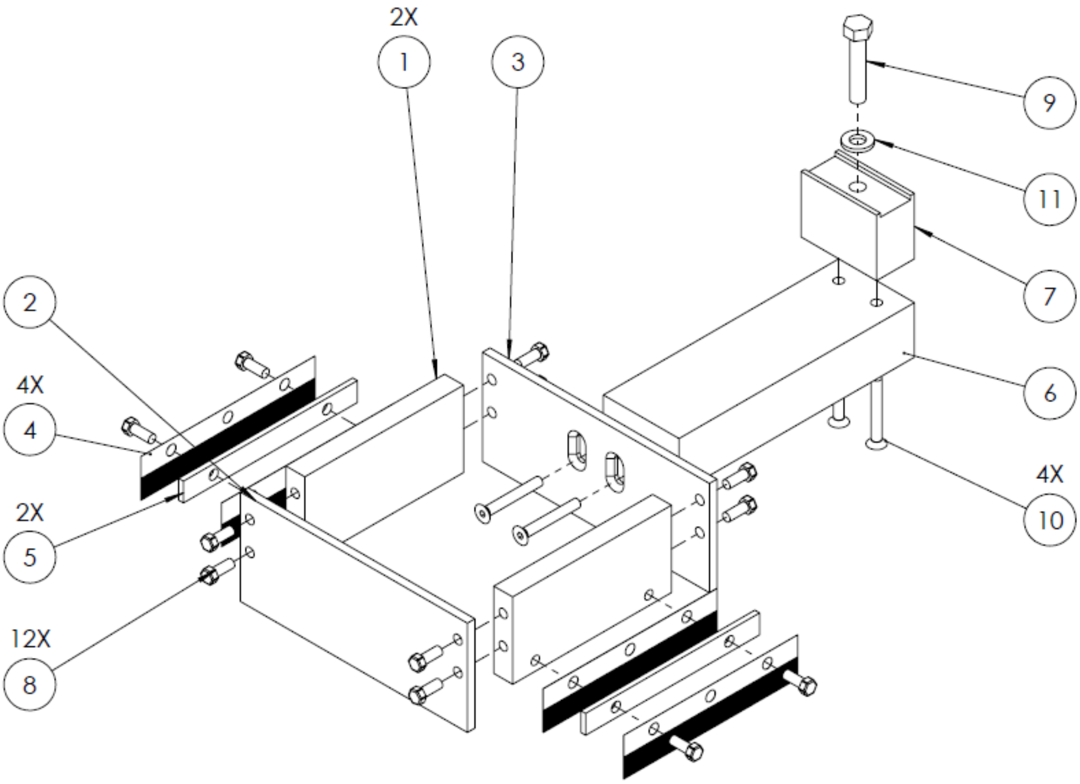
**External Integrated Project**
**Final Report**

**Increasing the efficiency of the material testing process for an electron beam melting (EBM) machine**

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## SUMMARY

A "state of the art" background research was completed in order to understand both the relevant technologies involved and needs of the customer. Including: the EBM technology, a material study, software analysis, and a market study. This report then demonstrates the concept development and selection phases, and the iterations of these concepts. Finally, this report covers the validation of our final design, along with costing, and a final product specification.

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# 1. INTRODUCTION

The focus of this engineering project is on the optimization of an electron beam melting machine (EBM). It aims at designing a system which allows new materials to be tested using a smaller quantity of material, thus increasing the efficiency of the whole research process.

The project is executed under the supervision of the program administrator, M. Frédéric Vignat, in addition with advisory assistance from our client, M. Guilhem Martin.

# 2. UNDERSTANDING EBM

## A. HOW DOES EBM WORK?

Additive manufacturing (also known as 3D printing) is a process that is used to produce a 3D object. By firstly designing the required part using a 3D CAD package (discussed later), this technique builds an object by binding several layers of material together to create the desired part, as per design. Each of these layers has a predetermined thickness; this means that the final object gains volume after each new layer is added. Using this method, a part of almost any shape or geometry can be created. [1] This is shown in ***Figure 1***.

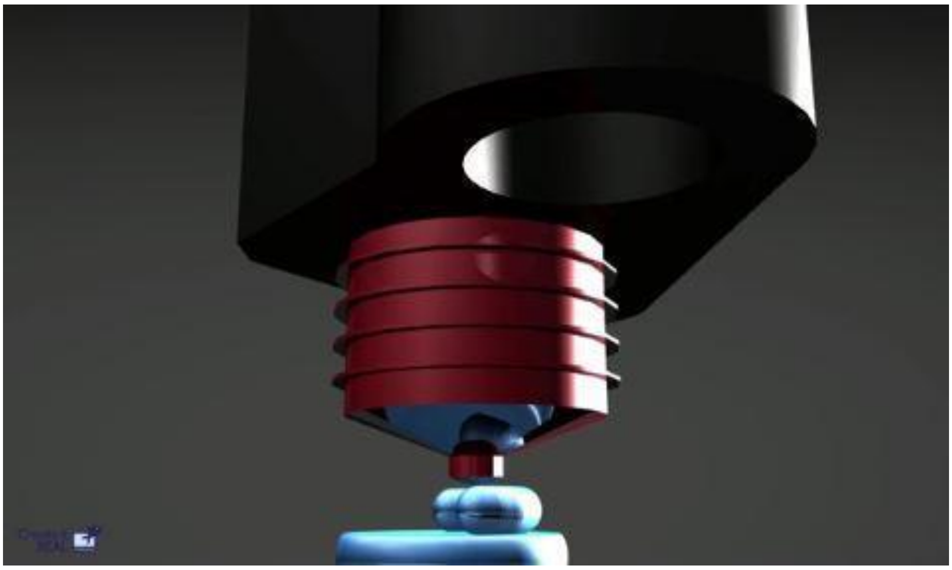


***Figure 1*** *– Image showing the nozzle of a standard 3D printer creating another layer of material, and hence building the part further.*

There are several different processes used in additive manufacturing depending on the material used including laminated, light polymerized and extrusion (shown in *Figure 1*). Another method called powder bed fusion is commonly used to bind metallic powders together using methods such as *selective laser melting* (SLM), *powder bed and inkjet head 3D printing* (3DP) and *Electron Beam Melting* (EBM).[2]

The powder bed fusion method uses either an electron beam or laser to meld and fuse metallic, pre-alloyed powder together, including powders made of steel, titanium, aluminium, and cobalt chrome alloys. The general method works as follows [3];

1. A layer of metallic powder, normally around a tenth of a millimetre thick (but can vary depending on what is required) is spread over the build platform.

2. An electron beam or laser fuses the powder spread over the build platform together. This will make up the first layer of the part or component required.

3. A new layer of powder is spread over the previous layer using a roller. The process explained above is then repeated, forming another layer of material.

4. This process is then repeated until the entire model is created. Unused powder is removed during post processing (detailed later).

The typical setup used in the powder bed fusion method is shown in ***Figure 2***. This arrangement is similar to the setup used in *EBM*; however the system shown below is slightly more simplistic when compared to what is used in *Electron Beam Melting* (shown in ***Figure 3***).

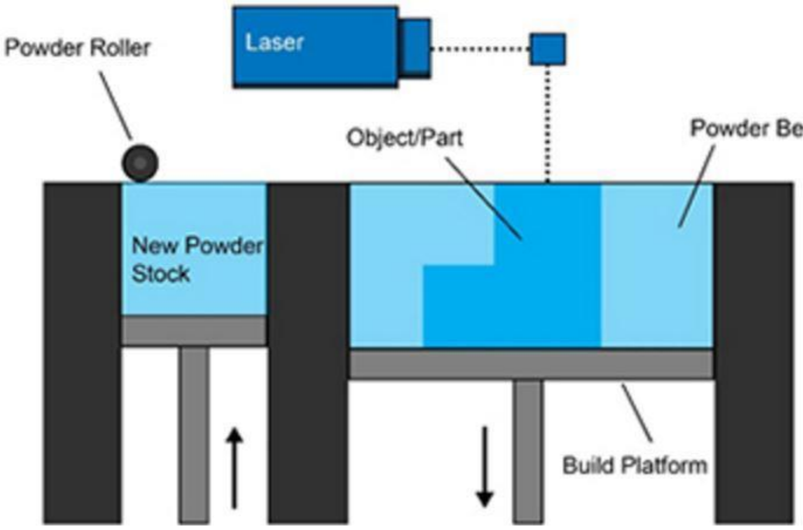



***Figure 2*** *– Image showing the typical setup used in the powder bed fusion method.*

One method using the powder bed fusion method, mentioned earlier, is Electron Beam Melting (EBM). The method used to create a part using EBM is similar to what has been detailed earlier, but with several differences. These are;

**<u>The use of an electron beam</u>**

While other powder bed fusion methods use a laser, EBM uses an electron beam, which is more efficient.

The EBM process is described below.

1. A current is applied to the tungsten filament, and the filament heated to a high temperature (typically between 2000-2500$^{0}$C). As a result of heating a metal to such a high temperature, electrons are released. These electrons are then accelerated via and electric field and a beam generated.

2. This beam is then run down a “drift tube” – this is a tube that is located between the tungsten filament and the build chamber. Within this tube, there are three lenses (or coils). The first, called the astigmatism lens, corrects the beam for astigmatism (effectively correcting the beam). The second, named the focus lens, focuses the beam into a small spot approximately 0.1mm wide. The final lens, named the deflection lens, scans the beam into the area that it is needed.

3. While this is happening, the part is being built in the build chamber. Inside the build chamber, there are two powder hoppers that contain the material that the part will eventually be made of. Below these hoppers lies the build table, where the part is made. The powder is spread over the build table (using the rake), but at a thickness approximately three times larger than what is needed.

4. The electron beam, focused to the area of the build table that the part will be built upon, then melts the powder. After doing this, the build table is moved downwards by the size

of the layer thickness, and the process repeated all over again. This continues until a full part has been made.

5. The final part of the process is to allow the created component to cool. Because of the high temperatures the process works in, this can often over eight hours. [4]

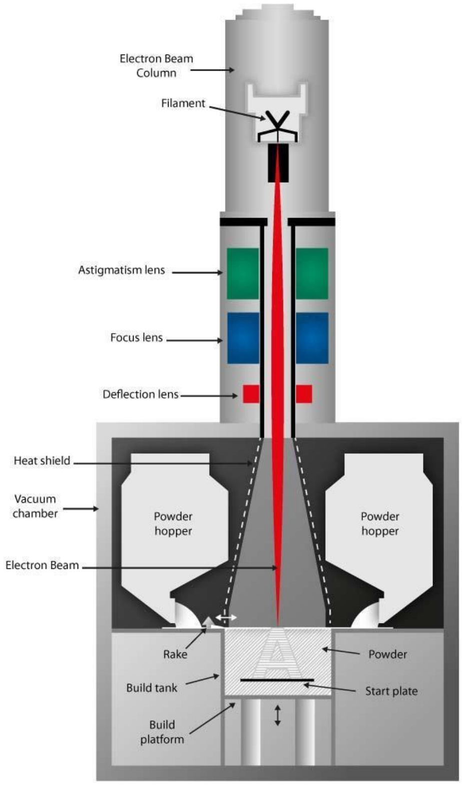



***Figure 3*** *– Image showing the typical setup used in Electron Beam Melting (EBM).*

**It is carried out in a vacuum at high temperatures**

EBM is always carried out in a vacuum. Arcam, a company that specialise in EBM machines, recommend a base pressure of 1 x $10^{-5}$ mbar or better throughout the entire build cycle. The reasoning for carrying out EBM in a vacuum is to maintain the purity of the alloys placed inside the machine. A second reason is to prevent a loss of energy that would be caused by fast moving electrons colliding with air molecules. Another advantage is that the vacuum does not allow the alloyed powder to react with any molecules in the air, such as oxygen.

Different to other additive manufacturing techniques such as SLM, EBM can only work with conductive materials; any impurities inside the build tank will make it harder for the metal to melt and bond together. Unlike other methods, EBM also allows complete melting of the metal powder. [5][6]

The high temperatures that EBM is carried out are for two reasons. The first, mentioned earlier, is the fact that the tungsten filament needs to be heated to such a high temperature to allow electrons to be released. The high build temperature also allows the part created to have a good form stability, remain void-free and have low residual stresses (as this temperature is constant).

The final part of EBM is to post process. The aim of post processing is to clean the component by removing excess powder, as well as increasing the density and structural strength. Parts made via EBM usually have a larger surface roughness than other techniques such as LBM (laser beam manufacturing), but this finish often depends on the quality of material brought. This is because a lower quality material (often cheaper) will normally have larger sized grains than a higher quality material, meaning that the finish is rougher.

Other activities carried out during post processing include;

- Removing the build envelope
- Removing excess powder
- Thermal processing
- Removal of supports
- Post-machining
- Surface finish [7]

## B. WHAT ARE THE ADVANTAGES AND DISADVANTAGES OF EBM?

There are many benefits and drawbacks to using EBM as a manufacturing technique. These are detailed and discussed below.

### I. ADVANTAGES

**Higher Efficiency**

EBM is much more efficient than other additive manufacturing methods. Because an electron beam is used, it means that the overall system has a higher efficiency, resulting in lower power consumption than normal.

This, over time, can save a large amount of money on factors such as electricity bills. Adding to this, EBM also has lower maintenance and installation costs. Down the line, an EBM machine would save the user a lot of money and time, as the prices of traditional fabrication equipment, such as other factors like manpower and storage costs would be greatly reduced.

**Shorter lead times**

This is due to a number of reasons. The first is that a part can be designed directly from a CAD model (assuming that it has gone through pre-processing via specialist computer software). Adding to this, the material needed to make the part often doesn't need to be ordered in specially to make a part, as it can be stored in bulk and used when required. Because the material is powder, the space needed to store it is a lot smaller than what would typically be needed.

Furthermore, due to the thickness of the layers and higher power, a part can often be built quicker. The amount of material added can be up to 80cm$^3$ per hour. [8] These high build speeds, added to the other factors detailed above, mean than a part can be designed and made quicker when compared to traditional manufacturing techniques. Indeed, several parts can be built at once as long as the build table is large enough.

**Lower internal stresses**

Because there is usually a large amount of excess powder, this often acts in an unintended way as a support. By anchoring any created parts to the build platform/table, any excess powder enables heat transfer away from where the powder is being melted – hence reducing thermal and internal stresses, as well as preventing warping in some cases.

This means that a completed part will often have metallurgic properties similar to heat treated materials. This eliminates the need for heat treatment phases, saving both time and money.

**Less material waste**

One of the biggest benefits of EBM is the minimal waste when compared to traditional manufacturing methods, because the unused material can be reused again in a later component. Adding to this, this material will remain pure due to the fact that EBM takes place within a vacuum.

## II. DISADVANTAGES

**Only conductive materials can be used**

For all the benefits of EBM, this is the most important disadvantage. The fact that only these types of materials can be used severely cuts down on the range that can be used with this method.

The aim of the design will be to ascertain whether additional materials can be used to manufacture using EBM.

**Long cooling times**

While one of EBMs main advantages is the fact that it can get a part from concept to post-production quicker than many other methods, it is not suitable for mass production (unless either small parts or multiple machines are brought). This is because of the long cooling times that parts made with EBM require (in some cases, over eight hours). [9]

The fact that warping is prevented if a part is cooled naturally is mentioned earlier, and is still true. However, if a part is cooled artificially or too quickly, unwanted stresses that lead to object distortion or warping can occur.

**Less accurate than other methods such as LBM**

Compared to other methods such as LBM (laser beam melting), EBM is inferior in several categories including accuracy, minimum size of layer thickness and surface roughness. It also has a smaller range of potential materials (as mentioned earlier).

A table comparing the two technologies is given in ***Table 1***.

***Table 1*** *– A table comparing a number of criteria for LBM (laser beam meting) and EBM (electron beam melting).*

Technology comparison – EBM – LBM

| | LBM | EBM |
|---|---|---|
| Size (mm) | 250 x 250 x 350*1 | 210 x 210 x 350*2 |
| Layer thickness (µm) | 30 – 60 | 50 |
| Min wall thickness (mm) | 0.2 | 0.6 |
| Accuracy (mm) | +/- 0.1 | +/- 0.3 |
| Build rate (cm³/h) | 5 – 20 | 80 |
| Surface roughness (µm) | 5 – 15 | 20 – 30 |
| Geometry limitations | Supports needed everywhere (thermal, anchorage) | Less supports but powder is sintered |
| Materials | Stainless steel, tool steel, titanium, aluminum,... | Only conductive materials (Ti6Al4V, CrCo,...) |

*1 SLM Solutions 250HL
*2 Arcam A2

**X rays are generated**

EBM is one of the only types of additive manufacturing that generates X-rays (done when the electron beam is stopped by the workpiece). The higher the voltage of the electron beam, the higher the frequencies of X-rays emitted, as well as the fact that they penetrate more and are harder to absorb.

Because of this, regular radiation checks must be done to ensure that none of the X-rays escape the machine. These checks are done at the highest beam voltage point, using a target made of tungsten. Unfortunately, this adds to the costs of maintaining the machine. [10] [11]

## A. WHERE IS EBM COMMONLY USED?

EBM has uses in several engineering industries. They can also be used for prototyping (in order to produce parts for form/fit and functional testing), small series parts (including bespoke, one off parts) and support parts (jigs and fixtures). It must be noted that small series parts often need post-processing to achieve better tolerances and/or surface finish). [12]

Other areas of interest include;

**Aerospace and Automotive**

These sectors benefit from EBM mainly due to its variable density system. In motorsport, the time taken to produce complex frame shapes can be reduced drastically. In these areas, parts made via EBM include turbine blades and pump impellers, as well as turbocharger wheels.

One of the main aims of these industries is to reduce weight as much as possible, to both save money and to increase performance. By using EBM, new designs that previously would have been impossible to either integrate into a design or actually manufacture can be created. As a result of this, advances within these industries can be made quicker compared to traditional manufacturing techniques.

**Biomedical**

In biomedical engineering, EBM is often used to maximise the strength of any prosthesis that has been designed. In some cases, these can be made to be stronger than the original bone strength that the part has been designed to replace. Examples of components include elbow, hip and knee implants/replacements (seen in ***Figure 4***).

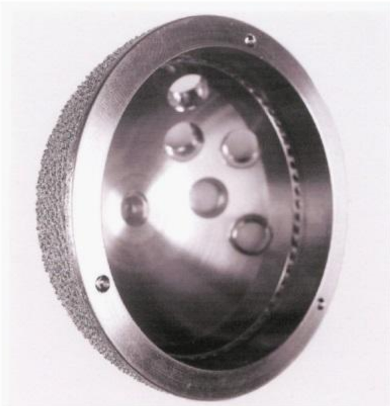


***Figure 4*** *- An EBM fabricated acetabular cup made from Ti-6Al-4V. This part would be used as a hip bone socket ingrowth.*

Another one of the main advantages of using EBM in this sector also includes the ability to customise an implant to a specific patient with minimal effort. This occurs because the implant is edited within the CAD software that it is designed in, before these changes are applied to the part that the EBM machine creates. In sub-categories such as the dental industry, this is doubly vital, as every tooth (again, a part that can be designed via EBM) is unique to the patient. [13][14][15]

# 3. MATERIAL CHOICE FOR THE MINI CHAMBER

In this section, the objective is to research what considerations should be taken into account when choosing a material for the mini chamber to be constructed from. Secondarily, a brief study into different types of stainless steels has been conducted.

When considering which material the chamber should be made out of, it is essential to think about all the environmental factors, both in use and not, that could have an effect on the material. In a chamber within an EBM machine, there are many different scenarios to consider.

## A. ENVIRONMENTAL FACTORS TO CONSIDER

Primarily, heat must be considered. The material of the chamber must resist temperatures that are high enough to melt the powder that is being used for the 3D part. Arcam have 4 official standard materials used in their EBM machine, being [16]:

- Titanium Ti6Al4V
- Titanium Ti6Al4V ELI
- Titanium Grade 2
- Cobalt-Chrome, ASTM F75

The in service temperature of the EBM machine is around 680-720°C. [17] This means that it is critical that the material which is chosen to be used for the chamber be able to withstand at least 720°C with an additional safety factor.

Secondly, the material needs to withstand a vacuumed environment. Firstly, in order to decrease the chance of contamination, but mainly because the electron beam needs a clear path, and not collide with any air molecules. This means that the chosen material has to be relatively strong, in order to maintain its shape under a pressure difference from the atmospheric pressure. It also needs to be nonporous, to ensure no liquid/gas is able to leak into the vacuum. Also, the material has to have a low rate of "outgassing", which is when a material will naturally release gasses that the material has stored. This can be due to the gasses being dissolved, absorbed, frozen or trapped within the material. [18] The gasses released contaminate the quality of the vacuum, repeatedly, as the liberated molecules can then be reabsorbed, contaminating the chamber again. A diagram showing the basics of outgassing is shown in ***Figure 5***.

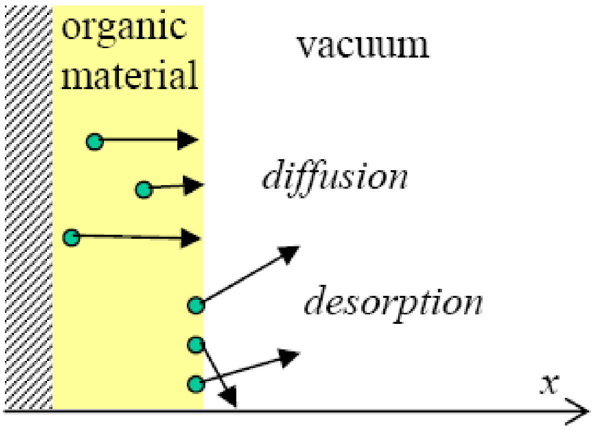



***Figure 5*** *- Diagram of Outgassing Phenomenon*

Thirdly, as the beam of electrons is controlled with two magnetic fields (one to focus the beam to the desired diameter, and one to deflect the beam to the desired point on the table) [19], it is fundamental to choose a material which is not magnetic. Otherwise, the magnetic field produced by the material would interfere with the two magnetic fields which are supposed to control the beam of electrons.

Fourthly, creep in materials is a phenomenon for the material to slowly deform permanently if it is under stress. Creep is important to consider in design engineering because it can occur even when the material is exposed to stresses less than the materials yield stress. Creep is also highly dependent on the temperature of the material during operation. [20] It is for this reason that it is important to consider creep when choosing the material for the EBM chamber, as this will be operated at very high temperatures. An example of the consequences of creep is shown in ***Figure 6***.

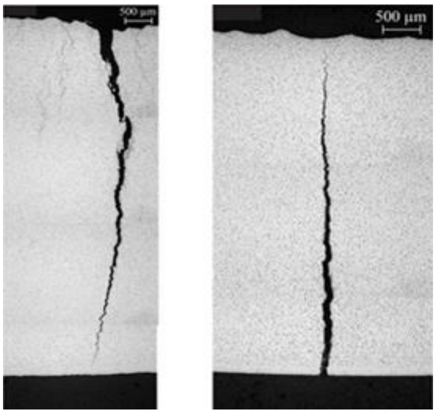



***Figure 6*** - *Example of crack caused by creep.*

If an unsuitable material was chosen, it could lead to disaster, such as the chamber melting. This would result in the molten titanium alloy (or other material being used for 3D part) and the unsuitable chamber material itself leaking from the machine, causing huge amounts of damage economically to the EBM machine and surroundings, and even more severely, it would be an extremely dangerous safety hazard. An additional safety factor is that the interaction between the electron beam and the 3D part which is being manufactured produces harmful x-rays, which would also escape in the event of the chamber failing.

Our client, M. Guilhem Martin, has reason to believe that the material used within the chamber is either super austenitic steel 304L or 316L. This is because of these steels excellent creep resistance and ability to be operated in extremely high temperatures, whilst fulfilling the need to be non-magnetic.

## B. DETERMINING THE CURRENT ARCAM CHAMBER MATERIAL

Since it is known that the material used in the current chamber produced by Arcam works sufficiently in the main chamber in the EBM machine, it is simplest to use this material again for our mini chamber within the Arcam chamber. To be sure which material is currently used, it is recommended to conduct a Scanning Electron Microscopy (SEM). SEM is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons, which also records the percentages of which elements the material is composed of. [21] An example of an SEM test I conducted on some dust particles at CERN is shown below, in ***Figure 7***.

| | | O | Fe | C | Si | Ca |
|---|---|---|---|---|---|---|
| Spot | 1 | 62.71 | 7.14 | 4.63 | 2.87 | 17.34 |
| | 2 | 60.61 | 2.02 | 6.96 | 1.78 | 12.8 |
| | 3 | 55.44 | 0.61 | 1.07 | 37.2 | 0.42 |
| | 4 | 33.7 | 63.62 | 0.88 | 0.58 | 0.33 |
| | 5 | 53.26 | 0 | 40.81 | 0 | 0.87 |
| | 6 | 34.78 | 63.8 | 0.78 | 0.16 | 0.27 |
| | 6 | 39.76 | 58.73 | 0.71 | 0.51 | 0.15 |
| | 8 | 37.32 | 60.28 | 0.54 | 0.44 | 0.13 |
| | 9 | 63.76 | 0.67 | 22.16 | 0.69 | 3.84 |
| | 10 | 66.33 | 0 | 23.18 | 0.13 | 4.14 |
| | Total | 507.67 | 256.87 | 101.72 | 44.36 | 40.29 |
| | Average (%) | 50.767 | 25.687 | 10.172 | 4.436 | 4.029 |

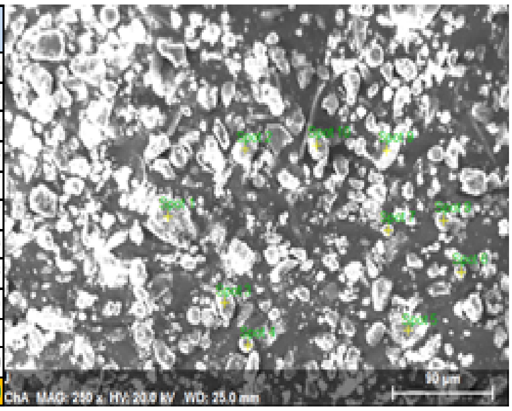



***Figure 7*** *– Ashby chart showing all metals.*

This shows the elemental composition by percentage, which can be used to determine which material is used.

## C. ASHBY CHARTS

Using the software 'CES Edupack', it is possible to plot materials based on certain attributes and filter the list of materials by characteristics as well. As shown below in ***Figure 8***, the maximum service temperature has been plotted against the price (£/kg), for all metals.

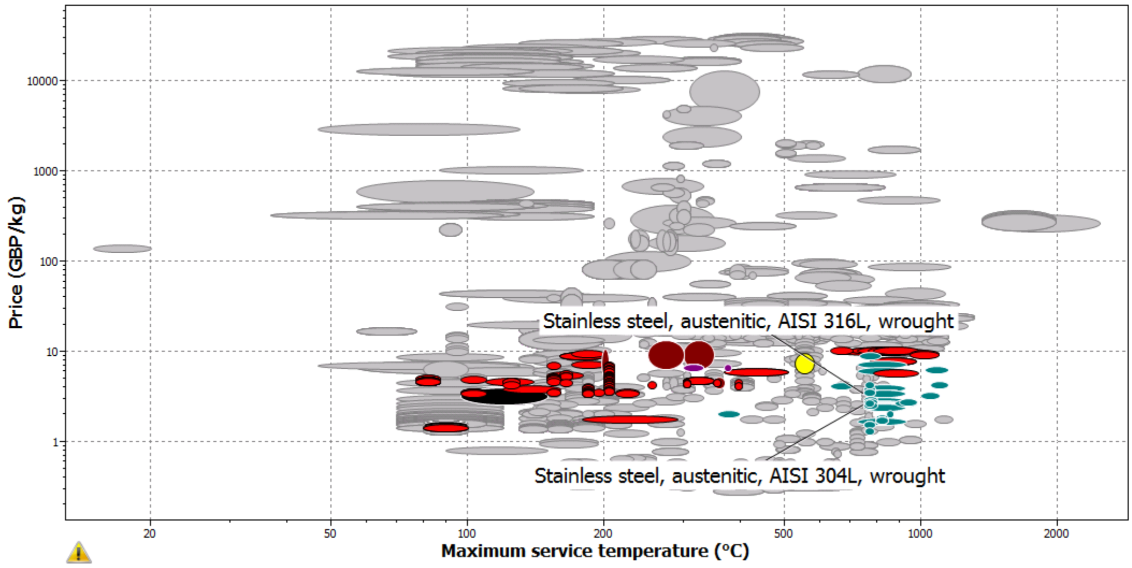



***Figure 8*** *- Ashby chart showing all metals.*

However, once the following filters are applied:

- only non-magnetic metals
- service temperature of at least 750°C (maximum operating temperature of 720°C, plus a safety factor of 30°C)
- Young's Modulus of at least 100GPa (enough to ensure the material has significant amount of strength to withstand atmospheric pressure difference)
- Minimum melting point of 1400°C (Safety factor of 2. High safety factor because metals lose a lot of structural strength well before the melting point)
- maximum price of £10/kg
- Thermal expansion coefficient (maximum of 20µstrain/°C, to minimise deformation),

It can be seen that stainless steels 304L and 316L are both good choices for the chamber to be made from, as M. Guihelm Martin predicted (shown in ***Figure 9***).

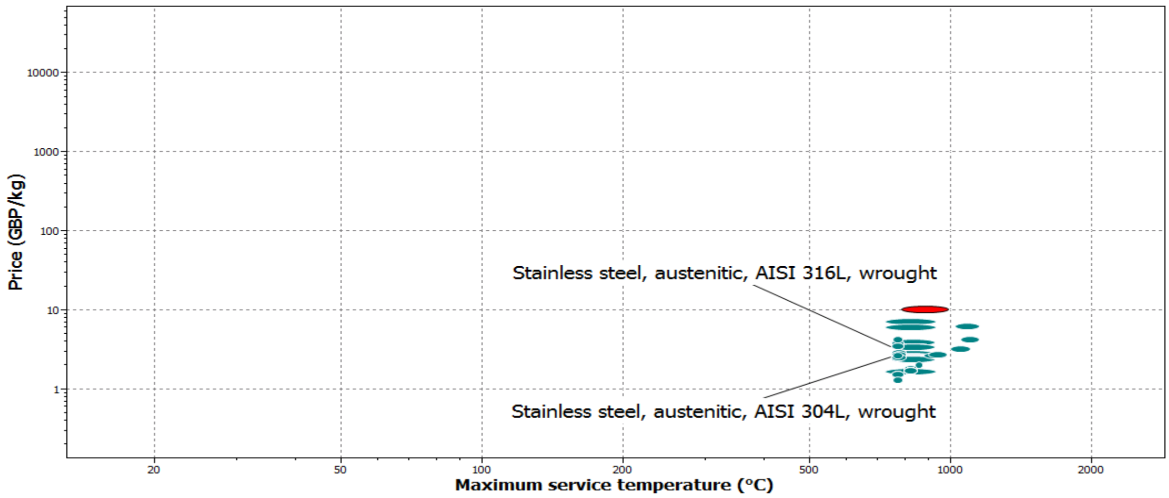



***Figure 9*** *- Ashby chart showing 'suitable' materials*

CES Edupack has no option to filter by creep resistance, however, CES Edupack does state that stainless steels have "high creep and rupture strengths". This further supports the choice of a stainless steel for the chamber material. To find out which material is creep resistant, there are many datasheets available, such as from the National Institute for Materials Science (NIMS). [22] Alternatively, to be 100% sure, a creep testing machine could be used. This machine produces a creep time dependent graph by calculating the rate of creep and the time it takes for the material to change.

CES Edupack also does not have any data on porosity and outgassing for stainless steels. However, Fermilab have stated that stainless steel 304 has a low level of outgassing, at $3.0x10^{-12}$ torr-L/sec-$cm^2$ (electro polished and baked for 30hrs at 250°C). [23] Additionally, other sources have declared stainless steel to be nonporous, as required for the mini chamber. [24]

## D. DIFFERENT STAINLESS STEEL GRADES

The difference between a 304 stainless steel and a 316 stainless steel is that the 304 stainless steel comprises of 18% chromium and 8% nickel, whilst 316 contains 16% chromium, 10% nickel and 2% molybdenum. [25]

Stainless steel 304 is more commonly used and is cheaper. However, stainless steel 316 is more corrosion resistant, due to the molybdenum that is added, meaning that it is more capable of resisting chemical attack. For this project, it is not necessary to resist chemical attack, and it is therefore recommended to use the cheaper stainless steel; 304.

Furthermore, there is the possibility to choose between stainless steel 304 and 304L. The 'L' denotes a carbon percentage less than 0.03%. The lower amount of carbon in the steel results in less outgassing, meaning that 304L stainless steel is necessary for ultra-high vacuum (UHV) chambers. According to the "School of Biological & Chemical Sciences at Queen Mary, University of London", a UHV is less than $<1x10^{-9}$ mbar. [26] Whereas, the vacuum of the Arcam A1 is much less than this boundary, being $<1x10^{-4}$ mbar. [27] Therefore, it is unnecessary to use the low carbon variant of 304 stainless steel; 304L. Thus, it is still recommended to use austenitic stainless steel 304 for the mini chamber and rake.

# 4. SOFTWARE AND ANALYSIS

In this project, we will need to recreate the chamber computationally. This is necessary for accurate simulation regarding the choice of material, and the dimensions of our solution.

We will use two pieces of software; one for modelling and one for analysis.

## A. SOLIDWORKS

**What do we want?**

We want to create a *CAD* model that allows us to simulate the thermal conditions in the EBM chamber, as well as design to the required geometry for fulfil the project conditions.

There are many options in the market such as SolidWorks (SW), CATIA, and Inventor…

**Why choose SolidWorks?**

While there are many programs available (e.g. SolidWorks, CATIA, Inventor etc.), we will choose SolidWorks due to many reasons.

Not all CAD programs can handle all file types. Our multi-physics analysis might require certain file sizes. SolidWorks files use "Microsoft Structured" storage file format, meaning that there are various files embedded within each SLDDRW (drawing file); such as SLDPRT (part files), SLDASM (assembly files), preview bitmaps and metadata sub-files. Various third-party tools can be used to extract these sub-files, although the sub-files in many cases use proprietary binary file formats. [28]

First of all its power, more than Inventor, less than CATIA (used for high requirements models, such as airplane turbines) but certainly enough for our simulation.

Also because of its learning curve, it is easier than other similar programs. This learning time will allow us to use the remaining time in other fields of the project. [29]

Last reason is because we want good results, this *CAD* model is very important for later simulations. SW is a worldwide reference and also matches very well with ANSYS that will be our simulation software.

**How?**

We will measure (physically) the dimensions of the chamber, and we will translate from paper to data with SW. Once we have this file we will be able to do all the simulation, essential for advancing in our project.

***Figure 10*** *- Interior of an Arcam A1 machine*

## B. ANSYS

**What do we want?**

We want to reproduce the chamber of the EBM that will allow us to choose wisely the best material and shape for the physical implementations that we will develop.

For reproducing this chamber we will use the finite elements method (FEM).

**Why choose ANSYS?**

After modeling, we need an analysis program. ANSYS goes well with CAD files, and is capable of an excellent meshing process. With this and FEM, we will get the accuracy needed for a good simulation.

ANSYS is commercial FEM that models and solves engineering problems in different fields such as fluid mechanics, acoustic, heat transfer, electromagnetism, etc. It presents a graphic interface in Windows environment that allows the user to tackle a huge spectrum problems in an interactive way.

It also focuses on multi-physics problems, and is therefore the perfect option for reproducing the EBM due to his complex equations.

There are many finite elements based programs such as COMSOL, with complex physics beyond our objective.

**How?**

We will mesh our CAD model (finite elements), as the area of these elements gets smaller the accuracy increases (and also the simulation time).

The area of the mesh can be changed along the model, based on the level of accuracy required, for example corners and edges need more accuracy than flat surfaces.

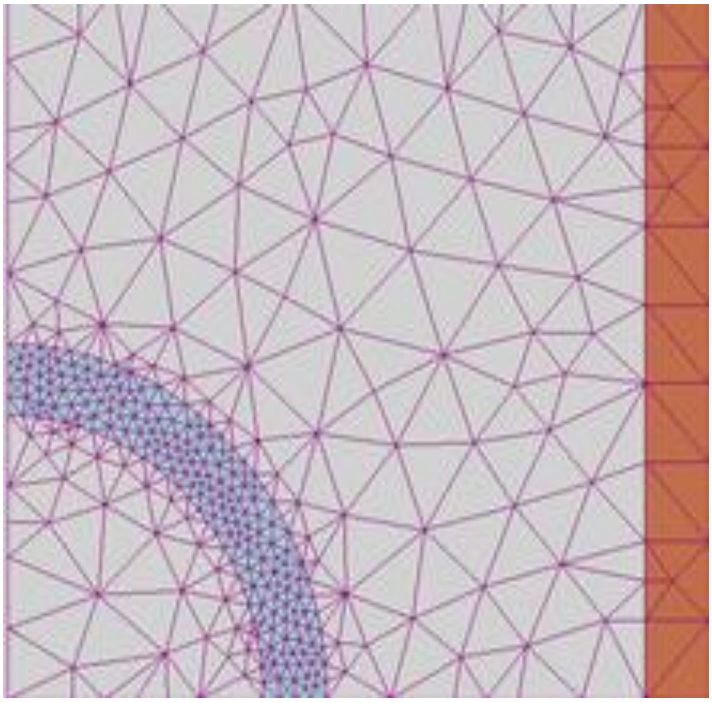


***Figure 11***

We will reproduce the physical model (focusing on the heat transfer), that will allow us to know the heat produced. Finally we will see how this heat is distributed along the chamber. With this information we will be able to choose the best material.

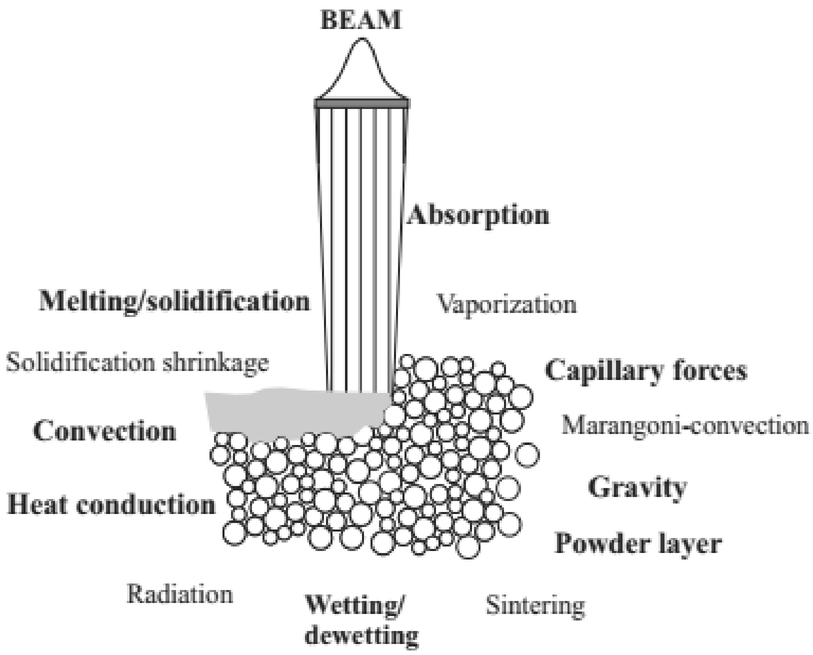

BEAM
Absorption
Melting/solidification
Vaporization
Solidification shrinkage
Capillary forces
Marangoni-convection
Convection
Gravity
Heat conduction
Powder layer
Radiation
Wetting/
dewetting
Sintering

***Figure 12***

# 5. MARKET STUDY

A market study in the research field; the development of new material for AM was done to understand the client's need better and to identify similar products in the market.

Based on AM Research Map developed by Direct Manufacturing Research Center and the Heinz Nixdorf Institute, University of Paderborn, Germany, an outstanding research intensity is prevalent in the field of new material discovery. [30] This is followed by other critical AM research fields as such mechanical properties, material quality and microstructure manipulation and material/ powder generation. Majority of participating research institutes are actively involved in the find of new materials, and are putting higher emphasis in this field compared to others. Further advancement in this field is regarded as necessary in order to advance AM towards Direct manufacturing (DM), thus increasing its penetration. Among the different AM technologies, Powder Bed Fusion Metal Technologies as such EBM also indicate the highest research activity in total compared to others such fused layer modelling and polymerisation. In average, more than six institutes are involved in each research field of this technology. **Table 2** indicates the different institutes that are actively involved in new material research field of Powder Bed Fusion Metal Technologies as recorded in the study.

**Table 2** - List of institutions with high research level in the field of new materials

| Research activity | Institution |
|---|---|
| Highly Intensive | Collaborative research center 814 (university of Erlangen Nuremberg, Germany)<br>Fraunhofer Institute for Manufacturing technology & advanced materials (Bremen, Germany)<br>Fraunhofer Institute for laser technology (Aachen, Germany) |
| Intensive | Additive manufacturing & 3D printing research group (university of Nottingham) |

***Figure 13*** relates current performance to the relevancy of different research fields. Although research of new materials is considered critical due to its low performance, sufficient attention has been put into it as shown by the high level of research intensity.

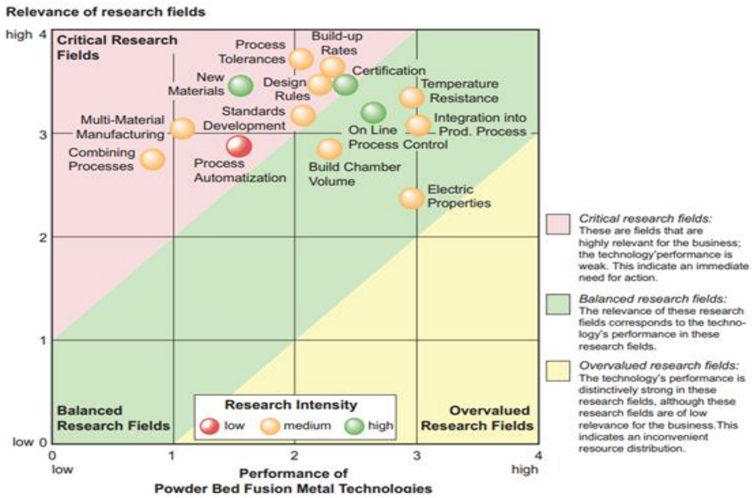



**Figure 13**: The relevance of different research fields in powder bed fusion metal technology against their performance.

Some materials development for EBM which has been actively viewed at other research institutes includes [31] [32];

- Aluminium and its alloys
- Steels
- Superalloys
- Intermetallics

- Refractory metals and alloys
- GRCop-84
- OFE Copper
- Niobium, C103 Niobium
- Beryllium Alloys
- Ti-Al
- Nickel Alloys (625, 718, M247)

## A. SIMILAR PRODUCT: MINIVAT AND MINIRAKE

A similar solution has been proposed by Francisco Medina from The University of Texas at El Paso, in order to reduce material used in each EBM production cycle. [5] The MiniVat & MiniRake system developed capable of reducing the amount of minimum material needed by more than ten times. On a normal Arcam A2 machine, a minimum of 90kg titanium powder is required in setting up, level the state plate and to be filled in the two hoppers. Whereas, the new design introduced would only require 2 - 10kg worth material in each production. This allows material research and testing to be done more effectively as smaller quantity of material are required each time. In addition, time taken to set up the system has been significantly reduced by six times, while heating of the build platform and cooling of the fabricated part is four times faster.

The MiniVat designed encompassed of an interchangeable cylindrical chamber insert, which allows quick installation and easy conversation back to the original build tank. Two sizes of cylindrical chamber were designed. ***Figure 14*** shows the CAD model of the chamber, with other parts in place. The table top attached acts as a cover to the original 250x250mm build tank opening. The design of the MiniRakes is shown by the 3D CAD in ***Figure 15(a) and (b)***. The original rake was locked into the back of the machine and the existing rake-moving mechanism will be utilised in the design. It encomposed of two rakes which enclose and move the powder at once. A second design as shown in ***Figure 3(b)*** was designed with spring loaded adjustments to allow a level distribution of the powder.

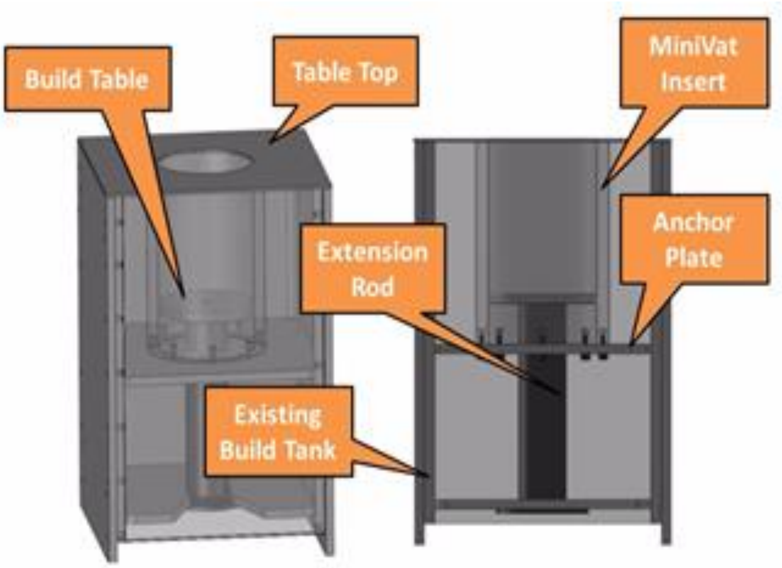



***Figure 14****: CAD model of the MiniVat chamber*

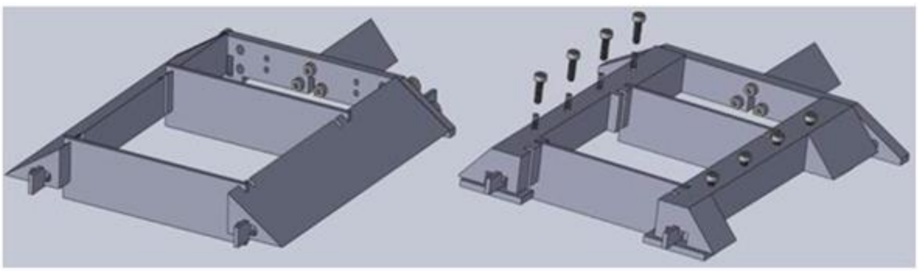


***Figure 15****: (a) 1st generation MiniRake (b) 2nd generation MiniRake*

The technical details of the system are as listed in **Table 3**.

**Table 3: Technical details of the MiniVat and the MiniRake**

| | |
|---|---|
| **Build capacity** | 5 - 10mm |
| **MiniVatZ build height** | 150mm (half the initial build tank height) |
| **MiniVat inner diameter & square start plate** | MiniVat1: 120mm/ 70mm<br>MiniVat2: 70mm/ 40mm |
| **Chamber material** | Demagnetised 304 stainless steel<br>(due to its high temperature tolerance & corrosion resistant) |
| **Build table material** | Original high temperature rope seal |

## B. PRODUCTION

Massive production is not necessary as the system modifications are made solely for experimental laboratory use, thus only a small number of prototypes would be produced at this stage. Minimum of two prototypes would be produced in order to detect any manufacturing flaws between the two models. The parts designed would be made in-house by manually machine solid metal blocks into the desired dimension. It would then be assembled and tested. Considering the designed chamber would mostly be metal, traditional machining processes such as milling and CNC machining or 3D-printing could be used. These facilities are accessible via the INP laboratories.

Some of the factors that need to be considered in deciding on which machining method to use are as follows;

- Surface finish
- Desired mechanical characteristics
- Level of complexity
- Part life
- Material
- Machining cost
- Machining time

A few potential stainless steel supplies have also been identified as follow; UGITECH, APERAM and OUTOKUMPU with the first to be a local supplier located not too far away from Grenoble. [33][34][35] The available bar size offered by UGITECH range from 0.3 to 60mm, in various condition such as annealed and work hardened. It is assumed that the designed mini chamber parts will be machined separately for assembly, and not produced from a single block as this would be too costly. When bought directly from the UGITECH mill, a tonne of previously suggested 304 stainless steel would cost €868 if it is hot rolled, while €706 for cold rolled bar with minimum purchase of 0.05 tonne (50 kg). [36] Hot rolled bar is more preferred due to its economical factor, apart from the fact that better mechanical properties offered by cold rolled bar is not required. Further choices would be made based on the availability of the material required at the time, in comparison with its cost.

## C. HEALTH AND SAFETY REGULATIONS

There is no obligation to adhere to certain health & safety standard as the optimisation aimed in this project is not for commercial use. However legal requirements could act as guidelines and should be implemented to a certain degree to meet a minimum health & safety level for its user. Members of European Economic Area (EEA) including France has widely implement the Machine Directive outlined by the Health and Safety Executive (HSE) into its national law. [37] This supply of new machinery regulation is in line with the European Machinery Directive 2006/42/EC, the

UK Health and Safety at Work etc Act 1974 and Supply of Machinery (Safety) Regulations 2008, just to name a few. It applies to machinery in general, including 'interchangeable equipment that only works when attached to other machine'. In brief, the regulations require manufacturers and their authorised representative to;

- Ensure the machinery is safe by meeting the relevant essential health and safety requirements (EHSRs) outlined. This include the provision of enough instructions in the end user's language
- draw up technical drawing for the machine
- issue a Declaration of Conformity with the machinery, or in the case of partly completed machinery, a Declaration of Incorporation
- Have a CE marking affixed to the machinery, with an exceptional on partly completed machinery that comes with a Declaration of Incorporation.

# 6. SPECIFICATION

After having completed the "State of the Art" section of the project, the next step was to create an initial product design specification (PDS), a document that listed what criteria the final product had to meet to be deemed successful. This specification was split into four parts;

- **General Requirements**
  - These are the headings that several specific requirements are grouped under. For example, several specific requirements in the PDS are grouped under the general requirement "Dimensions".

- **Specific Requirements**
  - These are the specific requirements (or deliverables) that the final product needed to meet. Using the same example as last time, specific requirements under the heading "Dimensions" included the maximum height, width and depth of the solution.

- **Acceptable Performance**
  - This is what the specific requirements were compared against, to ensure that they had been met. All of the criteria in this column were measurable, normally with numbers. Using the same example again, the acceptable performance would be a range of dimensions that the final design could not exceed.

By consulting with the client, the PDS was created using these guidelines. Although not necessary, a fourth column was also added to the PDS called "**Why?**" This column was placed in the PDS to justify the figures that were specified in the "Acceptable Performance" column.

The PDS for this project is below.

- **GENERAL REQUIREMENT:** Optimise the build of a test cube in the machine

| Specific Requirements | Acceptable Performance | Why |
|---|---|---|
| **Reduce the amount of powder used in the machine** | Maximum chamber volume of 200 $cm^3$ | Based on maximum capacity of 2kg for 9g/$cm^3$ (Titanium Ti6Al4V: 4.43 g/cc, Titanium Ti6Al4V ELI, Titanium Grade 2, Cobalt-Chrome ASTM F75) |

- **GENERAL REQUIREMENT:** Dimensions

<table>
<tr><th>Specific Requirements</th><th>Acceptable Performance</th><th>Why</th></tr>
<tr><td>Build Zone</td><td>50mm x 50mm x 20mm</td><td rowspan="3">Dictated by the client</td></tr>
<tr><td>Specific build table shape</td><td>Square build table</td></tr>
<tr><td>Thermal zone</td><td>15mm clearance</td></tr>
<tr><td rowspan="2">A build platform smaller than the current smallest available</td><td>Minimum size 70mm x 70mm</td><td rowspan="2">The smaller the build platform, the less unused material on the build platform</td></tr>
<tr><td>Maximum size 150mm x 150mm</td></tr>
</table>

| | | |
|---|---|---|
| **Maximum height of solution** | **60mm** if moving outside heat shield<br>**200mm** if permanently situated inside heat shield | To avoid clashing with the heat shield when moving |
| **Maximum width of solution** | **542mm** | To be able to fit inside the machine |
| **Maximum depth of solution** | **355mm** | |

- **GENERAL REQUIREMENT:** Materials

| Specific Requirements | Acceptable Performance | Why |
|---|---|---|
| **Needs to not affect the magnetic field inside the machine** | **Non-magnetic material** | Will affect the accuracy of the electron beam if magnetic |
| **Able to withstand high temperatures** | Safe service temperature higher than **720°C** | So the material does not lose key material properties under large temperatures |
| **Relatively low cost material** | Max price of **£10/kg** | To keep the material costs down |

- **GENERAL REQUIREMENT:** User Requirements

| Specific Requirements | Acceptable Performance | Why |
|---|---|---|
| **Relatively easy to install** | Preparation time faster than **15 minutes** | The current machine setup time using Medina's solution |
| **No sharp edges** | **Corners to be deburred** | To ensure users do not injure themselves |
| **To be relatively light** | Maximum weight of **10kg** (for table top assembly) | To ensure that the solution is easy to move by a person of average strength |

- **GENERAL REQUIREMENT:** Movement

| Specific Requirements | Acceptable Performance | Why |
|---|---|---|
| **To use existing power sources to evenly spread the powder** | To **make use of the rake mechanism** to spread the powder evenly | External power sources complicate the problem |

- **GENERAL REQUIREMENT:** Service Life

| Specific Requirements | Acceptable Performance | Why |
|---|---|---|
| **To have a relatively long service life** | A service life **the same as the rake** | To reduce servicing costs, and to provide a robust solution |

- **GENERAL REQUIREMENT:** Manufacturing and Production

| Specific Requirements | Acceptable Performance | Why |
| --- | --- | --- |
| **Able to meet the production demand** | Probably **2**; maximum order of **3** | Dictated by the client |
| **To be able to be made in budget** | Budget of **€10,000** | |

# 7. CONCEPTS

After completing the specification list, it was the perfect time to start some concept generation. The initial step was to use a morphological chart to generate many different ways of solving the problem, broken into its sub-functions. It was decided that there were 4 different functions to base the design around, including: distribution of powder, minimise initial powder investment, reuse existing powder, and ensure powder does not leak through gap. The morphological chart is shown in **Figure 16**.

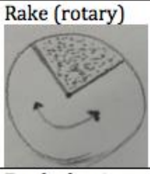
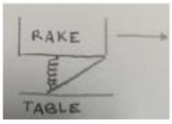
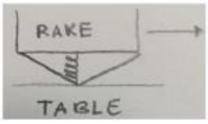
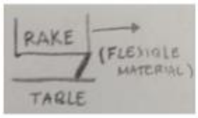
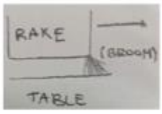
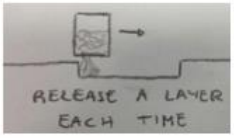
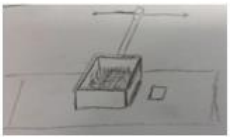
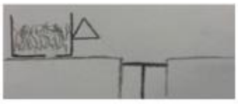
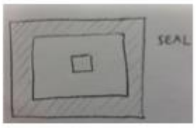
| FUNCTIONS | | | | | |
|---|---|---|---|---|---|
| **Distribution** of powder | Rake (rotary)  |   |   |   |   |
| **Minimize** initial amount of powder | Feed what is needed per layer |   |   |   | |
| **Reuse** existing powder | Rake (rotary)  |  |  |  | |
| Ensure powder does **not fall** into gap | Cover build table v1  | Cover build table v2  |   | | |

**Figure 16** – Morphological chart

As shown in the morphological chart, there are many different ways possible to complete the objective of the project. However, based on this chart, each of the team members chose to further just one of their ideas, and blend the other concepts within their own concept.

After the initial brainstorm, it was clear that the project was going to have multiple parts that need to be designed. So for the first iteration, the team decided it was most likely that the project would need to focus on two areas. Firstly, the 'rake', which would be the part that distributes the powder on the build table. Since the principal objective of the project was to minimise the initial powder investment, the rake would most likely be some form of a container, in order to reuse the powder that is already placed on the build platform, as opposed to brushing the powder off the entire table. Secondly, the 'chamber', which would be a smaller chamber required to be inserted within the current build chamber. This is necessary because if we kept the size of the current build chamber, the possibility to reduce the initial powder investment is drastically reduced.

For the rake, three concepts were put forward. Firstly, the current setup uses a rake with a linear motion, so a design based on this principal seemed the simplest. Secondly, a rake based on rotary motion was considered. And thirdly, a rake that deposited exactly the correct amount of powder on the build table was investigated. All of the concepts obliterated the need to have a hopper within the machine to store the vast amounts of powder required to deposit the powder onto the platform layer-by-layer. Instead, the concepts all contained the powder that would be used within the rake itself, already on the build platform.

For the chamber, two concepts were put forward. Both of the concepts would need to include a smaller chamber, so the difference in concepts was how the smaller chambers would be attached to the setup. Firstly, the mini chamber could be attached from the top, by fixing it directly underneath the build platform. Secondly, the mini chamber could be attached from the bottom, by fixing it onto the piston at the base of the machine, which raises and lowers the build table in order for the 3D part being produced to be able to be manufactured layer-by-layer.

## A. RAKE – LINEAR

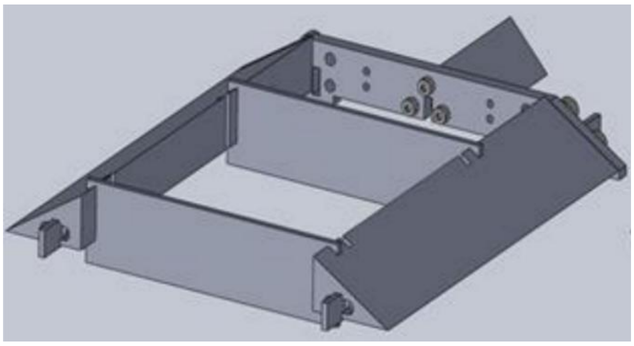


FIGURE 17 - LINEAR RAKE CONCEPT

As Occam's razor says "the simplest solution is usually the correct solution", it was very important to first consider using the current linear motion used for the rake in the standard Arcam setup. Therefore, to utilise this motion the only parts that would need to be altered would be the rake itself, and the part that connects the rake to the horizontally moving pulley system built-in to the Arcam machine. A linear motion concept which contains the powder is shown in **Figure 17**. The main advantage of this concept is its simplicity in using the linear motion, but other advantages include that it is very easy to install/assemble, and also that something like this has already been tested at another university in America [5], which proved to have impressive layer spreading accuracy.

## B. RAKE – ROTARY

A slightly more innovative solution than using the same linear motion was to convert this linear motion into rotary motion using a rack and pinion mechanism. The initial idea was to create a circular cage that fixes onto the build platform, which contains a wedge shaped container within the cage, which rotates due to the rack and pinion. This way the wedge shape can spread the powder over the build table as it rotates, whilst ensuring that the powder does not escape, and thus the powder is reused.

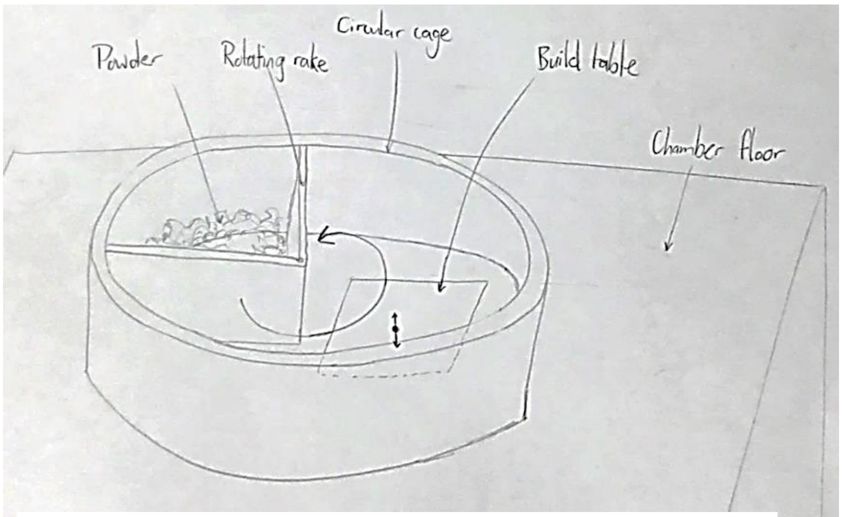



FIGURE 18 – 1ST ITERATION OF RAKE CONCEPT

The rotary concept is shown in **Figure 18**, accompanied by **Figure 19** from an eagle-eye perspective to show how the rack and pinion would be incorporated within the concept.

Later, a second iteration of the concept was developed, as it was realised that having a separate piece for the circular cage as the rotating rake introduced a possibility that the powder could get stuck between the two moving parts since it is hard to ensure a circular piece lines up perfectly with a straight piece, whilst maintaining a small enough clearance to guarantee that the incredibly fine powder alloys do not leak out of the rotating rake wedge. The second iteration is shown in **Figure 20**.

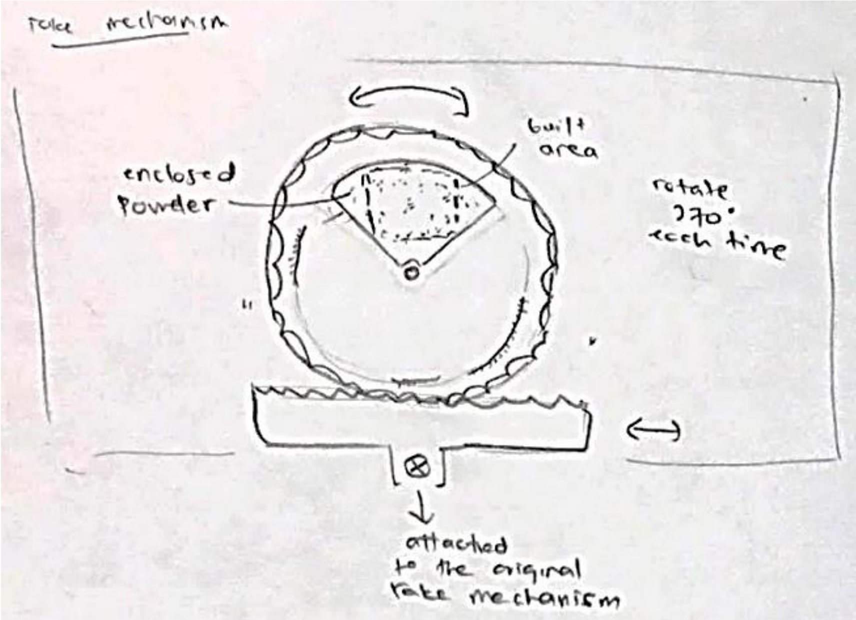



FIGURE 19 - RACK & PINION MECHANISM

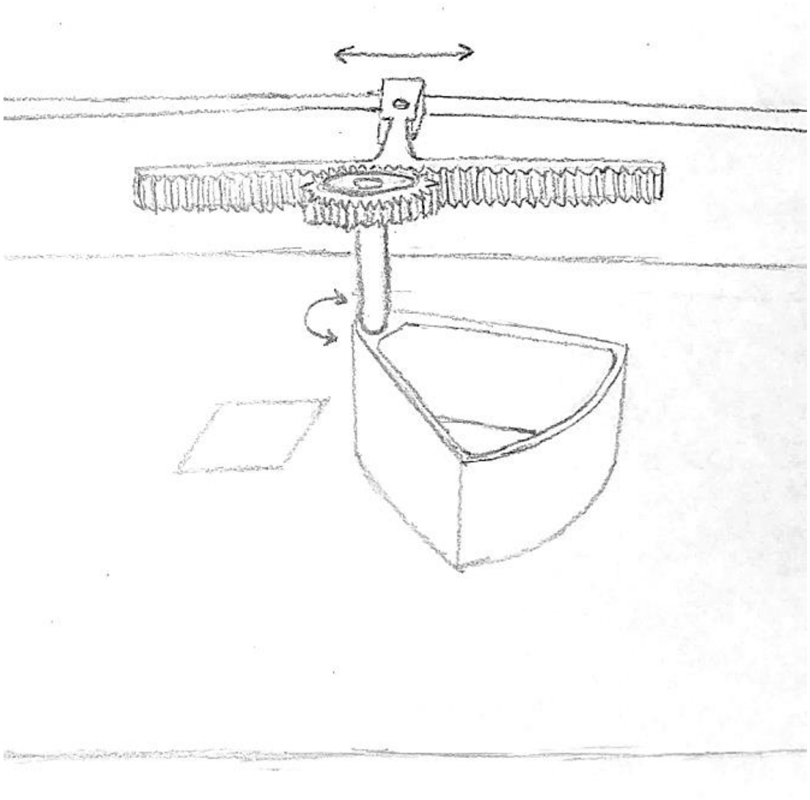


FIGURE 20 – 2ND ITERATION OF ROTARY RAKE

Not only does this version decrease the number of parts required, but additionally, using this version reduces the material costs and weight of the solution.

## C. RAKE – DEPOSIT

The third rake concept combines both the hopper and rake into a single unit, as shown in **Figure 21**. It utilised a narrow slit and an inclined base to release a single layer of powder each time. Powder would first be loaded, and as the rake translate across the lowered build table, 15µm layer of powder would be released. This process would then be repeated until the EBM process is completed. The advantages and disadvantages of this concept are listed in **Table 4**.

TABLE 4 – ADVANTAGES & DISADVANTAGES OF DEPOSIT CONCEPT

| Advantages | Disadvantages |
|---|---|
| • Contain the powder in a single unit<br>• Reduce initial amount of powder required significantly as only a layer of material released each time | • Powder might escape from the small opening<br>• Accuracy of spreading<br>• Time consuming<br>• High tendency to fail as the slit get clogged |

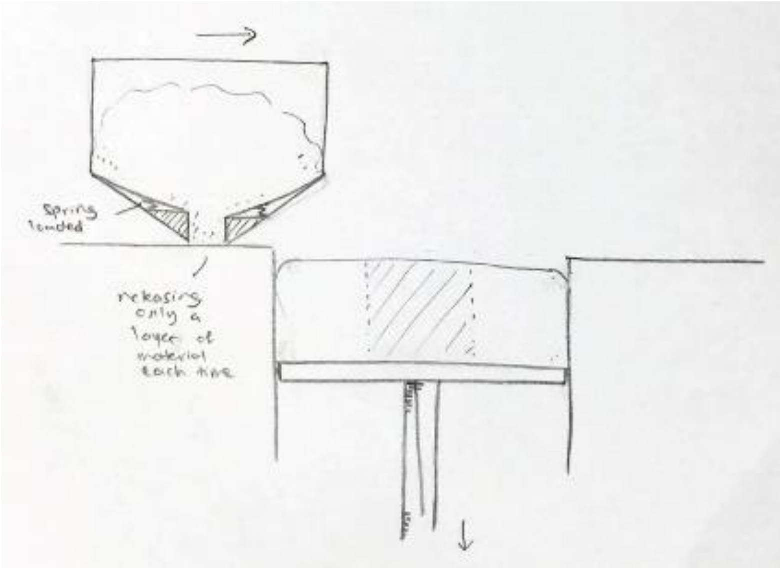



FIGURE 21 – DEPOSIT RAKE CONCEPT

One advantage of this concept is that it reduces the initial amount of powder required significantly, as an exact amount of powder is released each time. However, a tight sealing mechanism would be required, as the inclined base may result in unnecessary powder to escape. There is also a high risk of failing due to the slit become clogged.

## D. CHAMBER – SUPPORT FROM TOP

Having brainstormed using the morphological chart, it was quickly realised that there were only two realistic ways of securing the chamber – from the top, and from the bottom. The initial concept for supporting from the top is shown below.

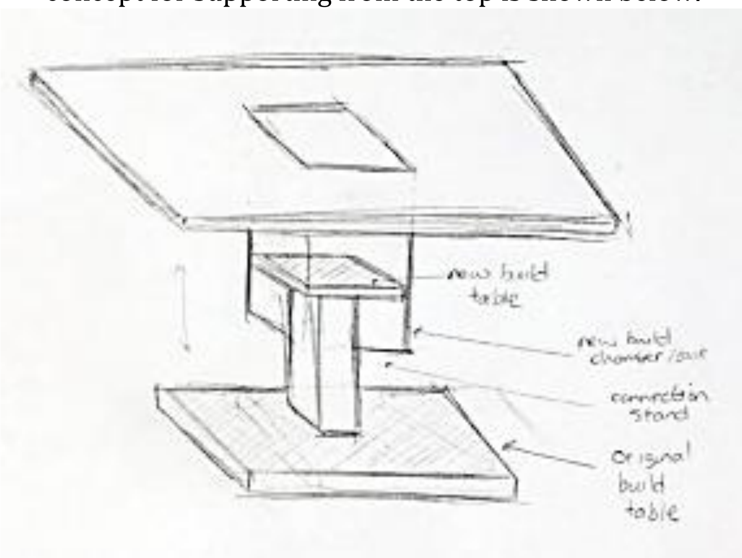



FIGURE 22 – SUPPORT FROM TOP CONCEPT

This concept reduced the size of the build table by reducing the size of the hole that the powder would fall through to approximately 70 – 80 cm square. This would then be placed on top of the pre-existing setup, and would be secured by creating a new build tank that is similar in shape and just smaller in size to the current setup. By doing this, the new setup would be secured by placing it into the hole that the existing build table was in.

A new build table would also be created, in order to fit into the hole created by the new build tank. This would be secured to the old build table (probably via either screws or a weld), with a gap between the two that would be approximately the same as the length of the new build tank. Then, when the old build table (which would still be attached to the pistons at the bottom of the machine) moved, the new build table would move by the same amount.

The advantages and disadvantages are listed in **Table 5**.

TABLE 5 – ADVANTAGES & DISADVANTAGES OF SUPPORT FROM BOTTOM CONCEPT

| Advantages | Disadvantage |
| --- | --- |
| • Simplistic<br>• Reduce the chamber capacity significantly<br>• Easy to install<br>• Reduce cooling time | • Extra support required<br>• Multi-stress concentrated areas |

# 8. CONCEPT SELECTION

## A. PUGH'S MATRIX

Upon completion of the concept generation stage, it was decided that the best way to converge to which concept the team would further develop was to use Pugh's Matrix. Pugh's Matrix is a tool used to facilitate a disciplined, team-based process for concept generation and selection. Several concepts are evaluated according to their strengths and weaknesses against a reference concept, called the datum. The datum is the best current concept at each iteration of the matrix [38].

Pugh's Matrix allows the team to:

- Compare different concepts
- Improve weaker concepts
- Arrive at an optimal concept that may be a hybrid or variant of the best of other concepts

In the case of the 'rake' concepts, this was split into its subsidiary criteria being: Reducing Initial Powder, Maintenance, Accuracy of Spreading, Ease of Manufacture, Ease of Installation, Simplicity, Cost, and Rate of Spreading. The team then voted on the importance of each of the criteria, which meant that each of the criteria could then be designated with an appropriate weighting. Then, each of team members compared each of the concepts to the datum, which was the standard rake setup in the Arcam A1 machine. Using this datum, the team's average rating was applied uniquely to each of the criteria, and multiplied against the weighting. The full Pugh's Matrix for the rake concepts can be seen below, in **Table 6**.

TABLE 6 - PUGH'S MATRIX FOR THE RAKE CONCEPTS

| Criteria | Weighting | Concept | | | | | |
|---|---|---|---|---|---|---|---|
| | | Linear | | Rotary | | Deposit | |
| | | Score | *Weighted* | Score | *Weighted* | Score | *Weighted* |
| *Reducing Initial Powder* | 5 | 2 | 10 | 2 | 10 | 1 | 5 |
| *Maintenance* | 4 | -0.5 | -2 | -0.5 | -2 | 0 | 0 |
| *Accuracy of Spreading* | 4 | 0 | 0 | 0 | 0 | -1 | -4 |
| *Ease of Manufacture* | 3 | -1 | -3 | -1 | -3 | -1 | -3 |
| *Ease of Installation* | 3 | 0 | 0 | -0.5 | -1.5 | 0 | 0 |
| *Simplicity* | 3 | -1 | -3 | -1 | -3 | -1 | -3 |
| *Cost* | 2 | -1 | -2 | -1 | -2 | -1 | -2 |
| *Rate of Spreading* | 1 | 1 | 1 | -1 | -1 | -1 | -1 |
| TOTAL | - | - | **1** | - | **-2.5** | - | **-8** |

According to this matrix, it can be determined that the linear motion concept is the most promising, with the rotary motion closely behind, and the deposit concept quite far behind. Therefore, when considering which prototypes to further develop, it is easiest to think about which concept we should not further develop; being the deposit rake.

The Pugh's Matrix had to be slightly altered when used again for the 'chamber' concepts. This time, the criteria were: Reducing Initial Powder, Maintenance, Ease of Manufacture, Ease of Installation, Simplicity, and Cost. With the same method applied as was done for the rake concepts, the results are shown in **Table 7**.

TABLE 7 - PUGH'S MATRIX FOR THE CHAMBER CONCEPTS

| Criteria | Weighting | Concept | | | |
|---|---|---|---|---|---|
| | | Support from Top | | Support from Bottom | |
| | | Score | Weighted | Score | Weighted |
| ***Reducing Initial Powder*** | 5 | 2 | 10 | 2 | 10 |
| ***Maintenance*** | 4 | -0.5 | -2 | -0.5 | -2 |
| ***Ease of Manufacture*** | 3 | -1 | -3 | 0 | 0 |
| ***Ease of Installation*** | 3 | 0 | 0 | -1 | -3 |
| ***Simplicity*** | 3 | -1 | -3 | -1 | -3 |
| ***Cost*** | 2 | -1 | -2 | -1 | -2 |
| TOTAL | - | - | **0** | - | **0** |

According to this matrix, the two concepts for the chamber are equally as promising. It is therefore necessary to compare the two concepts with an additional method in order to come to a more beneficial conclusion.

## B. CONCEPT SELECTION – 1 TO 5 SCALE

The previous concept selection method had led a tie between the initial chamber ideas (support from the top, and support from the bottom). As Pugh's had given these the same score, another method was needed to compare the concepts. This led to implementing the "1 to 5 scale" as an alternative method.

The 1 to 5 scale was used as following;

- Criteria was selected and weighted in order of importance. For continuity, the criteria and weightings were the same as what was used in Pugh's Matrix.

- The concepts were then ranked from 1 to 5, with;
    - 1 being **very poor**
    - 2 being **poor**
    - 3 being **average**
    - 4 being **good**
    - 5 being **very good**

These concepts were ranked individually, unlike Pugh's which made use of a datum. Having initially decided to rank only the chamber concepts, it was later decided to also rank the rake concepts using this method to validate the results from earlier. These results are in **Table 8 & 9**.

TABLE 8 – 1 TO 5 SCALE FOR THE RAKE CONCEPTS

| Criteria | Weighting | Concept | | | | | |
|---|---|---|---|---|---|---|---|
| | | Linear | | Rotary | | Hopper Rake | |
| | | Score | Weighted | Score | Weighted | Score | Weighted |
| ***Reducing Initial Powder*** | 5 | 4 | 20 | 4 | 20 | 3 | 15 |
| ***Maintenance*** | 4 | 3 | 12 | 4 | 16 | 2 | 8 |
| ***Accuracy of Spreading*** | 4 | 4 | 16 | 3 | 12 | 2 | 8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Ease of Manufacture* | 3 | 3 | 9 | 3 | 9 | 2 | 6 |
| *Ease of Installation* | 3 | 3 | 9 | 2 | 6 | 2 | 6 |
| *Simplicity* | 3 | 3 | 9 | 3 | 9 | 2 | 6 |
| *Cost* | 2 | 3 | 6 | 3 | 6 | 2 | 4 |
| *Rate of Spreading* | 1 | 4 | 4 | 3 | 3 | 2 | 2 |
| *TOTAL* | - | - | 85 | - | 81 | - | 55 |

TABLE 9 – 1 TO 5 SCALE FOR THE CHAMBER CONCEPTS

| Criteria | Weighting | Concept | | | |
|---|---|---|---|---|---|
| | | **Support from top** | | **Support from bottom** | |
| | | **Score** | **Weighted** | **Score** | **Weighted** |
| *Reducing Initial Powder* | 5 | 4 | 20 | 4 | 20 |
| *Maintenance* | 4 | 3 | 12 | 3 | 12 |
| *Ease of Manufacture* | 3 | 4 | 12 | 4 | 12 |
| *Ease of Installation* | 3 | 4 | 12 | 4 | 12 |
| *Simplicity* | 3 | 3 | 9 | 3 | 9 |
| *Cost* | 2 | 3 | 6 | 2 | 4 |
| *TOTAL* | - | - | **71** | - | **69** |

After carrying out the “1 to 5 scale” selection method, the following conclusions were drawn;

1. The results obtained using Pugh’s Matrix was consistent with the results here, and as a result the linear motion concept should be the one taken forward.

2. Again, the two chamber concepts were very close to each other on most criteria; however, supporting from the top was slightly cheaper (as there was no need for the extra material). As a result, it was decided to proceed with supporting from the top.

At the end of the concept selection process, the following decisions had been made;

- **Linear** for the rake
- **Support from the top** for the chamber

# 9. INITIAL PROTOTYPES

Two stages of prototyping were conducted throughout the project, with the following objective;

1st stage: Assist in the final concept selection

2nd stage: Testing of final design

In order to further justify our selection for the final rake concept, a basic cardboard prototype was made for both linear and rotary rake concepts. They were then tested with sugar granules and judged based on the following criteria:

- Distribution of powder
- Ease to manufacture and assemble
- Ease of installation

FIGURE 23 – INITIAL LINEAR RAKE PROTOTYPE

The linear rake prototype consists of three components, a bended rectangular box, an intermediary plate, and a protruded piece for user to hold on as shown in figure 3. When tested, an even distribution of powder was produced. It was also predicted to be relatively simple to manufacture as the geometry and fixings are not complex. Metal sheets and extrusions could be used, with basic machining done in house. The favoured linear motion mechanism also means that it could be directly connected to the current rake's connecting point.

FIGURE 24 – INITIAL ROTARY RAKE CONCEPT

Meanwhile, the rotary rake prototype was made of a single arc as shown in figure 4. The powder granules distribute as evenly as the previous prototype, and it was observed that the powder does not tend to accumulate towards the outer ring as it was suspected. Depending on the size of the start plate, the angle of rotation should revolve around 90º to 180º. In term of manufacturing, the main issue would be in finding suitable gear to translate the motion from linear into rotary. It would not be as simple to be installed and assembled as it is not installed directly to the current rake connecting point.

# 10. ITERATIONS OF DESIGN

## A. RAKE – 1ST ITERATION

The linear rake concept as shown in **Figure 25** was further explored to translate it into a CAD model. **Figure 25** illustrates the concept in detail. Most fixing on the plates was decided to be done using screws, while slots would be used to fix the front and intermediary plates. This allows it to be assembled easily, apart from adjustable between two fixed sizes. The slots also ensure the base of the 4 sides is at level as the plates' position could be adjusted vertically. A pair of brush-like, rake blades would be fixed on each of the side plates to ensure even spreading. The pair would be hooked onto a metal blade to secure it in place, before fixed into the under-slot of the side plates.

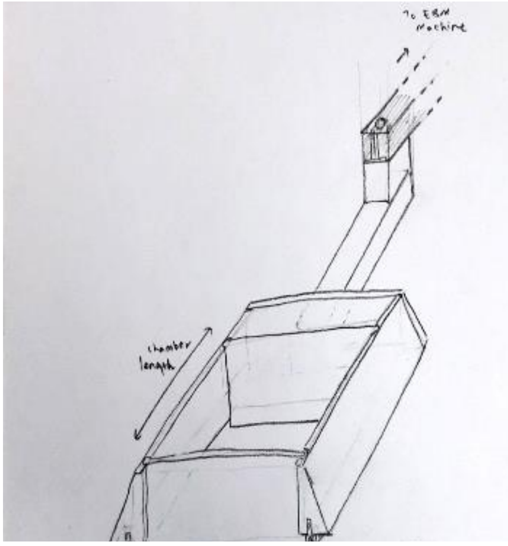



FIGURE 25 – 1ST ITERATION OF RAKE ISOMETRIC DRAWING

However, it was observed that powder may escape through the slot corners and it is possible to further simplify the design by eliminating the intermediary plate. There is also the need to further reduce the rake's mass, and the adjustable rake size function could be dropped as it is not listed in the top priority specifications.

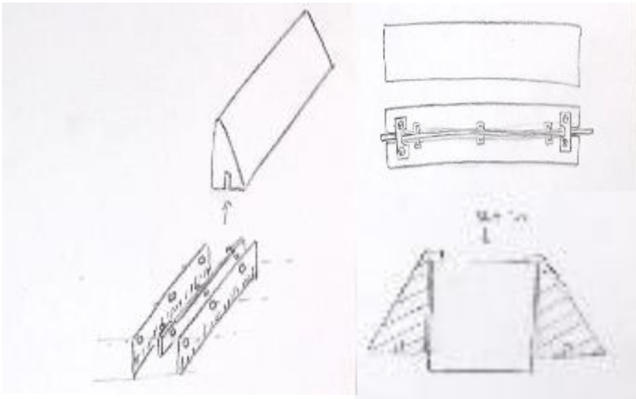


FIGURE 26 – DETAILED DRAWING OF 1ST ITERATION OF RAKE

The rake size was designed in reference to the standard Arcam A1 rake dimensions. The rake properties were calculated as follows;

$$Cake\ powder\ volume, cm^3 = chamber\ size * part\ height = 8 * 8 * 7 = 128$$

$$Rake\ max\ capacity, cm^3 = (height + clearance) * length * width = (4 + 1.2) * 10 * 8.4 = 436.8$$

Thus by taking safety factor of 2 for the rake efficiency;

$$Fill\ percentage = \frac{128*2}{436.8} * 100 = 58.6\%$$

In the case of testing Super Alloy Inconel 625 with density 8.44 g/cm$^3$, 2.16kg of powder would be required, which is within our specifications requirement.

## B. RAKE – 2ND ITERATION

Since the first iteration of the rake had some room for improvement, the following improvements were made. Firstly, the client decided that they wanted all the parts to be fixed in position while the EBM machine was in operation in order to ensure rigidity. Therefore, the two sides of the rake that were slotted in position were changed to be screwed into place.

Secondly, to simplify the rake, the intermediary plate between the rake and the powder compartment was eliminated, decreasing the number of parts and weight of the rake, whilst also reducing effort to manufacture.

Thirdly, to further reduce the weight of the rake, the parts were made thinner. Also, the slanted, triangular-like brush holders were changed to be flat faced, thus saving even more weight. This was possible because since our design was drastically reducing the amount of powder required, there would no longer be a need for a slanted brush face to plough the powder out of the way.

Fourthly, since it was desired for all the parts to be fixed while the machine is in use, yet also desired that between uses the user could adjust the clearance of the brush, the connecting beam was changed to be fixed by using slotted screw holes as opposed to standard screw holes. This allows the rake to be translated vertically ±5mm.

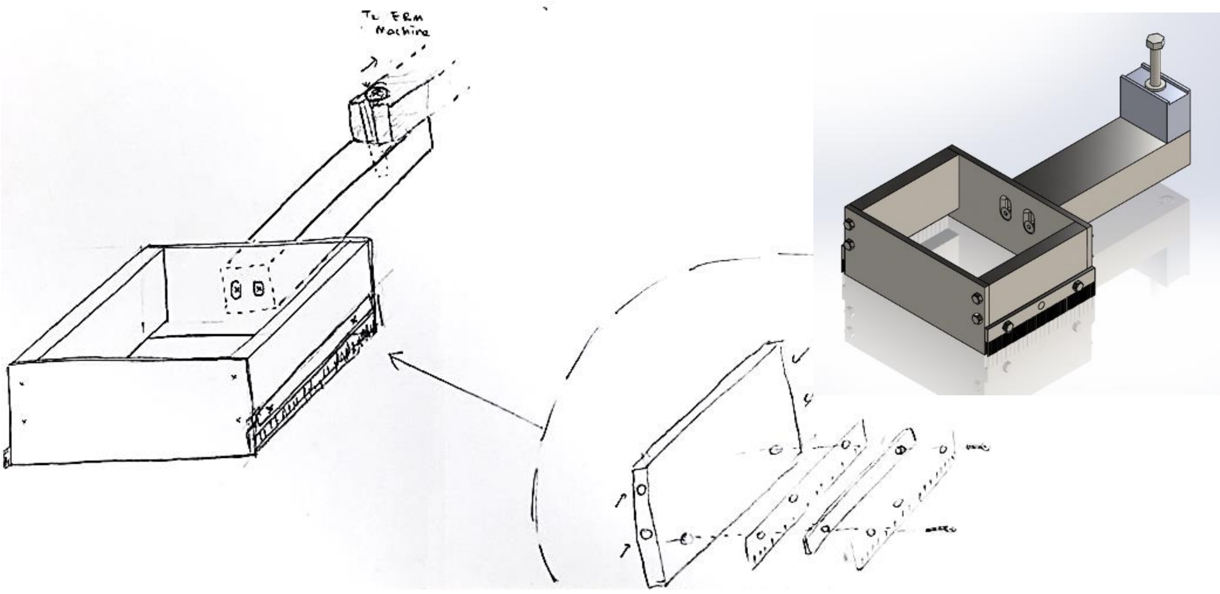


FIGURE 27 – 2ND ITERATION OF RAKE CONCEPT

## C. TABLE TOP – ITERATION 1

The first iteration of the table top design differed slightly from the initial concept. It was discovered that the table top currently attached to the build tank inside the machine could be removed and replaced with this design – meaning that the table top could now be screwed directly to the build tank using the same holes that were used at the time.

The first design modelled on SolidWorks combined the shape and fixings of the old table top with the features that the new build table needed to have. The only major differences when compared to the old table top were;

- The hole in the centre was now 80 x 80mm
- The thickness of the metal sheet was reduced from 4mm to 3mm, to save on weight. As the hole in the centre was smaller, this meant that weight reduction had to come from this.
- There were holes cut into the angled side pieces – again, to save weight.

An image of this first iteration is shown in **Figure 28**.

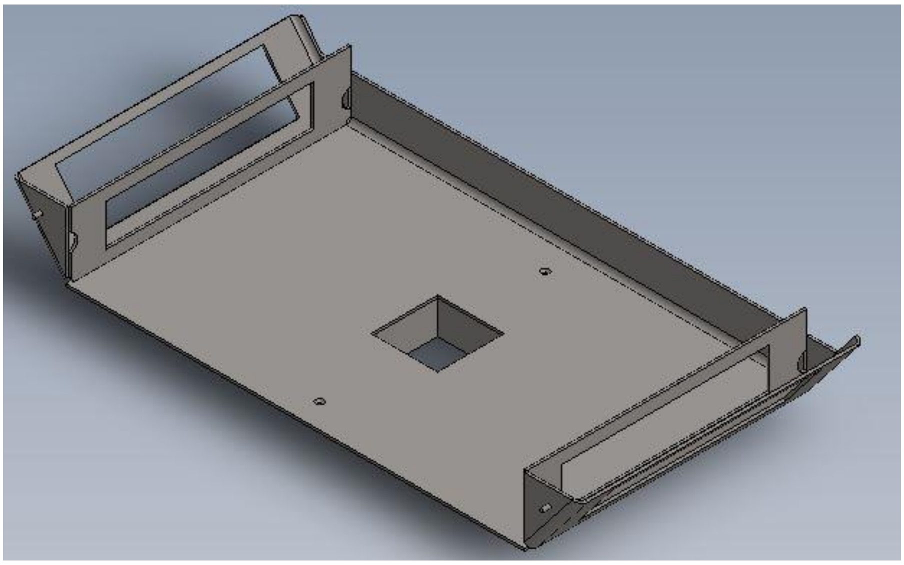


FIGURE 28 – 1ST ITERATION OF TABLE TOP

## D. TABLE TOP – ITERATION 2

After a meeting with the client, who identified several things that he didn't like in the design, a new design was agreed in principle. This simplified the first design into three main parts, and made the overall product cheaper and easier to manufacture.

The main differences between the first iteration and this were;

- The angled side pieces were removed from the design. For the table top already in the machine, the side pieces allowed powder from the hopper to make it to the flat part, before being spread by the rake. As all of the powder would now already be on the flat part of the table top, this part was not required. Removing this made the design simpler, cheaper and lighter.

- The side pieces were now curved, to allow the screws that the front guard would eventually attach onto to be supported. In the first design, these were attached via curved metal that was connected to the now removed angled section.

- The back flange was raised, in order to make the final design look neater, as well as giving more contact surfaces for the weld to be placed.

This new design (which turned out to be the final design) is shown in **Figure 29**.

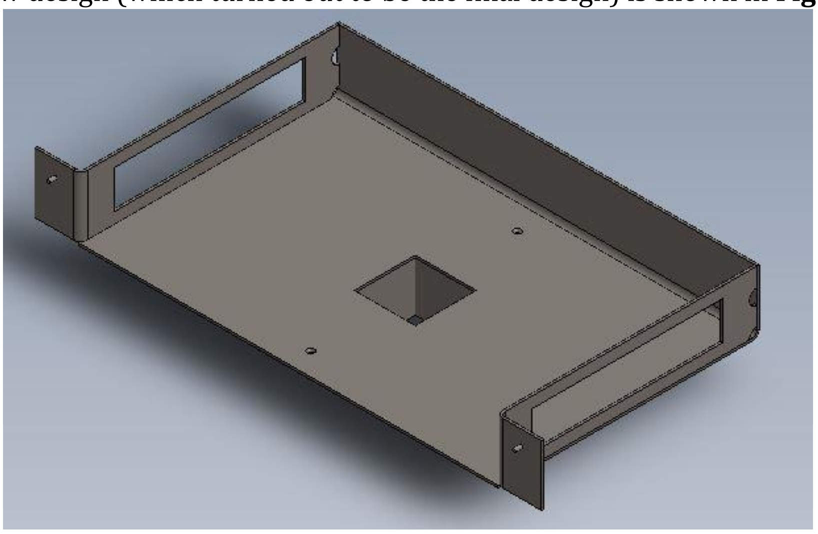


FIGURE 29 – 2ND ITERATION OF TABLE TOP

Changes to individual parts can be seen in the CAD files that are supplied with this report.

## E. BUILD TABLE – ITERATION 1

During the concept stage, the design of the table top and build table had always been considered as one part. However, as more information about what the build table had to contain was received, it was decided to separate this out into a separate section.

The new build table in the concept stage was placed on top of a "rod" that separated the new and old build tables. For the first iteration of CAD, this was tweaked slightly; the amount that the build table was level needed to be adjustable in-case the original build table was not level. It was also needed that the new build table was fixed.

The solution was to design redesign the existing build table. This build table (250 x 250mm in size), instead of being a solid plate, now had three holes in it. These holes contained "rivet – style inserts" – a threaded insert that could be securely fixed into the plate. From here, three bolts with a flat head were then screwed into these inserts, and it was these screws that were used to adjust the level of the new build table at the top (currently 76 x 76mm in size). Although the current system had four contact points for stability, calculations showed that for the build plate to be statically determinate, only three contact points were required (hence the three screws). A quick experiment (i.e. putting a plate on a surface with three contact points, then with four) proved that the calculations were correct.

For all this design, the objective to have the build table fixed in position was not met. In the end, it was decided that it was not important to include this for the following reasons;

- The build table currently in the machine was not fixed
- There was no way of balancing the build table using the screw method that allowed the build table to be fixed. The screw method was kept as it was the simplest way of adjusting height.
- Locking mechanisms that didn't involve screws would overcomplicate the design.
- Locking mechanism that did involve screws would not have enough access once a part had been built on the build table, and it was covered in powder.

The initial SolidWorks design is shown in **Figure 30**.

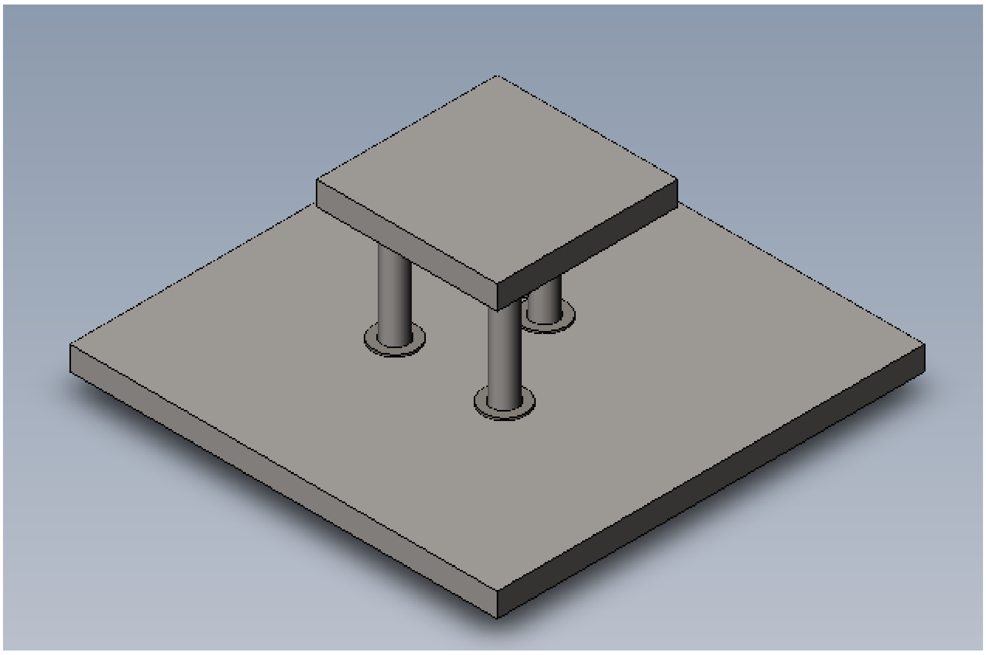


FIGURE 30 – 1ST ITERATION OF BUILD TABLE

## F. BUILD TABLE – ITERATION 2

For the second iteration of the build table, several things were changed. One was the method of ensuring that the 74 x 74mm new start plate was level. In the first iteration, the method used was three screws placed in a triangular formation; for the second however, while this method was still used, a second method used a bed of powder 30mm thick was placed on what would have been the original build table. This meant that there would be two possible configurations. In the first configuration, there was a small clearance between the build table and the build chamber. To solve this, the second configuration had a rope that as a seal between the two. As a result of this, the design of the bottom section was changed to two plates that screwed together, securing the rope in place. Finally, the design was fixed directly to the pistons to the bottom of the build tank. This was to get the optimum movement available, as well as making sure that the piece had no degrees of freedom. This is shown **Figure 31**.

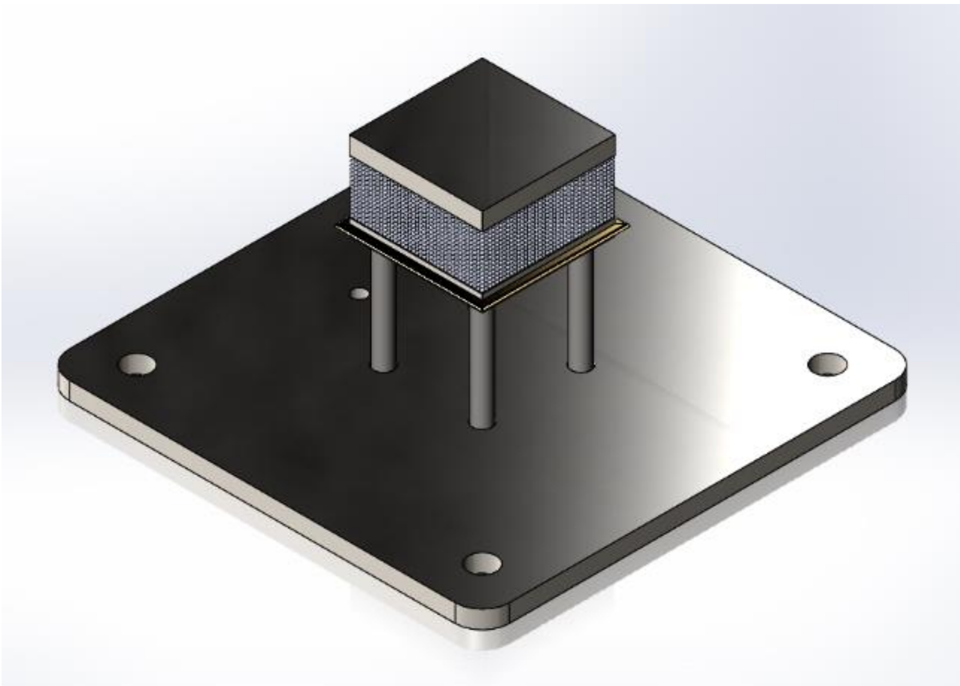


FIGURE 31 – 2ND ITERATION OF THE TABLE TOP

# 11. VALIDATION

## A. STRENGTH

Strength was not an issue for this project. This is because all of our parts were designed to be made out of steel, and the product will only be used to move roughly 2kg of alloy powder (plus the weight of the rake itself). However, just to ensure that this assumption is correct a brief beam analysis has been carried out, using the worst case scenario. This would be considered the beam that connects the rake to the machine, as demonstrated by the red circle shown in **Figure 32**.

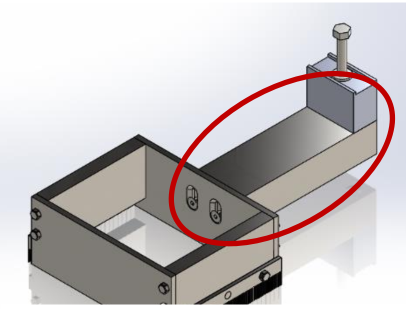


FIGURE 32 – SHOWING CONNECTING BEAM

Calculating it as a simply supported cantilever beam, with a simplified point force at the very end of the beam, using **Equation 1** [39].

$$\sigma = \frac{My}{I_x}$$ **Equation 1**

Where:
$\sigma$ = Bending stress ($Nm^{-2}$)
$M$ = Moment about neutral axis (Nm)
y = Perpendicular distance to the neutral axis (m)
$I_x$ = Area moment of inertia ($m^4$)

Firstly, substituting the moment equation for a cantilever beam, **Equation 2** below [40], into the bending stress equation:

$$M = Fl$$ **Equation 2**

Where:
$M$ = Moment about neutral axis (Nm)
$F$ = Force (N)
$l$ = Length of beam (m)

It is also necessary to calculate the second moment of area ($I_x$), using **Equation 3** [41].

$$I_x = \frac{bd^3}{12} \qquad \textbf{Equation 3}$$

Where:

| | | |
|---|---|---|
| $I_x$ | = | Area moment of inertia (m$^4$) |
| $b$ | = | Width (m) |
| $d$ | = | Height (m) |

The following rearranged equation can be obtained:

$$F = \frac{\sigma b d^3}{12ly} \qquad \textbf{Equation 4}$$

To calculate the maximum force this beam can withstand ($F$), $\sigma$ will be substituted with the yield stress of stainless steel 304 ($\sigma_y$), which is 215MPa [42]. Then, using the geometrical data of the beam, we get **Equation 5**.

$$F = \frac{215\times10^6\times0.04\times0.025^3}{12\times0.124\times0.0125} = 7224N \qquad \textbf{Equation 5}$$

Since the rake itself weighs 1.7kg in our design, moving at most 2kg of alloy powder, the beam must support 3.7kg (~36N). Compared to the beam's yield strength of 7224N, this means that there is a safety factor of 200. With a safety factor that immense, this proves that the initial assumption that strength in this project is not an issue was correct.

## B. THERMAL VALIDATION

In terms of a thermal validation, all the parts are designed to be made out of either stainless steel 304, or to use the current parts being used within the EBM machine. Since the maximum temperature in the EBM machine is 720˚C, and stainless steel 304 has a maximum service temperature of 870˚C [43], it can be assured that there will be no thermal issues.

## C. FINAL PROTOTYPE & TESTING

Once the detailed design and CAD model were completed, the team concluded that the best way to validate the product's functionality was to prototype and test it. For the final prototype the team laser cut from acrylic as many parts as possible. The rest of the parts were made by hand using various types of MDF wood fibres.

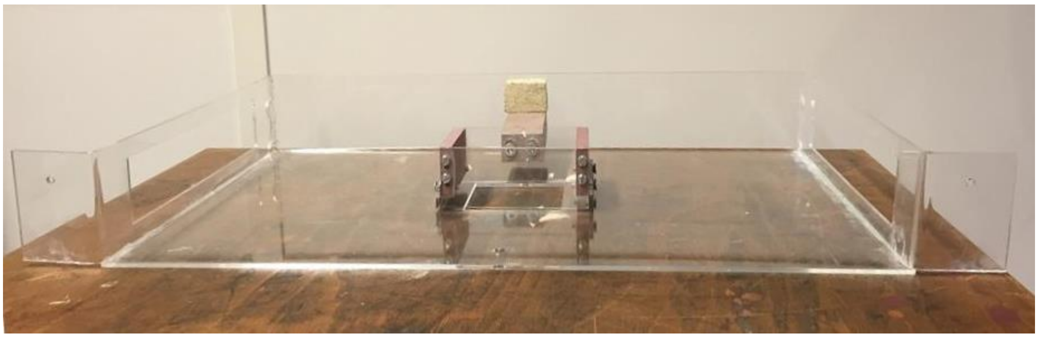


FIGURE 33 – FINAL PROTOTYPE

First, the spreading capabilities of the rake were tested, as shown in **Figure 34**.

FIGURE 34 – TESTING SPREADING CAPABILITIES

The test showed that the rake performs satisfactorily, for spreading the powder evenly, and was approved by the client. This is even despite that the prototype had several parts produced by hand, meaning it is significantly less accurate than the real, machined version will be.

FIGURE 35 – POWDER RETAINING SHAPE

The test also taught us more about the behaviour of the powder when it is within the rake container. As shown in **Figure 35**, it is clear that the powder retains its shape while the rake is subjected to translational motion, as the powder moves with the rake. This is good because there were concerns that the powder may remain in the same location relative to the platform, thus causing the powder to build up on one side of the rake container and overflow. However, since the actual powders that will be used will vary and do not have the exact same properties as this powder, the same result cannot be guaranteed for all the powder types.

Later, it was also tested to see if the rake could operate on the build platform, and deposit the powder in the build table hole. This is shown in **Figure 36**.

**Figure 36 –** Testing Prototype on Platform

This test was deemed a success, as the powder perfectly filled the build table hole, with a maximum imperfection in the layer spread of less than half a millimetre, as shown in **Figure 37**.

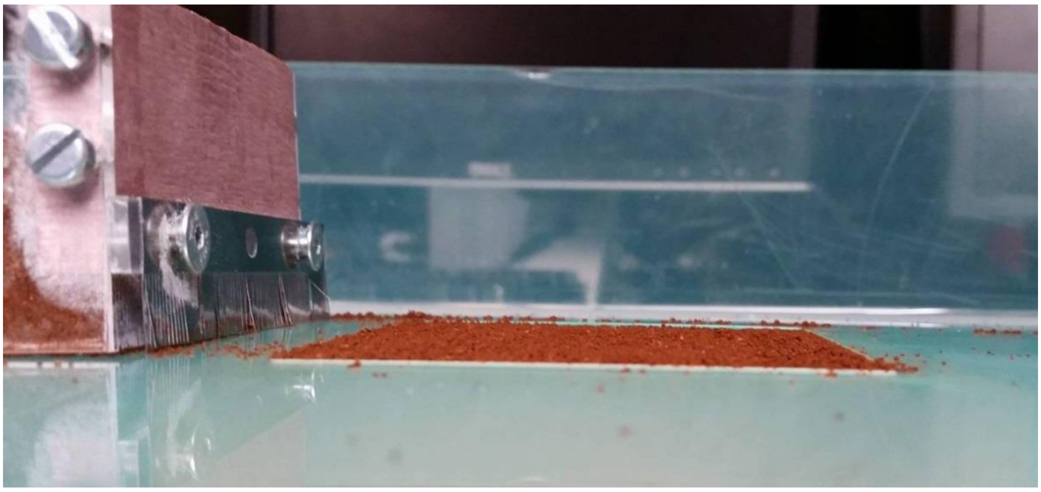


FIGURE 37 – DEMONSTRATING LAYER SPREADING ACCURACY

# 12. COSTING

After several attempts to contact local and international suppliers without , we had to find another way for estimating a cost for our product. Luckily, SolidWorks came with an inbuilt coster base don material and manufacturing prices.

## A. RAKE

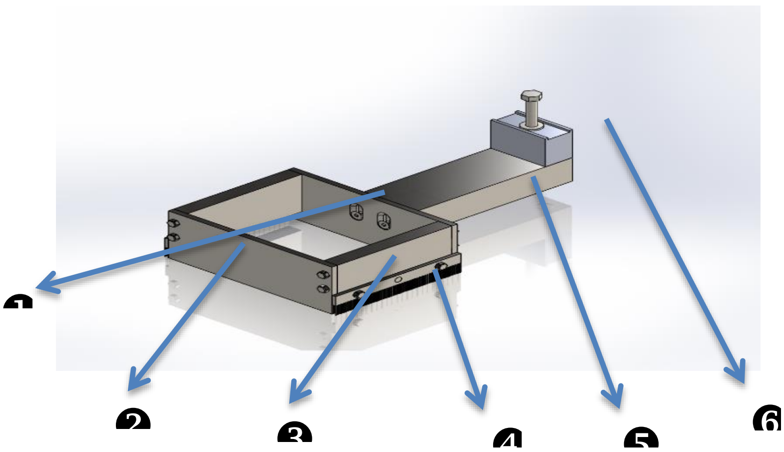



FIGURE 38 – PART BREAKDOWN OF THE RAKE

TABLE 10 – COST OF RAKE

| REFERENCE | COMPONENT | COST (€) |
|---|---|---|
| **1** | BACK SIDE | 11.88 |
| **2** | FRONT SIDE | 11.77 |
| **3** | RAKE SIDE | 12.19 |
| **4** | BLADE HOLDER | 10.18 |

| | | |
|---|---|---|
| **5** | SHAFT 1 | 51.57 |
| **6** | SHAFT 2 | 51.28 |
| | TOTAL | 148.89 |

## B. TABLE-TOP

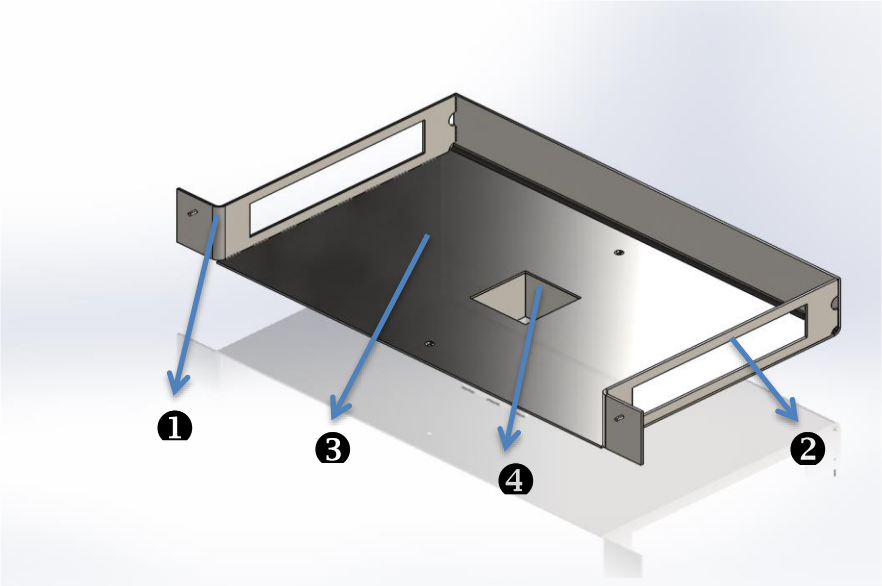



TABLE 11 – COST OF TABLE TOP

| REFERENCE | COMPONENT | COST (€) |
|---|---|---|
| 1 | **Left side** | **31.53** |
| 2 | **Right side** | **31.53** |
| 3 | **Base** | **120.60** |
| 4 | **Build tank** | **7.83** |
| | **TOTAL** | **191.49** |

## C. BUILD TABLE

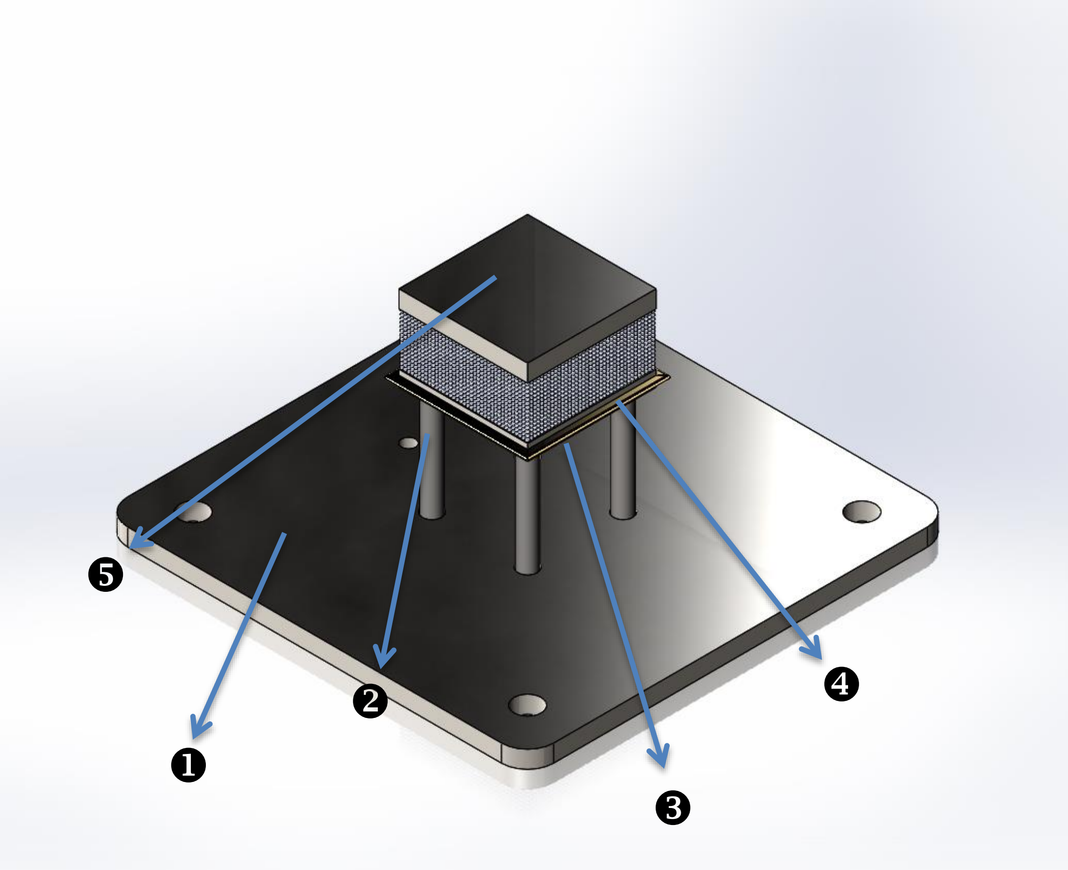



FIGURE 40 – PART BREAKDOWN OF BUILD TABLE

TABLE 12 – COST OF BUILD TABLE

| REFERENCE | COMPONENT | COST (€) |
|---|---|---|
| 1 | **BASE PLATE** | **41.13** |
| 2 | **HOLDING COLUMN** | **59.64** |
| 3 | **ROPE CONTAINER (BOT)** | **20.51** |
| 4 | **ROPE CONTAINER (TOP)** | **20.29** |
| 5 | **START PLATE** | **20.39** |
| | **TOTAL** | **161.96** |

As we can see the total budget totals at 502.34€ (we shall add some costs based on transport and assembly) which is perfectly within our specifications.

We have a limited budget of 10,000€, which didn't limit our expectations in terms of quality and precision.

# 13. PROJECT PLANNING

There are five project processes as outlined by the Project Management Body of Knowledge, PMBOK [44]; initiating, planning, executing, controlling and closing. These processes, especially planning are necessary in obtaining a successful project. The PMBOK were constantly reviewed and acts as a guideline to design Gantt chart and during risk assessment.

## A. GANTT CHART

Gantt chart was used during the project planning. It does not only act as an effective presentation tool to ease understanding on the project structure, but also to convey planning and scheduling precisely. It is a good communication tool between team members, client and the supervisor. The project structure was first understood in order to structure the project timeline and eventually to create the Gantt Charts. It consists of 4 phases, 5 stages and 3 tasks, as shown in **Figure 41**.

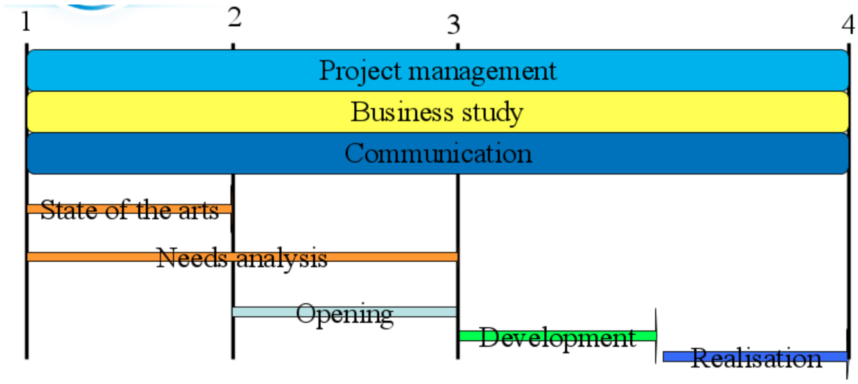



FIGURE 41 – GANTT CHART

In order to set milestones and deadlines in the project, deliverables were identified, as follow;

- State of Art report (Individually marked)
- Product specification, project planning & risk management plan
- Intermediary Defense
- Final Defense
- Final Report
- Weekly report
-

The expected finding at each stage and delivery dates were then identified and summarised in **Table 13**.

TABLE 13 - SCHEDULE

| Phase | Stage | Objective | Deliverable | Date |
|---|---|---|---|---|
| 1 | State of Art | To obtain better understanding of the project | State of Art report (Individually marked) | 10/3 |
| | Needs Analysis | Understand client's need better | Intermediary Defense | 3/5 |
| 2 | Opening | Concepts exploration | | |
| 3 | Development | Concepts development & selection | Final defense, Final report | 31/5, 13/6 |
| 4 | Realisation | Prototyping, simulation & evaluations | | |

Other important dates include:

- Meeting with Bath supervisor (Stephen Culley) - 22/3
- Meeting with Bath supervisor (Donny, Gwompo) - 31/5

Based on this knowledge, Work Breakdown Structure, WBS was then created as shown in **Figure 42**. It subdivides the stages into manageable activities, which could then be estimated, planned and assigned to a responsible team member [45]. The number of levels created was dependent on the level of details, risk and control each activity contain.

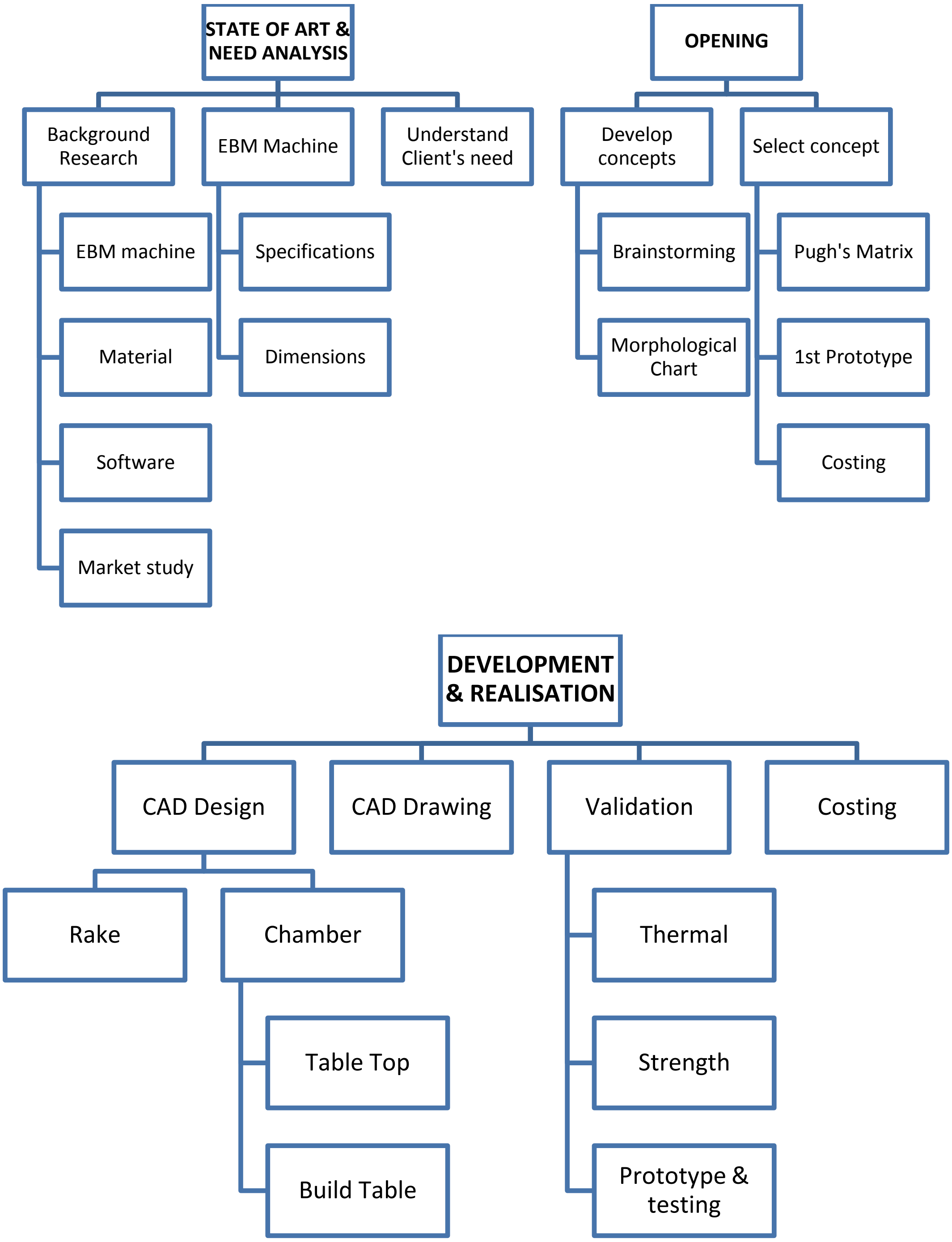
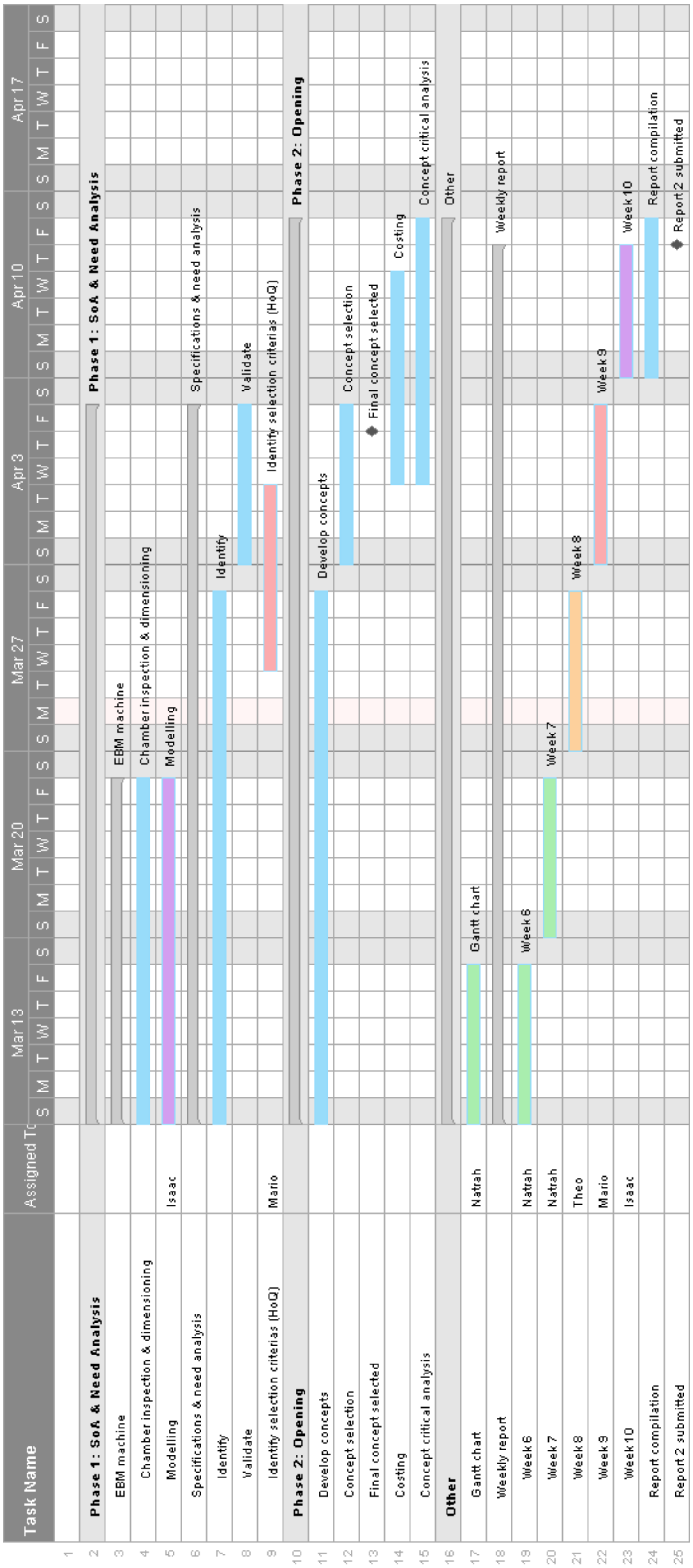
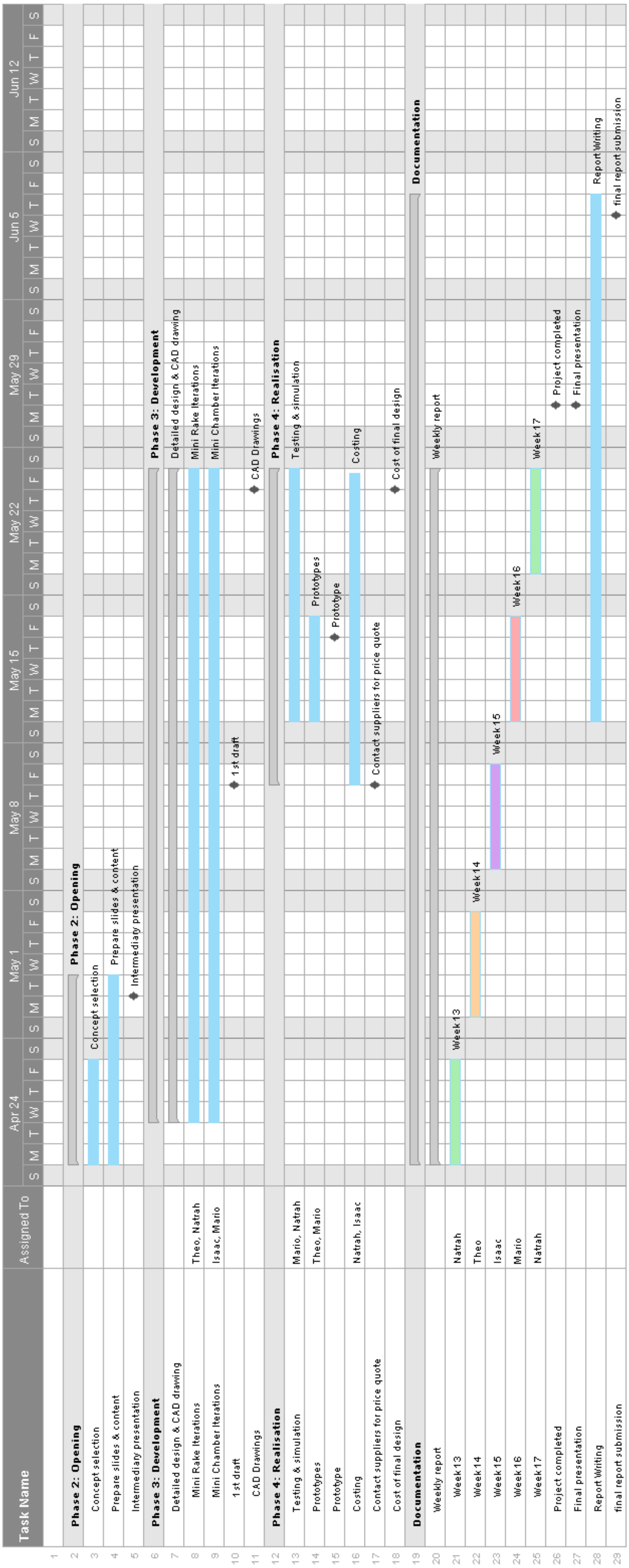



FIGURE 42 – WORK BREAKDOWN STRUCTURE

A Gantt chart was then produced by using the online project management software, Smartsheet.com as shown in **Figure 43** [46]. Milestones were events that need to occur based on project deadlines and important meetings; different colours were used to illustrate different people responsible. Both the WBS and Gantt chart are constantly updated and reviewed throughout the project to ensure it is still relevant. Some of the changes are due to:

- New discoveries which lead to expanded WBS
- Change in deliverables required at each stage
- Extended deadlines


Task Name
Assigned To
Mar 13
Mar 20
Mar 27
Apr 3
Apr 10
Apr 17
Phase 1: SoA & Need Analysis
EBM machine
Chamber inspection & dimensioning
Modelling
Isaac
Specifications & need analysis
Identify
Validate
Identify selection criterias (HoQ)
Mario
Phase 2: Opening
Develop concepts
Concept selection
Final concept selected
Costing
Concept critical analysis
Other
Gantt chart
Natrah
Weekly report
Week 6
Natrah
Week 7
Natrah
Week 8
Theo
Week 9
Mario
Week 10
Isaac
Report compilation
Report 2 submitted


Task Name
Assigned To
Apr 24
May 1
May 8
May 15
May 22
May 29
Jun 5
Jun 12
S M T W T F S
Phase 2: Opening
Concept selection
Prepare slides & content
Intermediary presentation
Phase 3: Development
Detailed design & CAD drawing
Mini Rake Iterations
Theo, Natrah
Mini Chamber Iterations
Isaac, Mario
1st draft
CAD Drawings
Phase 4: Realisation
Testing & simulation
Mario, Natrah
Prototypes
Theo, Mario
Prototype
Costing
Natrah, Isaac
Contact suppliers for price quote
Cost of final design
Documentation
Weekly report
Week 13
Natrah
Week 14
Theo
Week 15
Isaac
Week 16
Mario
Week 17
Natrah
Project completed
Final presentation
Report Writing
final report submission

The project progress was recorded in the form of weekly report (logbook), which each member took turns in writing each week. It is crucial in keeping track of the group's performance, to identify problem and solutions, and also as a mean to update the supervisor and client of the project's progress. The logbook is attached as **Appendix A**, and in summary its content include;

- Meetings with client & supervisor
- Previous week agenda
- Issues identified and possible solution
- Contribution of each member towards the project during the week
- A revision of the planning
- Next week's agenda

## B. RISK MANAGEMENT

Risk management was done to avoid losses in term of cost, quality, and to ensure deliverables could be completed on time. Potential risks were first identified based on WBS, as listed in **Table 14**. Risk priority numbers (RPNs) were then associated, to measure the risks and prioritize them accordingly [47]. It is the product of these three factors;

- Probability (P) - the likelihood for it to occurs (5 very likely, 1 remote)
- Severity (S) - how severe does it affect the project (5 hazardous, 1 none)
- Detection capability (D) - can it be detected (5 absolute uncertain, 1 almost certain)

TABLE 14 – RISK ASSESSMENT CHART

| Risk Category | Risk | P | S | D | RPN | Response category |
|---|---|---|---|---|---|---|
| **Design risk** | Design incomplete | 2 | 5 | 2 | 20 | Eliminate |
| | Inaccurate dimensions | 5 | 4 | 3 | 60 | Mitigation |
| | Inaccurate assumptions on technical issues | 4 | 4 | 4 | 64 | Mitigation |
| | Unforeseen EBM machine requirement | 3 | 4 | 4 | 48 | Mitigation |
| | Development of extra features which is not required | 2 | 2 | 3 | 12 | Mitigation |
| | Requirements are ambiguous | 3 | 3 | 3 | 27 | Mitigation |
| | Software incompatible issue | 2 | 3 | 3 | 18 | Mitigation |
| **External risk** | Delay in reply from suppliers & outside contractors | 4 | 2 | 3 | 24 | Accommodate |
| | Strikes | 2 | 1 | 4 | 8 | Accommodate |
| | PC broke down or loss of data | 3 | 5 | 5 | 75 | Eliminate |
| | Increase in cost due to market changes | 1 | 2 | 3 | 6 | Accommodate |
| **Project management risk** | Project purpose & need is not well-defines | 3 | 4 | 3 | 36 | Mitigation |
| | Project scope, schedule, objectives, cost and deliverables are not clearly defined or understood | 3 | 3 | 3 | 27 | Mitigation |
| | lack of coordination/ communication | 2 | 4 | 2 | 16 | Accommodate |
| | Delay in earlier activity which affect project timeline | 4 | 4 | 3 | 48 | Accommodate |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Unforeseen deliverables or set of data required | 3 | 3 | 4 | 36 | Mitigation |
| | Inconsistent cost, time and quality objective | 2 | 2 | 3 | 12 | Mitigation |
| | Low team motivation | 3 | 4 | 3 | 36 | Accommodate |
| | Lack of support from staff, supervisor or client | 3 | 4 | 4 | 48 | Accommodate |

It could be observed that bigger cautions should be given to the following very high RPN risks;

- inaccurate dimension
- Inaccurate assumptions on technical issues
- PC broke down or loss of data
- Unforeseen EBM machine requirement
- Delay in earlier activity which affect project timeline
- Lack of support from staff, supervisor or client

These were then responded via one of these actions;

- Eliminate: by either removing the source or plan an alternative action
- Mitigation: reduce the likelihood for it to occur
- Transfer: transfer the whole or part of it to a third party, for example through insurance or partnership
- Accommodate: accept the consequences of the risk by executing contingency plan.

## 14. CONCLUSION & FINAL PRODUCT SPECIFICATION

In conclusion, the project has been successfully conducted in four months. We came out with 3 rake concepts and 2 chambers initially, before selecting our final concepts. It was then further iterated and developed and the final product specifications are as listed in **Table 15**. The final designs were also further validated through prototyping, strength & thermal analysis. The project planning was monitored using Gantt chart and risk assessment chart. The CAD drawings are listed in **Appendix B**.

TABLE 15 – FINAL PRODUCT SPECIFICATION

| **Specification** | **Rake** | **Chamber** | |
|---|---|---|---|
| | | **Table Top** | **Build Table** |
| **Material** | AISI 304 Stainless Steel | | |
| **Diagram** | See drawing "ASM-RK-003 (3rd Iteration)" | See drawing "ASB-TT (Table Top Assembly)" | See drawing "ASM-BLD_TBL (Build Table Assembly)" |
| **Overall dimension, mm3** | 131.4 x 219.5 x 101.6 | 664 x 342 x 147 | 245 x 245 x 121 |
| **Weight, kg** | 2.14 | 7.13 | 5.69 |
| **Estimated cost per unit, €** | 150 - 160 | 190 - 200 | 160 - 170 |
| **Performance** | Max rake capacity: 436.8 $cm^3$<br><br>Fill percentage: 58.6%<br><br>Rake height adjustment: 5mm | Chamber size: 80x80x65mm<br><br>Volume of powder required: 256 $cm^3$ (sf 2) | Build zone: 50x50x20mm (15mm of thermal zone)<br><br>Start plate size: 74x74mm |

# 15. REFERENCES


1. Create It Real, 2014. 3D Printing Process [online]. Available from: http://www.createitreal.com/index.php/technology/process [accessed 19/02/2016].
2. Wikipedia, 2016. 3D printing [online]. Available from: https://en.wikipedia.org/wiki/3D_printing [accessed 21/02/2016].
3. Loughborough University, 2016. About additive manufacturing [online]. Available from: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/ [accessed 21/02/2016].
4. **HORN, T.,** NC State University. Material Development for Electron Beam Melting [online]. Available from: https://camal.ncsu.edu/wp-content/uploads/2013/10/Tim-Horn-2013CAMAL.pdf [accessed 21/02/2016].
5. **MEDINA, F.** Reducing Metal Alloy Powder Costs For Use In Powder Bed Fusion Additive Manufacturing: Improving The Economics For Production", PH.D, The University of Texas At El Paso, 2013.
6. Wikipedia, 2016.Electron Beam Additive Manufacturing [online]. Available from: https://en.wikipedia.org/wiki/Electron_beam_additive_manufacturing [accessed 23/02/2016].
7. Additively. Electron Beam Melting (EBM) [online]. Available from: https://www.additively.com/en/learn-about/electron-beam-melting#read-chain [accessed 23/02/2016].
8. **RIGO, O., ENGEL, C.** État actuel des fabrications additives pour les applications métalliques, 2013 [online]. Available from: http://www.slideshare.net/carstenengel/selective-laser-melting-versus-electron-beam-melting [accessed 23/02/2016].
9. CRP Meccanica. EBM, Electron Beam Melting [online]. Available from: http://www.crpmeccanica.com/ebm-electron-beam-melting/ [accessed 26/02/2016].
10. 3D Printer Pro. Electron Beam Melting, 3D printing and rapid prototyping services [online]. Available from: http://www.3dprinterpro.com/electron-beam-melting-service/ [accessed 26/02/2016].
11. PTR, 2016. EB Welding Glossary of Terms [online]. Available from: http://www.ptreb.com/Electron_Beam_Welding_Info/Glossary_of_Terms/ [accessed 26/02/2016].
12. Arcam, 2016. EBM Built Materials [online]. Available from: http://www.arcam.com/technology/electron-beam-melting/materials/ [accessed 02/03/2016].
13. http://sffsymposium.engr.utexas.edu/Manuscripts/2003/2003-41-Larsson.pdf
14. http://www.crpmeccanica.com/ebm-electron-beam-melting/
15. https://uu.diva-portal.org/smash/get/diva2:765202/FULLTEXT01.pdf
16. "EBM-Built Materials – way beyond average," Arcam AB, [Online]. Available: http://www.arcam.com/technology/electron-beam-melting/materials/. [Accessed 1 March 2016].
17. O. Rigo and C. Engel, "Selective Laser Melting versus Electron Beam Melting," Sirrus, 19 November 2013. [Online]. Available: http://fr.slideshare.net/carstenengel/selective-laser-melting-versus-electron-beam-melting. [Accessed 2 March 2016].
18. J. Strong and I. Bradley, "Chapter 3," in *Procedures in Experimental Physics*, Lindsay Publications, 1938.
19. M. Larsson, U. Lindhe and O. Harrysson, "Rapid Manufacturing with Electron Beam Melting (EBM) – A manufacturing revolution?," University of Texas, Austin, 2003.
20. "Creep - Strength (Mechanics) of Materials," Engineers Edge, [Online]. Available: http://www.engineersedge.com/material_science/creep.htm. [Accessed 2016 March 5].
21. "Technology Overview - Scanning Electron Microscopy," Nanoscience Instruments, Inc., [Online]. Available: http://www.nanoscience.com/products/sem/technology-overview/. [Accessed 5 March 2016].
22. "Creep Data Sheet (CDS)," National Institute for Materials Science (NIMS), [Online]. Available: http://smds.nims.go.jp/creep/index_en.html. [Accessed 6 March 2016].

23. M. Wong, "Review of papers regarding vacuum system and materials," Fermilab, 21 March 2002. [Online]. Available: http://home.fnal.gov/~mlwong/outgas_rev.htm. [Accessed 2016 March 6].
24. "More about Stainless Steel," Thomas Publishing Company, [Online]. Available: http://www.thomasnet.com/about/stainless-steel-80230204.html. [Accessed 6 March 2016].
25. "What is the difference between 304 & 316L Stainless Steel?," Holland Applied Technologies, 23 September 2013. [Online]. Available: http://hollandaptblog.com/2013/09/25/what-is-the-difference-between-304-316l-stainless-steel/. [Accessed 7 March 2016].
26. "What is Ultra High Vacuum (UHV)?," School of Biological & Chemical Sciences at Queen Mary, University of London, [Online]. Available: http://www.chem.qmul.ac.uk/surfaces/scc/scat4_1.htm. [Accessed 7 March 2016].
27. "Arcam A1 - The future in implant manufacturing," Arcam AB, [Online]. Available: http://www.arcam.com/wp-content/uploads/Arcam-A1.pdf. [Accessed 7 March 2016].
28. https://msdn.microsoft.com/en-us/library/windows/desktop/aa380369(v=vs.85).aspx
29. The 'real' learning curve, Ramy Harik
30. *Thinking ahead the Future of Additive Manufacturing – Exploring the Research Landscape*, 1st ed. paderborn: Heinz Nixdorf Institute, University of Paderborn, 2013.
31. Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM. (2016). *Electron Beam Melting - Fraunhofer IFAM*. [online] Available at: http://www.ifam.fraunhofer.de/en/Dresden/Sintered_and_Composite_Materials/electron-beam-melting.html [Accessed 4 Jun. 2016]
32. camal.ncsu.edu. (2016). *Material development for EBM*. [online] Available at: https://camal.ncsu.edu/wp-content/uploads/2013/10/Tim-Horn-2013CAMAL.pdf [Accessed 4 Jun. 2016].
33. "Home", *Ugitech.com*, 2016. [Online]. Available: http://www.ugitech.com/home/. [Accessed: 07- Mar- 2016]
34. "Aperam - About", *Aperam.com*, 2016. [Online]. Available: http://www.aperam.com/. [Accessed: 07- Mar- 2016].
35. "High performance stainless steel | Outokumpu", *Outokumpu.com*, 2016. [Online]. Available: http://www.outokumpu.com/en/Pages/default.aspx. [Accessed: 07- Mar- 2016].
36. *Alloy surcharge for direct sales from the mill*, 6th ed. Ugine Cedex, France: UGITECH, 2016.
37. *Supplying new machinery*, 1st ed. UK: Health and Safety Executive, 2011.
38. "Pugh Matrix," iSixSigma, [Online]. Available: https://www.isixsigma.com/dictionary/pugh-matrix/. [Accessed 8 June 2016].
39. Gere, J. M. and Timoshenko, S.P., 1997, Mechanics of Materials, PWS Publishing Company
40. A. W. Council, "Beam Design Formulas with Shear & Moment Diagrams," 2007. [Online]. Available: http://www.awc.org/pdf/codes-standards/publications/design-aids/AWC-DA6-BeamFormulas-0710.pdf. [Accessed 7 June 2016]
41. "Area Moment of Inertia," The Engineering ToolBox, [Online]. Available: http://www.engineeringtoolbox.com/area-moment-inertia-d_1328.html. [Accessed 8 June 2016].
42. "AISI Type 304 Stainless Steel," ASM Aerospace Specification Metals Inc., [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MQ304A. [Accessed 8 June 2016].
43. "Maximum service temperatures in air for stainless steels," British Stainless Steel Association, [Online]. Available: http://www.bssa.org.uk/topics.php?article=42. [Accessed 8 June 2016].
44. Project management Institute (PMI)., Guide to the Project Management Body of Knowledge (PMBOK), 1995
45. Burke, R. (1999). Project management. Chichester, England: J. Wiley.
46. Smartsheet. (2016). Online Project Management Software | Smartsheet. [online] Available at: https://www.smartsheet.com [Accessed 1 Jun. 2016].
47. Lewis, J. (1995). Project planning, scheduling & control. Chicago, Ill.: Irwin.

# APPENDIX

## APPENDIX A - WEEKLY REPORTS

### Week 2

- Client meeting: Client is Guilhelm Martin. Met on INP campus at 17:00, 9th Feb
- French test 10th Feb
- Research on EBM technology
- State of Art report discussion. Split topics into:
    - Theo – Materials
    - Isaac – EBM technology
    - Natrah – Local study
    - Mario - Software

Prepared by,

Theo Prins

### Week 3

- Research on EBM technology
- First contact with providers
- Research on different software (planning/modeling/simulating)
- Studying materials

### Next week plan

- Measure the chamber
- Deliver report

Prepared by,
Mario Vico

### Week 7

| Date | Activity |
|---|---|
| Mon, 14/3 | - Discussion & planning<br>- Set up group rules |
| Tues, 15/3 | Dimensioning & 3D modelling of EBM machine |
| Wed, 16/3 | - Brainstorming with the aid of 3-4-5 idea generation method<br>- Each member were required to prepare at least 3 ideas/ concepts before the discussion session |
| Thurs, 17/3 | - Individual research & concepts generation |
| Fri, 18/3 | Brainstorming |

Questions to be clarified includes (from brainstorming sessions):

- Size/ shape of the original build table? - assumed to be square
- How does the MiniVat installed into the system?
- How MiniRake attached?
- Any 'rubbery' material which can withstand high temperature?

### Next week's plan

Developing concepts & finalise specifications

Prepared by,
Natrah Aziz

## Week 8

Mon 21-Fri 25 March

| Date | Activity |
|---|---|
| Mon, 21/3 | - Individual work and research |
| Tues, 22/3 | - Meeting with Bath supervisor: Stephen Culley<br>- Dimensioning & inspection of EBM machine |
| Wed, 23/3 | - Concept generation |
| Thurs, 24/3 | - Individual research & concepts generation |
| Fri, 25/3 | (Good Friday) |

## Next week's plan

Further develop concepts & finalise specifications

Prepared by,
Natrah Aziz

## Week 9

Mon 28th Mar -Fri 1st Apr

| Date | Activity |
|---|---|
| Mon, 28/3 | - Refinement of the specifications list |
| Tues, 29/3 | - Concept development (in particular for how to attach small chamber) |
| Wed, 30/3 | - Scheduling for rest of term before April break and 2nd report due<br>- Allocation of work to members of group |
| Thurs, 31/3 | (Strike) |
| Fri, 1/4 | - Neat drawings of concepts, to be included in 2nd report<br>- Concept development in terms of functions and the usage of morphological chart |

## Next week's plan

Finish concepts, and choose which concept to take forward, or how to combine multiple concepts. This will be achieved by using Pugh's matrix and morphological charts.

Prepared by,
Theo Prins

## Week 10
Mon 4th Apr -Fri 8th Apr

| Date | Activity |
|---|---|
| Mon, 4/4 | • Further concept development and evaluation (mainly discussions of how each concept would be manufactured) |
| Tues, 5/4 | • Again, discussions into how each concept would be manufactured |
| Wed, 6/4 | • Improving the concepts via the feedback gathered from the group discussions on Monday and Tuesday |
| Thurs, 7/4 | • Further concept improvements, and the beginning of creating Pugh's Matrix to determine which concept will be used in the end. |
| Fri, 8/4 | • Using Pugh's Matrix to pick a concept for both parts of the design, and discussion of the results to ensure that the right decision was made. |

## Next week's plan
Prepared by,
Isaac Anderson

## Week 11

| Date | Activity |
|---|---|
| Mon, 11/4 | - Finish definitive concepts |
| Tues, 12/4 | - Discussion about the different concepts |
| Wed, 13/4 | - Prototyping |
| Thurs, 14/4 | - Critically discuss strengths and weaknesses of each concept (comparing concepts) |
| Fri, 15/4 | - Individual research |

## Next week's plan
Holidays

Prepared by,
Mario Vico

## Week 13

| Date | Activity |
|---|---|
| Mon, 25/4 | - Individual research |
| Tues, 26/4 | - Supervisor meeting |
| Wed, 27/4 | - Discussion & concept evaluation based on inputs from supervisor |
| Thurs, 28/4 | - Concepts exploration |

| | |
|---|---|
| Fri, 29/4 | - Discussion on project planning |

## Next week's plan
Preparation for intermediary presentation, translation of concepts into CAD drawing

Prepared by,
Natrah Aziz

## Week 14

| Date | Activity |
|---|---|
| Mon, 2/5 | - Preparation for interim presentation |
| Tues, 3/5 | - Presentation |
| Wed, 4/5 | - Measurement of parts; discussion with client |
| Thurs, 5/5 | - University holiday |
| Fri, 6/5 | - University holiday |

## Next week's plan
Finish CAD models
Clarify progress with supervisor

Prepared by,
Theo Prins

## Week 15

| Date | Activity |
|---|---|
| Mon, 9/5 | - Discussion about different arrangements |
| Tues, 10/5 | - Measurement of parts |
| Wed, 11/5 | - CAD modelling |
| Thurs, 12/5 | - Start manufacturing |
| Fri, 13/5 | - Discussion about bottom of chamber and prototyping |

## Next week's plan
Finish prototyping
Clarify progress with supervisor

Prepared by,
Mario Vico

### Week 16

| Date | Activity |
|---|---|
| Mon, 16/5 | - Holidays |
| Tues, 17/5 | - CAD modelling |
| Wed, 18/5 | - Manufacture and improve solutions |
| Thurs, 19/5 | - Prototyping |
| Fri, 20/5 | - Discuss about the current prototype |

### Next week's plan

Prepare presentation
2nd iteration of prototype

Prepared by,
Mario Vico

## APPENDIX B - CAD DRAWINGS

**(A3 CAD DRAWINGS ATTACHED ON NEXT PAGES)**