



Aalto University
School of Engineering

Nurul Anwar

Emerging tools in casting technology and future of Aalto ENG foundry

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Supervisor: Professor Juhani Orkas

Advisor: Kalle Jalava

Tekijä Nurul Anwar

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This work starts with a literary study of comparison between casting and metal additive manufacturing. After wards, it discusses the emerging tools of casting technology which are becoming popular, many of which are possible through different additive manufacturing technologies. At the end, recommendations are given as to which of these tools could be implemented at Aalto Engineering foundry lab.

Avainsanat Casting, additive manufacturing, rapid tooling, Aalto ENG foundry lab, 3D Scanning

Author Nurul Anwar

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Abstract

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Keywords Casting, additive manufacturing, rapid tooling, Aalto ENG foundry lab, 3D Scanning

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Nomenclature

AM	Additive Manufacturing
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
CT	Computed Tomography
DED	Directed Energy Deposition
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
ENG	Engineering
FDM	Fused Deposition Modelling
LCD	Liquid Crystal Display
LED	Light Emitting Diode
PBF	Powder Bed Fusion
RC	Rapid Casting
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
2D	Two Dimensional
3D	Three Dimensional
3DP	Three Dimensional Printing
µm	Micrometre

1 Introduction

1.1 Metal manufacturing processes

Metal manufacturing process today can be broadly divided into 3 different groups. These are subtractive (removing material from initial workpiece), forming methods (casting, forging, powder metallurgy) and additive manufacturing (3D printing, SLS printing) etc [1]. Each of these have their own set of advantages and disadvantages, the application requirement being the final decider of which technology to use. Requirement includes things like material, dimensional tolerance, cost, machinability, melting point etc. An oversimplified conclusion is to use subtractive machining for parts which need high dimensional accuracy and surface finish, casting for large parts and material not suitable for direct machining and use direct metal additive manufacturing for small parts with very complex geometries. A brief introduction to each process is given in the following sections.

Recent global manufacturing trend is shown below which are forcing changes in metal manufacturing technologies [2]:

- More variety and complexity in products
- Green manufacturing, reduction in carbon emission and reducing energy demand
- Market is more international, stiff competition
- Increased productivity at cheaper cost is wanted
- Sustainability of the whole process is sought

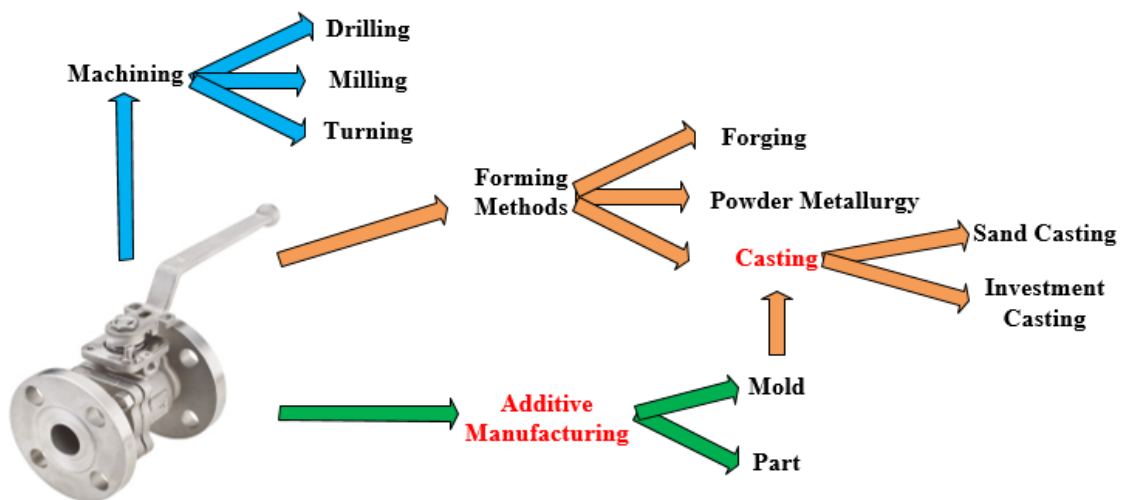


Figure 1: Various metal manufacturing routes for an example metal part (ball valve), adapted from [1]

This work is principally focused on casting and the new tools which are revolutionizing the casting industry, additive manufacturing being one of them. The ultimate goal is to find tools for possible future implementation at Aalto Engineering (ENG) foundry lab.

1.1.1 Casting

Casting is the oldest metal forming technique known to man. It has been used as far back as 4000 BC when it was used to make objects like ornaments, arrowheads etc [2]. Copper was cast using stones back then. In simple terms, casting is the pouring of molten metal into a cavity which conforms to the shape of the product wanted. When the molten metal cools down, the part is removed upon solidification and post processed as per requirement. There are many variants of casting and thousands of years of knowledge in this technology. Today it is used in the manufacture of variety of components like engine blocks, gearbox housing, crankshafts, power trains, railroad equipment, orthopedic implants, frying pans, jewelry, sculpture, huge components for hydraulic turbines etc. Casting is usually desired for the reasons stated below[2]:

- Ability to produce complex shape which can include internal cavities or hollows
- Ability to cast very large objects, or very small objects in one part
- Handle materials that are difficult to machine or process in other means
- Economic advantage
- Almost all materials can be cast in the final shape required, often needing very minor finishing operations

Overtime, three major changes have had impact on the casting industry. Firstly, the automation of the casting process which was made possible by advanced machinery and automated process control systems. This led to a significant reduction in labour costs, and increased productivity[2]. Secondly, the increase in demand for high quality castings with close dimensional tolerances[2]. Thirdly and most recently, the advent of additive manufacturing and the way it is revolutionizing the manufacturing industry. Many different variants of casting technology are now in use as shown in figure 2.

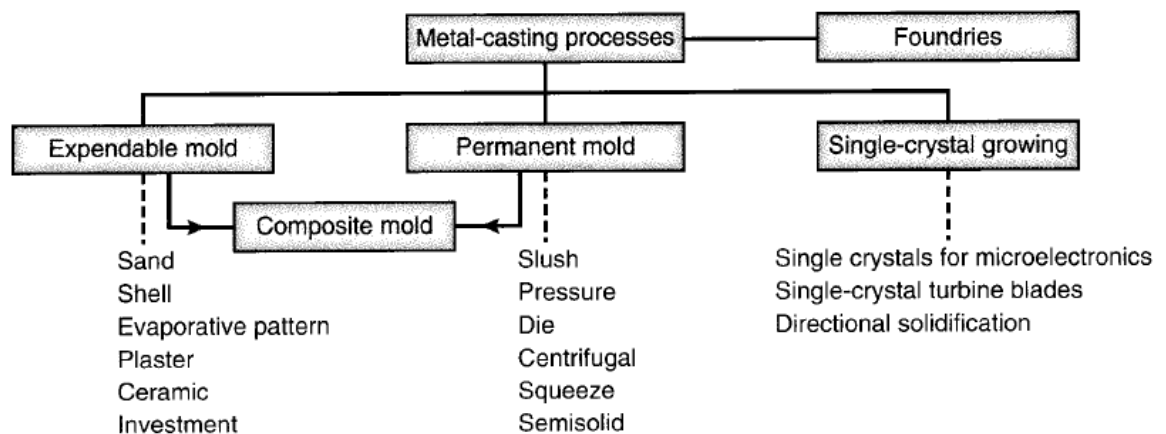


Figure 2: Different types of casting[2]

Among these, sand casting is one of the most used type of casting worldwide. A typical sand casting incorporates the steps shown in figure 3. A pattern is made which is then used to make a cavity in sand that conforms to the shape of final product wanted. Afterwards molten metal is poured into the cavity. Once the molten metal solidifies, the mould is broken and the product is processed to meet requirements and inspected before final delivery to the customer. Now, removal of one or more steps results in a great reduction in costs, time and tools required. Also, any possible methods of fast inspection speeds up the

process. Considerable research had been going on for quite some time for pattern less castings which can be achieved faster and cheaper.

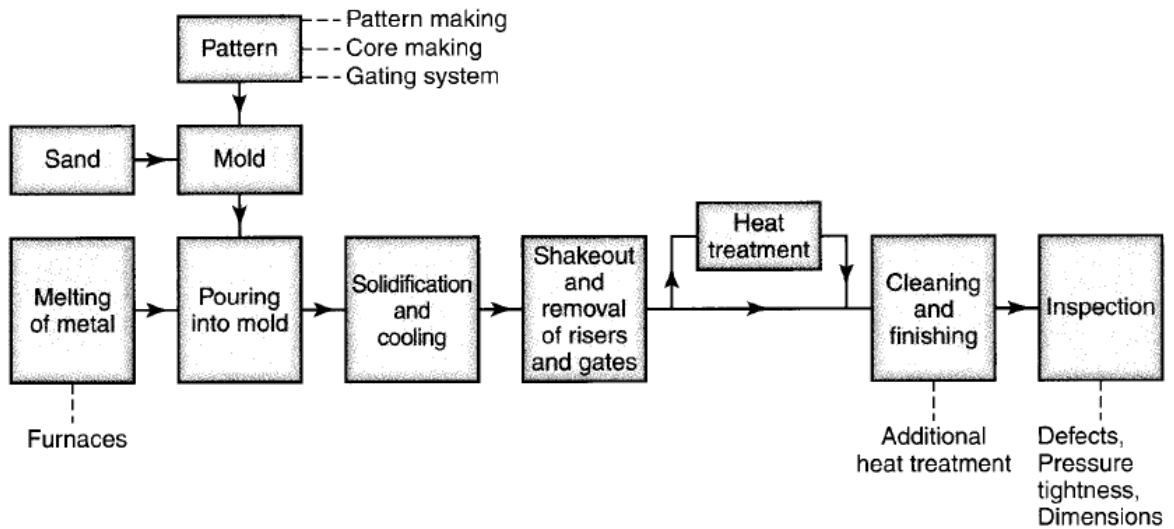


Figure 3: Typical sand casting process[2]

1.1.2 Subtractive Manufacturing

Subtractive machining involves cutting down an initial workpiece into the desired shape of the product. There is a variety of subtractive machining in use today. Examples include milling, turning, drilling, boring, shaping, hobbing, broaching, sawing etc. The widespread use of subtractive machining and the advent of CNC machining have seen a rise in the use of this method. CNC machining dominates a very significant portion of manufacturing industry today as very tight tolerances and good surface finish can be achieved through these. Some of these processes are also necessary as post processes for casting or additive manufacturing. One of the inherent problem of subtractive manufacturing is the wastage. Wastage occurs in the form of metal chips as the work piece is gradually reduced to the final desired shape.

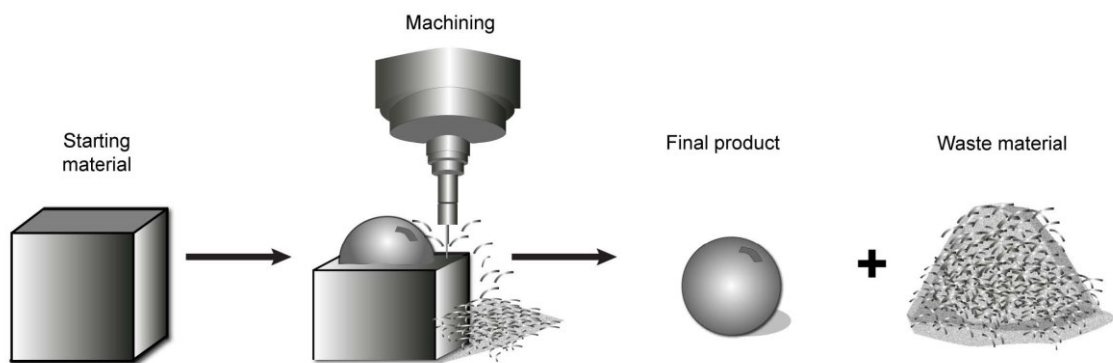


Figure 4: Subtractive manufacturing concept showing significant wastage[3]

1.1.3 Additive Manufacturing

Additive Manufacturing(AM) is the process of making a product out of digital data of 3D model, layer by layer. The technology started in 1980s as a means of rapid prototyping(RP)[4]. However it is no longer limited to rapid prototyping but rather is being used for end product manufacturing, Rapid Manufacturing(RM). AM continues to bring

more and more material under its belt, starting from food items to optical instruments and metals. However, in terms of conventional metal manufacturing, it is still quite expensive and slow[5]. Additive manufacturing is the most recent invention among the metal manufacturing technologies and has been becoming very popular ever since. The process gives freedom of design and also removes the requirement of tooling, also the waste is significantly less compared to subtractive manufacturing. As such, the popularity of AM was on the steepest rise in the last decade.

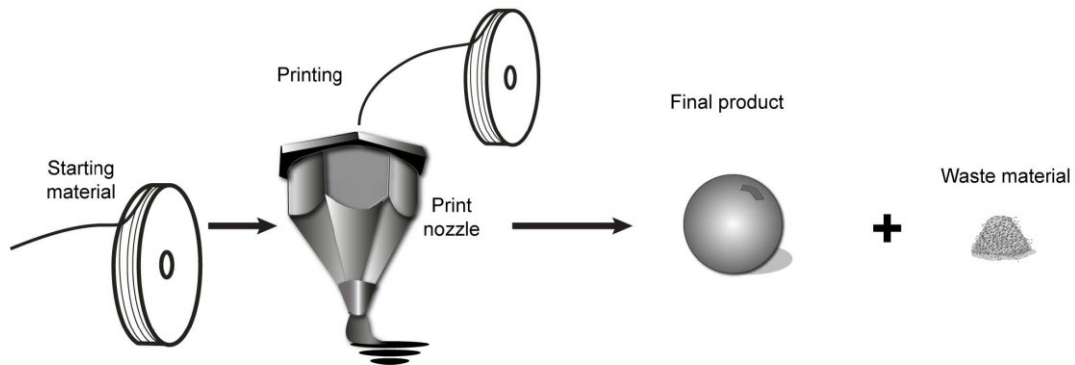


Figure 5: Additive manufacturing concept showing very little wastage[3]

While cost of production rises with increasing complexity for other techniques, AM offers product complexity at no additional costs. The recent popularity of AM has made foundries question themselves where their true strength lies. However, as will be seen in the following chapters, rather than thinking additive manufacturing as a competition, foundries can benefit extensively if they incorporate additive manufacturing into foundries as AM can be used in the making of tools required in foundries. When additive manufacturing is used to make the tools for casting, for example the pattern, core or cavity, the process assumes the name of Rapid Tooling(RT)[6]. The hybrid method can be used for more product complexity, reducing lead time and cost. When rapid tooling is applied at any steps in casting the process takes the name of Rapid Casting(RC)[7]. Global additive manufacturing market continues to rise very sharply.

1.2 Purpose of the study

The purpose of the study is to find emerging tools in casting which makes flexible manufacturing of castings easier, some of which could then be implemented at Aalto ENG foundry. Rising popularity of CAD/CAE/CAM, additive manufacturing and increasing automation everywhere are forcing changes in the casting industry as well. The oldest metal forming technique known to man is now reshaping to adapt to the changes in manufacturing industry: to achieve tighter schedules, produce better products, provide better customer service and survive in the competitive market. During the thesis, the 2D and 3D layout of the Aalto ENG foundry was also generated so that viable options can be more accurately recognized. Modified layout is suggested to accommodate new tools into the foundry. The layout made can be used for future reference and development of the lab as well.

Casting technology is also facing some fierce competition from other metal manufacturing techniques, namely subtractive manufacturing and more recently from metal additive manufacturing. As a background study, a benchmark comparison between metal additive manufacturing and casting is first shown in the work from literature review.

1.3 Methodology

1. Literature review to study the differences between metal additive manufacturing and casting.
2. Studying the new tools available for casting, greater focus is given on additive manufacturing.
3. Preparation of facility list at Aalto ENG foundry Lab.
4. Generation of 2D and 3D layout of the Aalto ENG foundry lab so that viable new tools could be more accurately recognized. AutoCAD 2018 was used for this purpose.
5. Searching for suitable products available in the market for Aalto ENG foundry.
6. Coming up with suitable proposals for the Aalto ENG foundry lab.

2 Metal additive manufacturing and casting

2.1 Metal additive manufacturing

As lucrative as it looks to produce a direct 3D metal print which could serve directly as the product, the 3D metal printing technology is far from perfect for universal applications. With growing amount of different additive manufacturing techniques available, sometimes it is also overwhelming to choose the right technique for the right product [8]. Currently, the metal additive manufacturing technology can be broadly divided into two different groups: Power Bed Fusion(PBF) and Directed Energy Deposition(DED)[5]. In this study, 3D metal print and direct metal additive manufacturing are used to mean the same thing.

2.1.1 Powder Bed Fusion

The principle of PBF technology is that a layer of powder is spread evenly over the build platform after which concentrated thermal energy is used to fuse regions of the powder bed according to the cross section of the 3D model. After one layer is finished, the build platform lowers by a height equal to layer thickness, a new layer of powder is spread by the recoater and the process continues[5]. The thermal energy could come from different types of source, for example a laser or electron beam. Depending on the type of powder and the source of energy, this technology can assume different names. Selective Laser Melting(SLM) is the term used when a laser is typically used for thermal fusion and coated metal powders are used as the raw material. The same process becomes Direct Metal Laser Sintering(DMLS) when uncoated pre-alloyed metal powders are used as the stock material[9]. Inert atmosphere is usually preferred in this process to prevent unwanted oxidation. Another variant of PBF technology is the Electron Beam Melting(EBM). In EBM, powder metal is heated in vacuum and layer by layer melting is carried out by an electron beam[10]. Figure 6 shows a schematic diagram of DMLS.

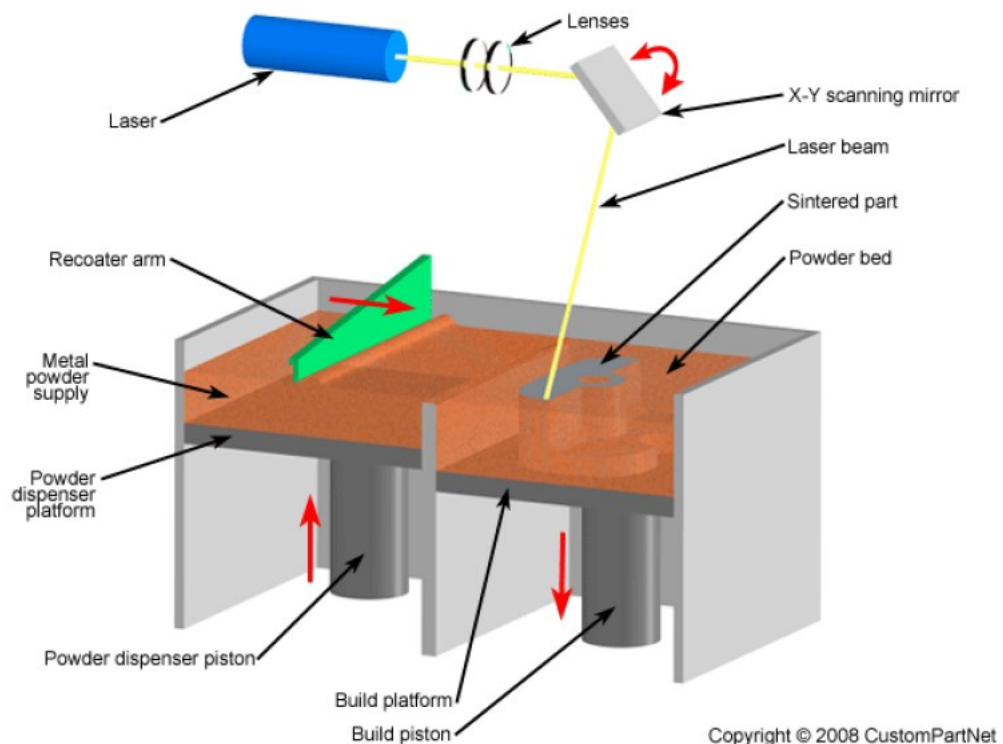


Figure 6: Schematics of DMLS process [10]

2.1.2 Directed Energy Deposition

In this technology, concentrated thermal energy in the form of laser or electron beam, is used to fuse the metal by melting as it is being deposited, the metal could be in both powder or wire form[4]. Direct Metal Deposition(DMD), Laser Engineered Net Shaping(LENS) and Electron beam Free Form Fabrication are typical examples of Directed Energy Deposition technology [11]. DMD uses powder metals and fibre laser which sit on a robotic arm. As such DMD finds its use in the tooling repair, feature addition to existing parts, and even the manufacture of new parts [10]. This means it can be used to prolong life of die casting and injection moulding dies by selective addition of wear-resistance alloys in critical locations[4]. EBFFF uses a vacuum and focuses electron beam to make a molten metal pool on a metallic substrate. Rapid Plasma Deposition on the other hand uses an argon plasma and metal wire. Molten droplets of the metal are accelerated towards the base plate by argon gas. Schematic of DED is shown in figure 7.

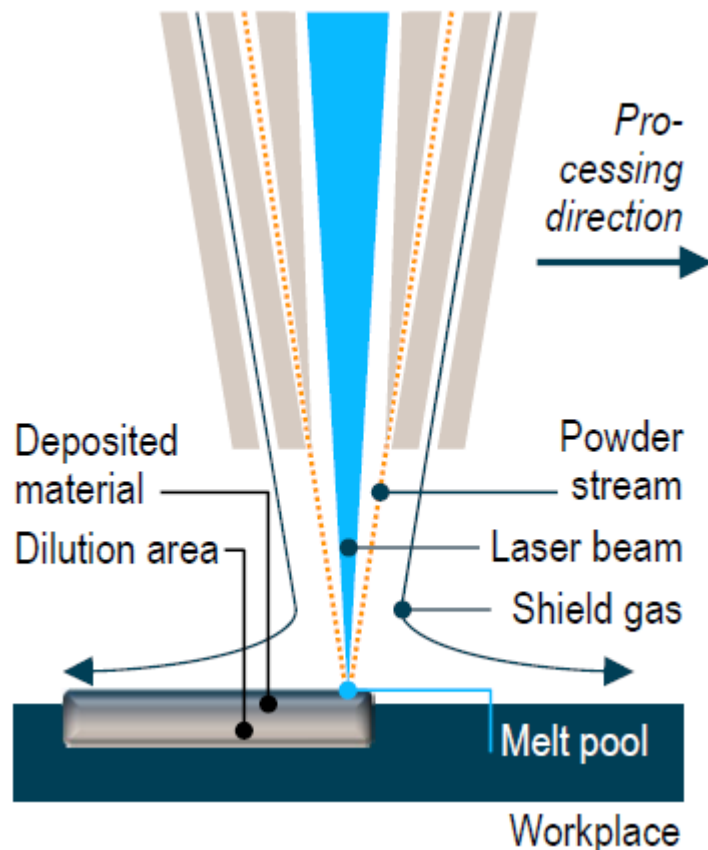


Figure 7: Schematics of the DED process[12]

DED is more suited for repair application rather than additive manufacturing of the whole part mostly due to compromised accuracy and requirement of post-processing[5]. The widely used technologies used for repair application are cold gas spraying, high velocity oxygen fuel spraying and laser metal deposition [12].

A brief comparison of parameters between PBF and DED could be seen in table 1 from a consultant company presented in 2013 additive manufacturing conference. The values might be different now[12].

Table 1: Comparison between PBF and DED technologies [12]

<i>Criteria</i>	<i>Powder Bed Fusion</i>	<i>Directed Energy Deposition</i>
<i>Build Speed</i>	5-20 cm ³ /h(40-160 g/h)	Upto 0.5 kg/h(70 cm ³ /h)
<i>Accuracy</i>	+/- 0.02-0.05 mm/ 25mm	+/- 0.0125-0.25 mm/ 25mm
<i>Detail capacity</i>	0.04-0.2 mm	0.5-1.0 mm
<i>Surface Quality</i>	R _a 4-10 μm	R _a 7-20 μm
<i>Max. part size</i>	500mm x 280mm x 325 mm	2 m x 1.5 m x 0.75 m
<i>Average System Price</i>	More than EUR 450k	More than EUR 500k
<i>Other remarks</i>	Suitable for direct manufacturing and rapid prototyping	Repair of components and modification of tooling

2.2 Comparison between casting and metal additive manufacturing

There can be no argument in the fact that pouring molten metal is always going to be cheaper than forming them point by point, layer by layer. However, a lot of other factors has to be considered for making an effective comparison. The need of making patterns and moulds in casting, complexity and volume of product, economy of production, material suitability are all factors that contribute to the decision making process.

2.2.1 Suitable parts and materials

Casting is suitable for many types, shapes and sizes, from a few grams to a thousand kilograms. Be it a very small jewelry or a large component of a ship, casting can be ideally used irrespective of the size. Also, complex geometries can be achieved with casting which can not be produced by subtractive metal forming methods. 3D metal print on the other hand can produce very complex geometries, more complex than traditional casting. This can result in significant weight reduction and be lucrative for parts in for example automotive or aerospace industry. However, 3D metal printing is very limited in the size it can produce. The size of the object is determined by the build volume of the printer in question and currently it is very much smaller than what casting can achieve[13].

Almost all the materials can be cast which has high fluidity in molten state and a small range of solidification[13]. Only a few metals like titanium are not usually cast. Titanium can also be casted, but using vacuum melting which is more expensive than traditional methods. 3D metal printing on the other hand is limited in the types of metals and alloys it can print. However, one unique advantage is that it can also print titanium metals which is quite difficult to manufacture with conventional methods. The reflection, absorption and density of titanium alloys are properly suitable for DMLS[13].

On the contrary, one of the most popular aluminium alloy is difficult to produce with laser melting. This is due to the high thermal conductivity and high reflectivity of aluminium which makes it difficult to melt aluminum[13], although research is on to bring aluminum under the radar of additive manufacturing. An example of such attempt is the mixture of aluminum powder with different metal powders or use of aluminium alloys like AlSi10Mg[14].

2.2.2 Workforce expertise

Expertise is required in making of the pattern, calculating allowances and the overall procedure. If thought from the initial procedure of making the pattern to final casting, it takes quite some time. A pattern is not necessary for 3D printing on the other hand. All that is required is a 3D CAD model. The printer takes care of the whole printing, and no intervention or expertise is usually required unless there is something wrong with the printer or the material feeding. Most of the 3D printers are able to run continuously without any break. However, it would be an over statement to say that no expertise is required for 3D printing at all. A lot of defects that occur in the final print has to be carefully overcome by adjusting machine parameters like power, laser spot size and shape after many trial and error for a particular material and product[15]. This requires a lot of understanding of the process, experience and many trial and error.

A conventionally manufactured product involves many different steps like casting, milling, forging, turning, drilling, welding, rolling etc.[5]. The removal of one or more steps usually means less expertise required, less costs involved and faster production. However, it is mention worthy that casting has been in use for quite a long time and considerable amount of knowledge, research and expertise is already available in this field.

2.2.3 Microstructure and related issues

Continuous microstructure is obtained with casting. A variation of grain size is seen across thinner to thicker sections or from the centre to the surface. Composition also varies from top to bottom, and macro segregation is also seen in heavy castings[13]. A finer grain is generally sought after for improved resistance to hot tearing, cracking and grain boundary corrosion[16]. Higher toughness, fatigue strength and ultimate strength is also achieved[16]. However, these advantages are generalized and does not apply to all alloys. Some alloys show hindered properties after grain refinement. Grain size and distribution is normally affected by the way the metal cools and cross section of the product being produced.

In metal additive manufacturing, grain size is very uniform and fine although boundary exists in spots and layers[13]. Microstructure could be controlled or affected by controlling many parameters of the process. For example, laser power, laser size, cooling rate etc. This also means that a great deal of understanding of the process is required to get the desired final outcome, unlike the popular belief that the printer does everything.

The fatigue strength of 3D metal printed parts are unusually low[17]. Unless this problem is rectified, direct metal printed parts can not be used for high cyclic loading applications. Porosity in the microscopic scale provides starting point for crack formation which makes them weak and susceptible to fracture[18]. Porosity may occur due to factors like particle size being greater than layer thickness, laser power being too low or too high, molten metal not flowing to desired direction etc[15].

Casting also has porosity issues but it can be engineered very well within required limits. It is not possible to achieve non porous product like rolling, but still a lot of knowledge and control techniques in casting help keep porosity issues under control which in turn results in product with required fatigue strength.

2.2.4 Defects

None of the metal manufacturing processes are entirely free from defects. However, it is important that the defects are in acceptable limit and steps are available to reduce such defects to ensure product quality. Metal additive manufacturing suffers from a lot of defects, the rectification of which still pose a lot of challenge and unless these defects are resolved, metal additive manufacturing is hopeless[17]. A thorough comparison of what percentage of actual product suffers from such defects in each process is out of scope in this work. However, a brief introduction of the type of defects experienced in the two technologies are given below.

Defects in casting

Casting can suffer from a number of defects related to filling of the mould, shape of the product, thermal defects and defects in appearance as well. Some common defects in casting includes hot tear, cracking, porosity, inclusion, metal penetration etc.

Hot tearing is one of the most serious defects castings can suffer from which appears in the form of a branching ragged crack[16]. It can be defined as an uniaxial tensile failure in a weak material[16].

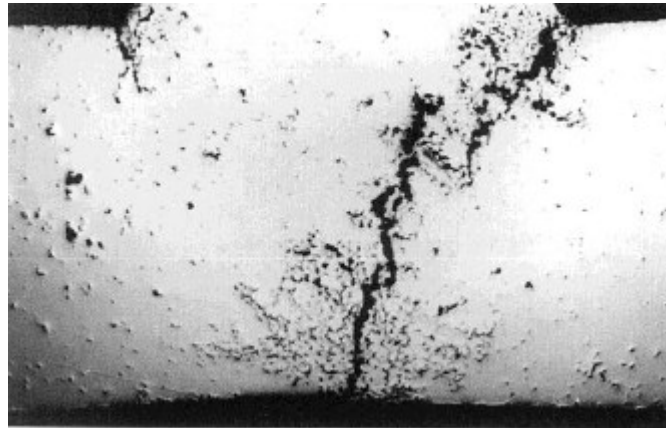


Figure 8: Hot tear[19]

While hot tearing occurs at a temperature above solidus, cold cracking takes place below solidus temperature. Cracking occurs in strong materials and is more straight and smooth than a hot tear[16]. It is also known as cold cracking.

Inclusion defects also occur in castings. Sand or slag are sometimes found inside the metal castings. Sand inclusion is one of the most common reasons of casting rejection[20]. Some portion of the sand mould are often broken down by the flowing metal which then floats at the surface[20]. They are also often difficult to diagnose as the defects can generally occur at many places.



Figure 9: Sand inclusion[21](left) and slag inclusion[21](right)

Gas porosity is also quite common in castings. These are normally from trapped air and steam, dissolved hydrogen in aluminum alloys, gas from vaporized lubricant etc[20]. As molten metal flows into the cavity, trapped air is compressed and they remain as small spheres of air in castings[20]. Shrinkage defects are also found in castings which happens when molten metal can not compensate for the shrinking of metal.

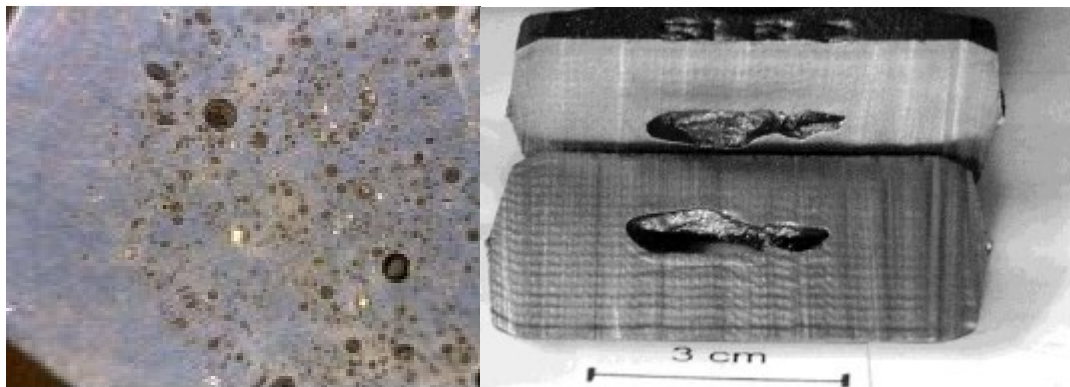


Figure 10: Gas porosity[20](left) and shrinkage cavity(right)[19] in cast products

Apart from the defects mentioned, other defects include misrun, metal penetration, distortion or warp etc. It may sound overwhelming that so many defects can occur in casting. However, there is considerable research available to avoid most of these defects and many of these can be avoided by proper casting design and pouring.

Defects in metal additive manufacturing

Although the general conception and advertising by the 3D printer manufacturer that the printer handles everything from start and finish, it is an overstatement to say the least. More often the printing fails and there are always defects in the final product. Some defects include residual stress, cracking, warpage, delamination and melt ball formation.

Residual stress is caused by the continuous expansion and contraction, heating and cooling during the process. When the tensile strength of the product is less than the residual stress, it leads to defects like cracking or warpage. Most commonly, the greatest residual stress occurs at the boundary between the printed part and the substrate it adheres to, causing the part to rip off from the build plate as shown in figure 11.

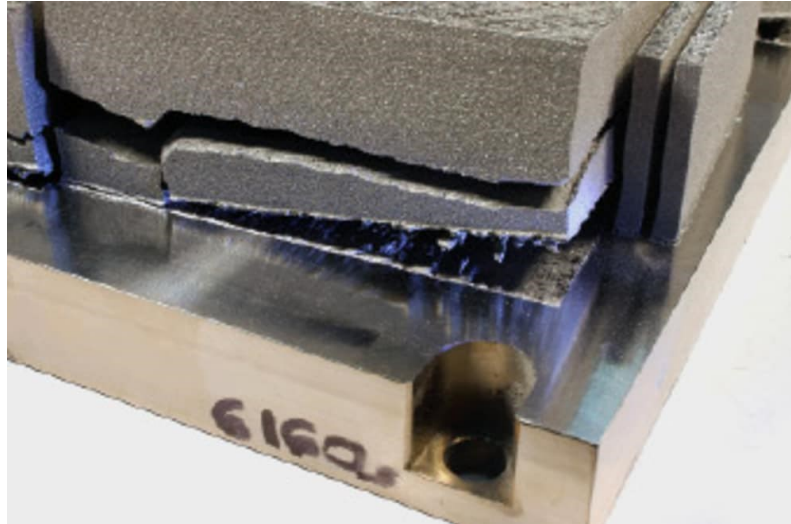


Figure 11: Defects in a titanium part from excessive residual stress[15]

Warping of the substrate material occurs when thermal stress becomes higher than the strength of the substrate material. When the substrate warps, it causes the part to warp too, which can cause the recoater arm to bump into the part.



Figure 12: Warping in a 3D printed metal part[15]

Cracking can also happen within the part depending on the part itself rather than the interface between part and build plate. This happens during the solidification of melted metal or when an area is heated further. These cracks can usually be repaired during post processing but not when a more serious form of cracking occurs, known as delamination. Delamination is the crack between layers which happen due to insufficient melting of powders or the remelting of layers beneath melt pool.

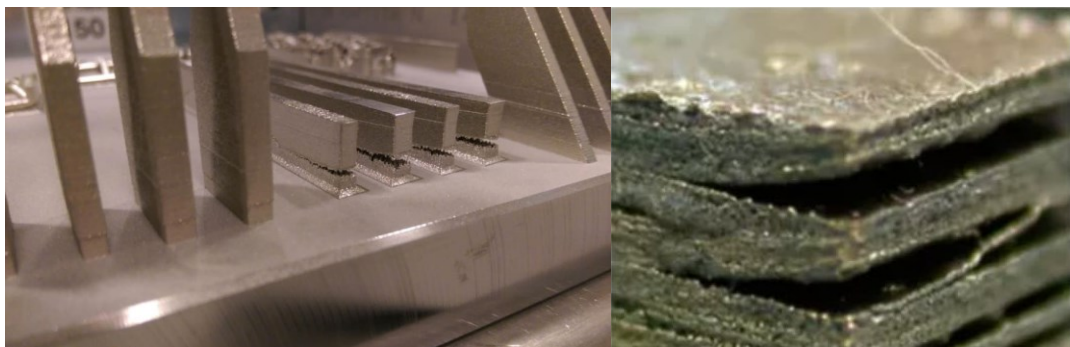


Figure 13: Cracking(left) and delamination(right) on 3d printed metal part [15]

Other problems that can occur are swelling of the part and melt ball formation. There are still many defects that occur in 3D metal printing, overcoming which requires the right combination of process parameters, experience and many trials and errors for a particular material and particular job. This also adds to the slow build rates that metal printing offers, discussed in section 2.2.6.

2.2.5 Surface finish and post processing

Both casting and metal additive manufacturing needs to go through considerable amount of post processing before they can be used in their intended application. As for surface finishing, the values quoted in table 1 are the best accuracies metal additive manufacturing can achieve. However, if such finish is desired, the best combination of machine parameter being used will slow down the process to a great extent and increase the cost many folds. It is therefore a more common practice that the part be printed with lower accuracies and then machined to their final tolerances. Shot peening, sand blasting, hot isostatic pressing and other heat treatments are used for 3D metal printed parts to improve their quality[18].

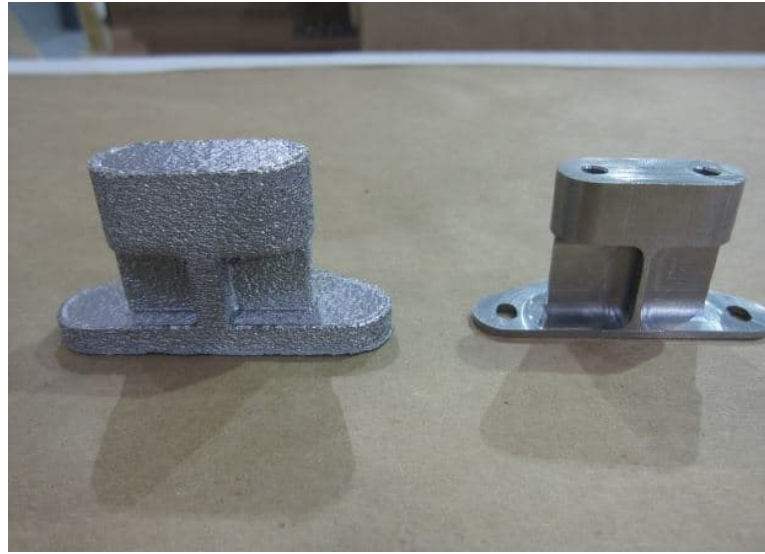


Figure 14: 3D metal printed part on left, machined 3D printed part on the right[15]

Casting also goes through considerable post processing. Gates, risers and channels need to be cut off from the final product. Sand blasting, shot peening, heat treatment could also be done depending on the application. As per Finnish standard association SFS-EN 1370, small-medium sand castings should have R_a values between $6,3 \mu\text{m}$ and $12,5 \mu\text{m}$. Investment casting should have R_a value of $1,6 \mu\text{m}$ which is better than what 3D metal prints can achieve.

2.2.6 Speed

Casting occurs quite fast, after the preparation of the mould, even pouring of molten metal in the range of kg/s is very common. However, the preparation of pattern and mould might require significant time depending on the production type and range. However, once the mould is ready, the pouring is very fast, even a thousand ton melt is usually poured under less than an hour's time[13]. The cooling of the metal is however, quite slow in the mould.

Direct metal print on the other hand is quite a slow process as stacking is done point by point and layer by layer basis. Cooling is fast owing to the fact that it is done point by point, however even a very small print can take upto hours or days. The current speed is in the likes of few hundred cm^3/h [5], [13]. This value is quite small and could only be justified for small scale tailored production, rather than mass production. The speed is also determined by the quality of the final build sought. For example, a more dimensionally accurate and better surface finished part requires a smaller layer thickness. And when a smaller layer thickness is used, the time taken can rise by many folds.

2.2.7 Raw material

As long as the material has required purity, it can be used as input raw material for casting. The shape has little or no effect once it can be molten. The same is not true for 3D metal printing. Metal printer requires metal powder as raw material which is very expensive. Powder properties within acceptable range are required which includes parameters like density, flowability, particle cohesiveness and size distribution, roughness, internal porosity, chemical composition etc. These bring about many induced instabilities which include[5]:

- Defective feeding
- Defective feeding of layers
- Porosity in finished product
- Convex shapes

While talking about raw material, it is noteworthy to consider the buy to fly ratio of the process. Buy to fly ratio is defined as how much of the input material is actually part of the final product. For conventional manufacturing processes using machining or traditional casting, this ratio could be as high as 10:1[5]. This is because there is a lot of wastage in subtractive machining processes in the form of metal chips, and also in casting as gates and risers are not part of the final product and must be cut off. Subtractive manufacturing is the worst in this scenario in that the chips can't be reused there and then, however in casting the unwanted parts can be melted and reused quite easily. 3D metal print can even offer a buy to fly ratio as lucrative as 1:1 sometimes[5]. The wastage that normally occurs is from the support structures sometimes required during 3D printing.

2.2.8 Economics of production

Cost of production will always be a major issue for all types of production. Although AM reduces required number of steps and workforce expertise requirement, expensive metal powder and very slow build rate contributes to the expense of metal 3D printing. The widespread use of AM could decrease powder and machine cost in future but it will still be slow and constrained by the size it can produce. However, a very unique economic advantage 3D metal printing provides is complexity without any added cost. Figure 15 demonstrates the relationship of cost with increasing complexity between additive manufacturing and conventional methods.

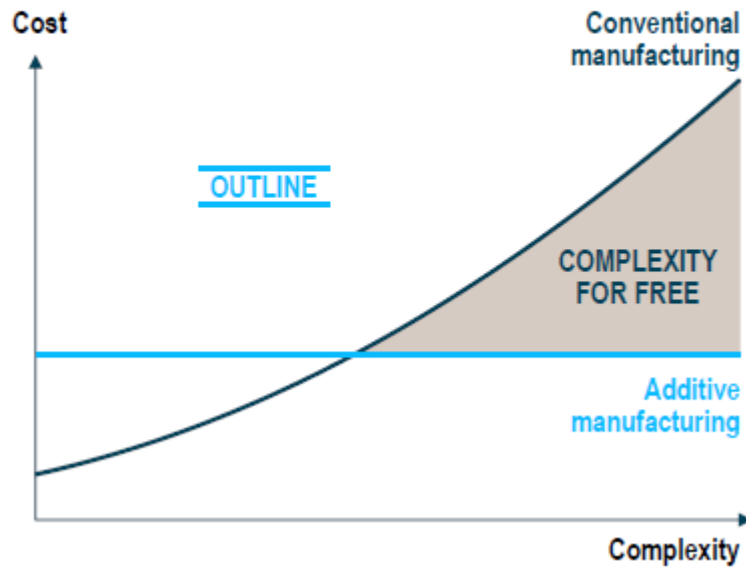


Figure 15: Schematic representation showing relationship between cost and complexity [12]

However, currently the AM process has to be customized for particular product requirements. An adaptation to a new material might take a very long time. Some production parameters and challenges are discussed below:

- Design: This includes features like geometry, overhang and support structures required.
- Process: The process parameters during the print. Examples include laser intensity, speed, laser size, number of lasers etc.
- Layout: The orientation of the print affects the properties of the print. The perpendicular and parallel planes of the plane of printing shows different properties.
- Post Processing: Depending on the product itself, a range of post processing might be required. These include heat treatment, shot peening, polishing, sand blasting etc.

2.3 Will metal additive manufacturing replace casting?

Direct Metal printing is not a total alternative to casting, at least not yet and it does not seem likely to be considered as a wholesome replacement of casting. The fatigue strength of metal AM is low and it has lot of defects, the speed is very low and raw materials expensive. Unless these problems are resolved along with solution for fast metal AM technologies, AM does not justify wholesome replacement of casting or subtractive technology for mass manufacturing.

At the moment, direct metal printing can only be justified for products which have a high buy:fly ratio, a complex shape, small size, slow machining rate or are too difficult and expensive to machine. AM is also justified if someone is producing spare parts and no tooling cost is required for single component prints. It is still very difficult to achieve mass

manufacturing through AM. There is no point in enforcing that one of the metal manufacturing method is a complete replacement of the other, but rather the fact that these are two different metal forming methods which have their own set of advantages and disadvantages. However, AM can actually complement foundries in a variety of ways as AM can be coupled with foundries in a hybrid method. Additive manufacturing can be used at various steps of casting industries and it can be used to improve productivity, reduce cost and be used for casting of more complex structures. The next chapter discusses the different steps in which AM can be used in foundries.

3 Emerging tools in casting technology

The previous chapter has explained why metal additive manufacturing is not a wholesome replacement for casting. Casting would prevail as a metal manufacturing method, however there are scope of improving the conventional methods. This chapter looks at the promising new tools. In a report by U.S department of energy, the energy requirement breakdown of foundry industry was analyzed as shown in figure 16. Melting of molten metal accounted for 55% of the total energy requirement[22]. There is little that could be done in this regard except for improving efficiency of furnace in use. This is out of scope of discussion in this study. However, what could be done is that designing better casting system which requires less molten metal, optimizing products so that they are lightweight, simulation of the process so that there is less failure and defects, better inspection methods to identify issues at each stage of casting etc.

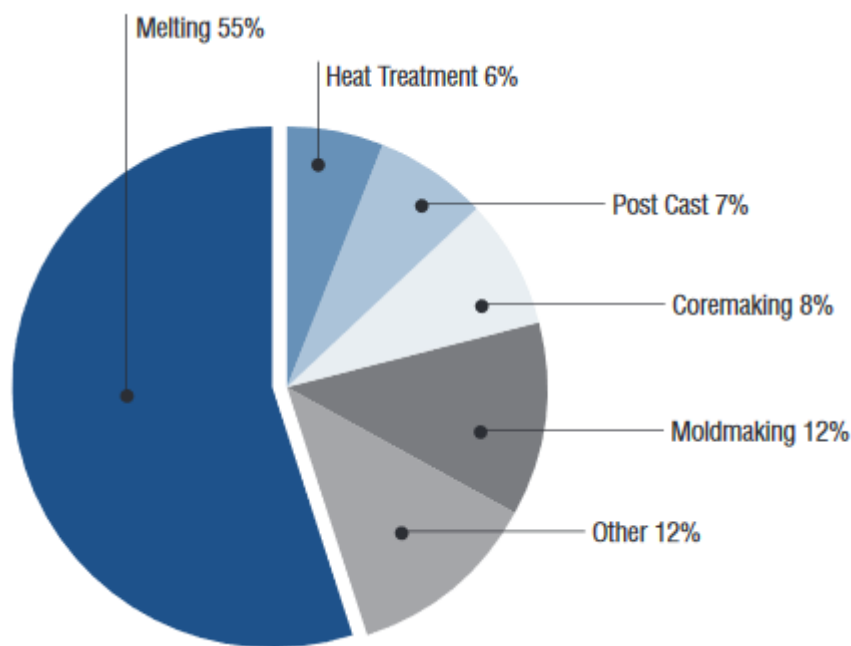


Figure 16: Energy usage breakdown in a typical foundry [22]

3.1 Additive manufacturing at different stages of casting

The versatility of AM has made it possible to be used at different steps of the foundry engineering. Figure 17 shows the different steps of casting and also the relevant AM technologies that can be used. There are many different reasons for using AM at various steps of casting. This includes reduction of cost, improve product qualities, reducing lead time etc. The issue of direct 3D metal printing, as a wholesome replacement of casting, has already been discussed in the previous chapter.

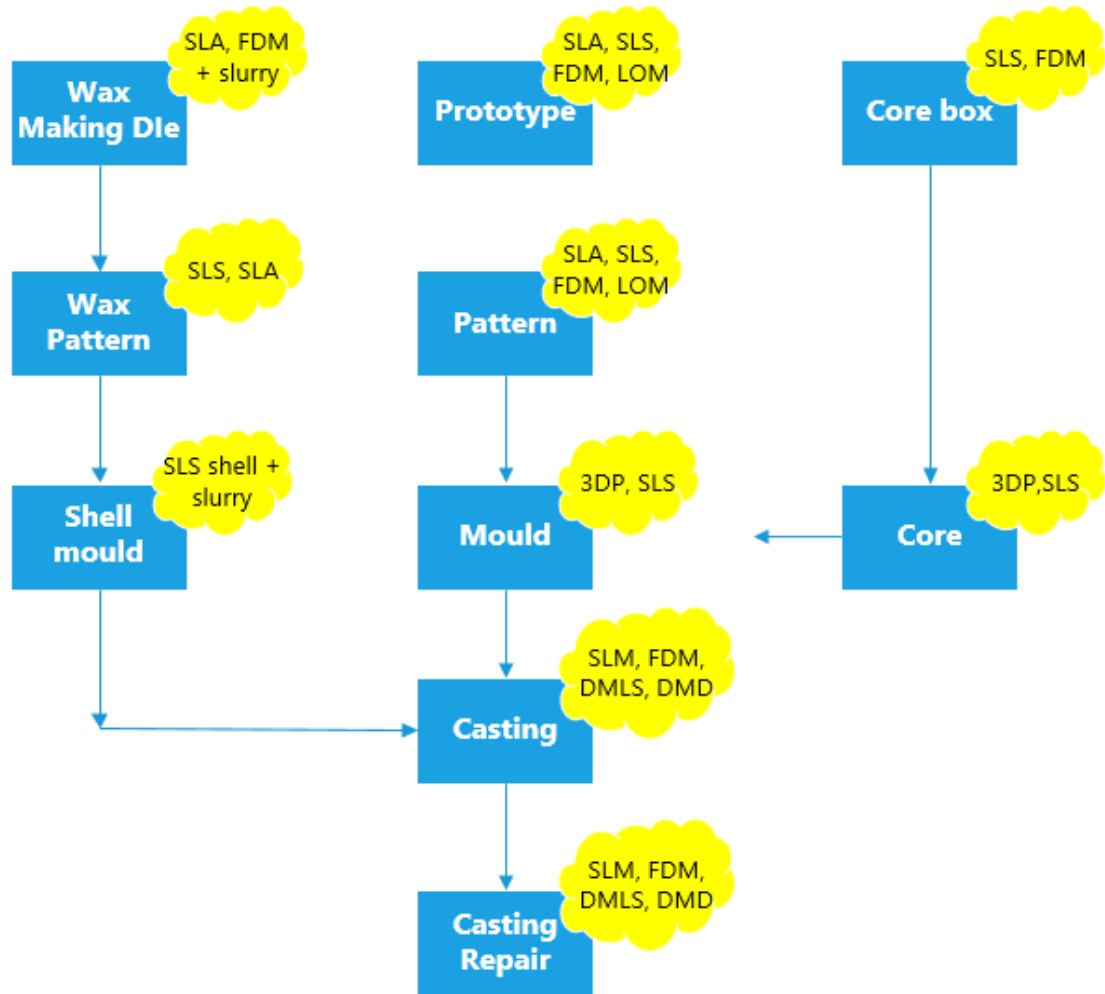


Figure 17: Different steps in which additive manufacturing could be used for casting, adapted from[13].

3.1.1 3D printing of pattern

The pattern in traditional casting can be made from anything like metal, wood or plastic depending on the intended use of the pattern. If it is going to be used once, or a few cycles then wear and tear is not an issue and it could be made from soft material. However, if a particular pattern is to be used for thousands of cycles then it is best to make it from hard materials which will not wear away so early. Direct 3D metal printing could be an option for this, although that would mean a large volume of same product casting. An easier approach is to print patterns from thermoplastic materials and then using it to make the mould. While many different technologies are in use today for making of patterns, Fused Deposition Modelling(FDM) and Stereolithography(SLA) are noteworthy among them. In FDM, the 3D model is made by extruding a semi molten thermoplastic material and then depositing it layer by layer as per the cross section of the 3D model[23]. The temperature control unit heats the filament material as it comes out to the required semi molten state. After the completion of one whole layer, the stage goes down by a height equal to layer thickness and the process is repeated until the whole model is completed.

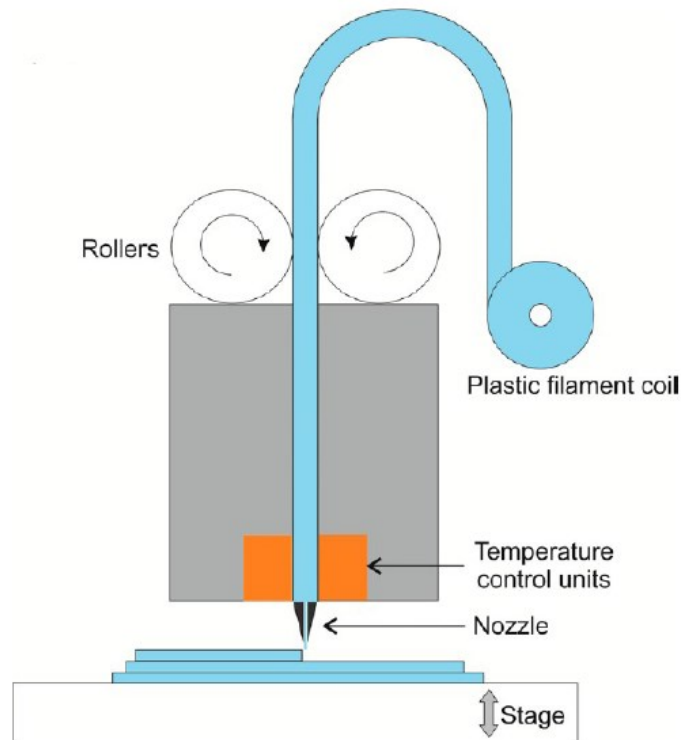


Figure 18: Working principle of fused deposition modelling[23]

Internal and surface defects on this process can arise from defective filament feeding, filament quality, slicing software etc. One advantage of FDM is its ability to print multi material object which allows user greater scopes of experimentation. The compatible materials with this printing technology are PC, polystyrene(PS), ABS, glass reinforced polymers, metals and also ceramics[23]. These could be used as permanent patterns for making sand moulds many a times. However, there is a problem of higher wear and tear with PS materials.

Figure 19(left) shows the schematic of SLA technology which involves direct curing of liquid resin. The build stage is situated just below the surface of liquid resin. A single laser moves row by row according to the cross section of the model until the layer is complete. Afterwards, the stage lowers to allow liquid resin to cover the surface and the process is repeated. Figure 19(right) shows a projection based curing method which allows for a whole layer to be cured at once by means of digital mirror device. The method is faster as whole layer can be cured at once. The stage is submerged by particular distance into the resin reservoir, and the laser cures liquid resin between stage and laser[23]. Once, a layer is complete, the stage rises by layer thickness for new layer to be printed. Process is repeated until the whole part is printed.

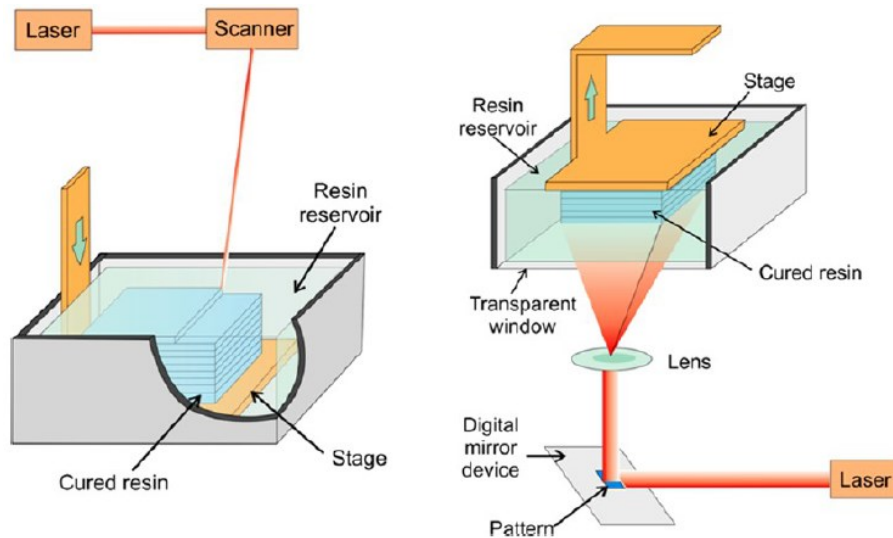


Figure 19: Working principle of Stereolithography, direct write curing process(left) and projection based curing method(right)[23]

Although FDM offers more speed and cheaper print, SLA is better in terms of dimensional accuracy and surface finish[24]. Hence, SLA might be the better choice of the two when it comes to industrial scale pattern printing as dimensional accuracy and surface finish are important considerations. Some problems in the use of thermoplastic patterns produced by additive manufacturing includes distortion during printing or by hot foundry sand, difficulties of repairing or modifying the printed patterns, added equipment and material costs etc[25].

Additive manufacturing can also be used for wax printing to be used in lost pattern casting. The technology in use is called multi jet printing. In this process a piezo printhead is used to deposit wax layer by layer[26]. The support material is used in this method is dissolvable which makes removal of support very easy and efficient[26]. One such machine, the ProJet MJP 3600W from 3D systems is already in use at Aalto ENG Production Engineering facility.

3.1.2 3D printing of sand mould

Sand mould and cores can be directly printed now a days using additive manufacturing techniques. This removes the need for laborious pattern making followed by making of the mould using the pattern. 3D printed sand moulds can be more complex than the traditional moulds. Once the mould is printed, it can be directly used to pour molten metal onto it to make the final casting product, although curing might be necessary with some types. Powder bed processes are the most popular now for this purpose where sand is spread out layer by layer and they are thermally or chemically bonded using different means. The most relevant additive manufacturing technology for this is the 3DP and SLS system although in recent times, 3DP is the most popular one for this process, because of its superior speed advantage.

3.1.2.1 Binder Jetting or 3DP method

The bigger players in the manufacturing of sand printers like ExOne, Voxeljet, and Viridis3D are all making Binder Jetting(3DP) sand printers. The process involves spreading a layer of sand premixed with an activator and then depositing binder in the required area according to the cross section of the part to be printed[27]. The binder then

joins the sand only where it was sprayed, and there are loose sand powder elsewhere which can be shaken off once the whole part is made[27]. Once a layer is complete, the build platform goes down by a distance of layer thickness and a new layer of sand is spread by the recoater and the process is repeated till part completion. The settling time of the resin is tuned so that it sets before the next layer of sand is spread on the bed. The unbound sand supports the part and hence no support is required in the process. The most used binder are furan and phenol although the health risk of furan should be considered as it is a possible human carcinogen[28]. The silicate binder is generally more favourable with high melting point metals[27]. However, one advantage with furan systems is that post curing is not normally necessary. Both phenolic and silicate binders require post curing[27].

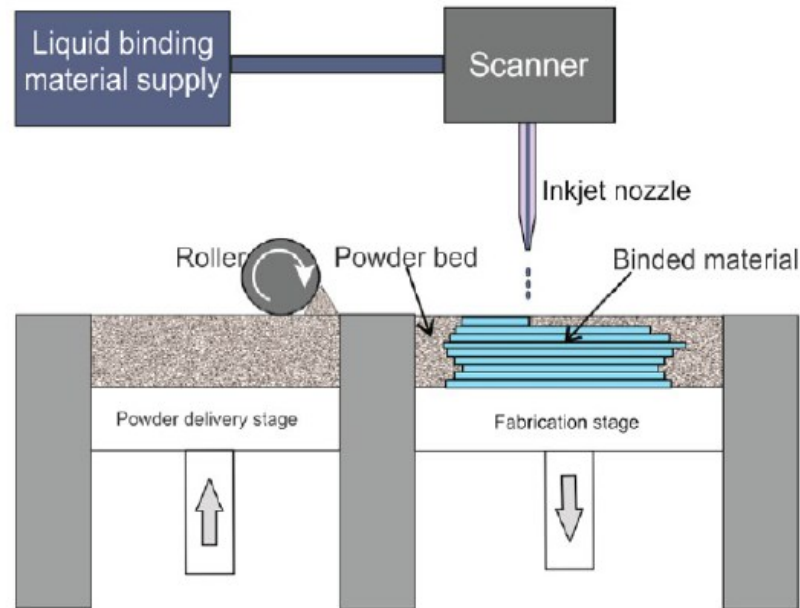


Figure 20: Schematics of 3DP binder jetting process[23]

Binder jetting process had been gaining more popularity for sand printing as it can produce good quality sand moulds in a relatively short period of time which allows for fast integration with the existing foundries. Complex moulding is also possible that can cast topologically optimized low weight part[27]. The properties of the mould depend on the binder used, the sand used, and also post processing of the printed mould. Usually, the printed moulds have to be cured in an oven. The time and temperature has been shown to significantly affect the mould, hence an optimum find is required for each type of sand and binder combination[27]. The printed mould can then be used for casting. Also, moulds larger than the build space of the printer can be achieved by printing smaller blocks and then assembling them to make the final mould.

The following are the parameters which affect sand printing[27]:

1. Powder type
2. Particle size of powder
3. Binder content
4. Printing speed and sand recoater
5. Activator content
6. Curing parameters: Time and temperature

Studies have found that the moulds produced by 3DP process has poorer density and surface roughness compared to traditional methods, but it is within an acceptable limit of traditional mould making[29]. But it is also true that the precisely controlled distribution of sand and binder results in other desirable qualities of the mould. These include maintaining the shape to a higher burn out temperature and lowering gas generation during casting as binder content can be carefully controlled[27].



Figure 21: 3D printed sand mould by Voxeljet printer and the casting made from it[30]

Very large forming space is already available with commercially available sand printers and the speed is also very fast compared to other additive manufacturing technologies. Hence, the 3DP sand printers look very promising for casting industries in coming future.

3.1.2.2 SLS technology

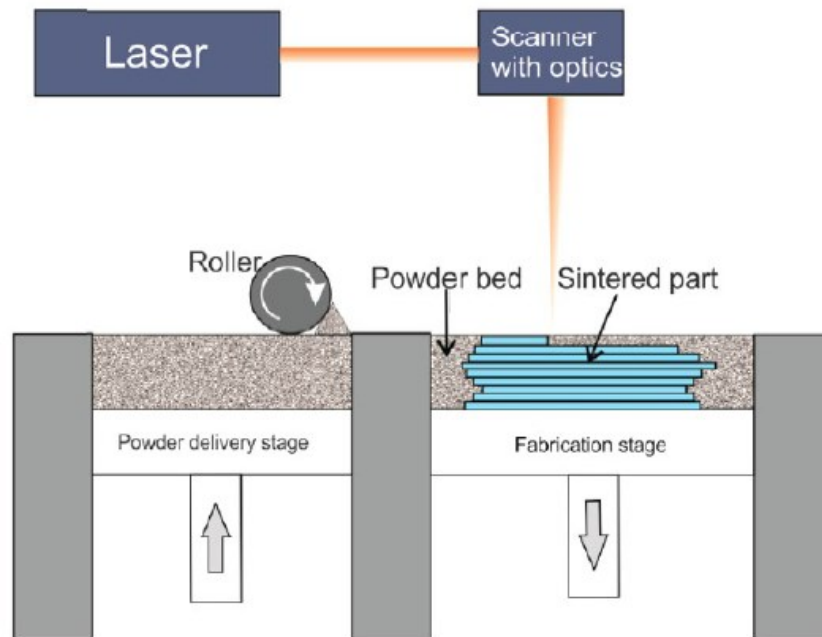


Figure 22: Schematics of SLS technology[23]

This is also a powder bed technology but instead of using a chemical binder like 3DP technology, SLS uses laser power to sinter the resin coated sand. The usual sand to be used in this process is the silica sand. Resin is normally required in higher quantities than traditional methods due to some burn off during the sintering process[13]. The different parameters that affect the final print includes laser power and spot size, scanning speed, preheating of the sand, layer thickness etc. Preheating of the current layer of sand makes it slightly bonded and hence opposes the abrasion caused by the sweeping of new layer of sand by the roller. This helps in the prevention of displacement of already printed part and also reduces the contraction of the printed part which in turn increases dimensional accuracy. The loose powders are also easily shaken off. The strength of the printed part is not enough for casting, usually less than 1 MPa, hence they have to be cured at an oven [31]. The strength normally increases with temperature but then there is a rapid decrease as the binder starts burning off. Gas release is reduced during casting if the 3D printed mould is baked at high temperature. Hence, as long as the strength requirement is met, the baking temperature should be as high as possible[13]. SLS for printing sand mould can only be justified for small quantities as the process is quite slow. Although the laser can move very fast, the beam is very slim which results in long printing times.

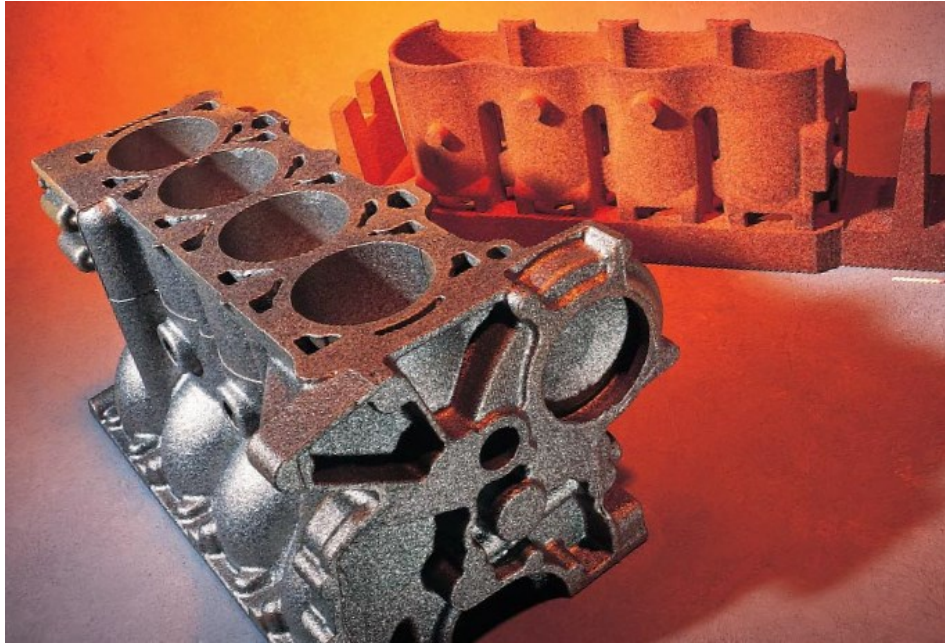


Figure 23: Engine block casted with EOSINT S750[32]

3.1.3 3D printing of ceramic shell for Investment Casting

This is an alternative to investment casting without having to make the wax pattern and making of a wax tree. Thus, the whole shell including the pouring cup, tree and the products, could be directly 3D printed. Investment casting in general has the advantages of being more reliable, producing tighter dimensional tolerances and more intricate designs. The ability to 3D print the ceramic mould itself removes the laborious process of making the wax pattern and wax tree. This process gained the name of Rapid Investment Casting (RIC). In the paper[33], the feasibility of making aluminium casting using Projet 660 (from 3D systems) is researched upon, by varying the thickness of shell and applying a number of infiltrates for post processing. The tolerance and surface roughness of the final products were also tested. The raw material used is calcium sulphate hemihydrate 80-90% by binder jetting of a water based binder. The shape of the casts made is shown in figure 24.

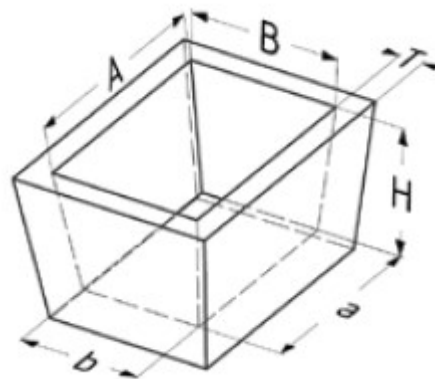


Figure 24: CAD model of printed ceramic mould[33]

The thickness t is changed from 2.5 mm to 4.0 mm and the affects were found out. All the moluds were free from burns or inflammation, which confirm that it has adequate thermal

resistance. However, for thickness below 3.5 mm, the printed moulds did not possess sufficient mechanical resistance to withstand the molten aluminium pressure. The study did not find any significant difference of surface roughness in final casting compared to traditional casting techniques. Most studies are currently aimed at working with aluminium and aluminum alloys. A great deal of research still needs to be done for this process to be commercially available or viable for industries.

3.2 Subtractive sand mould manufacturing

Sand milling is another way of making the sand mould without use of a pattern. When it comes to tight tolerances, CNC machines have remained a popular choice for long. The subtractive process can cut out intricate moulds and cores out of solid blocks of sand and binder[34]. Composition of the sand block depends on the material to be cast and other production parameters. This is a fast way of obtaining a sand mould straight from CAD data. The state of the art CNC machines also ensure very tight tolerances of sand mould which is difficult to achieve with the normal procedure. Despite the advantages though, this process has some disadvantages[34]:

- Sand falls down straight, unlike metal chips. This makes it very difficult to clean sand and also the machine is affected. The machining centres need replacement every 2 or 3 years.
- Sand particles are very abrasive and wears down the tooling very fast.
- Virgin sand is normally required for the making of the mould unlike typical foundry practices where the reclamation of the used sand is a normal practice. This will give rise to additional costs for buying more sand and also hurts the sustainability of the whole process.

A pattern less casting system was developed at VTT technical Research Centre of Finland and later further developed at Simtech Systems which uses a robot to make the mould directly from CAD model[35]. It is reported that both Audi and BMW started using Simtech's Technology. The company claims reduction in costs up to 40% and lead times reduction to 5 weeks from traditional 17 weeks in the manufacture of a prototype hydraulic hammer. The process also boasts occupational safety. This is achieved by the fact that the mould is made inside an enclosed robotic cell and harmful carcinogenic particles are successfully prevented from harming the foundry employees[35].



Figure 25: Simtech's robotic milling of sand[35]

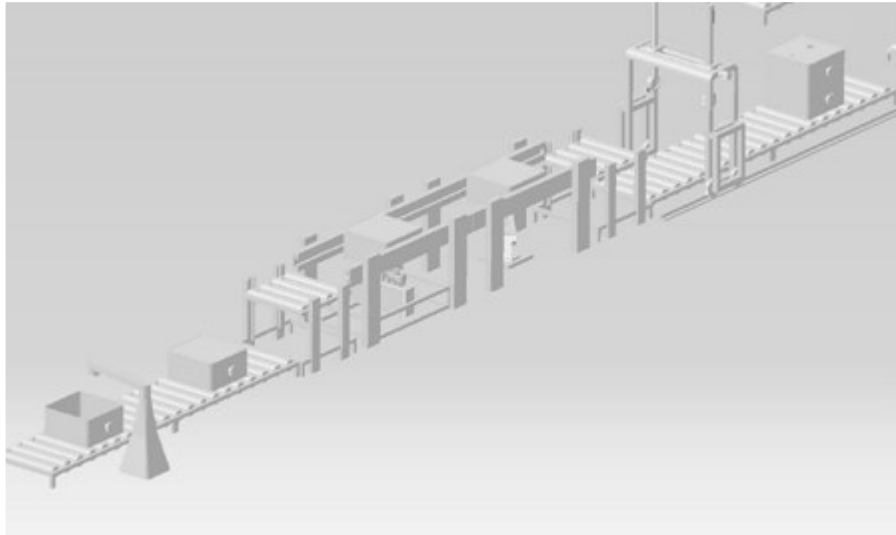


Figure 26: A moulding conveyor line[36]

A casting mould line as shown in figure 26 could be a solution to very agile foundry. The line consists of conveyor which carries the sand blocks forward and they get sequentially milled at each milling station. An inverted design is more suitable for such line, to avoid the problem of sand falling straight down as shown in figure 27. After rough milling, the last step of the conveyor is an industrial robot which does the complex geometries like undercuts[36]. No bottleneck is assumed as all the stations are expected to have similar processing times. The abrasive nature of sand causes a high rate of wearing of the tool and they need to be replaced quite soon. Some precautions are necessary to protect the machines from abrasive sand grains. An industrial grade vacuum system is the best choice, although mechanical seals could be a less expensive solution.

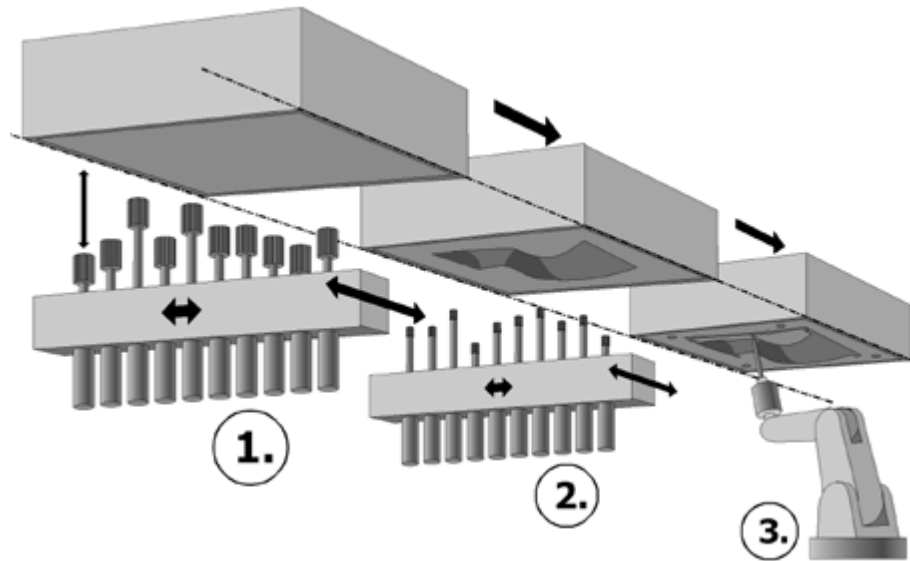


Figure 27: Progressive sand milling machine [36]

3.3 3D scanning technologies

3D scanners enable making of accurate digital 3D models of real life objects. Once in the digital form, modifications and analysis can be accurately performed[37]. They are proving to be excellent tools for reverse engineering and also an excellent tool for foundries for measuring and checking accuracy at each step of the casting process[38]. For example, the pattern, the mould and even the final product could be accurately modeled and checked with 3D scanners. This improves product quality and defects can be identified much faster and rectified[38]. A report in a foundry magazine describes inclusion of a 3D structured light scanner has helped the foundry deliver in upto 75% less time[38]. When an exact copy of an existing part is required(reverse engineering), 3D scanners can be used for making of the 3D model which can then be subsequently used in the making of final product. Also, sometimes an existing product can have wear and tear on its surface. These can be corrected in the CAD form before final production. Foundries also face a problem of storing patterns for a long time. With a 3D scanner, all the patterns could be stored in a digital form and printed whenever required, rendering storage of permanent patterns unnecessary.

3D scan data usually produces a cloud point or mesh data which can be used by reverse engineering surfacing softwares to build the 3D shape and subsequent alteration if need be. One such example is the Solidworks Power Surfacing RE which works quite well with the scan data[39]. As 3D scanners continue to gain more popularity, it can be expected that reverse engineering with 3D scan data will continue to improve.

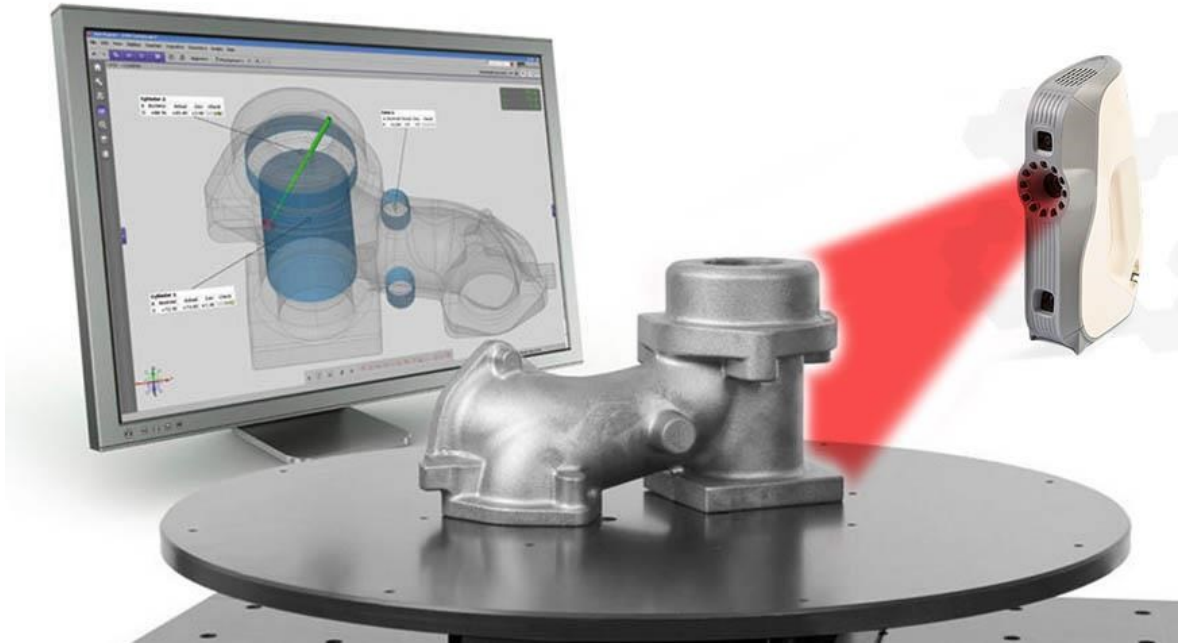


Figure 28: Illustration of 3D scanning for reverse engineering[39]

3D scanning are very useful where contact or mechanical method of inspection are not tangible. Also, the 3D scanners are usually light and portable which gives a great degree of freedom to the user. The technologies in use today for 3D scanning are laser, structured light, photogrammetry and computed tomography[40].

Laser Scanners

Laser scanners use triangulation method for capturing data. Unknown values could be calculated from a set of angles and lengths of a triangle. The method had actually been use for quite some time by surveyors for mapping and road construction. In this technology, the angles and distance between the scanner and the light source makes the base of a triangle. And the angle at which the projected light comes back to the scanner from the object forms a triangle from which 3D coordinates can be calculated. Repeated solution of many such triangles recreates a 3D representation of the actual object.

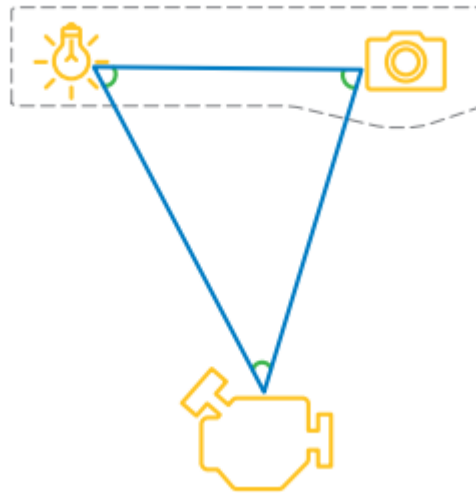


Figure 29: Triangulation method for 3D scanning[37]

Laser scanners provide reasonable accuracy and they are quite easy to use compared to mechanical contact methods of measurement like the coordinate measuring machine.

Structured light

These scanners consist of LCD or LED projectors and a number of cameras. Patterned light of alternating dark and light regions is projected onto the object being scanned. The geometry of the object is then generated by determining how the projected light was deformed at the field of view of the cameras. Triangulation is also used to calculate the distance to specific points[41]. The individual scans are very fast and hence this process suffers less from environmental disturbances. The object is rotated or the scanner is taken around the object to take next scans and the process is continued until the full 3D model is created. The digital model created can have very high accuracies as well, upto 0,05mm. The scanners are portable and handheld, which can be taken to a large casting, instead of bringing the casting to the scanner, which is very ideal for foundries. These scanners can keep track of the object in more difficult conditions than laser scanners can[42]. Compared to laser scanners and measuring arm, the structured light scanners have also the advantage of speed, ease of use and price[38].

There are two variants of this type, blue and white light. Although they both use the same technique and offer same accuracy, the best one to choose will depend on applications[41]. For example, blue light scanners have more tolerance in a room where other light sources are in operation. Structured light scanners have some disadvantages too. It can suffer from some problems of diffraction, reflectivity and transparency of the surface being scanned[41], but these can be overcome by spraying the objects with powders.

Photogrammetry

This method uses many photos of overlapping areas and depending on the changes between each successive photo, the geometry is calculated and 3D model is generated by a computer vision algorithm[40]. The process only requires a camera, a computer and a software to analyze and generate the model. A set of cameras can be used to take all the photos at once and reduce the time required. There are open source software available

already for this process. This process is however not suitable for engineering work as it suffers from low accuracy[40].

Computed tomography

Computed tomography(CT) scanners generate a 3D model from a large number of 2D X-ray images[40]. Unlike the other methods, this suffers from the problem that the object has to be placed inside the imaging compartment. Which makes it difficult when there are large castings in question. The device is quite expensive but it offers the best resolution and unlike the other techniques, it can model internal surfaces as well, not only the ones facing the scanner[40].

3.4 Concluding remarks

Additive manufacturing has a lot to offer to foundry engineering when it comes to design freedom and incorporation of intricate features. Foundries can achieve benefits through reduced labour and also customer's high interest in 3D printing. While printing plastic pattern has these advantages there are issues to be considered like extra equipment and material cost, distortion of pattern during printing or by hot foundry sand, difficulty in modification of printed pattern etc. Printing a sand mould directly even further reduces the number of steps. Sand printers can be ideally used for complex and low volume job. Not only that, sand printers can make intricate and very complex cores. Additive manufacturing of ceramic shell is still at a very early stage of its development but if it can achieve accuracy like investment casting, it might as well be a good foundry tool in future. The choice of which option to choose ofcourse depends on the application, but it is quite likely that additive manufacturing assisted casting will be a norm in the future.

There is some promise in sand milling, due to the speed and accuracy it offers. However, the abrasive nature of sand and also the requirement of using virgin sand remains an obstacle for this process. And if robotic sand milling is opted then there is extra cost of the robot itself. 3D scanners on the other hand show a lot of promise to be used at foundries. A digital model of real life object makes measurement and inspection much easier, also a very necessary tool for reverse engineering. Among the different 3D scanning options available, the handheld structured light scanner offers ease of use, speed and precision, portability and price advantage for foundries.

In the next chapter present scenario of Aalto Foundry will be discussed along with some market research so that recommendations can be made for future implementation.

4 Aalto Engineering foundry

4.1 Facility list

The type of casting done at the Aalto Foundry at the moment are sand casting, investment casting, shell moulding, lost foam moulding and gravity die casting. Among these sand casting and investment casting are the most commonly used casting methods at the lab. Below is a list of machines and tools available at the lab at the moment.

1. **Sand system:** There is a phenolic sand system which mixes an activator, phenol and silica sand. The mixed sand could be used directly as a no bake sand for sand casting. Phenolic systems are better than furan with view to the fact that furan is a possible human carcinogen.
2. **Furnaces:** There is a range of furnace available at the foundry.
 - Resistance furnace:** There is one resistance furnace which is used for metals with low melting point like Magnesium and Aluminum.
 - Induction furnace:** There are three induction furnaces at the lab. The drop down induction furnace is the most used now, which is for low melting point metals like aluminum and copper. Another one is coreless tilting type furnace and it can be used for iron-steel melting. The other induction furnace is uninstalled and out of operation at the moment, although it is assumed to be functional.
 - Dewaxing and sintering furnace:** This is used to melt and remove the wax patterns for investment casting. The ceramic mould is created once the wax is removed.
 - Ceramic furnace:** The ceramic furnace is used to heat treat the ceramic mould. The heat treatment increases the strength.
 - Vacuum induction furnace:** It is a high-vacuum induction melting system made to melt reactive metals under inert atmospheric conditions or vacuum. Can be used to cast directionally solidified castings like turbine blades.
 - Lab furnace:** There are two lab furnaces. Used to heat treat small mould specimens for testing purposes.
3. **Bead blaster:** The abrasive blasting is an ideal post processing smoother and shaper for castings.
4. **OES analyzer:** The optical spectrometer has the ability to analyze ferrous and Aluminum objects. The device is highly sensitive to contaminants and requires a clean room for efficient functioning. This also requires a supply of inert gas.
5. **Universal mould strength tester:** Used for measuring properties such as bending strength, tensile strength etc. of sand mould specimens.
6. **Wax working tools for investment casting:** Required in the making and modification of wax patterns, making of wax tree, and pouring cup for investment casting.
7. **Drying cabinet:** This is used in preparation of ceramic mould. After each layer of slurry and ceramic is added to the wax tree, they have to be dried before a new layer can be applied.
8. **Ceramic Slurry and Stucco:** For investment casting.
9. **Fume chamber:** All work involving the release of any toxic fumes could be done at this chamber.
10. **Wax printer:** There is a wax printer at production engineering facility which can be used for wax pattern printing.

11. **Post processing tools after metal solidification:** The standard tools for post processing cast products are available at the lab. This includes drilling, cutting, polishing, sand blasting etc. Other post processing services could at the moment be easily attained from the welding and production engineering lab nearby. There is also a high pressure water gun for proper cleaning of castings after they are taken out of the mould or shell.

4.2 *Layout of the Lab*

It is difficult to choose new tools for the lab without having an accurate idea of how much space is actually available to accommodate them. As no CAD layout files of the foundry could be found, a new one was made from scratch, shown in figure 30. All the dimensions shown are in millimetres. Some modifications were done to the layout. The vacuum furnace is going to be removed from the lab, which gives some empty spaces to work with. The furnaces on the left, the sand system and the bead blaster can not be moved or are not feasible to relocate. The remaining of the things are reshuffled to some extent so that the room on the upper left could now serve as a cleaner room to accommodate the wax printer and the OES analyzer(which needs clean environment for efficient functioning). The ceramic furnace is also brought to the left under the fume collecting funnel. The revised modified layout is shown in figure 31 which is used as the starting point to develop the 3D layout. And as can be seen from the layout, there is a free space measuring 5.7 m*3.2 m which can be used for new additions to the lab.

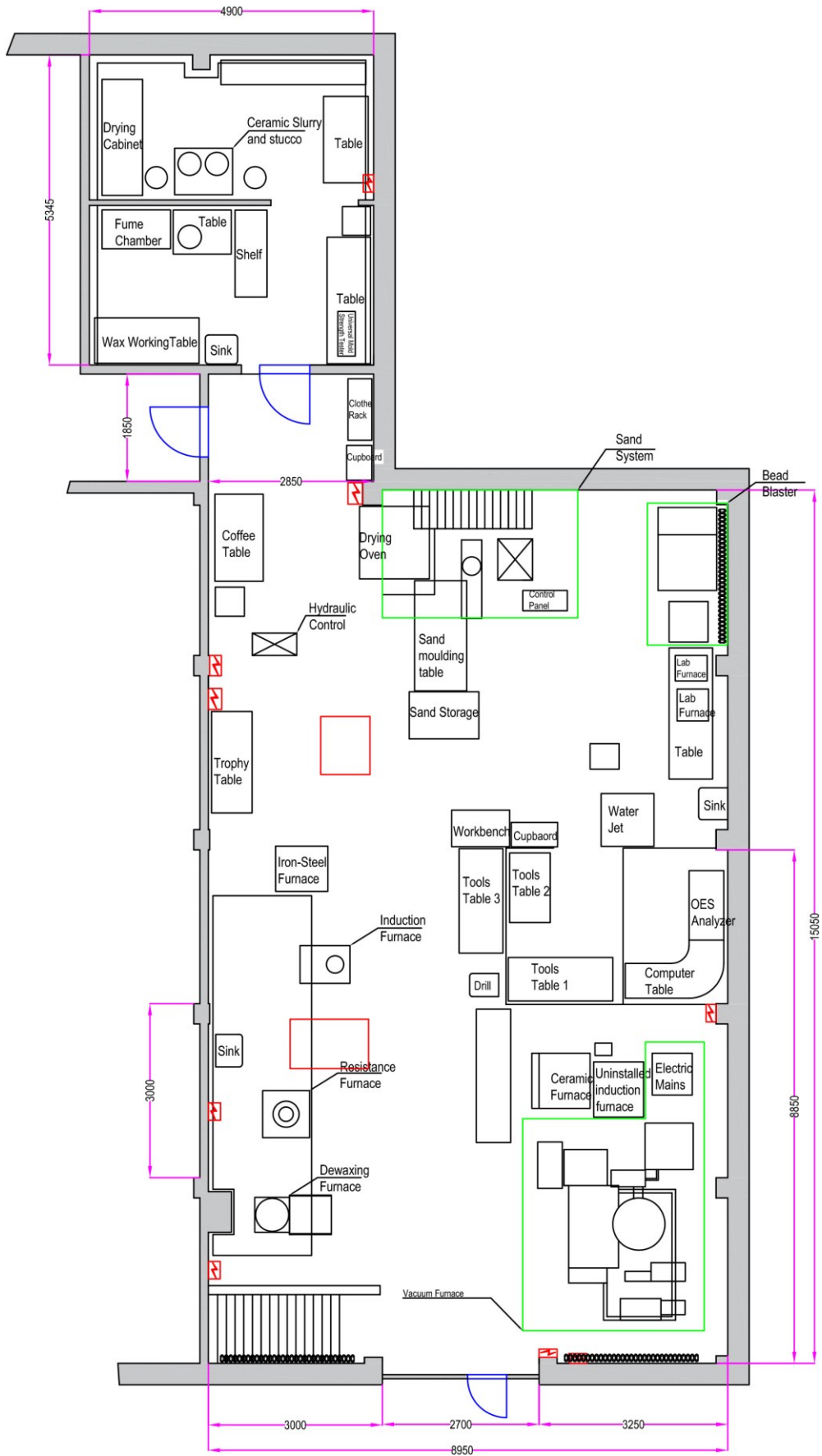


Figure 30: Existing layout

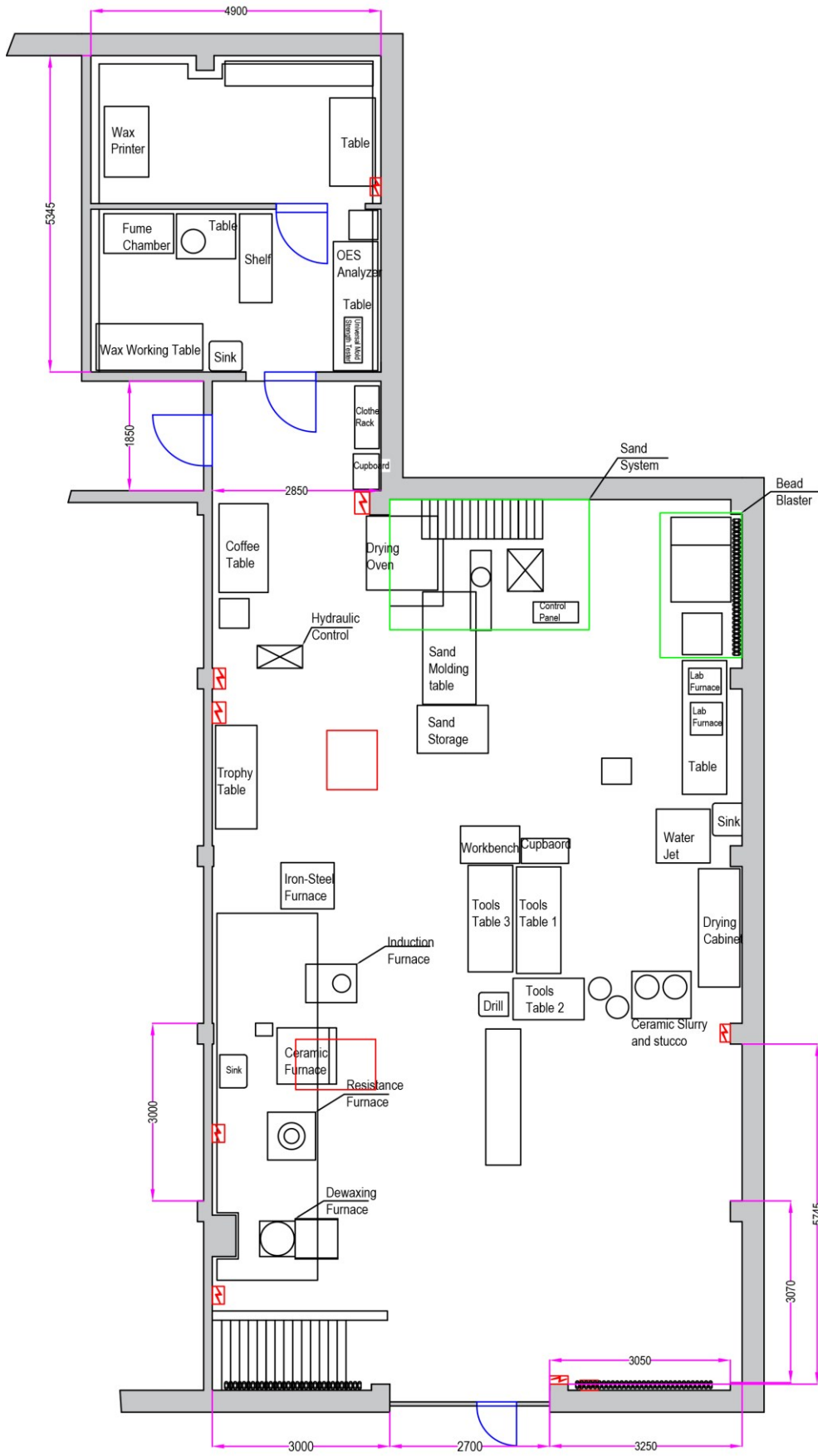


Figure 31: Proposed new layout of the lab

4.3 **Best possible tools for Aalto ENG foundry**

Sand casting and investment casting are the two types used mostly at Aalto ENG foundry. The volume of casting done is usually low which in most cases does not justify making a pattern that can withstand thousands of cycles. Hence, a 3D metal printer is both expensive and unnecessary for the lab for printing of dies. Although DED based technology could be used as repair tool for die casting, this is also expensive and unnecessary from the point of view of the lab. A thermoplastic pattern is useful for sand casting but 3D thermoplastic printers are quite readily available at Aalto premises from Addlab or other units, hence that is not required either. Wax printers are ideal for printing wax sacrificial patterns and using them for investment casting. There is already one wax printer available at the production engineering facility, and buying another is not necessary at the moment.

A sand printer to make direct sand moulds from 3D models would be ideal for the lab for many different reasons:

- The ability to make moulds directly renders making of patterns unnecessary. And since the volume of production is small and also the fact that, there aren't much of a pattern production facility at Aalto, this is ideal.
- A sand printer enables the moulds to be designed including the gates and channels. This also allows for topological optimization of the final product which reduces product cost.
- The dimensional accuracy and tolerance is within acceptable limits of traditional moulding but it can make more complex moulds than traditional methods.
- From the perspective of industrial foundries, or metal manufacturing as a whole, this process also has the advantage of speed. As will be seen in the following sections, 3DP binder jetting sand printers have very good printing speed. Manufacturer brochures even shows speed up to 85 L/h, which is very fast compared to other additive manufacturing methods.
- The build volume available in the commercial sand printers are already big enough for integration into foundries.
- There are also little tests done on 3D printed moulds and cores, and this provides an excellent research opportunity for the laboratory. This can also serve as a starting tool for other optimization regarding the technology itself, for example, finding better binders or tuning the printer for multiple sand and binder types.
- Another advantage of sand printing + casting, over direct metal printing is that, many small mould parts can be printed and then joined together to cast a object much larger than the build volume of the sand printer. However, in direct metal printing small parts joined together later with welding results in products with compromised qualities.

Some optimistic trends regarding sand printers are as follows:

1. The patents are going to expire in couple of years.
2. There are new manufacturers starting to appear. At least as many as 4 different manufacturers are found in China, and one in Poland(details given in the next section).
3. As more and more manufacturers are entering the market, the bigger players will be forced to reduce the cost and allow more flexibility to the users. For example, the freedom of using own sand and binders will reduce the prices by a big margin.

4. As more and more foundries start adopting sand printers, the rising market will result in more variation in products and attract new manufacturers and customers.

In addition to the sand printer, a handheld 3D scanner would be a suitable addition for the lab as well. These can make accurate digital model of real life objects, thus are proving to be valuable tools for reverse engineering and checking dimensional accuracies at each stage of casting. It can prove to be valuable not only for Foundry lab but for other units of Mechanical Engineering department of Aalto. The conclusion therefore is that, a sand printer and 3D handheld structured light scanner will be the most valuable addition for Aalto ENG foundry. The subsequent sections summarize some available options at the market pool.

4.4 Different models of sand printers from well-known manufacturers

A maximum of 5.7m * 3.2m space could be freed up at the lab for installing a new sand printer, however such huge printer is not actually required for the lab. An ideal space would be around 3m * 3m.

The well known sand printer manufacturers at the moment are ExOne, Voxeljet, Viridis 3D and Sentrol. Out of these ExOne and Viridis 3D are USA based companies, Voxeljet from Germany and Sentrol from South Korea. Sentrol is a new player in this field and they have entered this market in 2016[43]. Out of these, ExOne, Voxeljet and Viridis 3D are all manufacturing sand printers with 3DP binder jetting technology while Sentrol is making both 3DP and SLS technology sand printers. Below a short discussion is given about the different models available from each of the manufacturers that can be found. Z-Corp used to make binder jetting sand printers as well. However, after being acquired by 3D systems, they have no longer been producing sand printers. EOSINT also made SLS sand printers, but recently they have abolished this line of product.

ExOne

Table 2 shows the specifications of the 3 models of ExOne sand printers that are available now. Sand printers from ExOne are being used at many foundries already, the industrial scale printers are offering good speed and large build volume.

Table 2: Specifications of different sand printers from ExOne[44]

<i>Description</i>	<i>S print</i>	<i>S-Max</i>	<i>S-Max Plus</i>
<i>Build Volume</i>	800*500*400	1800*1000*700	1800*1000*600
<i>Layer Thickness</i>	240-500 μm	240-500 μm	240-500 μm
<i>Build Speed</i>	16-36 L/h	60-85 L/h	60-85 L/h
<i>Weight</i>	3500 kg	6500 kg	5800 kg
<i>Dimension</i>	3270*2540*2860mm	6900*3520*2860 mm	3860*3470*2890 mm
<i>Technology</i>	Binder Jetting	Binder Jetting	Binder Jetting
<i>Powder</i>	Silica Sand	Silica Sand	Silica Sand
<i>Binder</i>	Furan, phenolic or silicate.	Furan	Phenolic
<i>Bending Strength</i>	No info	No info	No info
<i>Other Remarks</i>	This is the smallest size from ExOne. Price range 500-600k Euro.	Costs about 800k Euro.	Expected to Cost similar to S-Max.

Since Aalto Foundry is already using phenolic sand system for no bake sand casting and has expertise in this regard, it makes the most sense to use phenolic system. And also because Furan is a possible human carcinogen S print with phenolic system is the right choice for Aalto Foundry if it can be afforded. The build speed is appreciable and the size also fits the available space at the Lab. The speed of upto 36 L/h is very fast and good enough for Aalto foundry. The technology is proven and is being adopted by foundries worldwide to improve their product and increase productivity.

Voxeljet

Voxeljet from Germany is also making some good quality sand printers. The VX 4000 is not listed in the table as it is way too big for the Aalto Foundry. The VX1000 is the biggest the foundry can fit and it costs an estimated 600k Euro. VX200 could be a compromise with the tightest budget, but the build space is very small and no data on building speed is quoted in the product brochure. Table 3 shows 3 different models from Voxeljet.

Table 3: Specifications of different sand printers from Voxeljet[30]

<i>Description</i>	<i>VX 200</i>	<i>VX 1000</i>	<i>VX 2000</i>
<i>Build Volume</i>	300*200*150 mm	1000*600*500	2000*1000*2300
<i>Layer Thickness</i>	300µm+	300µm+	300µm+
<i>Build Speed</i>	No info, 'very fast'	No info, 'very fast'	47 L/h
<i>Weight</i>	450 kg	3500 kg	5500 kg
<i>Dimension</i>	1700*9000*15000mm	2800*2400*2300 mm	2500*4900*2700 mm
<i>Technology</i>	Binder Jetting	Binder Jetting	Binder Jetting
<i>Powder</i>	Silica Sand	Silica Sand	Silica Sand
<i>Binder</i>	Phenolic/Furan, not explicitly specified	Phenolic	Phenolic
<i>Bending Strength</i>	More than 220 N/cm ²	More than 220 N/cm ²	More than 220 N/cm ²
<i>Other Remarks</i>	This could be enough even though the volume is small.	Best if it could be afforded, specifications are quite closer to S print of ExOne	Too large. Unnecessary for the Lab. Cost estimate is around 1000k Euro.

Viridis3D and Envisiontec

Viridis 3D and Envisiontec brought forward the robotic additive manufacturing system. The advantage of this system is that it provides a large build volume and also the print is not confined within the printer but rather the print could be on any worktable, suitable for the practical conditions of any foundry. The print head is attached to an industrial robot(ABB) which does the work for both sweeping of sand and distributing the binder. The speed is quite high and from design to casting can happen very fast, cutting lead time of any unique component manufacturing drastically. It has been described as game changer for metal casting[45]. Table 4 shows some specifications of Viridis 3D robotic additive manufacturing system.

Table 4: Specifications of Viridis3D sand printer[46]

<i>Description</i>	<i>RAM 123/224</i>	<i>RAM 236/336</i>
<i>Build Volume</i>	28" wide printhead	38" wide printhead
<i>Layer Thickness</i>	200-500 µm	200-500 µm
<i>Build Speed</i>	Not specifically mentioned	
<i>Weight</i>	Not given	
<i>Dimension</i>	Not given	
<i>Technology</i>	Binder Jetting	
<i>Powder</i>	Sand GFN65	
<i>Binder</i>	Modified Furan	
<i>Bending Strength</i>	120 N/cm ² and 255 N/cm ² (Oven Baked)	
<i>Other Remarks</i>	As it uses an industrial robot, the cost will be quite high for a low production need.	

It must be noted that the inclusion of an industrial robot in this product raises the price.

Sentrol

Sentrol has only recently started making sand printers[43]. They are the only ones to produce sand printers with both SLS and 3DP technology.

Table 5: Specifications of sand printers from Sentrol

<i>Descript ion</i>	<i>Sentrol SLS</i>			<i>Sentrol Binder Jetting</i>	
	SS 600	SS600G	SB300	SB400	SB 1000
<i>Build</i>	600*400*40	600*400*40	210*297*100	300*420*15	1700*1000*17
<i>Volume</i>	0	0		0mm	00
<i>Layer Thickne ss</i>	200 µm+	200 µm+	100 µm+	100 µm+	100 µm+
<i>Build Speed</i>	0.029 L/h	1.108 L/h	Upto 0.018 L/h	Upto 0.018 L/h	100 L/h
<i>Weight</i>	500 kg	500 kg	100 kg	300 kg	1000 kg
<i>Dimensi on</i>	2200*1380*	2000*1220*	1500*1000*12	1700*1000*	10000*10000*
<i>Type</i>	2455	2490	00mm	1700	10000
	Laser Sintering		Binder Jetting		
<i>Powder</i>	Resin Coated Sand	Resin Coated Sand	Proprietary Moulding Sand	Proprietary Moulding Sand	Proprietary Moulding Sand
<i>Binder</i>	Laser Sintered	Laser Sintered	Furan, Phenolic, Silicate	Furan, Phenolic, silicate	Furan, Phenolic, Silicate
<i>Bending Strength</i>	No Data				
<i>Other remarks</i>	The build speed is quite low, except for SB 1000. But SB 1000 shows a huge dimension, which looks unlikely. This could be a mistake at their website.				

SLS technologies are still lower priced than the 3DP processes. However, the speed quoted in Sentrol brochure is very low and can rarely be justified in the printing of big sand moulds. They could rather be a good addition for the making of small intricate cores. All the models except SS600G are very slow. SB1000 is appears to be very big and industrial size, although the data presented (speed: too high, size: too big, weight: too small for the size) looks quite contradictory.

EOSINT

Eosint also produced sand printers but they have recently abolished this line of product. The technology they used was SLS. Some specifications found from archive are given in table 6 for better comparison with other products.

Table 6: Specifications of Eosint S750 sand printer[32]

<i>Description</i>	<i>EOSINT S750</i>
<i>Build Volume</i>	720* 380*380 mm
<i>Build Speed</i>	Upto 2.5 L/h
<i>Layer Thickness</i>	200 μ m
<i>Technology</i>	Laser Sintering, 2 x 100W CO ₂ Laser
<i>Dimension</i>	1420*1400*2150 mm process cabinet. Other peripherals are also needed. Total installation space recommended is 4.5m*4.6m* 2.7m.
<i>Weight</i>	2200 kg
<i>Scan Speed</i>	3.0 m/s

The size of this model was quite compatible with the Aalto Foundry and the speed was also moderate. However, the laser sintering machine is no longer available for purchase as EOSINT decided not to pursue the product anymore.

4.5 Lesser known sand printer manufacturers in the market

Apart from the big manufacturers, many new manufacturers of sand printers are starting to emerge. This is a very good sign for this line of product. More players will definitely help end the monopoly and bring down the price.

Sand made was a startup from Poland which unveiled a small SLS sand printer in 2015. Although the build volume is very small, the printer could have been an ideal addition for printing complex cores rather than the whole mould. However, the company is being liquidated now. Some specification of Sandmade's LS1 are given below.

Table 7: Specifications of Sandmade LS1 sand printer[47]

<i>Description</i>	<i>Sandmade LS1</i>
<i>Build Volume</i>	150*150*150 mm
<i>Build Speed</i>	Not explicitly mentioned, but expected to be very slow.
<i>Layer Thickness</i>	60-350 μ m
<i>Technology</i>	Laser Sintering, 40W CO ₂ Laser
<i>Dimension</i>	Not found
<i>Weight</i>	Not found
<i>Scan Speed</i>	5.0 m/s

As encouraging as it might be to see new startups on this line of product, buying such products always suffer from uncertainties. There is little guarantee of post purchase help. Also, how well these printers function is an issue.

VTECH Additive Manufacturing Solutions from China has sand printers with SLS technology. For a sand printer, the laser power seems to be very low. Hence, although a printing speed is not provided by the manufacturer it can be assumed that it will be very slow.

Table 8: Specifications of sand printers from Vtech additive manufacturing solutions[48]

<i>Description</i>	<i>VT S320</i>	<i>VT S500</i>
<i>Build Volume</i>	320*320*450 mm	500*500*400mm
<i>Layer Thickness</i>	200-500 μ m	
<i>Build Speed</i>	Not specifically mentioned	
<i>Scanning Speed</i>	4 m/s	6 m/s
<i>Dimension</i>	1760*1070*2050mm	2070*1280*2080mm
<i>Technology</i>	Laser Sintering	
<i>Powder</i>	Coated Sand	
<i>Laser</i>	CO ₂ 30W	CO ₂ 55W
<i>Bending Strength</i>	Not specified	
<i>Other Remarks</i>		

Nanjing Baoyan Automation Company Limited is another company which is making sand printers with 3DP technology. The specification of the printers look quite good for Aalto foundry. Both MP 400 and 800 could be good addition to the lab. However, not much information could be obtained apart from those below. No confirmation about building speed either.

Table 9: Specifications of sand printers from Nanjing Baoyan Automation Company[49]

<i>Description</i>	<i>MP 400</i>	<i>MP 800</i>
<i>Build Volume</i>	350*290*250 mm	800*550*450 mm
<i>Layer Thickness</i>	150-500 μ m	
<i>Build Speed</i>	Not specified	
<i>Scanning Speed</i>		
<i>Dimension</i>	1400*950*1300 mm	3300*2600*2900
<i>Technology</i>	Binder Jetting	
<i>Powder</i>	All types of sand	
<i>Binder</i>	Furan and Phenolic	
<i>Bending Strength</i>	Not specified	
<i>Other Remarks</i>		

Wuhan EasyMade Technology from China is another company which is making sand printers based on 3DP technology. The specifications could be seen in table 10.

Table 10: Specifications of sand printers from Wuhan EasyMade Technology[50]

<i>Description</i>	<i>Easy 3DP-500</i>	<i>Easy 3DP-1000</i>	<i>Easy 3DP 1500</i>
<i>Build Volume</i>	500*500*300	1000*600*400	1500*1000*800
<i>Layer Thickness</i>	100-500 μ m		
<i>Build Speed</i>	20-30 sec/layer		
<i>Weight</i>	Not Given		
<i>Dimension</i>	Not Given		
<i>Technology</i>	3DP binder jetting		
<i>Powder</i>	Many different sand options		
<i>Binder</i>	Phenolic		
<i>Bending Strength</i>	Not Given		
<i>Other Remarks</i>			

The Easy 3DP-500 has a size suitable for Aalto lab. Build speed is not given explicitly but from the information provided, a preliminary calculation shows a build speed of 3L/h. This could be a reasonable speed provided the purchase price is reasonable. The machines use phenol as binder. The price tag for this product is around 130k Euro. Easy 3DP-1000 has a price tag around 240k Euro, while the largest is priced around 390k Euros. From personal communication, it was also known that the binder has to be bought from the manufacturer, while the sand could be bought from other sources. However, the price of the binder was above 40 Euro per litre and that is quite high considering the binder now in use at the lab costs less than 1 euro per litre. 1 year warranty is also promised but they still do not have any European representative yet for fast post purchase assistance.

The last manufacturer in this list is Shining 3D from China which has brought a range of products for the 3D industry, both in the form of printers and scanners. The company offers sand printers with SLS technology, specifics of these can be seen in table 11.

Table 11: Specifications of sand printers from Shining 3D[51]

<i>Description</i>	<i>EP-C3650</i>	<i>EP-C5050</i>	<i>EP-C7250</i>
<i>Build Volume</i>	360*360*500 mm	500*500*500	700*700*500 mm
<i>Layer Thickness</i>	80-300 μm	80-300 μm	80-300 μm
<i>Build Speed</i>			
<i>Weight</i>			
<i>Dimension</i>	2500*1300*2200	2000*1300*2300	2000*1500*2650
<i>Technology</i>	Laser Sintering		
<i>Powder</i>	Resin coated sand		
<i>Laser</i>	55W CO ₂	55W CO ₂	100 W CO ₂
<i>Scanning Speed</i>	5 m/s	6 m/s	8 m/s
<i>Other Remarks</i>			

The smallest printer EP-C3650 quotes around 90k Euro, the midrange EP-C5050 at 110k and the largest EP-C7250 around 155k Euro. As with the other Chinese manufacturers, the laser power of EP-C3650 and EP-C5050 looks very small for sand printers. Hence, they are expected to be slow.

4.6 3D scanning options

A comparison between the different 3D scanning technologies was shown in the previous chapter. The structured light handheld scanners will be the most suitable addition to Aalto ENG foundry. They are the least expensive, their speed and ease of use justifies their inclusion. No such scanners are available currently at Aalto Production Engineering lab or ADDLab.

Artec 3D

Artec 3D offers two different hand held structured light scanners, the Artec Eva and Artec Space Spider. Eva is very fast and suitable for common applications. However, spider has a greater precision although it is slower than Eva. Both the scanners can be used together so that the speed of Eva and precision of Spider can be utilized at once to generate models good enough for engineering purpose at a tremendous speed. Some of the specifications are given in the table 12.

Table 12: Specifications of 3D scanners from Artec 3D[52]

<i>Description</i>	<i>Artec Eva</i>	<i>Artec Space Spider</i>
<i>Ability to capture texture</i>	Yes	Yes
<i>3D resolution</i>	0.5mm	0.1 mm
<i>3D point accuracy</i>	0.1mm	0.05 mm
<i>3D accuracy over distance</i>	0.03% over 100 cm	0.03% over 100 cm
<i>Texture Resolution</i>	1.3 MP	1.3 MP
<i>Colors</i>	24 BPP	24 BPP
<i>Light source</i>	Flash bulb	blue LED
<i>Working distance</i>	0.4-1 m	0.2-0.3m
<i>Video frame rate</i>	16 fps	7.5 fps
<i>Exposure time</i>	0.0002s	0.0002s
<i>Data acquisition speed</i>	2 million points/s	1 million points/s
<i>Multi core processing</i>	Yes	Yes
<i>Dimensions</i>	261.5x158x63.7mm	190x140x130mm
<i>Weight</i>	0.85 kg	0.85 kg
<i>Output formats</i>	OBJ, PLY; WRL, STL, AOP, ASCII, PTX, E57, XYZRGB	
<i>Output format for measurements</i>	CSV, DXF, XML	CSV, DXF, XML
<i>Processing capacity</i>	40 million triangles/ 1GB RAM	
<i>OS</i>	Windows 7, 8, 10	
<i>Computer requirements</i>	i5 or i7, 12 GB RAM	i5 or i7, 18GB RAM
<i>Calibration</i>	No special requirement	

One recent example of use of 3D Scanner was found at foundry magazine website, which describes how a foundry named Wilman Industries at Cedar Groves, United States have used the 3D scanner Artec Eva to their advantage. Wilman Industries is a green sand and no bake casting industry. The Artec 3D Eva Scanner has helped in documenting and tracking the dimensional accuracy of their patterns and castings. The ease of use, the large field of view and the resolution of this scanner has helped the foundry capture data faster than laser scanners[38]. But the scanner which was originally only aimed for dimensional measurement have very soon found new uses at the foundry like analysis of tools, scanning of moulds and patterns, reverse engineering and problem solving etc[38]. However, for engineering purposes, the Artec space spider or the combination of both offers better solution. Eva alone costs around Euro 13k, Spider around Euro 20k. But the combo is offered by Artec at a price of 26k Euro. In addition to these, the license of processing software has to be bought from Artec.

Shining 3D

Shining 3D from china has two variants of handheld scanners. Their specifications are given in the table 13.

Table 13: Specifications of 3d scanners from Shining 3D[51]

<i>Description</i>	<i>EinScan-Pro</i>	<i>EinScan-Pro+</i>
<i>Scan modes</i>	Handheld HD, Handheld Rapid Scan, automatic scan, fixed scan	Handheld HD, Handheld Rapid Scan, automatic scan, fixed scan
<i>Accuracy</i>	Automatic: 0.05mm Handheld HD: 0.1 mm	Automatic: 0.05mm Handheld HD: 0.1 mm
<i>Texture Scan</i>	Normally No, Yes with purchase of colour pack	Normally No, Yes with purchase of colour pack
<i>Speed</i>	Handheld HD: 15 frames/s	Handheld HD: 550000 points/sec
<i>Aligning method</i>	Markers and feature	Markers and feature
<i>Outdoor operation</i>	No	No
<i>Light Source</i>	White LED light	White LED light
<i>Output data format</i>	OBJ, STL, ASC,PLY	OBJ, STL, ASC,PLY
<i>Weight</i>	0.8 kg	0.8 kg
<i>Turntable loading capacity</i>	5 kg	5 kg

The Einscan pro+ is only slightly updated version of Einscan pro. Most of the specifications are same. However, the Einscan pro+ is more suitable when it comes to larger objects as it can scan faster. Powder spray is recommended before scanning when there is transparent, reflective or very dark object is being scanned. The variation in price between the two are not that much either. Einscan-Pro is priced around 5k Euros and Einscan-Pro+ around 6k Euros. The turntable and automatic scan mode are expected to deliver very good scan results. Also, the price is very reasonable. These can be bought as tests to confirm the need of 3D scanners. If satisfactory results are found, the higher range products could then be bought.

Other scanners

Scanners from only two makers are listed here just to give an idea about the price range and types available. There are many manufacturers available in the market today, quotation and comparison of all of them is out of scope for this thesis. Handheld laser scanners can be a good addition too. However, they are heavier on the price tag. An example is HandyScan 700 from Creaform. Although it offers very good resolution, the price is expected to be over 40k Euros. A good list of 3D scanners for comparison, comprising of both price, technology and introduction videos could be found in [53]. Other manufacturers of 3D scanners include GOM and Faro.

5 Possibilities and challenges with new tools

The recommended procurement of a sand printer and 3D scanner would serve as the starting step for going digital and paving way for smart foundries. The incorporation of more digital processes into foundries is required to keep up with global manufacturing trend. As for Aalto Foundry, the purchase of a 3D sand printer presents challenges, risks and possible gains. These are demonstrated in the SWOT analysis, figure 32.

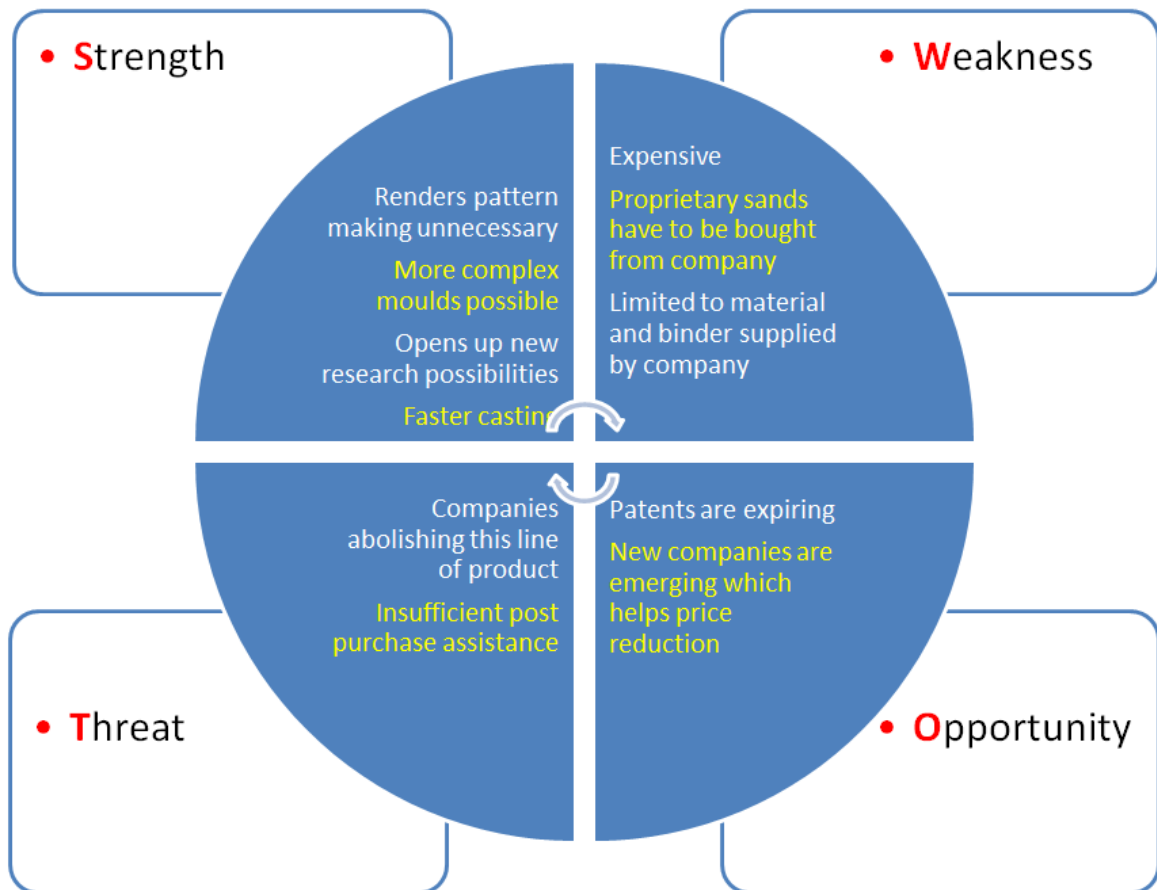


Figure 32: SWOT analysis for the purchase of a sand printer

Foundries are beginning to adopt the hybrid method of 3D printing the sand mould and then using it for casting. The process gives advantage of both additive manufacturing and casting. Complex shapes can be cast very quickly and accurately. An example is the company 3Dealise based in London, which uses this hybrid method of casting and estimates the cost to be 100 Euro per kg of product, whereas metal printing costs more than 10 folds this cost. The values were based on a presentation given in 2015 at Additive world conference. Apart from the fact that this process is gaining industrial preference, 3D printed sand mould and cores and their effect on the final casting brings in lot of research opportunities for Aalto foundry lab. These include the effect of curing and printing parameters on the final cast. Printing parameters are things like printer speed, powder type, particle size, activator content, binder content etc. while curing parameters include curing time and temperature.

Some challenges regarding a procurement of sand printer for Aalto ENG foundry includes:

1. Sand printers are still quite expensive. Even the ones with small build volumes cost couple of hundred thousand euros from the well known manufacturers.
2. There are few manufacturers and models to choose from.
3. In most cases, the sand and binder has to be bought from the manufacturer. This limits researching abilities for the lab and also increases cost.
4. Post purchase assistance. There are instances where even well known companies have abolished this line of product (example: EOSINT), or a company being sold to other company and new company not pursuing these products(example: Z corp). Sandmade was a Polish company which started making very cheap and small SLS sand printers. The company however started its liquidation process very recently.

The 3D scanners are proven technology for reverse engineering. And with the addition of sand printers, from 3D scanning to final casting could be achieved very fast. Together with production engineering department, a reverse engineering project or course could be a valuable addition for students as well. For Aalto foundry, a greater use is in the dimensional checking at each stage of casting. For example, measuring the pattern, the mould, and even the final product against CAD data brings in new opportunities. A rotating platform can help with faster and accurate digital 3D model making.

Aalto ENG foundry also has some collaboration with ARTS and sculptures are usually plaster casted in a lost pattern method. The patterns are made with wax. This can be done differently with the help of 3D scanner and sand printer. The digital model can be created from the sculpted wax(or clay) and then sand mould can be 3D printed. This process also allows making copies from one single wax pattern. The wax or clay used for sculpting can be reused for new sculptures.

The 3D mock up of the lab, together with the proposed new tools and modifications is shown in figure 33, more images can be found in Appendix 1. The sand printer shown in the mock up is VX1000 from Voxeljet. A large rotating platform is also shown in the representation.

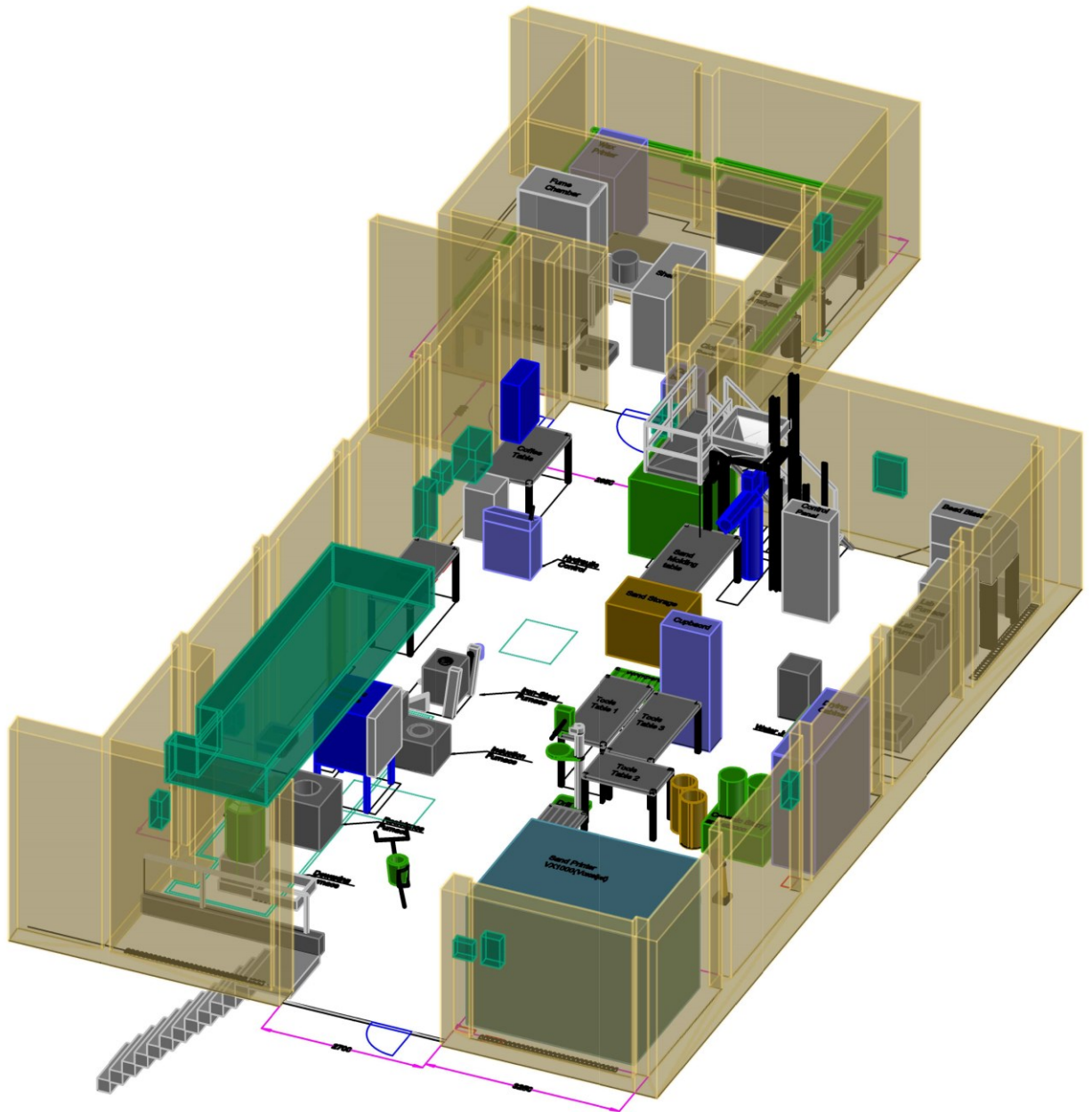


Figure 33: 3D representation of how the future of Aalto foundry may look like

6 Discussion

6.1 Results

The comparison between direct metal additive manufacturing and casting from literature study has shown why metal additive manufacturing can not be a wholesome replacement of casting. At the moment metal additive manufacturing can only be justified for products which have very complex structure, a small size, small production volume and are too difficult or expensive to produce using the conventional methods like subtractive manufacturing or casting. However, the versatility of additive manufacturing has given rise to new tools for foundries. Additive manufacturing could be used for printing plastic pattern, wax pattern, sand mould and ceramic mould. It can also be used in the printing of metal patterns or the repair of dies for die casting etc. Other emerging tools that were discussed are subtractive sand mould manufacturing and 3D scanners. After careful consideration of the existing condition of Aalto ENG foundry, the conclusion is that a sand printer and a 3D scanner will be valuable new additions to the lab.

For industrial scale sand printers, the SLS technology was found to be quite slow but it could be used for the lab if it offered reasonably good speed, for example the EOSINT S750 which offered 2.5L/h of build speed. However, 3DP technology shows better promise in terms of speed. This is also reflected in the fact that the major sand printer manufacturers are producing 3DP sand printers. SLS being produced only by Sentrol. Even though the new manufacturers cost 2 or 3 folds less than the well known manufacturers, they still cost more than 100k Euros. And there are not much of guaranteed post purchase assistance, or proper certifications. The ideal purchase recommendation for a sand printer is given below:

- Voxeljet: VX1000 (VX 200, only with the tightest budget)
- ExOne: S-print
- Viridis3D: RAM 123/224
- Sentrol: SS600G

Buying from the lesser known and new manufacturers is not recommended at this point. This is because at the initial point of development many bugs are expected in all products. It can also not be ascertained how much of post purchase assistance could be obtained from these manufacturers in case of need and emergency. Also, it could not be known if the products are certified to be imported into EU. Even if procurement decisions are taken for these, a visit in person and product demo is first recommended.

For 3D scanners, the Artec Eva was claimed to be good enough for iron foundry. However, for engineering purposes, a greater accuracy facilitates the purpose even further if it is going to be used for dimensional inspection. Hence, Artec Spider will be a better addition to the lab. The company also have combo reduced price package if both Eva and Spider are bought. When used in conjunction, Eva's speed and Spider's accuracy together gives an accurate model at a very fast speed. The Einscan Pro+ from Shining 3D has a very competitive price, this could be tried out first as well to find out if the technology truly holds promise for the lab. The higher range products could then be sought afterwards.

Modified 3D layout to accommodate the new tools is prepared as part of the thesis study. These would be useful for other development of lab and for future reference. More images of the layout work can be found at Appendix 1.

6.2 Challenges and future work

A great deal of time and effort was given in the making of 2D and 3D layout of the lab. An accurate layout is required not only for this work but for any future reference and development of the Lab. AutoCAD 2018 was chosen for this as it is quite handy for layout making purpose. However, since it is not parametric software, the making was quite time consuming. A video was also generated during the process which will help in demonstration purpose for the lab.

Ofcourse the next step of this thesis could be the actual implementation of the tools at Aalto ENG foundry Lab. Apart from the technology used in the tools, list of manufacturers along with their product specifications are presented in this thesis as well, so as to have a better overview of the market situation. Price estimates were given wherever possible, which are in no way exact and can be subject to change at any time. But, these can be used by authorities when procurement decisions are taken for the lab. It must also be emphasized that proposed change in layout was done assuming that the vacuum furnace is going to be removed from the lab. Unless and until this happens, it will be quite difficult to accommodate the sand printer in the lab.

The price of sand printers and the restrictions imposed by the manufacturers in terms of raw materials still hinders the widespread use of sand printers in foundries. If proprietary sand and binder has to be constantly bought or imported from the manufacturer it poses a serious difficulty both in terms of economics and flexibility. While the technology shows a lot of promise, unless the price goes down it is very difficult for small foundries to acquire this product. But as discussed in the previous chapters, some optimistic trends of new manufacturers entering the market pool and patents expiring can be seen. Limitation on production volume is still an issue, it might find its use for build to order or prototyping purposes. Another unique advantage for the use of sand printer is that only the mould is produced, the rest of the casting remains as it is, based on knowledge of so many centuries. Hence, its integration into foundries only brings changes in the making of moulds. Not only this mode of hybrid manufacturing but other hybrid manufacturing methods involving additive manufacturing, subtractive manufacturing and casting are expected to be normal in coming days. Industries might be switching between technologies or hybridizing them up as per product requirement, production volume and time constraint but achieve maximum economic advantage at the same time.

Like sand printers, 3D scanners are relatively new technology as well that are starting to find themselves in industries. The mesh structure that they normally produce could be used directly for exact print or measurement and inspection purposes. However, if a 3D model is required from scan data which can be altered as per requirement then reverse engineering softwares are required. This process requires some engineering know how and there is a learning curve involved. Surfacing and reverse engineering softwares are emerging and they will improve in coming future. May be it will be fully automated in future when 3D scan data can be used directly for editing. There are also some concerns that the scanners are not accurate enough, or are having difficulties in some particular types of products or surfaces. However, it can be argued that the relatively young technology is definitely going to improve in coming days and it is already quite good enough to be tried and tested at the lab for possible different uses already mentioned in previous chapters.

7 Conclusion

The versatility of additive manufacturing is forcing changes across all manufacturing and it is also offering new opportunities in many forms. New methods of additive manufacturing are being unveiled rapidly and it can be quite overwhelming in choosing the right technique for the right purpose. As a bench mark study, a comparison between direct metal printing and casting was first shown in this work which points towards the strengths and weaknesses of both the processes. And it also proves that neither can be a wholesome replacement of the other. However, foundries have the option to embrace AM and use it to their advantage rather than being stubborn and repelling AM. The hybrid method of casting using additive manufacturing can produce more complex products and bring down the lead time of products. The different ways of doing so was also discussed.

For Aalto Foundry, the new additions suggested are a sand printer and a 3D scanner after careful study of the tools available and space available at the lab. Although, the market pool of sand printer is still very small, new manufacturers coming to this product over the world is a positive sign which will bring down cost in near future. More manufacturers of sand printers will also mean more variants of products available for foundries. This will enable even small foundries to adopt the AM enabled techniques. The use of 3D scanners is increasing as well, across all manufacturing and in foundries. Overtime, it can be expected that these tools will be a norm in foundries across the globe, and expertise will be required for them. Hence, their inclusion can be valuable for future teaching and research purposes of Aalto ENG foundry.

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Appendices

Appendix 1. Different views of the proposed layout

Appendix 2. Visuals of some of the products listed in chapter 4

Appendix 1: Different views of the proposed layout

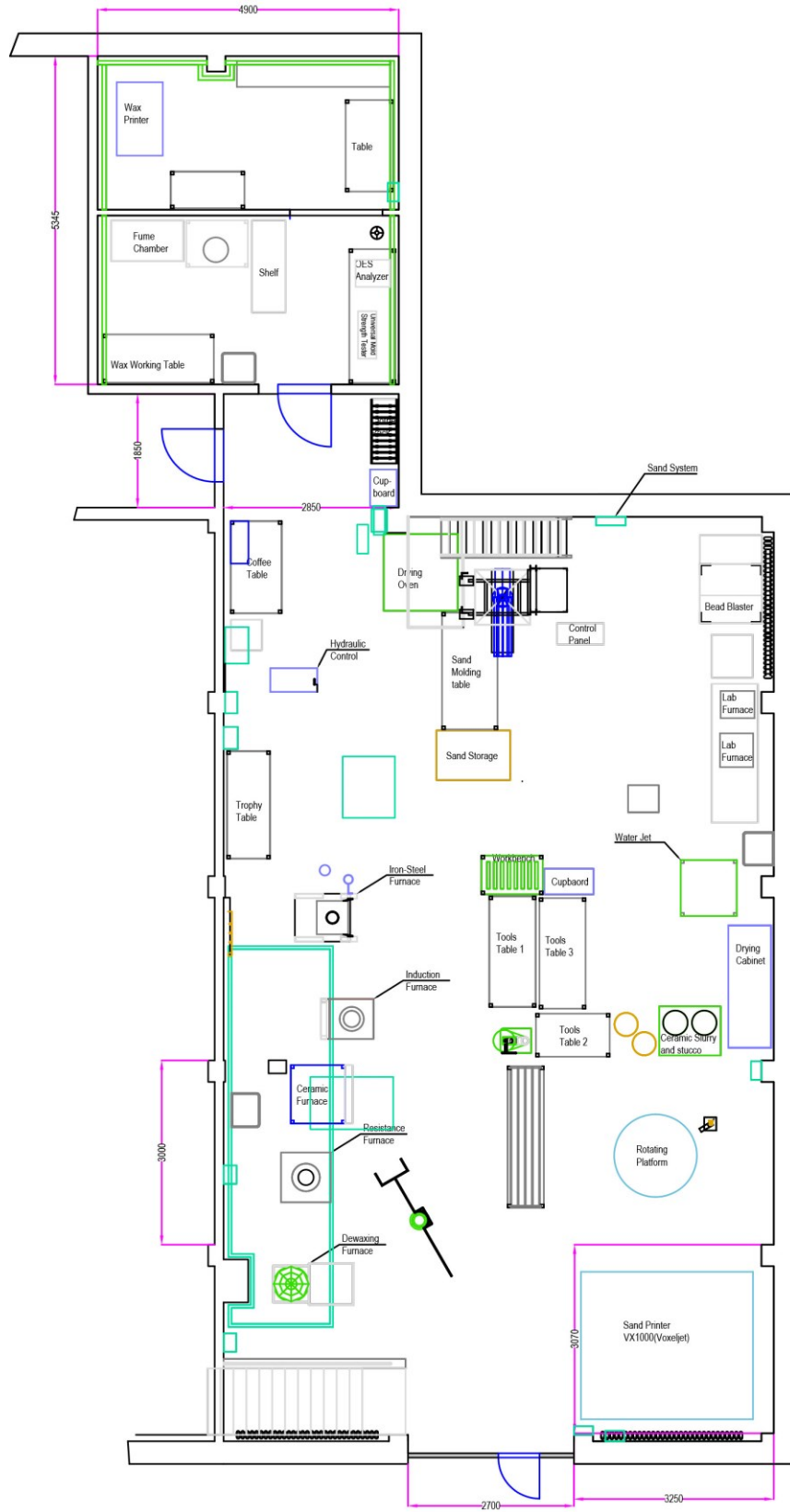


Figure: Modified 2D layout with new tools



Figure: 3D mock up, View 1(walls hidden)

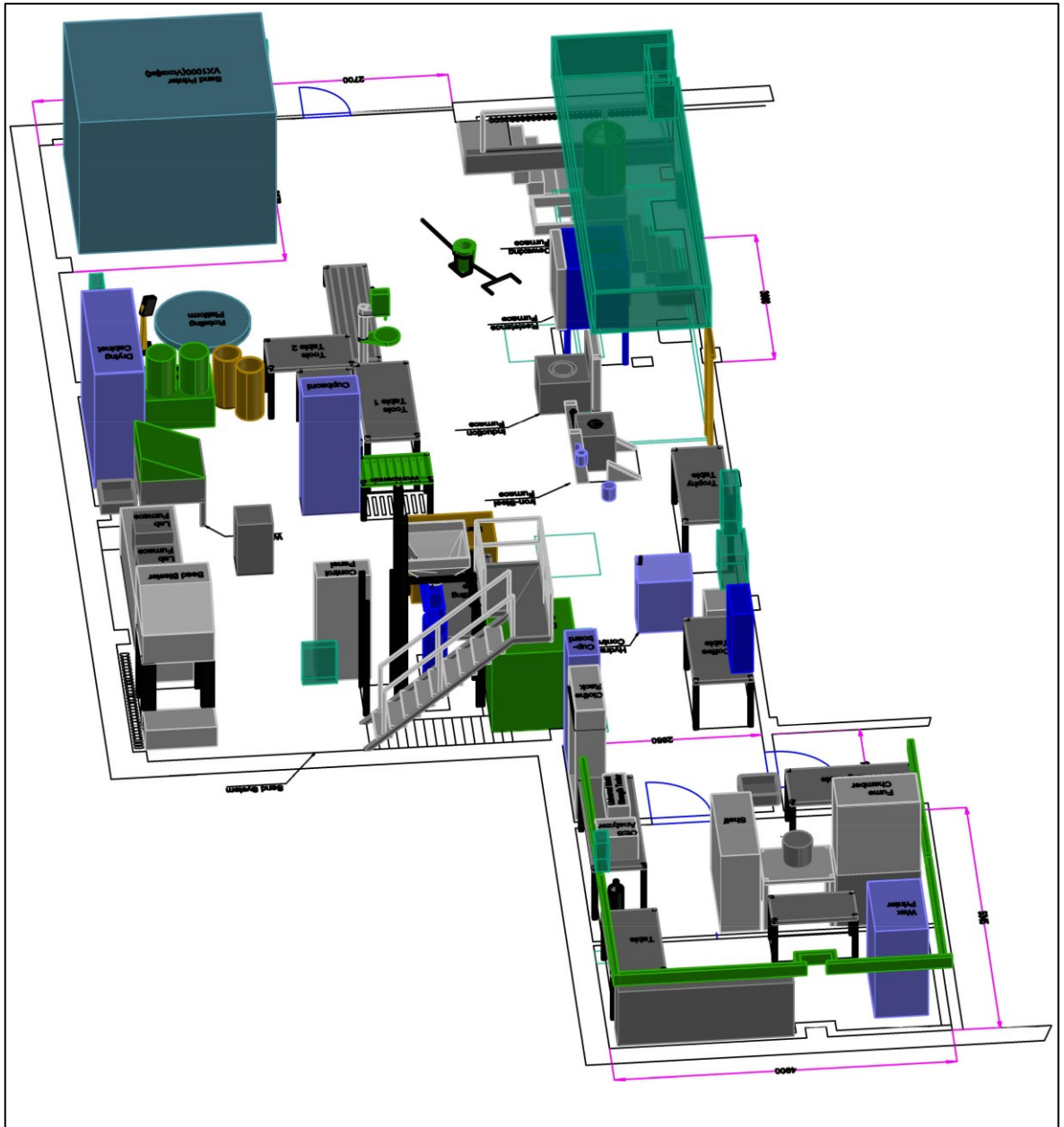


Figure: 3D mock up, View 2(walls hidden)

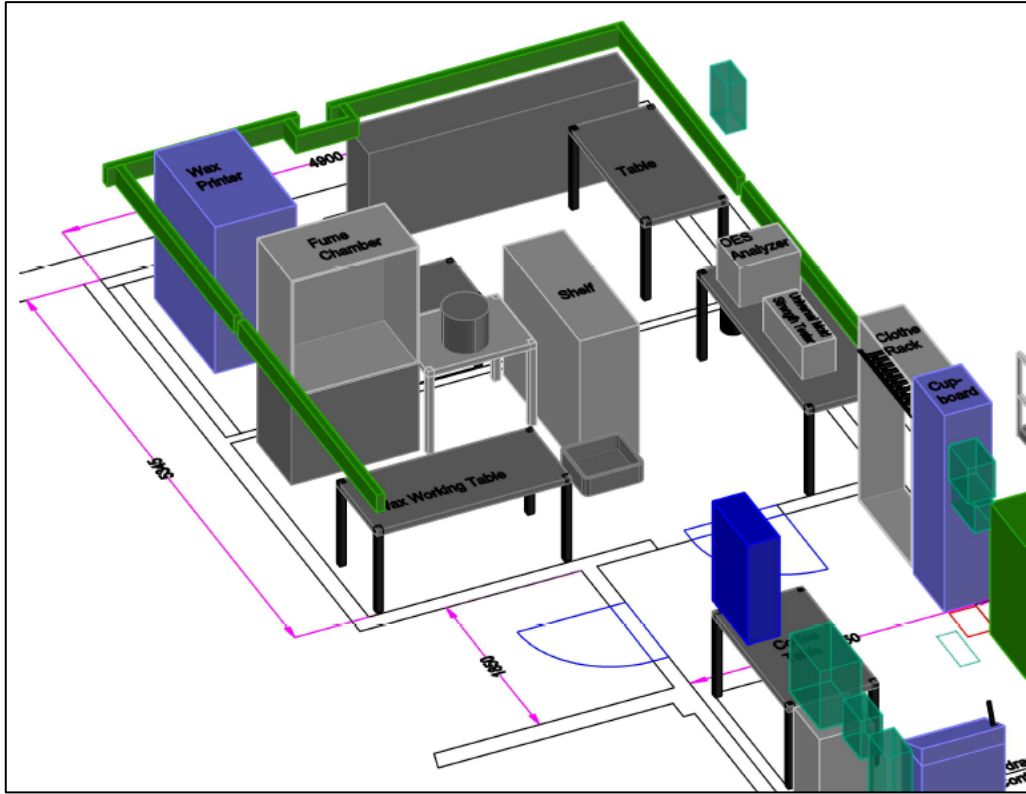


Figure: Clean room close up

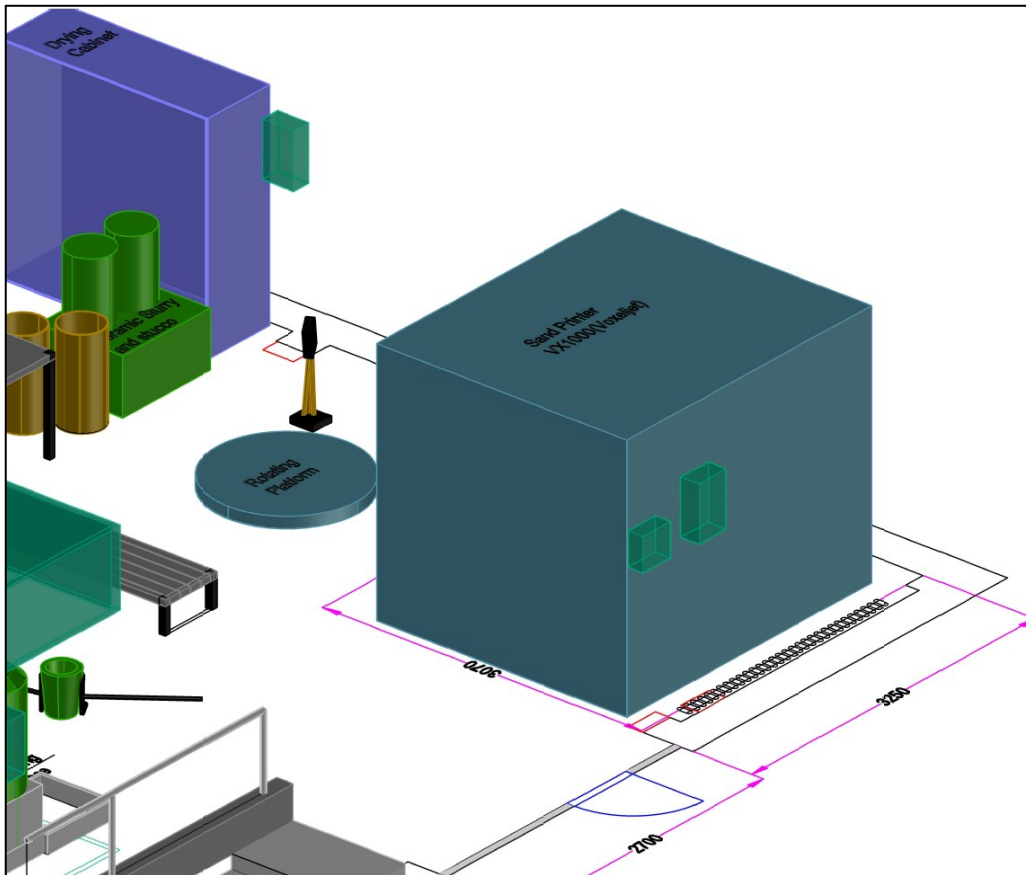


Figure: New tools close up

Appendix 2: Visuals of some of the products listed in Chapter 4



ExOne S-Print



Voxeljet VX1000



Sentrol SS600G



Viridis 3D



VTECH Additive
Manufacturing, VT S500



Nanjing Baoyan Automation
MP-800



Wuhan Easymade Technology
Easy 3DP



Sand Made
LS1