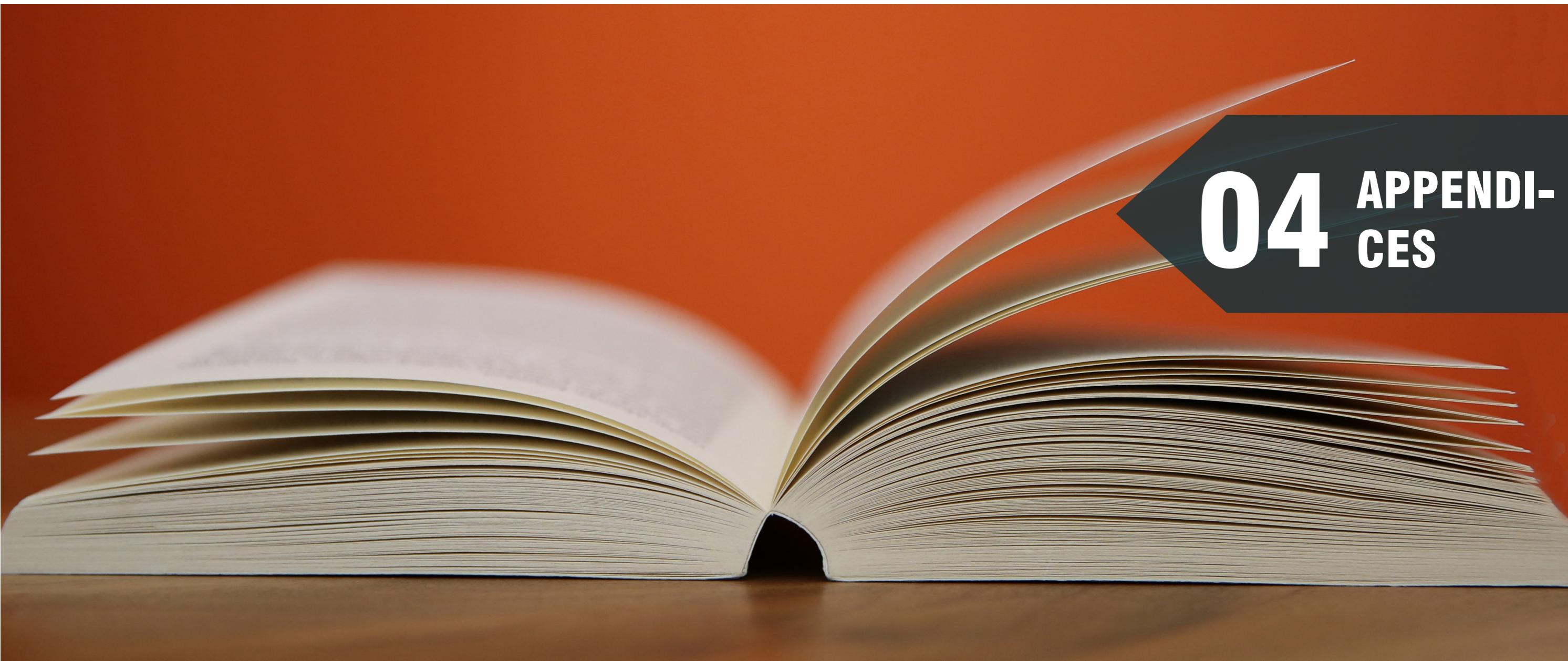
04 APPENDICES

Fig. 4.1 Appendices [17]

Numerical Control is a machining method which is principally used in machine tools. The Numerical Control Machine (CNC) is defined as being controlled by the set of instructions called the program. The program must be done upstream and transfer to the Numerical Control Machine. This program includes all the step that the CNC must perform. The program can be typed by the users, but it is a very long method if the object to do has a complicated shape and many operations. The most used and the easiest method is the utilisation of computer software: with this method, we have just to create the different operations in 3D in the software and add the different settings (cutting speed, advance, cycle times...) of every operation. The CNC technology can be applied to a wide variety of operations like drafting, assembly, inspection, sheet metal working, etc. But it is more prominently used for various machining processes like turning, drilling, milling, shaping etc. [39].

A Numerical Control Machine is made of the following different elements:

- The tools for every operation.
- The tool holders.
- The machining inserts.
- An automatic tool changing device.
- And many different little, but important operations for the security, the control, the lubrication, extract of shavings, etc. [40]

Fig. 4.2 First Control Numerical Machine developed by Parsons [18].

Starting talking about Numerical Control Machine at the beginning of the 19th century when Joseph-Marie Jacquard invent a weaving loom with perforated strips or complicated weaves [41].

Then, in the 1880s, the American mathematician Hermann Hollerith used the same types of punched card like Jacquard for the processing of data [41].

The Numerical Control was developed by John Parsons like a production method for stiffened aircraft skins. Parsons, while working at his father's Traverse City, Michigan-based Parsons Corp, had previously archived works for a rotor blade template. First, he used an IBM 602A, which is an electromechanical calculator capable of addition, subtraction, multiplication, and division to calculate coordinates. And he used this calculator with a Swiss jig borer, which is a type of machine tools invented at the end of World War I. So, it was possible to produce templates from data on punched cards [40,42].

After 1949, Parsons works were the base for many Air Force research projects at the Massachusetts Institute of Technology (MIT) which needed to develop more efficient manufacturing methods for modern aircraft. World War II, the components used to fabricate jet aircraft became more complex and required more machining. Following extensive research and development, an experimental milling machine was constructed in MIT's Servomechanisms Laboratory. On March 1952, Richard Kegg and the MIT Labs held the first demonstration of the NC machine. The machine tool builders gradually began developing their own projects to introduce commercial NC units. The MIT tried to design a part programming language that could be used in controlling N.C. machines [40,42,43].

After this success, Parsons and Stulen, his engineer boss, choose to continue and to industrialize their project. So they work during five years and the 14th of january 1958, the patent was finally left. It is titled "Motor Controlled Apparatus for Positioning Machine Tool" and sounds like the birth of the digital control machine. General Electric became the first manufacturer of these machines before the Japanese brand FANUC in 1962.

4.1.2 Materials

The Numerical Control Machining is able to adapt the production to different materials.

Ferrous Metals [44]:

General Steel

1. Composed of iron and carbon (with sometimes vanadium and chromium for more hardness).
2. Resistant and flexible.
3. Using: car, machines, tools, etc.

Stainless steel

1. Higher corrosion resistance.
2. Higher cryogenic toughness.
3. Higher work hardening rate.
4. Higher hot strength.
5. Higher ductility.
6. Higher strength and hardness.
7. A more attractive appearance.
8. Lower maintenance.

Cast iron

1. Cast iron is an iron allows which contain an important part of carbon.
2. Very hard, but breakable too.
3. Generally, iron, cast pieces are mould.

Non-Ferrous Metals [9]:

Brass and bronze

1. In part composed of copper.
2. The simple brass contains copper and zinc.
3. Bronzes are alloys of copper and tin.
4. Sometimes with others steels like lead, silver, nickel or magnesium.
5. This alloy are harder and more resistant than, but also easier to

Copper

1. Reddish color.
2. Ductile, soft and malleable.
3. Lasting because easy to recycle.
4. Easily machinable because of its properties.

Titanium

1. Comparable with steel
2. Good resistance at corrosion.

Aluminium

1. Color: white & bright.
2. Soft, malleable, resistant at oxidization.
3. Using: for the manufacture of light piece or structure.

3. Big mechanical performances.
4. Expensive compared to other steels.

Plastics:

PVC, PMMA, bakelite, Polyamide 6, etc. [44]

Alloy fire resistant:

Heat resistant alloys of iron, nickel and cobalt are used where high temperature performance. They present a creep strength, tensile strength, low-cycle fatigue response, high-cycle fatigue response, fracture toughness, creep rupture behavior, cyclic rapture (creep-fatigue interaction) behavior [45].

Conclusion:

The machining method can be applied to many materials, both metals (ferrous or non-ferrous) and non-metallic.

4.1.3 Current Material

Currently, Buchholz Hydraulik is using an alloy called *Cast Iron EN-GJS-400-15U (EN-JS1072)*, which present the folowing mechanical properties [46, 47]:

Nominal thickness	30 mm
Tensile Strength (R_m)	370 - 400 MPa
Elastic Limit ($R_{p0.2}$)	250 MPa
Elongation to the Rupture (A)	15 %
Hardness	150 - 180 HB
E-Modulus	169 GPa
Density	7.1 g/cm^3

Table 4.1 Current Material Properties [46, 47].

4.2 3D PRINTERS
4.2.1 History

1980

The First Rapid Prototyping (RP) was filed by Hideo Kodama in Japan.

1986

Charles Hull deposited the first patent for Stereolithographic (SLA) and founded 3D systems.

1987

SLA-1 machine was introduced.

1988-89

Carl Deckard from the University of Texas brought a patent for Selective Laser Sintering (SLS) technology, which was issued by DTM Inc., and then acquired by 3D systems.

1988-89

Scot Crump (co-founder of Stratasys Inc.) filed a patent for Fused Deposition Modelling.

1992

FDM patent was issued to Stratasys.

1993

Solidscape was founded.

2007

Shapeways: collaborative co-creation service. It is a 3D market-place (to get feedback from consumers and other designers and then affordably fabricate their products).

2005

Zcorp launched the Spectrum 2510, the very first high-definition color 3D printer.

2004

RepRap Project, open-source initiative to create a self-replicating 3D printer.

2002

Startups fabricated a functional miniature kidney that was capable of filtering blood and producing diluted wine in an animal.

2000

MCP Technologies introduced the SLM technology.

1999

The scientists at the Wake Forest Institute for Regenerative Medicine printed synthetic scaffolds of a human bladder and then coated them with the patient's own cells. The process had little to no risk of rejection because it is made with the patient's cell.

Fig. 4.3.a Chronological history of 3D Printing [19,20,21].

2008

- Darwin, the first self-replicating printer comes to life.
- The first 3D printed prosthetic leg, without the need for any later assembly, comes to life.

2009

- FDM patents fell into the public domain.
- Sculpteo was created, an online printing services.
- DIY 3D printer kits hit the market.
- MarkerBot: collaborative co-creation service. It provides an open-source DIY kits for makers to build their own 3D printers and products.
- Dr. Gabar Forgarcs used a 3D bioprinter to print the first blood vessel.

2010's mentality

Industrial sector rethink about additive manufacturing as a reliable production.

Small and big companies take advantatge of the low prototyping price that offers 3D printing.

2010

- Engineers from University of Southampton design and fly the world's first 3D printed aircraft, which was built in only seven days with a budget of 5,000 Dollars.
- Urbee is the first 3D printed prototype car presented.

NOW

- 3D printers are more efficient, faster and give acces to new 3D printing materials.
- Price of 3D printer has fallen/ the accuracy of 3D printing has improved.

2014

- NASA brought a 3D printer in space to make the first 3D printed object off the earth.
- Many medical advances: tissues, organs and low-cost prosthesis.

2012

Create a customized three-dimensional prosthetic lower jaw, that was implanted into an 83 years old woman suffering from a chronic bone infection.

2011

- New materials appear, as 14k gold and sterling silver.
- Conell University began to build a 3D food printer.

Fig. 4.3.b Chronological history of 3D Printing [19,20,21].

4.2.2 Types of 3D Printing Techniques

Below are the different methods that are currently being used by additive manufacturing technologies applied to the industry:

Fused Deposition Modelling (FDM)

FDM technology is the most common 3D printing method in desktop 3D printers. The thermoplastic filament is heated and extruded in X and Y coordinates through the extrusion head, while the printing surface is lowering the object layer by layer in the Z direction.
In this way the object is printed from bottom to top. If there is a case that a model has protruding parts, you will need support structures that can be removed once the printing is finished. This type of 3D printer is a cost-effective way to develop a product and quickly create prototypes in the small business and education sectors, as it is capable of manufacturing robust parts efficiently and quickly [48].

Stereolithography (SLA)

Stereolithography is characterized by being the oldest 3D printing technology. This technology works by exposing a layer of liquid photosensitive resin to a UV laser beam to harden and solidify. Once the laser runs through a layer of resin in the desired pattern, it begins to harden. Next, the model's printing platform, located in the liquid tank of the printer, lowers one layer and the laser begins to form the next layer. Each layer is built on the previous one.

As with 3D FDM printing technology, protruding parts printed with these types of 3D printers will need support structures. Once the printing is completed, the object should be rinsed with a solvent. Sometimes it is also baked in a UV oven to finish the processing.

The SLA technology creates objects with smooth surfaces and a lot of detail. It is increasingly popular in sectors such as jewelry and cosmetic dentistry for the creation of malleable molds [48].

Digital light processing (DLP)

It is a technology very similar to SLA since they share many aspects in common, such as the hardening of the resin.

The DLP technology uses an electrical network of computer controlled micromirrors arranged in a mold on a semiconductor chip. These tiny mirrors lean back and forth. When a mirror is tilted, it reflects light, reflecting a bright pixel. While the mirror is tilted to the opposite side, the pixel will turn dark. This type of technology is used in film projectors, mobile phones and also for 3D printing. One of the benefits it presents for 3D printing is its speed: you can print layers in an instant.

The types of DLP 3D printers are used mainly in professional areas and allow to manufacture robust parts with excellent resolution. Also lovers and fans of 3D printing are building their own 3D printers based on DLP technology using beams of light or even smart phones to harden the resin [48].

Selective laser sintering (SLS)

It is similar to the SLA, but the main difference is that this type of 3D printer uses powder material in the printing area instead of liquid resin. A laser is used to selectively sinter a layer of granules that binds the material to create a solid structure. When the object is completely formed, it is allowed to cool in the machine before removing it.

The SLS is widely used for the development of products and the rapid creation of prototypes oriented to commercial industries. Likewise, it is useful for the manufacture of final products of limited use, such as parts used in the industrial sector (for example, pieces of machinery). The materials used in the SLS can vary from nylon, glass and ceramic to aluminum, silver and even steel [48].

Selective laser melting (SLM)

The SLM technology uses a high-power laser beam to completely melt metal powders into three-dimensional solid pieces.

The typical materials used in these types of 3D printers are: stainless steel, aluminum, titanium and chrome-cobalt. SLM technology is used in the aerospace or orthopedic industry to create pieces with complex geometries and thin-walled structures, with hidden channels or empty spaces [48].

Electron beam fusion (EBM)

It uses a beam of electrons controlled by computer. This technique is carried out with a high vacuum pressure and using high temperatures that reach up to 1000 ° C to completely melt the metal powder.

This type of 3D printer can use metals such as pure titanium, Inconel718 and Inconel625 to manufacture aerospace parts and medical implants. Currently it is a very slow and expensive technology [48].

Laminated Object Manufacturing (LOM)

It uses layers of paper, plastic or metal laminates coated with adhesive, which melt under heat and pressure, and are cut with a laser or a blade controlled by computer. After this, a machining and drilling process is sometimes carried out. The 3D object is created layer by layer, and after cutting the excess material, it can be sanded or sealed with paint.

Compared with the types of 3D SLA or SLS printers, the dimensional accuracy of the LOM technology is slightly lower. However, LOM is one of the most economical and fastest 3D printing methods to create large pieces [48].

Binder injection (BJ)

Binder injection is an additive manufacturing process. This type of 3D printer uses two materials: a powder-based material (often plaster) and an adhesive agent, which acts by joining the layers of dust. In general, the binder is extruded in liquid form from a print head as in a conventional 2D inkjet printer. Once a layer is finished, the printing surface goes down and the process repeats itself.

This technology is used in 3D printing with ceramic, metal, sand or plastic [48].

Currently in 3D Printing it has been using different materials. The most commonly used materials in additive technologies are plastics, though there are another materials which are also used nowadays, as metals, ceramics, biomaterials and food. Above these lines each of them are explained more in detail [49,50,51]:

Plastics

PLA
The PLA is used in resin format for digital light processing (DLP) and stereolithography, on the other hand it can be used in filament form for the FDM process. It is biodegradable, so it does not have very high durability.

ABS
It is used in FDM printers in filament form, so that makes it easy to transport and use. This material is a very strong plastic and also the most popular plastic type in 3D printing. However, there are other types of plastics used in 3D printing that have more specific characteristics.

Nylon or Polyamide 6
This plastic is usually used in powder form with the sintering method or in the FDM process in filament form. Polyamide 6 is more expensive than PLA or ABS because it is used for specific material properties. Nylon is strong, flexible and durable and good for complex models with intricate design, functional products, moving parts, cases, holders, and adapters.

High Impact Polystyrene (HIPS)
This filaments are used for dissolvable support structures in FDM printers. The characteristics of HIPS are so similar to the ABS, but this material could be dissolved with a liquid hydrocarbon called limonene. It could be used in FDM printer with more than one print head, this two heads ABS could be in one head and HIPS in another head using it as a support material. With this process it is possible to remove HIPS and left ABS using limonene.

LayBrick and LayWood
LayBrick depends on the temperature that is used to change his properties, depending on the heat of extrusion it can be smoother or rougher.

On the other hand, LayWood, if the temperature is increased, it will result in darker color of wood.

T-Glase or Polyethylene terephthalate
T-Glase is the most glass-like compared to other 3D printer filaments.

Metals

Stainless Steel
This material is in powder form and is used in melting, sintering and EBM processes. This silver material can be plated with other materials to achieve a gold or bronze effect.

Gold and Silver
These materials are very useful in the jewelery industry. Also they are very strong and processed using powder.

Titanium
This metal is supplied in powder form and is one of the strongest metal materials used in 3D industrial printers.

Other Metals
Aluminium, maraging steel, Iconel – In718, Iconel – In625, cobalt chrome and copper are also used in 3D printing.

Ceramics

This new material is more durable than metal and plastic. It can support extreme heat and pressure, it doesn't rust or wear away and it requires a lot of temperature to melt and be processed.

Bio Materials

They are synthetic or natural materials that can be used for constructing artificial organs, prostheses, bones or tissue. Bio materials can now be used in 3D printing for a medical applications. There are studies that are examining living tissues with the goal of developing applications to print humans organs and externas tissues to used it in transplants and in body parts where replacement is needed.

Food

The most common food for 3D printing is chocolate. Others printers can work with sugar, candy, pasta and meat. 3D printers can also create interesting and complex shapes and designs using powdered or liquid edible material and puree.

4.3 SUPPLIERS SELECTION
4.3.1 Overview of the differents suppliers

Nowadays, numerous companies are providing 3D metal printing systems. Every providers are distinguishes in different criteria with their owns technologies, there owns material and with prices which could be really different. The following tables are composed of the twenty-one most interesting providers on the market which could correspond to the valve application.

Criteria	Companies						
	SLM	SLM	EOS	EOS	Concept Laser	3D Systems	AddUp
Country	Germany	Germany	Germany	Germany	Germany	USA	France
Machine	SLM® 280 2.0	SLM® 500.	EOSINT M 290	EOSINT M 280	M2 Cusing	ProX DMP 320	FormUpTM 350
Technology	Selective Laser Melting	Selective Laser Melting	Direct Metal Laser Sintering (DMLS)	Direct Metal Laser Sintering (DMLS)	Selective Laser Melting	DMP	Selective Laser Melting
Materials	Copper-based alloys, Tool and stainless steel, Aluminum-based alloys, Nickel-based alloys, Titanium-based alloys, Cobalt-based alloys	Copper-based alloys, Tool and stainless steel, Aluminum-based alloys, Nickel-based alloys, Titanium-based alloys, Cobalt-based alloys	Aluminium AlSi10Mg, Nickel Alloy HX, Nickel Alloy IN625, Stainless steel 17-4 PH, Stainless Steel CX, Stainless Steel 316L, Titanium Ti64, Titanium Ti64 ELI, Titanium TiCP	Aluminium AlSi10Mg, Stainless steel 17-4 PH, Stainless Steel 316L, Stainless Steel CX, Nickel Alloy HX, Nickel Alloy IN625	Stainless steel, Titanium alloys, copper alloys, Nickel based alloys	Ti Gr 23, Ti Gr 1 316 L Stainless Steel Ni 718	Ti6Al4V, AlSi10Mg 316 L Stainless Steel Inconel 718 18Ni300
Build Volume	280 x 280 x 365 mm3	500 x 280 x 365 mm3	250 x 250 x 325 mm3	250 x 250 x 325 mm3	250 x 250 x 280 mm3	275 x 275 x 420 mm3	350 x 350 x 350 mm3
Speed	10 m/s	10 m/s	7 m/s - 4,5 m/s	7 m/s	7 m/s - 4,5 m/s	-	10 m/s
Price	750000$-1M$	1M - 2M $	700000$	700000$	> 250000$	700000$	-

Table 4.2 Different 3D printing systems suppliers-1 [52,53,54,55,56,57,58,59,60]

Criteria	Companies						
	Arcam	DMG Mori	DMG Mori	DMG Mori	DMG Mori	Optomec	Optomec
Country	Sweeden	Germany and Japan	Germany and Japan	Germany and Japan	Germany and Japan	USA (México)	USA (México)
Machine	Arcam A2X	Lasertec 30 SLM	Lasertec 65 3D	Lasertec 65 3D Hybrid	Lasertec 4300 3D Hybrid	LENS MR-7	LENS 850-R
Technology	Electron Beam Melting	Selective Laser Melting	Laser Deposition Welting	Laser Deposition Welting + Milling	Laser Deposition Welting + Milling + Turning	LENS Technology (Laser Engineered Net Shaping)	LENS Technology (Laser Engineered Net Shaping)
Materials	Ti6Al4V, Alloy 718	AlSi10Mg0,5, Inconel 625 316 L Stainless Steel Titanium Tool Steels	Stainless Steel, Tool Steel Nickel based alloys, MMC Coating Cobalt alloys Copper alloys	Stainless Steel, Tool Steel, Titanium Nickel based alloys MMC Coating Cobalt alloys Copper alloys	Stainless Steel, Tool Steel, Titanium Nickel based alloys, MMC Coating Cobalt alloys Copper alloys	Inconel 625, Ti6Al4V 316 L Stainless Steel	Inconel 625, Ti6Al4V 316 L Stainless Steel
Build Volume	200 x 200 x 380 mm3	300 x 300 x 300 mm3	Diam. 650 x 560 mm	Diam. 500 x 400 mm	Diam. 660 x 1500 mm	300 x 300 x 300 mm3	900 x 1500 x 900 mm3
Speed	8000 m/s	-	-	-	-	60 mm/s	60 mm/s
Price	250000$-1.4M$	-	250000$	-	-	-	-

Table 4.3 Different 3D printing systems suppliers-2 [52,53,54,55,56,57,58,59,60]

Criteria	Companies						
	Trumpf	Xact Metal	Ex-ONE	Markforged	Desktop metal	Vader systems	Pollen AM
Country	Germany	USA	Germany	USA	USA	USA	France
Machine	TruLaserCell 3000	XM 300C	M-FLEX	METAL X	Production	Polaris	pam series M
Technology	Laser Metal Deposition/ Cutting	Metal Powder-Bed Fusion	Binder Jetting	Atomic difusion	Jetting techonologie	Liquefied metal	Metal Injection Moulding
Materials	Stainless Steel, Titanium Aluminium	Stainless Steel: 316L, 17-4PH, 15-15, 400Series, Super Alloys: 718, 625, Cobalt Chrome F75, Hastelloy X Tooling Steels: Maraging M300, H13 Bronze	420 Stainless Steel infiltrated with Bronze, 17-4PH Stainless Steel, Iron Infiltrated with Bronze, Alloy IN 625	Stainless steel aluminium, tool steel inconel, titanium	17-4 stainless steel, A-2/ D-2 tool steel, 316L stainless steel, inconel 625, titanium Ti-6Al-4V	No material provide	
Build Volume	800 x 600 x 400 mm3	254 x 330 x 330 mm3	400x250x250 mm3	300 x 220 x 180 mm3	330x330x330 mm3	305 x 305 x 305 mm3	Ø 300 H 300 mm
Speed	85 m/min	500 mm/s	30-60 sec./layer	-	-	-	-
Price	-	Dual Scan: 175.000 $/ Quad Scan: 275.000 $	450000$	100000$	420000$	250-350000$	-

Table 4.4 Different 3D printing systems suppliers-3 [52,53,54,55,56,57,58,59,60]

4.3.2 Report of six selected suppliers

CONCEPTLASER
a GE Additive company

Fig. 4.4 Concep Laser Logo [22]

One provider of metalbased additive manufacturing technology is the "Concept Laser GmbH" which is located in Germany. It is one of the world's leading providers of machine and plant technology for 3D printing of metal parts.

Machines

They offered one additive manufacturing solution for our metal valve, the M2 cusing Metal laser melting system, with a Building envelope LaserCUSING® of 250x250x280 mm³. This solution distinguish in the designed in line with ATEX guidelines for materials safety and the physical separation of the process chamber and handling area to make them user-friendly and safe to operate. This machine is also adapted to a robust and suitable operation. The laser source and filter technology are integrated within the system for a low space demand and the large filter surface area of 20 m² allows to reduce the filter change intervals. Finally the Water-floodable filter allows to guarantee that the filter can be changed safely [61].

Build envelope (L x W x H)	250 x 250 x 280 mm³
3DOpctics configuration, dual configuration: with switching unit	Fibre Laser 200 W (cw), optional 400 W (cw)
Build rate	2 - 20 cm³/h (depending on material / laser power)
Variable layer thickness	20 - 80 *10^{-6} m
Beam Focus diameter	50*10^{-6} m, optional variable focus move (50*10^{-6} m- 500*10^{-6} m)
Max. scan speed	7 m/s. 4.5 m/s for variable focus move
E-Connection / Powder input	Max power consumption 7.4 KW
Compressed air requirement / Consumption	Compressed air 5bar
Dimensions (L x W x H)	2542 x 1818 x 1987 mm³
Weight (without / incl. powder)	approx. 2300 kg [2]

Table 4.5 M2 Cusing Characteristics [61,62]

Materials

CL 42TI Commercially Pure Titanium

It´s possible to use this material with the M2 Cusing machine. Those properties are not really adapted with the valves properties researched because they are especially large. But the gap is not huge and the properties are respected [63].

R_m	610 ± 10 N/mm²
R_p	550 ± 20 N/mm²
E-Modulus	110 GPa
A	18 ± 2 %

Table 4.6 CL 42TI Commercially Pure Titanium properties

CL 80 CU Copper Alloy

It´s possible to use this material with the M2 Cusing machine [64].

R_m	400 N/mm²
R_p	500 N/mm²
E-Modulus	120
A	5%
Hardness	171

Table 4.7 CL 80 CU Copper Alloy properties

EOS is a German company based in Krailling which is working on industrial 3D printing technologies. This company is a pioneer and a world leader in the field of Direct Metal Laser Sintering (DMLS). They offered two differents solutions for additive manufacturing of metals:

Fig. 4.5 EOS logo [23]

Machines

The EOS M 290, with a building volume of 250 x 250 x 325 mm, distinguishes in a fast, flexible and cost-effective production of metal parts. But also in some functions like an intuitive user interface, an intelligent software concept with a combination of open and standardized parameter sets and an improved filter system which is specially designed for the industrial production [65].

The EOSINT M 280, with a building volume of 250 x 250 x 325 mm³, is the perfect solution for direct, cost-efficient manufacturing of high-quality metal tool inserts, prototypes and end products. It distinguishes with a high level of productivity and ergonomic periphery, which make the system ideal for the economical and batch-size optimized additive manufacturing of components throughout all phases of the product life cycle [66].

Those two differents solutions offer more or less the same functions, which distinguish them is the intuitive software and the Comprehensive quality assurance to have a real-time quality assurance of all production for the EOS M 290. For the EOSINT M 280, there is the possibility

to choose between an optimized surface and a productivity using according to the material and the possibility to choose the quality laser between 200 W and 400 W.

In the following, the specify characteristics of each machines are presented:

Build envelope (L x W x H)	250 x 250 x 325 mm³
3DOpctics configuration, dual configuration: with switching unit	Yb-Fibre Laser ; 400 W
Variable layer thickness	20 - 80 *10⁻⁶ m
Beam Focus diameter	100*10⁻⁶ m (0.004 in)
Max. scan speed	7 m/s. 4.5 m/s for variable focus move
E-Connection / Powder input	Max power consumption 8.5 KW / typical 3.2 kW
Compressed air requirement / Consumption	7000 hPa; 20 m³/h
Dimensions (L x W x H)	2542 x 1818 x 1987 mm³
Weight (without / incl. powder)	approx. 1250 kg
Price	700 000 Dollars

Table 4.8 EOS M290 Characteristics

Build envelope (L x W x H)	250 x 250 x 325 mm^3
3DOpctics configuration, dual configuration: with switching unit	Yb-Fibre Laser ; 200 W or 400 W (optional)
Variable layer thickness	20 - 80 *10^{-6} m
Beam Focus diameter	100*10^{-6} m - 500 *10^{-6} m
Max. scan speed	up to 7 m/s
E-Connection / Powder input	Max power consumption 8.5 KW / typical 3.2 KW
Compressed air requirement / Consumption	7000 hPa; 20 m^3/h
Dimensions (L x W x H)	2542 x 1818 x 1987 mm^3
Weight (without / incl. powder)	approx. 1250 kg
Price	700 000 Dollars

Table 4.9 EOSINT M280 Characteristics

Materials

Stainless steel 17-4 PH

It´s possible to use this material with both machines [67]:
- EOSINT M 280 400Watt
- EOS M 290

R_m	770 ± 20 N/mm^2
$R_{p0.2}$	720 ± 10 N/mm^2
A	21 ± 2%
Thickness of the layer	20 µm
Density	7,77 g/cm^3

Table 4.10 Stainless Steel 17-4PH properties

Stainless steel 316L

It´s possible to use this material with both machines [68]:
- EOSINT M 280 400 Watt
- EOS M 290

R_m	640 ± 50 N/mm^2
$R_{p0.2}$	530 ± 60 N/mm^2
A	40 ± 15%
E-Modulus	185 GPa
Hardness	89HRB
Thickness of the layer	approx. 0.3 - 0.4 mm
Density	min. 7.9 g/cm^3

Table 4.11 Stainless Steel 316L properties

Fig. 4.6 Arcam (GE Additive Company) logo [24]

Since 1997 the Swedish start up, Arcam, has been offering a cost-efficient and pioneer Additive Manufacturing solution for production of metal components. They have developed and patented the Electron Beam Melting (EBM) technology, which enables to print using beam of electrons combined with metal powders. They are operating in a global market providing freedom in design combined with excellent material properties and high productivity. This start up offers 3 metal 3D printers with this technology, although there is just one which is meeting our requirements, Arcam A2X.

Arcam A2X is the ultimate additive manufacturing solution, designed specifically for production of functional parts within aerospace manufacturing, as well as general industry. Nowadays, it is also an ideal tool for universities as well as researches at important universities and research institutes worldwide focusing on process development of new materials.

The machine is offering a specifically design able to withstand extremely high process temperatures, up to 1100º C, which leads to the elimination of residual stress and ensures superior material properties. They provide a wide range of materials, all of them tested to verify their extensive mechanical and chemical properties.

Arcam is offering a selection of materials, as Titanium Ti6Al4V, Titanium Ti6Al4V ELI, Titanium Grade 2, Cobalt-Chrome, ASTM F75 and Nickel Alloy 718. For all of these materials the company provides metal powder, process settings and support. In addition, they are providing explosition-protected vacuum cleaners, powder handling trolleys and a range of powder recovery system for safe and efficient powder recycling. Below these lines, you could see the mechanical properties that this machine is offering, as well as from their materials [69,70].

	Arcam A2X
Technology	Electron Beam Melting
Build envelope (L x W x H)	200 x 200 x 380 mm³
Cathode type	Lungsten filament
Beam Focus diameter	250 µm
Max. beam power	3000 W
Max. scan speed	7 m/s. 4.5 m/s for variable focus move
Average inert gas consumption	He consumption, build process: 1 litre/h He consumption, build cool down: 50-75 litres/build cycle
E-Connection / Powder input	3 x 400 V, 32 A, 7 Kw
Compressed air requirement / Consumption	Vacuum base pressure: 5 x 10-4 mbar (chamber pressure before start of process)
Build atmosphere	2 x 10-3 mbar (partial pressure of He)
Dimensions (L x W x H)	1850 x 900 x 2200 mm³
Weight (without / incl. powder)	1700 kg
Price	€250.000 to €1.4 m

Table 4.12 Arcam A2X Characteristics [70,71]

Titanium Ti6Al4V
Titanium provides a high strength, low weight ratio and outstanding corrosion resistance, although pure titanium is not as strong as titanium alloys are. In the case of this alloy, Ti6Al4V (Grade 5), it is the most widely used titanium alloy, due to it features good machinability and excellent mechanical properties. Please check the following data table for more specific information [72].

Mechanical data	Formula symbol and unit	Ti6Al4V
Tensile strength	R_m [MPa]	1020
Yield strength	$R_{p0,2}$ [MPa]	950
Elongation	A [%]	14
Reduction area	Z [%]	40
E-Modul	E [GPa]	120
Rockwell Hardness	[HRC]	33

Table 4.13 Mechanical properties of Ti6Al4V [72]

Titanium Ti6Al4V ELI
As in the previous titanium alloy, it is presenting similar characteristics with a few differences. Ti6Al4V ELI (Grade 23) contains reduced levels of oxygen, nitrogen, carbon and iron. As ELI means "Extra Low Interstitials", this material provides improved ductility and better fracture toughness. Revise the following table for more specific data [73].

Mechanical data	Formula symbol and unit	Ti6Al4V ELI
Tensile strength	R_m [MPa]	970
Yield strength	$R_{p0,2}$ [MPa]	930
Elongation	A [%]	16
Reduction area	Z [%]	50
E-Modul	E [GPa]	120
Rockwell Hardness	[HRC]	32

Table 4.14 Mechanical properties of Ti6Al4V ELI [73]

Titanium Grade 2

Titanium presents an excellent mechanical properties, it is available in different grades, unalloyed or alloyed. For this case, this is an Unalloyed Comercially Pure (CP) Titanium Grade 2 of 4 Grades, where Grade 1 has the highest formability and Grade 4 has the highest strength and moderate formability. In the following table you coulf find more mechanical properties of it [74].

Mechanical data	Formula symbol and unit	Titanium Grade 2
Tensile strength	R_m [MPa]	570
Yield strength	$R_{p0,2}$ [MPa]	540
Elongation	A [%]	21
Reduction area	Z [%]	55

Table 4.15 Mechanical properties of Titanium Grade 2 [74]

Cobalt-Chrome, ASTM F75

Arcam ASTM F75 is a non-magnetic CoCrMo alloy exhibiting high strenghth, corrosion resistance, and excellent wear resistance. Thanks to the excellent material qualities and high hardness of the material, it allows polishing components mirror-like finishes and ensures long product life. Further increase productivity, surface quality and is abled for complex geometries. Below these lines is shown the data sheet from this alloy after the heat treatment (post processing) which is recommended after the printing [75].

Mechanical data	Formula symbol and unit	Cobalt-Chrome, ASTM F75
Tensile strength	R_m [MPa]	960
Yield strength	$R_{p0,2}$ [MPa]	560
Elongation	A [%]	20
Reduction area	Z [%]	20
Rockwell Hardness	[HRC]	34

Table 4.16 Mechanical properties of Cobalt-Chrome, ASTM F75 [75]

Nickel Alloy 718

Nickel Alloy 718 is the last material that Arcam launched, as a qualified material for use in Arcam's EBM system. The material properties comply with chemical requirements of UNS N07718 and properties of ASTM F3055-14 specification. Below this lines you could check the mechanical properties of Inconel 718, such as the official company is not providing the specific mechanical properties of this alloy. [76,77]

Mechanical data	Formula symbol and unit	Nickel Alloy 718
Tensile strength	R_m [MPa]	140
Yield strength	$R_{p0,2}$ [MPa]	80
Elongation	A [%]	30
Rockwell Hardness	[HRB]	102

Table 4.17 Mechanical properties of Nickel alloy 718 [76,77]

Fig. 4.7 ExOne logo [25]

One provider of metalbased additive manufacturing technology is ExOne which is a German company. ExOne 3D printers are using Binder Jetting technologies with industrial materials to provide their solutions at a lower operating cost. The Binder Jetting technology is a process in which a liquid binding agent is deposited to join powder particles [78].

They offered one additive manufacturing solution for our metal valve, the M-FLEX which is a perfect machine to print solutions in a record time. The M-FLEX owns a 400 x 250 x 250 mm³ building volume and manly a fast builds speed of 30-60 seconds per layer. Moreover, ExOne provide a complete package with the M-Flex printer, recycling equipment, the materials, a curing oven and a furnace. This one is adapt for complex operations, with a high productivity and simplify operations [79].

	M-FLEX
Technology	Binder Jetting
Build envelope (L x W x H)	400 x 250 x 250 mm³
Scan speed	30-60 seconds/layer
Variable layer thickness	Variable with minimum of 0.15 mm
E-Connection / Powder input	208V-240V / 3 phases
Dimensions (L x W x H)	1675x1400x1855 mm³
Weight (without / incl. powder)	1020 kg
Price	450000 $

Table 4.18 M-FLEX Characteristics [79]

Materials

420 Stainless Steel Infiltrated with Bronze
It is a matrix material composed of 60% stainless steel and 40% bronze infiltrant. This material offers good mechanical properties and is available in both an annealed and non-annealed condition [80].

Tensile strength Rm [MPa]	496
Elastic limit Rp0,2 [MPa]	427
Elongation to the rupture	± 7%
E-Modulus E [Gpa]	147
Hardness	93 HRB
Density	7.86 g/cm³

Table 4.19 420 Stainless Stell Infiltrated with Bronze properties [80]

17-4PH Stainless Steel
It is interesting for its mechanical and corrosion resistance properties and cost-effectiveness [81].

Minimum thickness of the wall	1.5 mm
Tensile strength Rm [MPa]	1317
Elastic limit Rp0,2 [MPa]	1034
Elongation to the rupture	± 12 %
E-Modulus E [Gpa]	193
Hardness	41 HRC
Density	7.7 g/cm³

Table 4.20 17-4PH Stainless Stell properties [81]

Iron Infiltrated with Bronze
It is a matrix material composed of 60% iron and 40% bronze infiltrant. This material offers good mechanical properties, is able to be machined, welded and polished, and offers excellent wear resistance [82].

Tensile strength Rm [MPa]	407
Elastic limit Rp0,2 [MPa]	255
Elongation to the rupture	± 17 %
E-Modulus E [Gpa]	131
Hardness	72 HRB
Density	8.04 g/cm³

Table 4.21 Iron Infiltrated with Bronze properties [82]

Alloy IN 625
It is interesting for its excellent mechanical properties both at extremely high and low temperatures [83].

Tensile strength Rm [MPa]	676
Elastic limit Rp0,2 [MPa]	290
Elongation to the rupture	± 51 %
E-Modulus E [Gpa]	193
Hardness	84 HRB
Density	8.35 g/cm³

Table 4.22 Alloy IN 625 properties [83]

Fig. 4.8 TRUMPF logo [26]

One provider of metalbased additive manufacturing technology is Trumpf which is a German company. Trumpf is the only manufacturer in the world which provides both laser technologies for additive manufacturing, the laser metal fusion (LMF) and laser metal deposition (LMD). Moreover, Trumpf offers complete solutions comprising digitization, machines, and services.

They offered one additive manufacturing solution for our metal valve with the laser metal deposition (LMD) technology, the TruLaser Cell 3000 which is a perfect machine to print small to medium-sized components with top quality. The TruLaser Cell 3000 owns a 800x600x400mm3 building volume, a high precision (< 5 μm), a process flexibility and a simple to automate for higher quantities. This machine is also adapt for cutting and melting in two or three dimensions. [84]

	TruLaser Cell 3000
Build envelope (L x W x H)	800 x 600 x 400 mm³
Scan speed	85 m/min: axis B: 120 RPM
Beam Focus diameter	Depend on the laser
E-Connection / power input	Depend on the laser
Compressed air requirement / consumption	Max. 8000 W
Dimensions (L x W x H)	Depend on the laser
Weight (without / incl. powder)	Depend on the laser

Table 4.23 TruLaser Cell 3000 Characteristics

The TruLaser Cell 3000 is working with a separate laser which could be choose according to the requirements. The TruDisk lasers seems interesting because of a high-power solid-state laser for the welding, cutting, and surface processing of metals. This one is adapt for situations which require the combination of high power and maximum beam quality. [85]

The TruDisk lasers owns a wide range of product based on the following characteristics: laser power (starts to 1000W), power constancy at rated laser output, continuously adjustable power range, beam quality, numerical aperture, wavelength and minimum laser diameter.

For example, the TruDisk 16003 owns the largest adjustable power range until 16000 W :

Laser power	16000 W
Power constancy at rated laser output	± 1%
Continuously adjustable power range	320 W - 16000 W
Beam quality	12 mm.mrad
Numerical aperture	0.1
Wavelength	1030 nm
Minimum laser diameter.	30 µm

Table 4.24 TruDisk 16003 Characteristics

Materials [86]

Trumpf are providing a list of materials but without precise caracteristiques:

1. Stainless Steel : Stainless Steel 316L-A LMF, Stainless Steel 630-A LMF.
2. Cobalt-chromium alloys : BEGO Mediloy S-Co, Cobalt-Chrome CoCr-B.
3. Copper Alloys : Bronze 90/10-A LMF
4. Nickel-based alloys : Nickel Alloy 718-A LMF
5. Titanium alloys : Titanium Ti2-A LMF, Titanium Ti64 ELI-A LMF
6. Tool steels : Tool Steel 1.2709-A LMF, Tool Steel 1.2709-B LMF

SLM SOLUTIONS

One provider of metalbased additive manufacturing technology is the "SLM Solutions Group AG" which is located in Lübeck, Germany. SLM Solutions focuses on the development, assembly and sale of machines and inte -

Fig. 4.9 SLM Solutions logo [15]

grated system solutions in the field of selective laser melting (SLM®) [10].

This company has been selected after the Scoring Model as the one to be suggested to the company. For that reason, its report is in the main section in the point 2.2.2.

4.3.3 Overview of the six possible machines

After the six companies has been introduced, a table is made with the general characteristics of one machine of each company. Tha machine which is compared, is chosen based on the properties of each machine, and which of them are meeting better the requirements from the company. This not means that the other machines from the companies that have been explained are not meeting the requirements, although just one from each supplier should be compared to contrast them. Thanks to this selecteion below these lines you could get a better overview contrasting the different options.

	The SLM 500 [13]	M2 Cusing [62]	The EOSINT M280 [89]	TruLaserCell 3000 [84]	Arcam A2X [70]	M-Flex [91]
Supplier	SLM	Concept Laser	EOS	Trumpf	Arcam	ExOne
Country	Germany	Germany	Germany	Germany	Sweeden	Germany
Technology	Selective Laser Melting	Selective Laser Melting	Direct Metal Laser Sintering	Laser Metal Deposition / Cutting / Welding	Electron Beam Melting	Binder Jetting
Build envelope (L x W x H)	500 x 280 x 365 mm³ (reduced by the substrate plate thickness ca. 25 mm)	250 x 250 x 280 mm3	250 x 250 x 325 mm3	(800 x 600 x 400) mm3 x ± 135º / (X x Y x Z x B)	200 x 200 x 380 mm3	400 x 250 x 250 mm3
Laser System	Twin (2 x 400 W), Twin (2 x 700 W), Quad (4 x 400 W), Quad (4 x 700 W) IPG fiber laser	Fibre laser 200 W (cw), optional 400 W (cw)	Yb-fibre laser, 200 W or 400 W (optional)	Depends on the Laser, they provide 5 types of it: TruDisk, TruPulse, TruFiber, TruDiode, TruMicro	——	——
Cathode type	——	——	——		Tungsten filament	——
Positioning Accuracy	——	——	——	Linear Axes (X,Y,Z): 0.015 mm / Rotary Axes (B): 0.2º	——	X/Y 0.0635mm, Z 0.100mm (set by layer thickness)
Variable layer thickness	25 μm – 75 μm	20 - 80 μm	——	——	——	Variable with minimum of 0.15 mm
Build rate	Up to 171 cm³ / h	2 - 20 cm3 /h (depending on material / laser power)	——	——	——	30-60 seconds/layer
Min. feature size	150 μm					
Beam Focus diameter	80 μm – 115 μm	50 μm, optional variable focus move (50 μm – 500 μm)	100 - 500 μm	Depends on the Laser	250μm	——
Max. beam power	——	——	——	——	3000 W	——
Max. scan speed	10 m/s	7 m/s, 4,5 m/s for variable focus move	up to 7.0 m/s	85 m/min; axis B: 120 RPM	Max. EB translation speed 8000 m/s	——
Axis Acceleration	——	——	——	17m/s2; axis B: 130 rad/s2	——	——
Inert gas supply	——	2 gas connections provided N2 generator external (optional)	——			
Average inert gas consumption	In process: 5-7 l/min (Argon) Purging: 70 l/min (Argon)	< 1 m3 /h	Argon: 4,000 hPa; 100 l/min	——	He consumption, build process: 1 litre/h He consumption, build cool down: 50-75 litres/build cycle	——
Size powder tank	90 l	——		——	——	——
E-Connection / power supply	400 Volt 3NPE, 64 A, 50 / 60 Hz, 8 – 10 kW	400V 3/N/PE, AC, 32 A, max. 7.4 kW	32 A	Depends on the Laser	3 x 400 V, 32 A, 7 Kw	208V-240V / 3 phases
Compressed air requirement / consumption	ISO 8573-1:2010 [1:4:1]: 50 l/min @ 6 bar	___ / 5 bar	maximum 8.5 kW / typical 3.2 kW	max. 8000 W	Vacuum base pressure: 5 x 10-4 mbar (chamber pressure before start of process)	——
Build atmosphere	——	——	——		2 x 10-3 mbar (partial pressure of He)	
Dimensions (L x W x H)	5200 x 2800 x 2700 mm3	2542 x 1818 x 1987 mm3	2,200 x 1,070 x 2,290 mm3 / Recommended installation space: min. 4.8 x 3.6 x 2.9 m3	Depends on the Laser	1850 x 900 x 2200 mm3	1675 x 1400 x 1855 mm
Weight (without / incl. powder)	Approx. 2400 kg / approx. 3100 kg	approx. 2.300 kg	approx. 1,250 kg	Depends on the Laser	1 700 kg	1,020 kg
Reference clamping system	——	EROWA, System 3R / others on request (optional)	——	——	——	——
Filtering System	——	integrated, with a 20 m2 lter surface		——	——	——
Operating conditions	——	15 - 35°C	——	Depends on the Laser	——	——
Nitrogen generator	——		Integrated			
Price	Between $1 - 2 million [87]	> $ 250,000 [88]	$700,000 - Including delivery, installation, training and a one-year service contract [90]	——	€250.000 to €1.4 m [71]	base model: $450,000 [92]

Table 4.25 Comparison of the six machines [13,87,62,88,89,90,84,70,71,91,92]

4.4 THICKNESS CALCULATIONS

Diameter (mm)	Material Resistance Titanium (Mpa)	Thickness (mm)	Material Resistance Aluminium (Mpa)	Thickness (mm)	Material Resistance Stainless steel (Mpa)	Thickness (mm)
5	860	0,3	215	1,5	380	0,8
10	860	0,7	215	3,0	380	1,6
15	860	1,0	215	4,5	380	2,4
20	860	1,3	215	6,0	380	3,2
25	860	1,7	215	7,5	380	4,0
30	860	2,0	215	9,0	380	4,8
35	860	2,4	215	10,5	380	5,6
40	860	2,7	215	12	380	6,4
45	860	3,0	215	13,5	380	7,2

Table 4.26 Thickness calculation [93]

05 REFEREN-CES
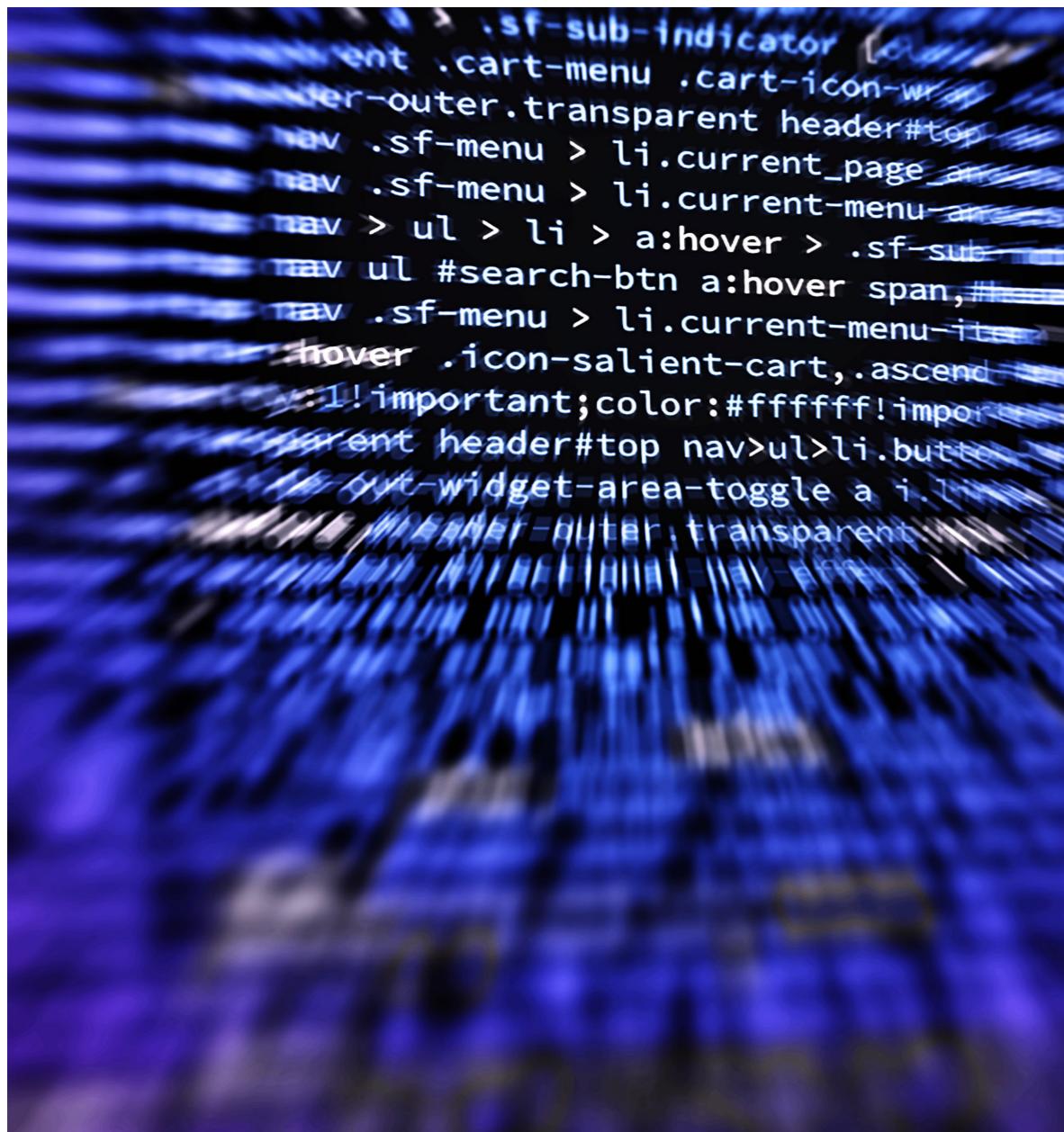
Fig. 5.1. References [27]

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02   [1]   N.N.: European Project Semester Spring 2018, Project Proposal No 1: Buchholz-Hydraulik; Buchholz-Hydraulik; Schwentinental; 2017

04   [2]   Buchholz-Hydraulik: Company; http://www.buchholz-hydraulik.de/en/company/; 05.04.2018

05   [3]   Feldmann, Carsten; Pumpe, Andreas; 3D-Druck – Verfahrensauswahl und Wirtschaftlichkeit; Springer Gabler; Wiesbaden; 2016

02 MAIN SECTION

21   [4]   Hoffmeister, Wolfgang: Investitionsrechnung und Nutzwertanalyse; Kohlhammer; Stuttgart; 2000

21   [5]   Geisler, Rainer: Industrial Software Applications; De Gruyter; Berlin/Munich/Boston; 2015

21   [6]   Teuscher, Heinz: Betriebswirtschaft – Einführung in die Problemstellungen und Lösungskonzepte der Betriebswirtschaftslehre;Compendio Bildungsmedien AG; Zürich; 2011

26   [7]   Zangemeister, Christof:Nutzwertanalyse in der Systemtechnik; Wittmannsche Buchhandlung;München;1970

27   [8]   Stollenwerk, Andreas: Wertschöpfungsmanagement im Einkauf; Gabler Verlag; Wiesbaden; 2012

27   [9]   Irlinger, Wolfgang: Kausalmodelle zur Lieferantenbewertung; Gabler Verlag; Wiesbaden; 2012

31   [10]   SLM Solutions AG: About us; https://slm-solutions.com/about-slm/about-us?_ga=2.82555158.1279152311.1523433136-1133409644.1523433136; 12.04.2018

31   [11]   SLM Solutions AG: Machines; https://slm-solutions.com/machines?_ga=2.52066729.121599862.1524043594-1133409644.1523433136; 12.04.2018

32   [12]   SLM Solutions AG: Selective Laser Melting Machine SLM® 280 2.0; https://slm-solutions.com/products/machines/selective-laser-melting-machine-slmr280-20; 12.04.2018

Page

33   [13]   SLM Solutions AG: Selective Laser Melting Machine SLM® 500; https://slm-solutions.com/products/machines/selective-laser-melting-machine-slmr500; 19.04.2018

35   [14]   SLM Solutions AG: 3D Metals – Discover the variety of metal powders; https://slm-solutions.com/sites/default/files/downloads/201en171023-01-001-powder_web.pdf; 19.04.2018

48   [15]   SLM-Solutions: powder; https://slm-solutions.com/sites/default/files/downloads/201en171023-01-001-powder_web.pdf; 10.06.2018

50   [16]   Rowlandpub: Ti6AL4V; http://www.rowlandpub.com/WjprxgYn/; 10.06.2018

50   [17]   Titaniumengineers: Ti6AL4V; http://www.titaniumengineers.com/ti-6ai-4v.html; 10.06.2018

51   [18]   Roymech: metal prices; http://www.roymech.co.uk/Useful_Tables/Matter/Costs.html; 10.06.2018

51   [19]   Greenwoodmagnetics: differencebetween304and316stainlesssteel; https://greenwoodmagnetics.com/fr/resource/what-is-the-difference-between-304-and-316-stainless-steel/; 10.06.2018

51   [20]   mtm-inc: hownonmagneticare304and316stainlesssteels; https://www.mtm-inc.com/ac-20110117-how-nonmagnetic-are-304-and-316-stainless-steels.html; 10.06.2018

51   [21]   bssa: 316L stainless steel; https://www.bssa.org.uk/faq.php?id=24; 10.06.2018

51   [22]   bssa: 316L stainless steel; https://www.bssa.org.uk/faq.php?id=24; 10.06.2018

51   [23]   reliance-foundry: 316L stainless steel; http://www.reliance-foundry.com/blog/304-vs-316-stainless-steel; 10.06.2018

53   [24]   quora: stainless steel; https://www.quora.com/Which-stainless-steels-are-magnetic; 10.06.2018

53   [25]   tkmna: stainless steel; http://www.tkmna.com/wcm/idc/groups/internet/documents/web_content/mdaw/mdiz/~edisp/d_004673.pdf; 10.06.2018

53   [26]   upmet: stainless steel; https://www.upmet.com/sites/default/files/whitepapers/precipitation-hardening-stainless-steels.pdf; 10.06.2018

53   [27]   flowcontrolnetwork: differencebetween17-4ph316l; https://www.flowcontrolnetwork.com/whats-the-difference-between-17-4ph-316l-stainless-steel-in-pressure-sensors-transducers/; 10.06.2018

54   [28]   iron-foundry: en-gjs-400-15; http://www.iron-foundry.com/en-gjs-400-15-ggg40-cast-iron.html; 10.06.2018

Page

54   [29]   dijkkamp: en-gjs-400-15; http://www.dijkkamp.nl/en/materials/ggg40-en-gjs-400-15/; 10.06.2018

56   [30]   Geisler, Rainer: Industrial Software Applications; De Gruyter; Berlin/Munich/Boston; 2015

57   [31]   N.N.: 3D-Druck-Jährliches Wachstum von bis zu 23% erwartet; https://www.plm-it-business.de/additive-subtraktive-fertigung/jaehrliches-wachstum-von-bis-zu-23--im-3d-druck-erwartet_id_27173__dId_2146400__app_510-452643_.htm; 09.06.18

57   [32]   N.N.: Der industrielle 3D-Druck wird wachsen; https://www.com-magazin.de/praxis/hardware/industrielle-3d-druck-erwachsen-1530491.html; 09.06.18

57   [33]   N.N.: Additive Manufacturing und Industrie 4.0 - Zukunft und Stand der Gegenwart; https://www.3d-grenzenlos.de/magazin/specials/additive-manufacturing-und-industrie-4-0-27171373/; 09.06.18

58   [34]   Stevenson,Kerry: A Look Inside SLM Solutions' New 3D Metal Printers; http://www.fabbaloo.com/blog/2017/6/2/a-look-inside-slm-solutions-new-3d-metal-printers; 07.06.18

58   [35]   N.N: 316 and 316L Stainless Steel Sheet; https://www.upmet.com/products/stainless-steel/316316l; 07.06.18

58   [36]   Phillips Corporation: 3D Printing Solutions; https://www.gsaadvantage.gov/ref_text/GS03F080CA/0T0814.3MDPDD_GS-03F-080CA_PHILLIPSADVANTAGEPRICELISTSCHEDULE365118.PDF; 12.06.18

58   [37]   N.N.: Industriestormpreise steigen weiter; https://www.energate-messenger.de/news/179819/industriestrompreise-steigen-weiter; 07.06.18

60   [38]   Kremin-Buch, Beate: Strategisches Kostenmanagement; Gabler; Wiesbaden; 2007

04 APPENDICES

68   [39]   Haresh Khemani, Bright hub engineering: What is numerical control machine; https://www.brighthubengineering.com/manufacturing-technology/55670-what-is-numerical-control-machine/; 10.04.2018

68   [40]   Wikimedia Foundation, Inc: History of numerical control; https://en.wikipedia.org/wiki/History_of_numerical_control; 11.04.2018

69   [41]   Batisseurs Numeriques: Histoire de la machine outil; http://www.cnc-book.com/6330-historique-de-la-machine-outil.html; 10.04.2018

Page

69   [42]   CMS North America Inc: A Brief History on CNC Machining; https://www.cmsna.com/a-brief-history-on-cnc-machining-c-56_68.html; 11.04.2018

69   [43]   The John W. Sutherland Research Page: Introduction to Numerical Control Machining; http://www.mfg.mtu.edu/cyberman/machtool/auto/nc/intro.html; 10.04.2018

70   [44]   lejournaldejoliette: Les différents types de matériaux utilisés en usinage; https://www.lejournaldejoliette.ca/actualites/societe/313571/les-differents-types-de-materiaux-utilises-en-usinage; 12.04.2018

71   [45]   forging industry association: Iron, Nickel and cobalt heat resistant alloy; https://www.forging.org/forging/design/45-iron-nickel-and-cobalt-heat-resistant-alloys.html; 18.04.2018

71   [46]   European Steel and Alloy Grades: EN-GJS-400-15U (EN-JS1072); http://www.steelnumber.com/en/steel_composition_eu.php?name_id=1533; 16.04.2018

71   [47]   CLAAS GUSS GmbH: Gusseisen mit Kugelgraphit EN-GJS (GGG); http://procast-guss.de/pdf/02_TH_G_Kug.pdf; 16.04.2018

76   [48]   Locker, Anatol: 9 tipos de impresoras 3D – Guía de tecnologías de impresión 3D; https://all3dp.com/es/1/tipos-de-impresoras-3d-tecnologia-de-impresion-3d/; 13.04.2018

79   [49]   N.N.: Types of 3D Printing Materials and 3D Print Uses; https://www.allthat3d.com/3d-printing-materials/; 19.04.2018

79   [50]   N.N.: Materiales para impresión 3D en metal; http://www.materialise.com/es/manufacturing/tecnologia-de-impresion-3d/impresion-3d-en-metal; 19.04.2018

79   [51]   N.N.: Materiales de impresión 3D (IV): Metales en polvo; http://hxx.es/2016/01/12/materiales-de-impresion-3d-iv-metales-en-polvo/; 19.04.2018

81   [52]   fabbaloo: new-3d-metal-printers; http://www.fabbaloo.com/blog/2017/6/2/a-look-inside-slm-solutions-new-3d-metal-printers; 14.06.2018

81   [53]   engineering: EOS-M-290; https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/7829/Metal-Sintering-Meets-Industrial-Needs-with-the-EOS-M-290.aspx; 14.06.2018

81   [54]   engineering: EOS-M-290; https://www.engineering.com/DesignerEdge/DesignerEdgeArticles/ArticleID/7829/Metal-Sintering-Meets-Industrial-Needs-with-the-EOS-M-290.aspx; 14/.6.2018

81   [55]   aniwaa: m2-cusing; https://www.aniwaa.fr/produit/imprimantes-3d/concept-laser-m2-cusing/; 1 4.06.2018

Page

81   [56]   design-point: 3d-systems-prox-320; https://www.design-point.com/hardware/3d-systems-prox-320/; 14.06.2018

81   [57]   aniwaa: lasertec-65-3d; https://www.aniwaa.fr/produit/imprimantes-3d/dmg-mori-lasertec-65-3d/; 14.06.2018

81   [58]   engineering: M-Flex; https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/7618/ExOne-M-Flex-Production-Metal-3D-Printer.aspx; 14.06.2018

81   [59]   engineering: Metal-X-3D; https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/14071/Metal-X-3D-Printer-Brings-Metal-to-the-Workshop-for-Under-100K.aspx; 14.06.2018

81   [60]   aniwaa: desktop-metal; https://www.aniwaa.fr/produit/imprimantes-3d/desktop-metal-production/; 14.06.2018

83   [61]   concept-laser: concept-laser-machines; https://www.concept-laser.de/en/products/machines.html; 20.04.2018

83   [62]   concept-laser: M2 cusing Metal laser melting system; https://www.concept-laser.de/fileadmin/Blaue_Broschueren/1708_M2_cusing_EN_update_1__Eigendruck_X3.pdf; 20.04.2018

84   [63]   concept-laser: concept-laser materials; https://www.concept-laser.de/fileadmin//user_upload/Datasheet_CL_42TI.pdf; 20.04.2018

84   [64]   concept-laser: concept-laser materials: https://www.concept-laser.de/fileadmin//user_upload/Datasheet_CL_80CU.pdf; 28.05.18

84   [65]   Electro optical systems: Materials for Metal Additive Manufacturing; https://www.eos.info/eos-m290; 19.04.2018

85   [66]   Electro optical systems: Materials for Metal Additive Manufacturing; https://www.eos.info/systems_solutions/metal/systems_equipment/eosint_m280; 19.04.2018

86   [67]   Electro optical systems: Materials for Metal Additive Manufacturing; https://www.eos.info/material-m; 28.05.18

86   [68]   Electro optical systems: Materials for Metal Additive Manufacturing; https://www.eos.info/material-m; 28.05.18

88   [69]   Jamie D.: A Comprehensive List of all the Metal 3D Printer Manufacturers; https://www.3dnatives.com/en/metal-3d-printer-manufacturers/; 27.05.2018

Page

88   [70]   Arcam EBM®: Welcome to Manufacturing UNBOUND; http://www.arcam.com/wp-content/ uploads/arcamebm-corp-brochure-fnlv3.pdf; 27.05.2018

88   [71]   Drs. Ing. R. Abdoel: Additive Manufacturing (3D-Printing) & Life long Learning; http://www. 3dprintingmaterialsconference.com/wp-content/uploads/2014/06/Abdoel-Pres_CoE_Ob jexlab_3DMaterialsConference_20juni2014_v2-.pdf; 28.05.2018

89   [72]   Arcam EBM system: Ti6Al4V Titanium Alloy; http://www.arcam.com/wp-content/uploads/Ar cam-Ti6Al4V-Titanium-Alloy.pdf; 28.05.2018

89   [73]   Arcam EBM system: Ti6Al4V ELI Titanium Alloy; http://www.arcam.com/wp-content/ uploads/Arcam-Ti6Al4V-ELI-Titanium-Alloy.pdf; 28.05.2018

90   [74]   Arcam EBM system: Grade 2 Titanium; http://www.arcam.com/wp-content/uploads/Ar cam-Titanium-Grade-2.pdf; 28.05.2018

90   [75]   Arcam EBM system: ASTM F75 CoCr Alloy; http://www.arcam.com/wp-content/uploads/Ar cam-ASTM-F75-Cobalt-Chrome.pdf; 28.05.2018

91   [76]   Prototype Today ®: Arcam Announces Inconel 718 For EBM Systems; http://www.prototype today.com/arcam/arcam-announces-inconel-718-for-ebm-systems; 28.05.2018

91   [77]   Aircraft Materials: Nickel Alloy 718/ Inconel 718®; https://www.aircraftmaterials.com/data/ nickel/718.html; 28.05.2018

91   [78]   ExOne: What is binder jetting ?; http://www.exone.com/Resources/Technology-Overview/ What-is-Binder-Jetting; 17.05.2018.

91   [79]   ExOne: M-FLEX production 3D printer; http://www.exone.com/Systems/Production-Printer s/M-Flex; 17.05.2018.

92   [80]   ExOne: 420 Stainless Steel Infiltrated with Bronze; http://www.exone.com/Portals/0/Resour ceCenter/Materials/X1_MaterialData_420SS.pdf; 24.05.2018

92   [81]   ExOne: 17-4PH Stainless Steel; http://www.exone.com/Portals/0/ResourceCenter/Materials/ PSC_X1_MaterialData_17-4_SS_US_012018.pdf; 24.05.2018

93   [82]   ExOne: Iron Infiltrated with Bronze; http://www.exone.com/Portals/0/ResourceCenter/Mate rials/X1_MaterialData_Iron.pdf; 24.05.2018

93   [83]   ExOne: Alloy IN 625; http://www.exone.com/Portals/0/ResourceCenter/Materials/X1_Mate rialData_AlloyIN625.pdf; 24.05.2018

93   [84]   Trumpf: trulaser-cell-3000; https://www.trumpf.com/en_INT/products/machines-systems/ laser-welding-systems/trulaser-cell-3000/; 26.05.2018

Page

94   [85]   Trumpf: trulaser-cell-3000 lasers; https://www.trumpf.com/en_INT/products/lasers/disk-la sers/trudisk/?LS=1; 30.05.2018

95   [86]   Trumpf: trulaser-cell-3000; powders;https://www.trumpf.com/en_INT/products/machi nes-systems/3d-printing-systems/truservices-powder/; 30.05.2018

96   [87]   Kerry Stevenson: A Look Inside SLM Solutions' New 3D Metal Printers; http://www.fabbaloo. com/blog/2017/6/2/a-look-inside-slm-solutions-new-3d-metal-printers; 23.05.2018

96   [88]   Aniwaa: M2 Cusing Concept Laser 3D printers; https://www.aniwaa.com/product/3d-prin ters/concept-laser-m2-cusing/; 23.05.2018

96   [89]   Electro optical systems: Laser sintering system EOSINT M 280; https://cdn0.scrvt.com/eos/ e1dc925774b24d9f/8d4013a5bc26/EOS_System_Data_Sheet_EOSINT_M280_EN_V2_Web. pdf; 23.05.2018

96   [90]   Kyle Maxey: Metal Sintering Meets Industrial Needs with the EOS M 290; https://www.en gineering.com/3DPrinting/3DPrintingArticles/ArticleID/7829/Metal-Sintering-Meets-Indus trial-Needs-with-the-EOS-M-290.aspx; 23.05.2018

96   [91]   ExOne: M-Flex™; http://www.exone.com/Portals/0/Systems/M-Flex/X1_MFlex_US.pdf; 23.05.2018

96   [92]   Kyle Maxey: ExOne M-Flex Production Metal 3D Printer; https://www.engineering.com/ 3DPrinting/3DPrintingArticles/ArticleID/7618/ExOne-M-Flex-Production-Metal-3D-Printer. aspx; 23.05.2018

98   [93]   Muhs, D. et.al.: Roloff/ Matek Maschinenelemente; Vieweg+Teubner; Wiesbaden; 16.06.2017

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