ECONOMIC COMPARISON OF SELECTIVE LASER MELTING AND
CONVENTIONAL SUBTRACTION MANUFACTURING PROCESSES

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By

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ABSTRACT

As one of the leading techniques in additive manufacturing processes, selective laser melting (SLM) has shown great potential for commercialization and scale-up in various applications in industry. The ability to build near net shape endusable products shows advantages in some cases, with more freedom in product design and processing; greater part complexity; and increased ability to structurally optimize parts that are manufactured directly from powder metal materials. In this study, cost analyses of selective laser melting process is compared with conventional subtractive manufacturing (SM) processes. A generic cost models for SLM and SM processing were developed, and several case studies are used to illustrate the conditions and drivers that demonstrate cost advantages for SLM processing. Factors such as production volume and raw material price are analyzed to investigate the influence on fabrication cost. A part manufacturing complexity factor is also defined to provide insights regarding economic decision making for process selection.
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TABLE OF CONTENTS

1. Introduction ...................................................................................................................... 1
   1.1 General introduction to Additive Manufacturing (AM) .............................................. 1
   1.2 Additive manufacturing processes ............................................................................. 3
   1.3 Development of additive manufacturing ................................................................. 5
   1.4 Common additive manufacturing technologies by process category ...................... 6
   1.5 Common additive manufacturing materials .............................................................. 10
   1.6 Research motivations ................................................................................................. 12

2. Technical Aspects of Selective Laser Melting (SLM) .................................................... 13
   2.1 Metal Powder Bed Fusion (PBF) systems ................................................................. 13
   2.2 Selective Laser Melting (SLM) .................................................................................. 13
   2.3 Development of SLM ................................................................................................ 18
   2.4 Binding mechanism of SLS and SLM ........................................................................ 19
   2.5 Mechanical properties of SLM parts ......................................................................... 22
   2.6 Skin-core scanning strategy ....................................................................................... 25
   2.7 Post processing of SLM ............................................................................................. 27

3. Economic Aspects of AM and Selective Laser Melting (SLM) ......................................... 33
   3.1 Additive manufacturing global market ....................................................................... 33
   3.2 Metal AM systems market .......................................................................................... 34
3.3 Additive Manufacturing (AM) research trends ........................................... 36
3.4 Selective Laser Melting (SLM) research trends ........................................ 38
3.5 Cost estimations on additive manufacturing ............................................. 41
3.6 Economic overviews .................................................................................. 52
4. Methodology ................................................................................................. 54
  4.1 Cost estimation model for SLM process ....................................................... 54
  4.2 Cost estimation model of conventional SM process ..................................... 59
  4.3 Definition of part manufacturing complexity .............................................. 63
5. Results and Discussion .................................................................................. 67
  5.1 SLM cost model results ............................................................................. 67
  5.2 SM cost estimation results .......................................................................... 72
  5.3 Part complexity score ................................................................................ 74
  5.4 Cost comparison between SLM and SM .................................................... 76
  5.5 Other economic drivers for SLM ............................................................... 83
6. Conclusion and Future Research ................................................................. 87
  6.1 Conclusions ............................................................................................... 87
  6.2 Limitations .................................................................................................. 88
  6.3 Future research ........................................................................................... 88
REFERENCES ..................................................................................................... 90
APPENDIX ........................................................................................................ 98
LIST OF TABLES

Table 2.1 Differences between Electron beam melting and Metal laser sintering .......... 17
Table 2.2 Sample mechanical properties of SLM metal parts .................................. 24
Table 3.1 Typical titanium aero engine components buy-to-fly ratio .......................... 47
Table 4.1 Energy consumption rate for laser AM processes .................................... 57
Table 4.2 Regression model build time estimation .................................................. 58
Table 4.3 SEC for common subtractive manufacturing processes ............................... 61
Table 4.4 Unit energy consumption model for turning and milling ............................. 62
Table 5.1 Cost estimation comparison using five sample parts .................................. 68
Table 5.2 Cost estimation results of single part full bed using original production volume ........................................................................................................... 69
Table 5.3 Sensitivity Results on Small Volume Sample Part ...................................... 71
Table 5.4 Complexity test samples ........................................................................... 75
Appendix A: Spreadsheet based cost estimation model for Selective Laser Melting (SLM) process ........................................................................................................ 98
Appendix B: Spreadsheet based cost estimation model for Subtractive Manufacturing (SM) process ........................................................................................................ 99
Appendix C: Commercial metal PBF systems around the world ............................ 100
LIST OF FIGURES

Figure 1.1 Additive Manufacturing processes by different stages ..................................... 4
Figure 1.2 AM processes by raw material state ................................................................. 7
Figure 1.3 AM Process matrix by materials and channel ...................................................... 7
Figure 1.4 Metal AM processes by binding method .............................................................. 11
Figure 2.1 Schematic of a SLS/SLM system ........................................................................ 14
Figure 2.2 Two types of powder delivery systems in PBF ..................................................... 15
Figure 2.3 A typical schematic of PBF process ..................................................................... 16
Figure 2.4 (a) SLM system; (b) Key components of SLM machine ........................................ 16
Figure 2.5 Build rate and printing resolution comparison in Metal AM systems .............. 18
Figure 2.6 Material binding methods in PBF processes ......................................................... 19
Figure 2.7 Multiphase metal powder under micrograph ....................................................... 21
Figure 2.8 Laser parameter range for SLM process .............................................................. 22
Figure 2.9 Cross-section of titanium part built by SLM ....................................................... 23
Figure 2.10 Cross-section of stainless steel part built by SLM ............................................ 23
Figure 2.11 Mechanical properties comparison between SLM metal part and standard
bulk ..................................................................................................................................... 24
Figure 2.12 Part density and scanning velocity in different laser power settings .......... 25
Figure 2.13 Scheme of skin core dual laser scanning mechanism ....................................... 26
Figure 2.14 Vertical cross-section of steel part ................................................................. 27
Figure 2.15 Example of improved metal structure by thermal processing of DMLS........ 28
Figure 2.16 Example of part overhang structure failure .................................................. 29
Figure 2.17 Finished part buried in loose metal powders (upper); Remove loose powders
from the part using hand brush (lower) ........................................................................... 30
Figure 2.18 Example of support structures in a metal part .............................................. 31
Figure 2.19 A turbine blade before and after surface texture improvements ................. 32
Figure 3.1 Global AM market in diagram ......................................................................... 33
Figure 3.2 Market section by industries ............................................................................ 34
Figure 3.3 Metal AM system unit sell by years .................................................................. 35
Figure 3.4 Metal AM systems market share by companies ............................................... 35
Figure 3.5 Number of papers with keywords “selective laser melting” (source:
ScienceDirect) .................................................................................................................. 39
Figure 3.6 Number of papers with keywords “selective laser melting” (source: Scholar
OneSearch) ....................................................................................................................... 40
Figure 3.7 Cost per part by production volume for small lever part .............................. 42
Figure 3.8 Cost per part by production volume for medium cover ................................. 42
Figure 3.9 Tree graph of cost model scheme .................................................................... 43
Figure 3.10 Cost per part over production volume in line diagram .................................. 44
Figure 3.11 Comparison among AM cost estimation models .......................................... 45
Figure 3.12 Cost per part in different part orientation ....................................................... 46
Figure 3.13 Specific cos of AM titanium material required to be cost-efficient against
machining from solid process .......................................................................................... 47
Figure 3.14 Sample part (left) and cost breakdown (right) for AM process................. 49
Figure 3.15 (a) Redesigned landing gear; (b) major support; (c) top view..................... 50
Figure 3.16 Cost per assembly by production volume for HPDC and SLS ................. 51
Figure 3.17 Building time estimation model ................................................................. 52
Figure 4.1 Technical cost model structure ...................................................................... 55
Figure 4.2 Illustration the concept of complexity for free between additive manufacturing
and conventional manufacturing.................................................................................. 63
Figure 4.3 Average parts volume/block volume ratio in different manufacturing processes
......................................................................................................................................... 65
Figure 5.1 Sample parts for cost estimation..................................................................... 67
Figure 5.2 Part example for cost estimation: Bearing block.......................................... 69
Figure 5.3 Cost breakdown for SLM stainless steel sample part..................................... 70
Figure 5.4 Line graph of cost per part by annual production volume.............................. 71
Figure 5.5 Cost breakdown for SM machining part ......................................................... 73
Figure 5.6 Line graph of cost per part by annual production volume.............................. 73
Figure 5.7 Cost per part by complexity score in line diagram........................................ 76
Figure 5.8 Cost comparison between stainless steel and titanium by volume ratio (SLM)
........................................................................................................................................ 77
Figure 5.9 Cost comparison between stainless steel and titanium by volume ratio (SM) 78
Figure 5.10 Cost comparison by volume ratio and complexity score (stainless steel and
high production volume).............................................................................................. 79
Figure 5.11 Cost comparison by volume ratio and complexity score (titanium and high
production volume)................................................................................................. 80
Figure 5.12 Cost comparison by volume ratio and complexity score (stainless steel and low production volume) .................................................................................................................................................. 81
Figure 5.13 Cost comparison by volume ratio and complexity score (titanium and low production volume) .................................................................................................................................................. 82
Figure 5.14 Cost comparison by volume ratio two processes (stainless steel and titanium) .................................................................................................................................................. 83
Figure 5.15 Customized implant parts manufactured by SLM ................................................................. 84
Figure 5.16 Facial replacement metal part ........................................................................................................... 84
Figure 5.17 Micro-structure topology optimized brackets on airplane (left) and engine block (right) .................................................................................................................................................. 85
Figure 5.18 Model of perpendicular water channel (left) and design optimized channel for AM (right) .................................................................................................................................................. 86
Figure 5.19 Conformal cooling channels illustration (left) and internal cooling channel in a cutting tool (right) .................................................................................................................................................. 86
1. Introduction

1.1 General introduction to Additive Manufacturing (AM)

As one of the most popular recent technologies, 3-D printing is drawing more and more attention from the public. The concept of printing a three-dimensional part from the bottom up has made people realize its huge potential in everyday life. Today, more and more new companies are providing 3-D printing services to a variety of customers in numerous industries. From small customized toys and accessories to high complexity mechanical parts used in aerospace applications (Thompson et al., 2016), the concept of 3-D printing has become more ubiquitous, especially in the manufacturing industries.

Additive manufacturing (AM) is one of the key terminologies that reflects 3-D printing concepts. By building a part layer-by-layer, or sometimes by line and surface (Gibson, Rosen, & Stucker, 2010), additive manufacturing can fabricate an object directly from the 3-D model data with reduced scrap generation, unlike conventional subtractive manufacturing process where parts are made from bulk materials (Huang, Leu, Mazumder, & Donmez, 2015). In addition, the AM process also allows users to create an object with effectively minimum manual skills to operate the printing systems (Baumers, 2012). As for the conventional subtractive material manufacturing systems, the users or operators are usually required to have years of experience and a minimum level of skill sets to operate machines to perform milling, drilling, and honing, etc. Otherwise, for quality or safety issues, finished part requirements may not be met. With reduced machining requirements (and albeit with other operating skills needed), additive manufacturing could provide better opportunities for people to enter this industry. The booming sales of desktop additive manufacturing systems (Wohlers & Caffrey, 2015)
also implies that increasing number of people are willing to implement this technology in their daily lives to create functional or recreational items.

Some small companies have used this technology to produce finished items for customers. Wohlers Associates purports that these small companies could become the “largest and most significant application of AM technology” (Wohlers & Caffrey, 2015). The ability to produce end-useable parts could have an even bigger influence on the manufacturing industry than other technologies (Wohlers & Caffrey, 2015).

Concurrently, other concepts and terms that represents additive manufacturing have been developed with different aspects on the process. In the study from (Guo & Leu, 2013), terms like additive fabrication, additive processes, direct digital manufacturing, rapid prototyping, rapid manufacturing, layer manufacturing and freeform fabrication (Wohlers & Caffrey, 2015) used mentioned as similar concepts to additive manufacturing.

For the past 20 years (Guo & Leu, 2013), additive manufacturing technology have developed in a fast path and extend into different forms and using various materials. But just like ASTM defined, the key differences between additive manufacturing and subtractive manufacturing is that the former can join materials directly from 3-D model data (Piazza & Alexander, 2015). Until nowadays, additive manufacturing is still expanding and spreading its influence by bringing new technologies, materials, and a broader range of applications will be applied to more industrial sectors around the world (Wohlers & Caffrey, 2015).
1.2 Additive manufacturing processes

Since additive manufacturing processes share a lot of things in common by adding one layer of materials to another layer directly from 3-D CAD models, these processes can be divided into several stages based on function and purpose. Eight generic processes can be observed from additive manufacturing (Gibson et al., 2010):

Step 1: CAD design for 3-D modeling of the part.

Step 2: Convert CAD model to STL file, slice the 3-D model into multiple “layers” for manufacturing

Step 3: Transfer file to additive manufacturing machine. Adjustments and manipulations needed to make the file more accurate for AM building process

Step 4: Set up AM machine (i.e. parameters like scan speed, layer thickness, etc.)

Step 5: Building or additive manufacturing process. Depends on the mechanism of the process, build part layer-by-layer using raw material and bind the layers together as a whole.

Step 6: Remove finished parts from the platform or machine and clean up the loose materials in some processes.

Step 7: Postprocessing for finished parts. Actions like removing the supportive structures and cleaning up the object are needed for some processes. And for certain applications, heat treatment may be required to achieve functionality from the finished product.

Step 8: Application stages where additional treatment (i.e. lamination, painting, etc.) may be applied to the part before they are acceptable for the application. For multiple parts
applications, individual objects produced by additive manufacturing machine were assembled to put together a finished product.

In the flowing Figure 1.1, illustrated these 8 steps from CAD to part for generic AM processes taking a cup for example:

![Figure 1.1 Additive Manufacturing processes by different stages (Gibson, Rosen, & Stucker, 2014)](image)

For different approaches of additive manufacturing, emphasis on each step is taken differently. And for some processes, certain steps may be excluded due to material types and finished parts’ quality. For plastic materials, postprocessing might not be as much as a metal AM part.
1.3 Development of additive manufacturing

Additive manufacturing was always thought as one of the newer manufacturing technologies. But actually, the researches on the concept were introduced more than 50 years ago (Wohlers & Caffrey, 2015). Photopolymerization patents first had record of patents in the late 1960s, and as the development of computer and the following invention of computer aided design (CAD), achieving the concept of additive manufacturing became feasible and available (Kai, Fai, & Chu-Sing, 2003; Thompson et al., 2016).

The first commercial additive manufacturing system was introduced to the market in the late 80s using stereolithography (SLA) process (Wohlers & Gornet, 2014). This manufacturing process which used UV light-sensitive liquid polymers to build the lay-by-layer part, was the first available commercial additive manufacturing systems in the world (Wohlers & Gornet, 2014). Later, more methods of additive manufacturing were invented, various of materials and characteristics of finished parts were brought to the growing market. One of the leading technology at that time for additive manufacturing, laser sintering, was first noted by 3D Systems in the 1990s and defined as “selective solidification of layers of a powdered medium” (Shellabear & Nyrhilä, 2004).

Researchers realized the potential market for this commercial additive manufacturing market and started to deploy different methods to build objects. Fused Deposition Modeling (FDM), Laser Beam Melting (LBM), Electron Beam Melting (EBM), etc. were patented and brought to commercialization in succession in the late 90s and to the 2000s (Thompson et al., 2016).
As for the current time, the market for additive manufacturing has been growing exponentially and is predicted to keep rising in the next decades (Wohlers & Caffrey, 2015). Metal materials have been applied in the process to produce high-quality end-useable parts and the demand is still falling short to fulfill, especially for the powder bed fusion systems (Wohlers & Caffrey, 2015).

Original introduced for better performance in rapid prototyping, additive manufacturing has shown more advantages in design freedom and high customization. Since the demand for highly customized end part and zero-to-finish end-useable part were growing fast, additive manufacturing has come a step up from rapid prototyping and achieve different application readiness throughout the market (Berger, 2013). Manufacturing in dental and tooling applications as achieved high readiness and has become highly competed for conventional manufacturing process, due to the customization and cost advantages in those industry sectors (Berger, 2013; Wohlers & Caffrey, 2015).

Now the market for additive manufacturing has passed 2 billion euro and is predicted to be around 7.7 billion euro in the 2023 (Berger, 2013; Wohlers & Caffrey, 2015). With more exposure of the applications to the media and public, the market could expand even more and played a significant role in the “fourth industry revolution”.

1.4 Common additive manufacturing technologies by process category

There are several different types of additive manufacturing technologies that are used in the application across the whole industry. Based on the characteristics of the raw materials used in AM, the processes can be categorized into three major parts: liquid based AM, solid based AM and powder based AM. The following Figure 1.2 shows the
detail processes grouped by binding mechanism and specific technologies (Wong & Hernandez, 2012). Other studies on additive manufacturing have also shown different approaches to categorize layered manufacturing process (Figures 1.2 and 1.3) (Pham & Gault, 1998).

![Figure 1.2 AM processes by raw materials state (Wong & Hernandez, 2012)](image)

![Figure 1.3 AM process matrix by materials and channel (Gibson et al., 2010; Pham & Gault, 1998)](image)
But based on the fusion or solidification mechanism of the raw materials, or in some cases the geometric properties of the materials, more specific categories may be given to an additive manufacturing process (Gibson et al., 2010). According to ASTM F42 committee, the most common categories for current additive manufacturing processes were divided into seven sections (Monzón, Ortega, Martínez, & Ortega, 2015):

- Vat photopolymerization:
  This process uses liquid photopolymer materials. The polymers were solidified by selective scan of UV light to form a preferred shape of 2D layer.
  Stereolithography was one of the first process not only in this category but also the first commercialized system (Wohlers & Caffrey, 2015). Other materials like hydrogels (Gibson et al., 2010) can also be used in this process.

- Material jetting:
  The materials were directly deposited as droplets through printing head to form solid structure in the selective areas of a building layer (Wohlers & Caffrey, 2015). Polymer jetting as one of the popular AM technology was used to produce customized polymer products. Universities like Northeastern have set up 3-D printing studio to provide services using AM technologies (Northeastern library).

- Binder jetting:
  It is also known as the 3-D printing technology, is the most notable subset of AM processes (Piazza & Alexander, 2015; Weber et al., 2013). Liquid bonding material or agent was printed through a inkjet and fused with the powder bed (Wohlers & Caffrey, 2015). Unlike some of the powder bed fusion technologies, the moving inkjet head deposit binder droplets to bind powder together, leave the unused powder behind (Gibson et al., 2014).
• Material extrusion:
  Fused deposition modeling (FDM) is one of the AM technology in this category. And it is the most widely used additive manufacturing process by material extrusion (Gibson et al., 2014). Typical molten materials like wax and polymers were often used.

• Direct energy deposition:
  DED process applied and heat up the materials, which were only melted during deposition, at the same time to build solid substrate onto the melting pool (Gibson et al., 2014). A laser or an electron beam was usually used as energy source to provide thermal power to melt the feedstock materials.

• Sheet lamination:
  Unlike other processes using powder or liquid materials, sheet lamination uses sheets of materials to build the deposition layer instead of points of materials. When sheets were heated and pushed, layers of materials (i.e. papers, polymers and metals, etc.) were bonded by thermal adhesive coating (Cooper, 2001; Wong & Hernandez, 2012).

• Powder bed fusion:
  Standard PBF machines apply thermal energy directly on the powder bed to fuse materials in the selective area, and after a layer of materials cool down to form solid structures, another layer of powders were applied on top and repeat the process (Berger, 2016; Wohlers & Caffrey, 2015). Common materials like polymers and metals were used to produce 3-D product. Popular technologies like selective laser sintering (SLS) and selective laser melting (SLM) has shown great
application potential. More details on PBF and SLM will be discussed in the following sections.

1.5 Common additive manufacturing materials

When the additive manufacturing was first brought to commercialization, the applications were mainly focused on materials like polymers, wax and plastics (Gibson et al., 2014). As the development of this technology become more and more mature, near-net shape finished products can directly serve into functional parts and more materials have been applied in various of processes to try new applications (Guo & Leu, 2013). As researches conducted in plastic and resin materials for AM became popular, the possibility for metal AM products were unveiled and discovered. Metal materials were put into intense development research for potential of AM products (Guo & Leu, 2013; Thompson et al., 2016). A wider range of metal materials have been deployed into additive manufacturing process, which was a result of the booming sales of metal AM systems (Wohlers & Caffrey, 2015).

Common metal materials include but not limited to tool steels, stainless steels (i.e. 316L, 17-4 PH, etc.), titanium, Inconel, aluminum alloys and cobalt-chromium alloys (Wohlers & Caffrey, 2015). Other precious metal materials like gold, silver and platinum are often used in jewelry design and manufacturing.

By using metals in additive manufacturing, the products in some processes showed similar microstructures, density and characterizations to conventional manufacturing parts. As the researches and developments in additive manufacturing keep going strong, the collection of available AM materials is also keep growing bigger.
Figure 1.4 is a tree diagram of metal additive manufacturing processes defined by whether the metal materials were directly bind together. For processes like 3DP, SLA, polymer binder agents were used to fused the metal together using non-melting method, while in other processes like SLS and FDM partially melted metal powder can serve as binder. For direct binding processes, metal powders were fully melted and fully dense metal parts were built on the melting pool directly. (Guo & Leu, 2013)

![Metal AM processes by binding method](image)

In the meantime, ceramics and other composites were also introduced to the industry of additive manufacturing (Gibson et al., 2014). For indirect ceramic material PBF systems, ceramic powders were consolidated using binders like those in metal indirect SLS processes (Gibson et al., 2014). The stable characteristic and high resistance of heat and chemical of ceramic materials give it the advantages in many AM applications, and processes like SLS and SLM have been used to fabricate mixed material parts (Guo & Leu, 2013). Other medical applications using ceramic materials to replace conventional moulding process have gained success more than ever.
1.6 Research motivations

When additive manufacturing was first introduced to the manufacturing industry, it has been commonly discussed whether this technique has the potential to replace traditional manufacturing process. To achieve production using AM processes, the cost efficiency must be analyzed.

In this research, comparisons between selective laser melting (AM process) and conventional subtractive manufacturing process will be conducted and to find out under what conditions does SLM has more cost advantages. Moreover, when the term “complexity for free” was mentioned in a variety of literatures to explain the advantages of SLM, how does the complexity of a designed part affects the cost performances between these two processes? And in addition to the part complexity, are there any other factors to be considered for better SLM benefits?
2. Technical Aspects of Selective Laser Melting (SLM)

2.1 Metal Powder Bed Fusion (PBF) systems

Selective laser melting (SLM) as the key process to discuss in this study, belongs to the category of metal powder bed fusion (PBF), where metal powders were fully melted using laser as energy source to composite fused structure layer-by-layer.

Commonly, the power bed fusion processes have some features that shared by all different processes: a thermal source was used to induce fusion among material powders; a powder recoating process to adding another layer when the previous one was done; a controlling method to fuse the powders in designed regions (Gibson et al., 2014).

Plastic was first used as PBF raw material to build initial prototypes using this technology. But as the expansion of PBF, materials like complex polymers, metals and ceramic composites were more commonly used to the process. In some applications, PBF process have shown to be able to build end-usuable part directly from raw material and hence giving more freedom when it comes to part design (Gibson et al., 2010).

2.2 Selective Laser Melting (SLM)

As the one of the earliest commercialized AM processes in PBF, selective laser sintering (SLS) has gone far from the original prototype in UT Austin (Gibson et al., 2014). Selective laser sintering (SLS) and selective laser melting (SLM) both use laser as thermal source to provide energy for the powder fusion. And both processes have similar manufacturing flow.
Above Figure 2.1 shows the scheme of a SLM system. Laser beam was used to provide energy for fusion. And through multiple lenses and deflection mirrors, laser beam was focused on to selected region. As selective areas of the powder bed were melted and consolidated as designed, one layer of the model was manufactured. After each layer, a roller (Figure 2.2 a) or a scraper (Figure 2.2 b) pushes raw material powders from the feed container and adding another smooth layer to the powder bed, while the base plate drops down to allow new powders sit on top of the previous finished layer. Overflowed material powders will be pushed to the other container for reuse.
The above process was repeated until the whole 3-D model was built on the powder bed. To avoid distortion due to excess of residual stress from the laser energy, the powder bed was preheated before building process. Inert gas was also needed for most cases to provide insulation from outer environment to avoid oxidation of metal materials. Nitrogen or Argon were most commonly used to serve the purpose (Gibson et al., 2010). And for the economic purpose, some systems first created vacuum in the chamber and then filled the chamber with Argon to avoid oxidation with reactive metals like titanium. This approach can lead to lower cost without the need to use cheaper inert gas like Nitrogen while still maintaining low oxygen level inside the system (Renishaw).

A typical PBF process is shown in Figure 2.3 (illustrated by EOSINT system), and four steps were repeated to create the parts layer-by-layer. An example of SLM system (SLM 125 HL) was illustrated in Figure 2.4 (a), key components were showed in (b).
Figure 2.3 A typical schematic of PBF process (Gibson et al., 2014)

Figure 2.4 (a) SLM system; (b) Key components of SLM machine (Ahmed et al., 2016)

Electron beam melting (EBM) is also one of the common PBF processes that share a lot of similarity to SLM. They both can build fully dense part from metal powder (Aliakbari, 2012). But however, the thermal source for the two processes were different: EBM uses electron beam and SLM uses laser. Thus, the melting pool environment for EBM was
vacuum to provide better conductivity for electron beam where SLS/SLM process require less effort.

Other differences between EBM and SLS/SLM were discussed and compared in the book by Gibson et al. (2014) as follows. As can be seen from the following Table 2.1, EBM has much higher scanning speed than metal laser sintering process and thus the deposition rate is much higher in EBM. “Electron beam PBF enables higher build rates, but surface quality and choice of materials are more limited” (Berger, 2013).

Table 2.1 Differences between Electron beam melting and Metal laser sintering (Gibson et al., 2014)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Electron beam melting</th>
<th>Metal laser sintering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal source</td>
<td>Electron beam</td>
<td>Laser</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Vacuum</td>
<td>Inert gas</td>
</tr>
<tr>
<td>Scanning</td>
<td>Deflection coils</td>
<td>Galvanometers</td>
</tr>
<tr>
<td>Energy absorption</td>
<td>Conductivity-limited</td>
<td>Absorptivity-limited</td>
</tr>
<tr>
<td>Powder preheating</td>
<td>Use electron beam</td>
<td>Use infrared or resistive heaters</td>
</tr>
<tr>
<td>Scan speeds</td>
<td>Very fast, magnetically driven</td>
<td>Limited by galvanometer inertia</td>
</tr>
<tr>
<td>Energy costs</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Moderate to poor</td>
<td>Excellent to moderate</td>
</tr>
<tr>
<td>Feature resolution</td>
<td>Moderate</td>
<td>Excellent</td>
</tr>
<tr>
<td>Materials</td>
<td>Metals (conductors)</td>
<td>Polymers, metals and ceramics</td>
</tr>
<tr>
<td>Powder particle size</td>
<td>Medium</td>
<td>Fine</td>
</tr>
</tbody>
</table>

With higher build or deposition rate, the manufacturing time for other PBF processes were distinctively shorter than laser PBF. But however, the printing resolution decreased as the building speed increased, lead to poorer part microstructure and porosity. Moreover, post-completion processes for lower resolution parts were more complicated and more steps need to be taken to reach the same level of part requirement like surface roughness higher mechanical properties.
Figure 2.5 Build rate and printing resolution comparison in metal AM systems (Berger, 2016)

2.3 Development of SLM

The invention of powder bed fusion also came from the first commercial additive manufacturing process. Years after the first commercialized AM system, the first PBF process was developed at University of Texas at Austin using selective laser sintering (SLS) technology (Gibson, Rosen, & Stucker, 2015). As the research on PBF process gone further, more materials were added to the process by modifying the basics of the technology.
2.4 Binding mechanism of SLS and SLM

Just like mentioned in the previous section, metal PBF systems have provided solutions to various of metal and alloy powders to build parts that don’t require much post processing and are end usable. But different materials use different powder fusion mechanism to produce solid structure on the powder bed. Fig showed four fusion mechanisms in the current powder bed fusion processes (Kruth, Mercelis, Van Vaerenbergh, Froyen, & Rombouts, 2005):

Figure 2.6 Material binding methods in PBF processes (Kruth et al., 2005)

Since selective laser sintering (SLS) and selective laser melting (SLM) have very similar process steps, energy source and material range, a lot of confusion may happen to tell these two processes apart. In terms of materials, the term SLM is usually reserved only for metals (Kruth et al., 2005). And when it comes to the binding mechanism, two processes clearly stand out from each other.

Selective laser sintering (SLS) uses laser as energy source to heat the powder to the temperature where materials can fuse together on a molecular level (Noe, 2014). From
Figure 2.6 we can see, SLS uses solid state sintering, chemically induced binding and liquid phase sintering partial melting to conduct the fusion process (Kruth et al., 2005). In solid state sintering, the powders were heated to more than half melting point to full melting point (Kruth et al., 2005) where the free energy between particles got lower and powders were sintered together. For the second binding mechanism, chemical induced binding happens when different types of powders or atmospheric gases made chemical reaction with each other due to high temperature and form a solid structure (Gibson et al., 2014), and this usually happened with ceramic materials. Liquid phase sintering (LPS) or partial melting, fuses powders together by melt a portion of powder particles to serve as binder and solid particles (Gibson et al., 2014). The binder can either be the same materials or different materials. The process of Direct Metal Laser Sintering (DMLS) by EOS can be categorized into partial melting process where not all powder particles were fully melted (Kruth et al., 2005). But from EOS, the DMLS process was already able to produce fully dense parts using full melting mechanism of single component of ceramic and metallic powders (i.e. 1.4404 Steel), projects was started at the end of 1995 and multiple German institute has participated in this project (Shellabear & Nyrhilä, 2004).

Figure 2.7 shows the micrograph of metal powder under different phases in partial melting process. The structure and density of the solid part is not even and porosity is relative higher than homogeneous part.
For selective laser melting (SLM) process, full melting serves as the binding mechanism for metal powder particles. As one of most common mechanism of metal alloy and semi-crystalline polymers PBF process, powders in the melting pool were fully melted to a depth beyond the layer thickness to form bulk-like full dense structure (Gibson et al., 2015). And when the next layer of powders was applied, the energy from laser or other thermal sources like electron beam can re-melt a portion of the previous solid metal part and the newly-produced solid part can fuse together with lower layer welly to form high-density structures throughout the whole part. To form this homogeneous structure but also avoid balling or part porosity, certain limitation on the parameter of laser scan should be set. Figure 2.8 is an example of iron based SLM process laser parameter range use iron based powder mixture as material. Only parameters within the grey area can fully-dense metal parts be produced in continuous tracks.
2.5 Mechanical properties of SLM parts

The finished parts of SLM is a full density metal part with similar mechanical properties as bulk materials for subtractive manufacturing process. In the early studies of SLM metal parts, the mechanical properties in yield strength, tensile strength, etc. can be comparable to standard bulk materials, only the ductility was strongly reduced (Kruth et al., 2005). But this situation may be solved by using certain heat treatment as post-processing. The porosity of SLM part can achieve less than 1% (Wohlers & Caffrey, 2015) and thus the parts can be used directly in functional applications. In the following figures (Figure 2.9 and 2.10), cross-section of metal parts manufactured by SLM shows low porosity and evenly distributed structures throughout the part.
Figure 2.9 Cross-section of titanium part built by SLM (Kruth et al., 2005), shows homogeneous metal structure throughout the section.

Figure 2.10 Cross-section of stainless steel part built by SLM (Kruth et al., 2005), pores can be noticed in different scales.
From various studies, selective laser melting has shown the capability to create metal parts with similar or even better mechanical properties than conventional machining processes. Detail SLM part mechanical properties can be found in Figure 2.11 and Table 2.2. Different metal powders or alloy powders have been tested to manufacture solid metal parts using SLM, and the part density, mechanical strength, tensile strength properties, and surface roughness were analyzed and compared under different parameter setting of the SLM systems (Baufeld, Van der Biest, & Gault, 2010; Frazier, 2014; Kempen et al., 2013; Kruth et al., 2004; Rombouts, Kruth, Froyen, & Mercelis, 2006).

<table>
<thead>
<tr>
<th>Material</th>
<th>Stainless Steel 1.4404</th>
<th>Tool Steel 1.2343</th>
<th>TiAl6V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>480-520</td>
<td>780-840</td>
<td>1200-1400</td>
</tr>
<tr>
<td>Elongation (per cent)</td>
<td>10-15</td>
<td>2-3</td>
<td>1-2</td>
</tr>
<tr>
<td>Hardness</td>
<td>220-250 HV0.1</td>
<td>50-54 Rockwell</td>
<td>380-420 HV0.3</td>
</tr>
<tr>
<td>Surface finish (μm)</td>
<td>Rₚ 30-60</td>
<td>Rₚ 30-60</td>
<td>Rₚ 30-60</td>
</tr>
<tr>
<td>Accuracy (mm)</td>
<td>± 0.1</td>
<td>± 0.1</td>
<td>± 0.1</td>
</tr>
<tr>
<td>Density (per cent)</td>
<td>ca. 100</td>
<td>ca. 100</td>
<td>ca. 100</td>
</tr>
</tbody>
</table>

Table 2.2 Sample mechanical properties of SLM metal parts (Kruth et al., 2005)
2.6 Skin-core scanning strategy

Due to relatively lower build rate for selective laser melting, the cost of the part was usually high compare to other processes. Even with better finished parts qualities, the economic drive for commercialization made some compromises in the process to achieve lower manufacturing cost. Skin-core scanning strategy is one of the solutions to achieve much lower cost without sacrificing much mechanical properties of the finished parts.

Past research on the correlation between scanning speed and part density have been conducted in many applications, it showed that under the same laser power, the density decrease as the scanning speed increase (as shown in Figure 2.12) (Buchbinder, Schleifenbaum, Heidrich, Meiners, & Bültmann, 2011).

![Figure 2.12 Part density and scanning velocity in different laser power settings (Buchbinder et al., 2011)](image)

Figure 2.13 is a scheme of skin-core scanning using dual laser system. Since the inside or the core of the parts typically only need to achieve sufficient compressive strength but not so much in terms of accuracy, the build rate for inner section can be much higher than the
outer skin region to save build time and manufacturing cost (Shellabear & Nyrhilä, 2004).

![Diagram of skin-core dual laser scanning mechanism](image)

**Figure 2.13** Scheme of skin-core dual laser scanning mechanism (Schleifenbaum, Meiners, Wissenbach, & Hinke, 2010)

In SLS processes, the inner core section can have higher porosity and lower density than the outer region, like shown in Figure 2.14. But for SLM process, setting different parameters of the laser can achieve approximately 100% density in both skin and core section to assure same mechanical properties across the part (Schleifenbaum et al., 2010).
Figure 2.14 Vertical cross-section of steel part (Shellabear & Nyrhilä, 2004), porosity increases from core to skin

From a study conducted by Kretzschmar (2015), the cost per part of a SLM sample part was dropped drastically by 70% from 2400€ to 700€ by using skin-core scanning strategy (Kretzschmar, 2015).

2.7 Post processing of SLM

Like other additive manufacturing, post processing is essential to SLM process as well. When the manufacturing process finished, the solid metal parts were buried in the powder bed covered by unused metal powders.

Due to the special characteristics of additive manufacturing, the finished parts are usually near-net shape, not able to meet the functional or quality requirements yet. Thus, post processing is essential to additive manufacturing to make the products more desirable and functional. From processes to processes, some may only need minimum post processing to achieve the desire quality, some may need a series of steps after the parts were formed.
And the post processing can involve with a series of chemical, thermal or machining processes, here are some of the generic post-processing steps that many additive manufacturing processes require (Gibson et al., 2014).

For some applications, thermal process of the finished parts can be conducted in the AM system by re-heating and cooling down the chamber. By necessary thermal treatment, for example hot isostatic pressing (HIP), metal parts show further enhanced mechanical properties and structural quality (Gibson et al., 2014; Wohlers & Caffrey, 2015). Figure 2.15 shows an example of improving the micro structure of a metal part by post thermal processing in a DMLS part.

![Figure 2.15 Example of improved metal grain structure by thermal processing of DMLS part (Wohlers & Caffrey, 2015)](image)

Support structure for SLM designed parts are essential and without certain support defects and part failures may happen during manufacturing process. Figure 2.16 shows an
example of failed overhang structure. After the part is built on the platform, support material removal is usually the first step after the solid metal parts were manufactured in SLM. Because during the laser PBF process, the amount of heat absorbed in the melting pool region can lead to serious thermal contraction and part distortion, supportive structures were applied to erase some of the thermal stress or to avoid cracks and failures happening in the overhang structures. Hand saws and blades were used to remove supportive structures from the part and wire EDM is the typical tool to remove parts from the building platform (Wohlers & Caffrey, 2015).

![Example of part overhang structure failure](image)

Figure 2.16 Example of part overhang structure failure (Zeng, 2015), due to lack of support structures during SLM process

SLM parts were built on the platform and that needs necessary removal process to separate the parts from building plate. For natural support by loose powders, brushes (in Figure 2.17), vacuum and compressed air, etc. were used to remove unused powders from the parts (Gibson et al., 2015). For SLM processes, a high percentage of the unused...
powders can be recycled and processed for future application use. And because the manual operation in this process, post-process time often associate with the part volume and geometric complexity.

For some applications, complex support structures are designed depending on the application and part orientation. Figure 2.18 shows a metal built on SLM system with complex lattice structure support using the same material. Machining tools may be needed to remove these supports from the metal part.
Figure 2.18 Example of support structures in a metal part (CroftAM)

After the removal of supports from the finished parts, sometimes the surface and accuracy of the products were slightly different than designed to allow tolerance for future fabrication. SLM as one of the additive manufacturing process which can produce end-usuable product, finished parts of SLM have relatively higher surface roughness quality and accuracy, the surface finish $R_z = 30-60 \, \mu m$, average accuracy is less than 0.1 mm (Kruth et al., 2005), $R_a = 7.6-15.2 \, \mu m$ (Wohlers & Caffrey, 2015). To reach the desire surface texture and accuracy, bead blasting, sanding and hand-polishing should be applied to the part depends on the surface requirements (Gibson et al., 2014). Machining was also performed to some applications where certain additional structures or surfaces need to be fabricated using conventional subtractive manufacturing.
Last but not the least, quality inspections were also required for high-accuracy or high-quality applications. Tools like radiographic and CT scanning were performed to conduct non-destructive inspection in this steps (Wohlers & Caffrey, 2015).
3. Economic Aspects of AM and Selective Laser Melting (SLM)

3.1 Additive manufacturing global market

The global additive manufacturing market value has reached €3.1 billion (equivalent to $3.35 billion) and of which more than 300 million are for metal additive manufacturing (Berger, 2016). As shown in Figure 3.1, AM market is still on the rise and predicted to reach an enormous number of 20 billion euro around 2020 (Berger, 2016; Wohlers & Caffrey, 2015).

Figure 3.1 Global AM market in diagram (Berger, 2016)

As a technology with huge market potential to fill, more and more applications were developed to utilize this new manufacturing process to meet the demand. Figure 3.2 showed the market breakdown by industry sectors. Industrial/business machines,
consumer products, motor vehicles and aerospace were the top sectors for additive manufacturing. And from a report by Sculpteo, 44% of the respondents said they will increase spending in AM by at least by 50% (Sculpteo, 2015).

![Market section by industries](image)

**Figure 3.2 Market section by industries (Wohlers & Caffrey, 2015)**

### 3.2 Metal AM systems market

Metal parts manufactured by AM systems became more and more popular because of the manufacturing freedoms over conventional processes. Wohlers Associates have been collecting AM market for decades and the estimated AM metal unit sell was 543, gained a 54.7% growth compared to 2013 (Wohlers & Caffrey, 2015). In Figure 3.3, the growing trend for AM metal system can be seen over the years. AM metal system have come to an exponential increase point around 2012 and is estimated to keep growing.
To get a better view of SLM systems, metal PBF market was studied by Roland Berger. Market breakdown by companies of metal PBF systems was shown in Figure 3.4. EOS, Concept Laser and SLM Solutions were the big players in the game and German companies almost dominant the metal PBF market. Details on available commercial metal PBF systems around the world can be found in Appendix C.

Figure 3.4 Metal AM systems market share by companies (Berger, 2016)
3.3 Additive Manufacturing (AM) research trends

As one of the “hottest” topic in this era, the term “3-D printing” can always be heard from the newspapers, press and internet. Additive manufacturing as one of the concept in 3-D printing area, has been mentioned more and more as time goes by.

For the past decade, researches done in additive manufacturing or related areas has come to a gradual increase.

Some general literature reviews on additive manufacturing have been done in the recent years and from those papers a growing market of additive manufacturing technology can be seen in obvious. (Costabile, Fera, Fruggiero, Lambiase, & Pham, 2017) did a thoroughly research on the number of papers published in the additive manufacturing fields. By using ScienceDirect search engine, the data of number of papers in different areas of additive manufacturing were collected and shown in tables and graphs.

In the paper, they chose a timeframe of 20 years (1997 – 2016 May) to collect data for the research in additive manufacturing. Since this technology was rather new, this timeframe can be a good representation of previous and current research on additive manufacturing.

To better segregate the research into different sections, they used couple of keywords to investigate the influence respectively in their research. Six keywords were searched: 1) additive manufacturing overview and additive manufacturing technology, 2) additive manufacturing cost model and additive manufacturing business model, 3) additive manufacturing mechanical properties and additive manufacturing materials, 4) additive manufacturing supply chain, 5) additive manufacturing sustainability, 6) additive manufacturing lifecycle cost. (Costabile et al., 2017)
As result, for the past 20 years, there are more than 66,000 papers published with keywords in additive manufacturing. And overall, the number of papers each year increased gradually and embraced the high growth rate in the 2010s. Of those papers, 51% of which are focusing on additive manufacturing technology overview, 28% on additive manufacturing mechanical properties and materials, 11% on supply chain, and the rest on sustainability, cost and business models and lifecycle cost.

It was noticeable that the amount of research done in additive manufacturing cost models or business models were still on the inferior side of this technology. Only 4% of the papers have keywords in additive manufacturing cost model (Costabile et al., 2017).

But when I searched some of the keywords in ScienceDirect, the data came quite differently in terms of the number of papers published. When search by using keywords “additive manufacturing”, the number of papers showed up was 1246, which was far less than the result in the research paper by (Costabile et al., 2017), 78 papers of those mentioned “cost model” or “business model” in their abstract, title or keywords, and that is 6% of the total number of papers.

The wide difference could be caused by searching using certain abbreviations which was not included in my own research. Another thing is that a lot of the papers in additive manufacturing didn’t set keywords in AM related terms and rather focused on other perspective researches, such as microstructure properties or comparison studies. These factors came together made the exact researches done in additive manufacturing cost model difficult to analysis. However, both results showed that the amount of papers published on the cost side (4% and 6% of total AM studies) were still limited. This is probably due to the complex cost structures of additive manufacturing products and various of product characteristics. A ubiquitous cost model was not capable of giving
good estimation on such wide variety of products that can be produced using AM processes.

3.4 Selective Laser Melting (SLM) research trends

To have a better insight of how much research has been done in selective laser melting, to investigate the number of paper published with the keyword “selective laser melting” could be a good approach. Two search engines which can accurately filter by keywords and subject for scholar and academic papers, were used to collect data for number of papers published: ScienceDirect and Northeastern University Scholar OneSearch.

To start with the literature reviews on selective laser melting, keywords contain “selective laser melting” were used to filter out irrelevant papers with false “SLM” terms added in the subjects.

To narrow down the topics in selective laser melting technologies, certain keywords were used to find out the economic perspective of SLM. To search the database thoroughly, fields in keywords, title, abstract were all considered respectively, in case any potential information were missed by this method. Meanwhile, search results were compared among the three search engines to cross-check the accuracy of the results.

Of these three scholar search engines, ScienceDirect has the most detailed fields to be searched. By using the keyword filter, papers focusing on selective laser melting can be found more easily. See Figure 3.5 below the number of papers published year-by-year contain SLM as keyword.
It was obvious that the researches in selective laser melting has started to rise in the 2010s and will continue increase with a higher rate.

Figure 3.5 Number of papers with keywords “selective laser melting” (source: ScienceDirect)

The results from Northeastern Scholar OneSearch has also shown similar pattern in terms of the increasing focus on selective laser melting in Figure 3.6. A total number of 530 in ScienceDirect and 664 in Scholar OneSearch also showed that, researches in selective laser melting haven’t reached its limit yet. There are still plenty of room for this technology to be studied and improved.
While the total number of papers in selective laser melting was in a high growing rate, focuses on the economics or the cost effectiveness side were in the mainstream. Around 30% of the papers on Scholar OneSearch has keywords microstructure or properties. Only a handful of papers were found in all three search engines.

To better identity the cost focus in selective laser melting, a wider range literature review was conducted in additive manufacturing fields. In the research of (Costabile et al., 2017), a method to conduct keyword search was mentioned. And on the general aspects of additive manufacturing they inspected, a total of 3001 papers were found mentioning additive manufacturing cost model or business model. After trimming down to some of the top cited papers, some additive manufacturing cost models were found.

![Figure 3.6 Number of papers with keywords “selective laser melting” (source: Scholar OneSearch)](image)
3.5 Cost estimations on additive manufacturing

Hopkinson & Dickens proposed a descriptive cost model for additive manufacturing (Hopkinson & Dickens, 2003). This technology was initially used for rapid prototyping (RP), but the authors provided for the development of technology that would allow the realization of finished products in large scale. They compare the cost of three different kinds of additive manufacturing (stereolithography, fused deposition modelling and selective laser sintering) with one of the traditional molding process (injection moulding).

The cost estimation model for RP process used more of a descriptive method to breakdown the AM cost into three major sections: machine costs, labor costs and material costs (Hopkinson & Dickens, 2003).

The basic machine costs in combine with maintenance costs were used to calculate the machine costs per part. For simplification reason, ancillary costs were removed due to minimum influence on the total costs. Material costs were calculated separately for three AM processes base on different usage of the raw materials. Labor costs were also evenly distributed to cost per part to align the machine costs.

To test and validate the cost estimation model, two parts were selected: a small lever and a medium-sized cover part. Cost per part by different annual production volume were in the following figures (Figures 3.7 and 3.8) for both sample parts. It can be noticed that only the cost of injection moulding process decreases as the production volume increase. The costs for AM processes were kept at a constant value. This was because all machine and labor costs were already deducted to cost per part. The change in production volume doesn’t change the individual part cost. However, this assumption missed some important information in realistic applications. Machine cost and labor cost were usually calculated
by total machine cost and then divided into production volume. The flexibility of machine cost rate was not considered.

Figure 3.7 Cost per part by production volume for small lever part (Hopkinson & Dickens, 2003)

Figure 3.8 Cost per part by production volume for medium cover (Hopkinson & Dickens, 2003)
To fill in the gaps of the research by Hopkinson and Dickens, a new parametric model for AM cost estimation was introduced by Ruffo et al. (Ruffo, Tuck, & Hague, 2006). In their new model, missing parts from the Hopkinson and Dickens model were filled in addition to the division of total cost of build. The cost was separated into direct cost (material driven) and indirect cost (time driven). The scheme of cost structure can be seen in the following Figure 3.9.

Figure 3.9 Tree graph of cost model scheme by (Ruffo et al., 2006)
Unlike Hopkinson and Dickens model, machine cost and labor cost were defined as time-driven cost elements. Fixed cost over production volume can be avoid and changes in the cost can be better captured. Moreover, energy consumption of AM process was first included into total cost estimation, despite the small percentage of overall cost.

And for the sample part, the same lever was used in their study. Detailed costs were calculated in their model and the decreasing trend of cost per part was captured as production volume increases. The zigzag shape in the graph (Figure 3.10) also showed the effect of adding a new line or new bed to the whole cost. Every time a new line or new bed was added to the production, the price was lifted suddenly due to the significant increase of machine cost. But it eventually dropped down by dividing new machine cost over production and until the next line was added to.

Figure 3.10 Cost per part over production volume in line diagram (Ruffo et al., 2006)
The performances of the cost estimation models were also compared using the same lever part. The cost advantage of AM in low production volume manufacturing was obvious from Figure 3.11. But as production volume reached certain high level, injection moulding became competent because lower machine cost and shorter manufacturing time.

Figure 3.11 Comparison among AM cost estimation models (Ruffo et al., 2006)

And for the first time, they observed the effects of part orientation to total cost. From Figure 3.12, the results showed that different part orientation may lead to different cost tendency and it is more economic to use different configuration for optimal manufacturing design (Ruffo et al., 2006).
Although the model by Ruffo et al. has set a benchmark for future AM cost estimation, there are some limitations to this model as well. For example, post-processing as one of the key steps of AM was not considered. The cost of post-processing may not be the significant element to total cost but may lead to more detailed investigation of cost components.

A simple cost estimation model was addressed by Allen (2006) first investigated the relationship between manufacturing cost and part buy-to-fly ratio. The cost of machining from solid billet and additive manufacturing were illustrated using highly material-related cost model. Typical aero components buy-to-fly ratios (shown in Table 3.1) were also used to find breakeven point for both processes.
Table 3.1 Typical titanium aero engine components buy-to-fly ratio (Allen, 2006)

<table>
<thead>
<tr>
<th>Component</th>
<th>Billet weight (kg)</th>
<th>Component wt (kg)</th>
<th>Buy:Fly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercase</td>
<td>182</td>
<td>30</td>
<td>6.06:1</td>
</tr>
<tr>
<td>Simple Duct Flange 1</td>
<td>67</td>
<td>11.14</td>
<td>6.01:1</td>
</tr>
<tr>
<td>Simple Duct Flange 2</td>
<td>67</td>
<td>7.66</td>
<td>8.75:1</td>
</tr>
<tr>
<td>Complex Duct Flange 1</td>
<td>149</td>
<td>7.65</td>
<td>19.48:1</td>
</tr>
<tr>
<td>Complex Duct Flange 2</td>
<td>206.6</td>
<td>10.28</td>
<td>20.10:1</td>
</tr>
<tr>
<td>Large Blisk</td>
<td>810</td>
<td>97</td>
<td>8.35:1</td>
</tr>
</tbody>
</table>

In Figure 3.13, the line of buy-to-fly ratio in different specific AM material cost showed the cost breakeven points for both processes. Simple estimation and economic decisions can be made by looking at this graph. For visual purpose, x-axis was scaled.

Figure 3.13 Specific cos of AM titanium material required to be cost-efficient against machining from solid process (Allen, 2006)

In the book by Gibson et al. (2010), the cost of additive manufacturing was put into four main categories. Like Ruffo et al., the high-level cost model was divided into material cost, labor cost, and with the addition of machine purchase cost and machine operation
cost. Cost = P (machine purchase cost) + O (machine operation cost) + M (material cost) + L (labor cost) (Gibson et al., 2010).

In the model from the book, material recyclability and supportive structure were considered and added to the material cost. More importantly, specific build time of AM process was given and the time has a close relationship with number of layers in the part and the build rate of the process. In this model, maximum number of parts per build was also calculated using the dimension of designed parts and the dimension of the machine.

The discussions on life-cycle cost of AM was also important future researches as they broke it down to 6 categories. Tooling service and retirement costs were discussed in separate chapters.

Despite being used in the book, the model by Gibson et al. still not include post-processing cost. And because the calculation on build time was too specific and dimension-oriented, the model was hard to use on generic cost estimation applications.

Later in the research by Baumers et al. (2012), the cost elements from Ruffo et al. (2006) was further investigated. Economic and energy aspects of AM process were also discussed and analyzed. For part complexity, a voxel approximation method was introduced to convert AM part into voxel based geometry. Build time and energy estimation calculations were closely related to total voxel of the part.

Five different parts were chosen to test the model for cost and energy estimation. The errors for both full build and single part manufacturing were collected and showed less than 10% error (Baumers et al., 2012).
A C++ based software was designed to calculate the cost of AM based on application inputs. Several AM systems were used over various of metal and polymers to test the model performance. Furthermore, different build configurations were also studied using different AM systems.

Lindemann et al. (2012) also proposed an activity based cost model for additive manufacturing. AM process were simplified into four sub-processes: building job preparation; building job production; support and part removal (manually); and post processing for properties improvements (Lindemann, Jahnke, Moi, & Koch, 2012).

As post-processing was first included into AM cost estimation, this process based cost model could capture more elements in AM process and help better understand the economic elements in it (Costabile et al., 2017). Figure 3.14 shows the part sample and detail cost breakdown.

Figure 3.14 Sample part (left) and cost breakdown (right) for AM process (Lindemann et al., 2012)
Just like mentioned before, the ability to produce end-usable part from AM process gives it huge potential in the manufacturing industry. Atzeni and Salmi (2012) compared the cost of high-pressure die-casting and selective laser sintering (SLS) using a sample of an aircraft landing gear (Figure 3.15).

![Figure 3.15](image)

Figure 3.15 (a) Redesigned landing gear; (b) major support; (c) top view. (Atzeni & Salmi, 2012)

Cost per assembly was also investigated under different production volume and the breakeven point for HPDC and SLS process were showed in the following Figure 3.16. Just like the cost model by Hopkinson and Dickens (2003), the machine costs for SLS process were over-simplified and not able to capture the trend by production volume.
Figure 3.16 Cost per assembly by production volume for HPDC and SLS (Atzeni & Salmi, 2012)

Unlike previous AM cost estimation models, the model by Rickenbacher (2013) was on selective laser melting (SLM) to find out the economic potential to replace conventional manufacturing processes. Total manufacturing costs were break down into seven process costs: preparation cost, build job assembly cost, machine setup cost, SLM building cost, part removal cost, part separation cost and post-processing cost (Rickenbacher, Spierings, & Wegener, 2013).

A building time estimation method was also created using regression model. 24 building jobs were measured and building time was calculated as follows in Figure 3.17. Five regression coefficients were built using parameters like number layers, total building volume, total surface area, part quantities an total support surface (Rickenbacher et al., 2013).
\[ \sum_{i} T_{\text{build}}(P_i) = a_0 + a_1 \cdot N_i + a_2 \times V_{\text{tot}} + a_3 \times S_{\text{supp tot}} + a_4 \times \sum_{i} N_i + a_5 \cdot S_{\text{tot}} \]

where
- \( T_{\text{build}} \): building time;
- \( P_i \): part with \( i \)th geometry;
- \( a_0, \ldots, a_5 \): regression coefficients;
- \( N_i \): number of layers;
- \( V_{\text{tot}} \): total volume of building job;
- \( S_{\text{supp tot}} \): total surface area of the support structures;
- \( N_i \): quantity of parts with \( i \)th geometry;
- \( S_{\text{tot}} \): total surface area of the build job.

Figure 3.17 Building time estimation model (Rickenbacher et al., 2013)

For this model, analysis on each step was taken further. The addition of pre- and post-processing cost completed the SLM process. But however, the regression time estimation model was not validated in the paper and energy consumptions were not considered (Costabile et al., 2017).

In the most recent cost estimation model by Schroder (2015), detailed AM processes were studied over seven main stages (Schröder, Falk, & Schmitt, 2015). Sensitivity analysis was conducted for two products at different production quantities in AM process and results showed that high savings in cost per unit can be achieved when production capacity was utilized to the maximum.

### 3.6 Economic overviews

The market potential for AM is enormous. AM is on the edge of fast growing and the impacts are still yet to be fully discovered. With such influence, the economic advantages of AM will play a big part on how this technology will be used in the industry.
One way or another, from previous literatures, all cost estimation models of AM had captured the total cost of AM process in different perspectives. As time goes by, we can see later researchers built more detailed model by improving and adding new elements to previous models.

It is hard to say that a cost estimation model for AM was absolutely accurate and has everything considered. But as the development of AM technology and the rising competence of AM process, more aspects of the total costs were put under investigation. From early constant cost model to the latest activity-based cost model, additive manufacturing has shown great potential manufacturing end-usable parts to replace conventional manufacturing processes. And under certain conditions, AM proves cost-efficiency than material removal processes.

Selective laser melting as one of the most common end-usable functional part manufacturing process, has also shown potential in applications to replace traditional manufacturing. Yet SLM cost estimation models still have room to improve, the foundation of the economic and business analysis has been built up.
4. Methodology

To better investigate the economic advantages of SLM and answer the research questions proposed, several approaches were taken to conduct the research.

First, cost estimation model for both selective laser melting (SLM) and conventional subtractive manufacturing (SM) processes were created to get a generic cost estimation results for a given part designs. Then volume ratio and part complexity score were defined to represent the general part complexity for manufacturing. Several cases were also used for cost comparison between the two processes under different manufacturing settings and scenarios. And last but not the least, other descriptive economic drivers were discussed to further find out the advantage of SLM process.

4.1 Cost estimation model for SLM process

To discover the economic advantages of selective laser melting products, the cost estimation should not only be accurate enough to catch change of inputs, but also need to be generic to avoid been affected by individual application differences. In other words, the cost estimation method should be able to capture the overall cost tendency with changes in certain parameter of the application. The priority of the new method is to see when the part complexity changes, how does the overall costs of the SLM manufacturing process change.

Over the past few years, several scholars have developed well-structured cost estimation model for some of the additive manufacturing process. Empirical detail-oriented cost models (Hopkinson & Dickens, 2003), the indirect-direct category cost models (Baumers,
2012; Ruffo et al., 2006) and process based cost models (Rickenbacher et al., 2013; Schröder et al., 2015) all played their good parts in additive manufacturing cost estimation. With the inspiration of studies of economic assessment on HIP process (Maziarz & Isaacs, 2001), the approach of designing a technical cost model for SLM was applied. Figure 4.1 shows a data structure for cost estimation model design.

![Figure 4.1 Technical cost model structure derived from (Maziarz & Isaacs, 2001)](image)

To better estimate the cost of SLM produced parts, the techno-economic cost model was built using input data found in previous studies and researches. The structure of the cost estimation model is shown in Figure 4.1. With inputs from various aspects, the part cost can be calculated by different production volume and other manufacturing settings. The objection of the new model is to include all necessary elements of SLM processes but not
too specific on the part dimension to give generic cost estimation based on application overall geometry and materials.

This is a spread-sheet based cost model. Input changes can lead to direct total cost per part change and it’s easy for data visualization to see the trend of cost by using different parameter settings.

Based on previous cost models (Gibson et al., 2010; Ruffo et al., 2006), the cost of SLM part was divided into five main sections: main machine cost, auxiliary cost, material cost, energy cost and labor cost.

Main machine cost = Machine purchase cost * Number of machines

Auxiliary cost = Hardware cost + Software cost + Consumable cost + Maintenance cost + Wire erosion machine cost + Building area cost

From which hardware and software cost were calculated by dividing purchase cost by lifespan years. The rest of the cost data can be found in previous studies and online sources.

Material cost = Material unit cost * (Total part mass + Total material waste mass)

Of which the total part mass includes both part and supportive structures. Total material waste comes from unused raw material powders that are not recyclable.

Energy cost was calculated by using specific energy consumption data from previous papers (Baumers, Tuck, Wildman, Ashcroft, & Hague, 2011). The amount of energy consumed equals to SEC multiply by the total part mass. This estimation on energy cost may not be the most accurate one, but due to its small influence on total part cost (Kretzschmar, 2015; Ruffo et al., 2006), this estimation calculation can simplify the
process and get more generic estimation regardless of part dimension specifications.

Table 4.1 shows energy consumption results in several AM processes by different scholars. SEC for SLM process was chosen as 96.82 MJ/kg (Kellens et al., 2010).

<table>
<thead>
<tr>
<th>Study</th>
<th>Technology variant</th>
<th>Energy consumption result</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luo et al. (1999)</td>
<td>Stereolithography</td>
<td>74.52 – 148.97 MJ/kg</td>
<td>Energy consumption not empirically measured</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>107.39 – 144.32 MJ/kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FDM</td>
<td>83.09 – 1247.04 MJ/kg</td>
<td></td>
</tr>
<tr>
<td>Mognol et al. (2006)</td>
<td>3D Printing</td>
<td>7.56 – 13.68 MJ per part</td>
<td>Single part build experiments, in various orientations</td>
</tr>
<tr>
<td></td>
<td>FDM</td>
<td>1.80 – 4.50 MJ per part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DMLS</td>
<td>115.20 – 201.60 MJ per part</td>
<td></td>
</tr>
<tr>
<td>Sreenivasan and Dowell (2009)</td>
<td>LS</td>
<td>52.20 MJ/kg</td>
<td>Empirical energy results not reported</td>
</tr>
<tr>
<td>Kellens et al. (2010a &amp; 2010b)</td>
<td>LS</td>
<td>129.73 MJ/kg*</td>
<td>Full build experiments</td>
</tr>
<tr>
<td></td>
<td>SLM</td>
<td>96.82 MJ/kg*</td>
<td></td>
</tr>
<tr>
<td>Baumers et al. (2010)</td>
<td>SLM</td>
<td>111.60 – 139.50 MJ/kg†</td>
<td>Single part and full build experiments, compared</td>
</tr>
<tr>
<td></td>
<td>EBM</td>
<td>61.20 – 176.67 MJ/kg†</td>
<td></td>
</tr>
</tbody>
</table>

* - Calculated from data provided by Kellens et al. (2010a, 2010b)
† - Calculated from data provided by Baumers et al. (2010)

Table 4.1 Energy consumption rate for laser AM processes (Baumers et al., 2011)

As for the labor cost, the calculation was high dependent on manufacturing time. The building process of SLM was high automated and doesn’t need much human intervention.

When it comes SLM build time estimation, different methods and models showed different perspectives on AM building processes. A neural-network based model for SLS build time estimation was introduced by Munguia et al. (2009), part height, volume and bounding box volume were used as inputs and a three layer artificial neural networks (ANN) model was built to estimate the build time (Munguía, Ciurana, & Riba, 2009). The results of the ANN model were impressive, and it maintained an average 2.8% error.
(Munguía et al., 2009) when compared to actual build time. Another popular build time model was created by Rickenbacher et al. (2013) in which a regression model was used (Rickenbacher et al., 2013). To build the proper regression, number of layers, total build volume, support surface area, number of parts and total surface area were used based on 24 build job samples (Rickenbacher et al., 2013).

For the ease of use in the cost model, the build time estimation chose similar process to Rickenbacher et al. (2013). A regression model was built based on the data provided in their study. But however, to investigate the influence of part complexity in a broader view, support surface areas and total surface areas were removed from original regression model. Since the surface area was harder to measure compare to volume values because certain software needs to be used for scanning and calculation. Table 4.2 shows the new regression model build time estimation results and the differences with original data.

<table>
<thead>
<tr>
<th>Build Number</th>
<th>Tbuild (h)</th>
<th>N(L)</th>
<th>N(P)</th>
<th>Vtot (mm³)</th>
<th>Est. Tbuild (h)</th>
<th>Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.783</td>
<td>850</td>
<td>5</td>
<td>11405</td>
<td>6.9649</td>
<td>-1.182</td>
</tr>
<tr>
<td>2</td>
<td>24.783</td>
<td>3123</td>
<td>3</td>
<td>17625</td>
<td>18.1989</td>
<td>6.584</td>
</tr>
<tr>
<td>3</td>
<td>5.767</td>
<td>1282</td>
<td>2</td>
<td>2610</td>
<td>6.9145</td>
<td>-1.147</td>
</tr>
<tr>
<td>4</td>
<td>25.517</td>
<td>3774</td>
<td>18</td>
<td>35832</td>
<td>26.1036</td>
<td>-0.587</td>
</tr>
<tr>
<td>5</td>
<td>12.067</td>
<td>1485</td>
<td>13</td>
<td>15906</td>
<td>11.4662</td>
<td>0.601</td>
</tr>
<tr>
<td>6</td>
<td>12.183</td>
<td>1485</td>
<td>10</td>
<td>17653</td>
<td>11.5144</td>
<td>0.669</td>
</tr>
<tr>
<td>7</td>
<td>12.200</td>
<td>1485</td>
<td>10</td>
<td>17963</td>
<td>11.5744</td>
<td>0.626</td>
</tr>
<tr>
<td>8</td>
<td>11.750</td>
<td>1485</td>
<td>10</td>
<td>16496</td>
<td>11.2903</td>
<td>0.460</td>
</tr>
<tr>
<td>9</td>
<td>12.483</td>
<td>1287</td>
<td>15</td>
<td>17746</td>
<td>11.1255</td>
<td>1.358</td>
</tr>
<tr>
<td>10</td>
<td>6.550</td>
<td>690</td>
<td>22</td>
<td>13863</td>
<td>8.3655</td>
<td>-1.816</td>
</tr>
</tbody>
</table>

Table 4.2 Regression model build time estimation; Tbuild is the original building time, N(L) is the number of layers in the build and N(P) represents the total number of parts on the build plate, Vtot is the total build volume, data source from (Rickenbacher et al., 2013); Estimated Tbuild is calculated from the cost model in this research and errors were also calculated compared to original build time data.
The new regression model performance may not be as good as the original regression model with an average 12% estimation differences. But the ease of parameters simplified the process of measuring part geometry dimensions. For more universal build time estimation on a new part, the new regression model was capable of estimating build time with enough accuracy.

Estimation model:

$$\text{Build time} = \Delta_0 + \Delta_1 \times L + \Delta_2 \times N + \Delta_3 \times V_{\text{total}}$$

Of which $\Delta_0 = 0.4497$, $\Delta_1 = 0.0045$, $\Delta_2 = 0.0967$, $\Delta_3 = 0.0002$

The R square for the regression equals to 0.891 which indicates overall well-done performance.

In Appendix A, a detail view of SLM cost estimation model can be found. The cost of a stainless-steel part was calculated using specific manufacturing settings.

**4.2 Cost estimation model of conventional SM process**

The main objective of this paper is to find out the economic performance of SLM process when compared with conventional subtractive manufacturing process. Machining processes were used to produce high quality end-usable parts for the past decades and the continuous development of machining technologies have shown manufacturing potentials in new applications and new materials. As material removal rate increases over the years, the quality and accuracy of machining processes also reached new level. With multiple-axis CNC machine, parts with high geometric complexity could be manufactured by “traditional” subtractive manufacturing processes.
For the comparison in economic performances between these two processes, a cost estimation model was built for subtractive manufacturing (SM) process. Like SLM cost estimation model, the cost for SM was also separated into five main sections: main machine cost, manufacturing auxiliary cost, material cost, energy cost and labor cost.

The main machine cost came from depreciation cost of SM machine purchase cost over lifespan years. From Shehab et al. (2002), the machine cost rate equals to 33.14 $/h (Shehab & Abdalla, 2002). To capture total machine purchase cost, reverse calculation was used based on overhead and annual operation data provided. Equipment cost = $250,000 over lifespan of 8 years and 30% of additional overhead cost. From the model by Shehab et al. (2002), EDM cost rate was also considered when machining sample parts. Traced back to the origin literature from Yeo et al. (1997), EDM machine rate was calculated using the same method and machine purchase costs were the same (Yeo, Ngoi, Poh, & Hang, 1997).

Here is an assumption made for SM cost estimation based on the model from (Shehab & Abdalla, 2002; Yeo et al., 1997): Machine purchase costs were the same for different process fabrications. For the simplification of tool change and machine change requirements.

Like illustrated in SLM cost estimation, auxiliary cost also contains building area cost which took the same value as in SLM process. Since the comparisons were focused on part complexity, differences in machine volume were not considered.

Material cost was calculated by multiply bounding box volume (consider as bulk material volume) by material unit cost. One thing important is that, the material unit cost for SM
metal bulk is not the same as SLM raw metal powder. Material cost data can be found online respectively (Custompart.net).

Specific energy consumption of machining processes was studied and collected by (Yoon et al., 2014). In the following Table 4.3, SEC for milling, turning, drilling and grinding were compared sourcing from various literatures. SEC for high tensile steel was used in SM cost estimation for energy cost calculation.

<table>
<thead>
<tr>
<th>Process</th>
<th>Specific energy consumption (J mm$^{-2}$)</th>
<th>Work material</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.8*</td>
<td>Mild steel</td>
<td>Kara and Li$^{22}$</td>
</tr>
<tr>
<td>Milling</td>
<td>14.5*</td>
<td>High tensile steel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28.5*</td>
<td>S45C</td>
<td>He et al.$^{57}$</td>
</tr>
<tr>
<td></td>
<td>11.1-151.8</td>
<td>1018 Steel</td>
<td>Diaz et al.$^{62}$</td>
</tr>
<tr>
<td></td>
<td>30–188</td>
<td>S45C</td>
<td>Li et al.$^{54}$</td>
</tr>
<tr>
<td></td>
<td>43.5-90.0*</td>
<td>Al 6061</td>
<td>Pervaiz et al.$^{63}$</td>
</tr>
<tr>
<td></td>
<td>2.3-4.9</td>
<td>Aluminum</td>
<td>Dahmus et al.$^{64}$</td>
</tr>
<tr>
<td></td>
<td>10.0-60.0</td>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td>Turning</td>
<td>9.8*</td>
<td>Brass</td>
<td>Kara and Li$^{22}$</td>
</tr>
<tr>
<td></td>
<td>7*</td>
<td>Mild steel</td>
<td>Li et al.$^{65}$</td>
</tr>
<tr>
<td></td>
<td>2.7-9.8*</td>
<td>Brass</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.3-12.3*</td>
<td>Mild steel</td>
<td>Mativenga and Rajemi$^{58}$</td>
</tr>
<tr>
<td></td>
<td>12.9-36.2*</td>
<td>Steel (EN8)</td>
<td></td>
</tr>
<tr>
<td>Drilling</td>
<td>65*</td>
<td>Grey cast iron</td>
<td>He et al.$^{57}$</td>
</tr>
<tr>
<td></td>
<td>9-38</td>
<td>Grey cast iron</td>
<td>Neugebauer et al.$^{66}$</td>
</tr>
<tr>
<td>Grinding</td>
<td>343.4-1982.6</td>
<td></td>
<td>Li et al.$^{67}$</td>
</tr>
</tbody>
</table>

* Calculated

Table 4.3 SEC for common subtractive manufacturing processes (Yoon et al., 2014)

Another energy consumption model used MRR as input to tune the SEC for turning and milling at different MRR (Table 4.4), the R-square value also showed good performance
of this model (Kara & Li, 2011). For the stand-by power consumption, average value from turning was used, $P_0 = 1.5$ kW.

<table>
<thead>
<tr>
<th>Machine tool</th>
<th>Model</th>
<th>$R^2$</th>
<th>$P_0 (kW)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>Colchester Tornado A50</td>
<td>SEC = 1.494 + 2.191/MRR</td>
<td>0.993</td>
</tr>
<tr>
<td></td>
<td>Mori Seiki NL2000MC/500</td>
<td>SEC = 3.600 + 2.445/MRR</td>
<td>0.927</td>
</tr>
<tr>
<td></td>
<td>IVEGAL AX 20</td>
<td>SEC = 2.093 + 4.415/MRR</td>
<td>0.981</td>
</tr>
<tr>
<td></td>
<td>Mori Seiki SL-15</td>
<td>SEC = 2.378 + 2.273/MRR</td>
<td>0.940</td>
</tr>
<tr>
<td></td>
<td>Nakamura TMC-15</td>
<td>SEC = 3.730 + 2.349/MRR</td>
<td>0.929</td>
</tr>
<tr>
<td>Milling</td>
<td>Fadal VMC 4020</td>
<td>SEC = 2.845 + 1.330/MRR</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>Mori Seiki Dura Vertical 5100</td>
<td>SEC = 2.830 + 1.344/MRR</td>
<td>0.947</td>
</tr>
<tr>
<td></td>
<td>DMU 60P</td>
<td>SEC = 2.411 + 5.863/MRR</td>
<td>0.997</td>
</tr>
</tbody>
</table>

$^a$ The units of SEC and MRR are kJ/cm$^3$ and cm$^3$/s respectively.
$^b$ $P_0 (kW)$ is the fixed power consumption when machine is stand-by [10].

Table 4.4 Unit energy consumption model for turning and milling (Kara & Li, 2011)

Last but not the least, machining processing time was calculated using volume of removed materials and the MRR for SM machine. Set-up time and post processing time were set to 0.75 h and 0.6 h respectively, and part reloading time was set to 0.01 h (Polgar, 1996). Tool change time = 0.5 min, which indicates that it is negligible in the process time estimation.

Appendix B shows the spreadsheet-based cost model for SM. Sample part was the same as in the SLM model. All input parameters can be modified for other applications.
4.3 Definition of part manufacturing complexity

Complexity for free, as one of the biggest advantages of AM processes, has been addressed in numbers of literatures and consultancy reports. As shown in Figure 4.2, the cost of additive manufacturing process doesn’t change as the complexity changes, while the cost of conventional manufacturing has a positive correlation with the part complexity (Berger, 2013). It is reasonable to think that with adding materials layer-by-layer, the overall part complexity doesn’t significantly affect the total production. But for conventional subtractive manufacturing processes, increase of part complexity means that more set-up and fabrications need to be applied to the part and more tools need to be used.

Figure 4.2 Illustration the concept of complexity for free between additive manufacturing and conventional manufacturing (Berger, 2013)

Some studies have defined the complexity for a manufacturing part. A 2-dimensional shape complexity algorithm was implemented in the research by Baumers et al. (2016) to investigate the correlation between complexity and energy consumption (Baumers, Tuck, Wildman, Ashcroft, & Hague, 2016). Another algorithm based on bitmap image and
traces pixel coordinates was created for 2D shape complexity analysis (Volarevic & Cosic, 2005). These types of part complexity analyses were too specific and require detail digital model of the part to perform algorithm. For cost-wised complexity study, a more generic and easier method should be used to capture the basic dimensional complexity but also omit part individual difference.

Allen (2006) brought in the concept of buy-to-fly ratio to describe the generic complexity of aerospace part (Allen, 2006). This is the ratio of total bounding box volume by part volume, which can demonstrate the cavities and internal structures overview for the part as one of the complexity metrics.

In addition to buy-to-fly ratio, other ratios were introduced to better represent the shape complexity of the part. Parts volume/number of facets, and Parts volume/surface area ratios were derived from STL file and introduced to the complexity (Valentan, Brajlih, Drstvensek, & Balic, 2008). As mentioned in previous sections, the surface area of the part needs to be measured or calculated using certain software, so this ratio is removed. Same situation with number of facets which need to be calculated using mathematical algorithms. The purpose of the new metrics is to capture enough part complexity by first sight and basic dimension data, in addition to empirical manufacturing analysis.

It is obvious from Figure 4.3 that the average buy-to-fly ratios for SLM parts were significantly bigger than machined parts. Buy-to-fly ratio is the reverse of parts volume/block volume ratio.
Figure 4.3 Average parts volume/block volume ratio in different manufacturing processes (Merkt, Hinke, Schleifenbaum, & Voswinckel, 2012), shows that average ratio for SLM parts are much lower than that on machined parts.

To better compare AM and SM processes under the same conditions, here we bring in the concept of volume ratio. The volume ratio equals to the ratio of a part’s bounding box volume versus its actual volume.

\[
\text{Volume Ratio} = \frac{V_{\text{bounding box}}}{V_{\text{part}}}
\]

Bounding box is the largest 3-dimentional virtual structure that all surfaces and structures of the final part touches the boundary of the box. This is a little different than the buy-to-fly ratio since no raw metal bulk is needed in AM process. And the concept of BTF ratio does not apply for AM.

For part with higher complexity, the machining processes may take much longer due to change of fabrication tools and working surfaces. A 3-axis CNC machine can only fabricate one surface orientation at a time, which limits the manufacturing freedom when working on parts with multiple working surface orientations. Frequent part orientation change, fixture change and unloading-reloading processes lead to inefficient time use and
high manual intervention in the process. 5-axis CNC machine may help reduce the amount of changes of part orientations, but the limits on tool angel and cut depth also shows incomplete freedom of manufacturing.

To better analyze the effect of part complexity on SM machining cost, number of working surfaces of a part and number of tools needed in the manufacturing process were used as metrics for complexity. These two values can be easily estimated using empirical method and can demonstrate the influence of complexity on SM processing time. But these two values won’t affect the SLM manufacturing process because of the fabrication freedom in AM process.

These three chosen values for part complexity can reflect the difficulty of manufacturing using conventional method:

- Volume ratio of the part: Bounding box volume/part volume.
- Number of tools needed: The total number of fabrication types, reflects the tool change process in conventional manufacturing process.
- Number of machining surfaces: The total number of part orientation changes.
- Number of machines: The total number of subtractive machines needed for complete fabrication of the designed part.

These four parameters will be analyzed and tested using sample parts data. The cost comparison results between SLM and SM manufactured part will be shown and discussed in the following chapter. More specific economic comparison between two processes will be discussed in the following chapter.
5. Results and Discussion

5.1 SLM cost model results

For SLM cost model performance, five sample parts (Figure 5.1) were chosen to validate the cost estimation results. These parts have specific dimension and part volume data, which serve good examples for the model. The original costs were calculated using model elements from Ruffo et al. (2006).

![Sample parts for cost estimation](image)

Figure 5.1 Sample parts for cost estimation (Baumers et al., 2012)

The rest of the parts from example were put into the cost estimation model. The results are in the following Table 5.1. In the original study by Baumers et al. (2012), five parts were manufactured together in the same build plate as a batch with different number parts. The production volume for each part was calculated using the total build time of the mixed production. Annual manufacturing time was set to be 5000 hours as in the literature and same manufacturing settings were applied to the cost estimation model for these same five sample parts (Baumers et al., 2012).
Table 5.1 Cost estimation comparison using five sample parts

All parts were simulated on a single part full build production situation in SLM manufacturing. Due to the differences in part dimensions, parts per build differed for all five parts. The single part production situation provided more room in space utilization for each part than mixed production. The parts per build for each case were greater than those in the original study (Baumers et al., 2012).

The build time differences were obvious in Table 5.1. This is caused by manufacturing settings. In the original research, the AM system capacity was pushed to the maximum while all five parts were built together on a single building platform. But however, in the cost estimation here, all parts were built separately based on a full build situation. Each example may not be fully using the machine capacity, which leaves opportunity for potential cost reduction. Multiple citations in the literature show the impact of capacity usage on the manufacturing cost in AM systems. To further validate the cost estimation performance, a single sample was used for comparison.
Figure 5.2 shows the dimensional details of a bearing block. It was chosen for single part comparison because cost and build time results were also gathered in the original study by Baumers et al. (2012).

Figure 5.2 Part example for cost estimation: Bearing block (Baumers et al., 2012)

The following Table 5.2 shows the cost estimation results. Production volume was calculated using the build time from original study on single part production (Baumers et al., 2012). The cost difference drops to 10% from 33% by using the same manufacturing settings. With fewer sample parts for comparison, the reduced cost difference shows that the cost model’s ability to capture necessary elements in the whole manufacturing process.

<table>
<thead>
<tr>
<th>Parts Per Build</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Volume</td>
<td>193</td>
</tr>
<tr>
<td>SLM Cost ($)</td>
<td>$884.78</td>
</tr>
<tr>
<td>Difference</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 5.2 Cost estimation results of single part full bed using original production volume
To simulate a general production situation, the production volume was set at 5000 to examine the effect of each parameter on the total cost per part.

The cost breakdown and the cost per part tendency resulted as follows in Figure 5.3 and Figure 5.4. The pie chart shows that the main cost elements for SLM part came from main machine cost and auxiliary cost which were responsible for 65% of the total cost. Material cost comes up to around 30% while energy and labor cost were relatively insignificant.

![Figure 5.3 Cost breakdown for SLM stainless steel sample part](image)

Figure 5.4 shows the effect of production volume on part cost in the model. As production volume goes up, the cost per part drops down quickly in the low production volume level. This is because the machine cost and auxiliary cost are amortized over the number of parts manufactured. As mentioned in Chapter 3, the zig-zag shape in the line occurs due to the addition of a new manufacturing line when the machine capacity has reached its maximum.
To further investigate different factors’ influence on the cost, sensitivity analyses were conducted over six different parameters. Each parameter was increased and decreased by 10% to see the effect on total cost. Low production volume (annual = 1) and high production volume (annual = 1000) were selected for different production scenarios. For consistency, the bearing block was explored.

<table>
<thead>
<tr>
<th>Factor Name</th>
<th>Low Production</th>
<th>High Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support Rate</td>
<td>0.01%</td>
<td>1.22%</td>
</tr>
<tr>
<td>Machine Purchase Cost</td>
<td>4.40%</td>
<td>3.02%</td>
</tr>
<tr>
<td>Material Price</td>
<td>0.02%</td>
<td>2.76%</td>
</tr>
<tr>
<td>Part Volume</td>
<td>0.01%</td>
<td>1.44%</td>
</tr>
<tr>
<td>Post Processing Time</td>
<td>&lt;0.01%</td>
<td>0.09%</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>2.13%</td>
<td>1.46%</td>
</tr>
</tbody>
</table>

Table 5.3 Sensitivity Results on Small Volume Sample Part
Table 5.3 shows that the machine purchase cost is the major factor in both low and high production volume. In the extreme low production scenario, the major cost comes from machine and auxiliary machine cost. The changes in machine purchase cost can lead to changes in total cost. While in the high production volume case, which represents a generic industry production situation, the cost was more evenly spread out. Machine purchase cost, material cost and maintenance cost were all main factors for total part cost.

5.2 SM cost estimation results

Cost breakdown and cost per part over production volume are shown in Figure 5.5 and Figure 5.6. The material cost was the major component for total part cost which accounts for around 46% of total cost. Because the SM processes included machining or removing materials form the metal bulk, this material dominant cost structure can be foreseen. The energy cost in this situation only is only responsible for 0.27% which is essentially negligible.

Empirical analysis on the bearing block fabrication process was taken. By estimation, there are 7 machining surfaces for the bearing block and 6 different of fabrication tools. Only one CNC milling machine is assumed to be needed to finish the manufacturing process. Due to the number of tools, surfaces and machines needed in the part, individual processing time using SM process was significantly increased, leading to much higher labor costs. If the part reloading and tool change processes were fully-automated, the labor cost percentage would significantly decrease.
Because maximum production capacity for one SM machine is much higher than a SLM machine, the bump of adding new machine happened at a much greater production volume compared to SLM process.

Figure 5.5 Cost breakdown for SM machining part

Figure 5.6 Line graph of cost per part by annual production volume
5.3 Part complexity score

As mentioned before, 1) the number of tools needed, 2) the number of surfaces (change of part orientation) and 3) the number of machines needed were two factors that can affect the manufacturing complexity by subtractive manufacturing process. In the following cases, the effect of number of changes in machining process on total part cost was illustrated by cost difference per part.

For consistency, bearing block was used as sample part as baseline. The complexity of fabrication process is explored using the previously discussed three parameters: number of tool changes, surface changes and machine changes. These parameters for the baseline case are: 6 tools, 7 surfaces and 1 machine. Assumptions are made that all machine purchase cost and auxiliary cost are the same to simplify the calculation and ease out the specific differences.

These three parameters can be examined separately but we want to see how these three work as one complexity metric and the performance of it. By increase one unit of one parameter and keep everything else the same, a unit of cost differences can be calculated for each parameter.

Based on the proportion of cost differences by three parameters, the numerical influence on cost can be defined as 0.08:0.32:30.63 for the example part. The complexity of the part for fabrication can be defined as follows:

\[
\text{Complexity} = 0.2 \times (N_t - 1) + 0.32 \times (N_s - 1) + 41.43 \times (N_m - 1)
\]

\(N_t = \) number of tools, \(N_s = \) number of surfaces, \(N_m = \) number of machines.
These three parameters can be estimated through empirical methods based on the part characteristics for other cases.

Table 5.4 shows 17 alternative scenarios with different complexity parameters (including baseline) to investigate the part complexity score. The part dimensions and bounding box volume were kept the same as the bearing block. Each parameter setting represents theoretical additional complexity added to the original design. The cost per part by complexity score is calculated in the following Table 5.4.

<table>
<thead>
<tr>
<th>Nt</th>
<th>Ns</th>
<th>Nm</th>
<th>Complexity Score</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>7</td>
<td>1</td>
<td>2.32</td>
<td>$156.88</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>1</td>
<td>2.64</td>
<td>$157.20</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
<td>1</td>
<td>5.52</td>
<td>$160.08</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>1</td>
<td>6.80</td>
<td>$161.37</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>1</td>
<td>10.00</td>
<td>$164.57</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>1</td>
<td>14.96</td>
<td>$169.53</td>
</tr>
<tr>
<td>15</td>
<td>75</td>
<td>1</td>
<td>24.80</td>
<td>$179.38</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>2</td>
<td>32.95</td>
<td>$187.54</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>2</td>
<td>35.27</td>
<td>$189.86</td>
</tr>
<tr>
<td>10</td>
<td>35</td>
<td>2</td>
<td>42.23</td>
<td>$196.83</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>3</td>
<td>63.58</td>
<td>$218.20</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>4</td>
<td>94.85</td>
<td>$249.50</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
<td>4</td>
<td>105.49</td>
<td>$260.14</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>5</td>
<td>130.92</td>
<td>$285.60</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
<td>5</td>
<td>142.92</td>
<td>$297.61</td>
</tr>
<tr>
<td>30</td>
<td>75</td>
<td>6</td>
<td>179.15</td>
<td>$333.87</td>
</tr>
<tr>
<td>30</td>
<td>75</td>
<td>10</td>
<td>301.67</td>
<td>$456.50</td>
</tr>
</tbody>
</table>

Table 5.4 Complexity test samples; Nt = number of tools, Ns = number of fabricated surfaces, Nm = number of machines used.

Figure 5.7 shows the trend of cost per part by increasing complexity scores. The linear correlation between the two parameters shows good consistency with the cost model. In
addition, part complexity score can serve as an alternative single parameter for cost estimation for a given part.

5.4 Cost comparison between SLM and SM

a. By volume ratio

Buy-to-fly ratio (BTF) is the value of bounding box volume/part volume. It represents the part overall three-dimensional complexity by how much material should be removed from the bulk material by machining process. For same bounding volume parts, a low BTF part takes less space and requires more fabrication than high BTF parts, leading to increased fabrication time and cost.

The same sample part was used for cost comparisons using two different types of materials. Production volume and part complexity scores remain unchanged as the baseline to examine the effect of volume ratio. Two different materials were tested -
titanium as the more expensive material and stainless steel as the cheaper one. Detail results were shown in the following Figure 5.8 (SLM) and Figure 5.9 (SM) for comparison.

For the SLM process, the cost per part shows a significant reduction with increasing volume ratio (efficient materials utilization). When the volume ratio reaches a relatively high level (approximately 9), the cost trend becomes stable. This is because as volume ratio increases, the total amount of materials required is reduced. Up to a certain level, the material cost become insignificant and other cost sections become dominant.

Figure 5.8 Cost comparison between stainless steel and titanium by volume ratio (SLM)

However, the trend for SM processes differs from SLM. The cost differences are not as great as SLM as the volume ratio increases. The cost remains rather stable for the entire range of different volume ratios. For the SM process, the dominant material cost comes from the metal bulk purchase. Regardless of the volume ratio, the total amount of material purchased remains the same.
b. By part complexity score

The effect of the part complexity score can be examined solely by changing complexity parameters. Other parameters were set the same for comparison. For this case, five different complexity score samples were selected representing different levels of manufacturing difficulties. In Figures 5.10 and 5.11, the cost of SM processes was marked in blue (or blue alike) color and the complexity score increases from light to dark. The cost of SLM process was marked in red for better readability.

The cost of SM processes increase in parallel as the complexity score increases. The influence of volume ratio was negligible, as mentioned in the previous discussion. In both figures, two green circles represent the cross-over points of SLM and SM processes (the point at which the volume ratio of two processes share the same cost). The cost
advantages of SLM process appear on the right side of the cross-over points where the cost of SLM is less than the cost of SM.

For higher complexity score part (CScore = 142.92), the cross-over point (ratio = 20) moves left than lower complexity score part (CScore = 105.49, ratio = 41). SLM process shows more cost advantages in parts with higher complexity scores. Higher the complexity score, more processes, time and cost occur in conventional SM process which gives more advantages for SLM under the same conditions.

![Cost Comparison (SStein, PV=5000)](image)

**Figure 5.10** Cost comparison by volume ratio and complexity score (stainless steel and high production volume)

When comparing these two figures, no obvious differences showed in cross-over points. Either the difference in materials are not as important as other factors, or the influence of material cost needs further analysis.
c. By production volume

It was mentioned in some literature that SLM has more cost advantages in low production scenarios (Hopkinson & Dickens, 2003; Ruffo et al., 2006). To investigate the effect of production volume on the cost comparison results, another low production setting was examined and tested.

Production volume of 100 piece per year was set for this manufacturing scenario. This is a good simulation of low production manufacturing situation and will drive the cost per part in different breakdown structures.

From Figure 5.12 and 5.13, the costs of SM processes remain parallel, due to the linear correlation between cost and complexity score. In this low production situation, both SLM and SM costs rise drastically when compared to the high production volume situation. However, the SLM process becomes more cost efficient than most of the SM
processes at this low production volume. The cross-over point for SLM and SM (CScore = 42.23) lies at a volume ratio of 2.5. Compared to Figure 5.10 and 5.11, it can be seen as that these two processes do not have a cross-over point in Figure 5.12 and 5.13.

When comparing these two production volume settings, SLM stands out more in low production volume. In this case, low production volume favors the SLM process over the SM process. With lower production volumes, the advantages of SM process’s high manufacturing capacity per machine is not in play, since the high equipment costs are not amortized over large production volumes.

![Cost Comparison (SSeal, PV=100)](image)

Figure 5.12 Cost comparison by volume ratio and complexity score (stainless steel and low production volume)

And again, the two types of material did not show obvious differences in cross-over points. Different manufacturing settings must be examined to determine more noticeable differences in materials.
d. By cost of material

Another manufacturing setting was explored to see the influence of materials. At 5000 annual production volume and 130.92 complexity score, the cost comparison between SLM and SM shows clear cross-over points in both materials (Figure 5.14).

The green circle in the graph represents the cross-over point for titanium material and the black circle is for stainless steel. In this case, the green circle is at the left side of the black circle which means that titanium, as the more expensive material, has greater cost advantages than stainless steel. In general, for parts with higher complexity, more expensive materials show greater cost efficiencies than less expensive materials.

Figure 5.13 Cost comparison by volume ratio and complexity score (titanium and low production volume)
5.5 Other economic drivers for SLM

Customization

The use of AM in rapid tooling shows its economic advantages immediately. At low volume production, highly customized and complexed parts can be manufactured by additive manufacturing with lower cost.

To produce metal parts with high complexity, the economic advantages of SLM lies in the freedom of fabrication. Regardless of the shape complexity, SLM processes do not need to add or change tool sets or changes part orientation, not to mention that one machine can be utilized for the entire manufacturing process. This gives SLM the advantages not only in cost, but also in lead time and material savings compared to conventional subtractive manufacturing process.
In the medical industry, SLM has been used to manufacturer highly-customized prosthetic and implant parts. Figure 5.15 and 5.16 show metal implant parts customized for patients and manufactured by SLM process by Renishaw. For example, dental replacement parts that usually takes days to make were now manufacturing for demand. And with the material range expand from just metal, ceramic and compound material parts were available for numerous applications.

Figure 5.15 Customized implant parts manufactured by SLM (Razvan & Ancuta, 2016)

Figure 5.16 Facial replacement metal part (Renishaw)
**Weight reduction in aerospace applications**

In the aerospace industry, the reduction of weight can lead to huge cost savings. For some applications, topology design in part structures can build the part with same mechanical properties but at a reduced weight. In Figure 5.17 is a structure topology optimized brackets use on airplane. The new design has a much lighter weigh but due to structural optimization it can reach the same functional requirements. Other parts on the aerospace industry have used similar method for part weight reduction.

![Figure 5.17 Micro-structure topology optimized brackets on airplane (left) and engine block (right) (Berger, 2016; Thompson et al., 2016)](image)

**Complex internal structures**

Complexed conformal cooling channels were usually hard to be realized by conventional manufacturing process, especially by subtractive machining. On the left of Figure 5.18 is a water redistribution manifold design for conventional manufacturing process. Due to process limitations, conventional manufacturing process can only fabricate straight through cooling channels. The new design (Figure 5.18 right) changes the path of the channel to allow optimal contact and can reduce vibration forces by 90% (Thompson et al., 2016). Example of complex conformal cooling is shown in Figure 5.19.
For parts that are unable to be realized through conventional manufacturing processes, SLM may be a good option. It is hard to estimate the cost and time for manufacturing using conventional subtractive manufacturing process, but when compared with parts with similar conventional design, the functional advantages of SLM can be obvious.
6. Conclusion and Future Research

6.1 Conclusions

In this paper, the selective laser melting (SLM) process was discussed regarding its economic performance. The development of SLM system and the characteristics of SLM were studied and compared. A breadth of literature on additive manufacturing (AM) and cost modeling was reviewed, and a new techno-economic cost model for SLM process was built. Several cost comparisons between SLM and conventional subtractive manufacturing processes were discussed using sample cost calculations.

Results show that SLM has economic advantages over SM machining process when production volumes are relatively low. However, analyses for more complex parts with higher volume ratios show cost advantages for SLM processes. Using the newly defined complexity score, the cost for both conventional SM machining process and SLM process increases as the complexity score increases. However, SLM shows more cost efficiency for high complexity scores than SM processes. Material selection also plays a role when part complexity reaches higher levels. More expensive materials show more competitiveness over SM processes than less expensive materials.

Other descriptive economic parameters like structural optimization and customization were discussed. When a part requires mass customization, or structural/weight optimization, AM may be a better choice. But further numerical analysis needs to be conducted to get detailed comparison results. As for complex internal structures, SLM can be used to manufacture parts that are infeasible for conventional SM processes.
6.2 Limitations

This thesis discussed the economic performance for selective laser melting. But however, the techno-economic cost estimation model was only useful when the part dimensional complexity was obvious at first sight. Moreover, the cost models for SLM and SM provided only a generic cost estimation tool, and some of the assumptions may not be suitable for other part manufacturing processes. The economic comparison was based on empirical experience and application overview. For specific manufacturing applications, more analysis would be necessary. Multiple manufacturing situations should also be considered based on real manufacturing conditions.

6.3 Future research

For numerical metric of a part complexity, more factors could be calculated through modeling. A more detailed and complex cost model for SLM could be developed using various input options. A streamlined cost estimation could also be developed for part manufacturing processes. The accurate cost estimation should not only focus on the machining section but also the entire process from raw material to end-of-life to give cost-wise insights for design. In addition, lifecycle costs of SLM products should be analyzed to fully discover any other case-specific economic advantages.

Some researchers have begun to address the production side of SLM process. Mixed production and streamlined automation for SLM process were introduced and are under development (Berger, 2016). Automation and integration with conventional manufacturing process were also studied and the potential behind it was prominent.
As the adoption of SLM systems in the industry become more and more prevalent, the market will drive the process to a more economic efficient state. Some technology consultancies have predicted that with more applications made under AM processes, the powder material price will fall to compete in the market (Berger, 2016; Wohlers & Caffrey, 2015). As the deposition rate is able to be increased, the cost and time savings in SLM can achieve even larger goals.
REFERENCES


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ProtoLabs. How DMLS Can Be Used to Produce Reliable Metal Parts. *3D printing with DMLS creates complex, durable, lightweight metal parts.* Retrieved from https://www.protolabs.co.uk/resources/design-tips/designing-for-direct-metal-laser-sintering/


**APPENDIX**

**Appendix A: Spreadsheet based cost estimation model for Selective Laser Melting (SLM) process**

<table>
<thead>
<tr>
<th>Production Input</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Volume</td>
<td>5000 parts</td>
</tr>
<tr>
<td>Total Production Volume</td>
<td>5264 parts</td>
</tr>
<tr>
<td>Production Hours per week</td>
<td>100 hr</td>
</tr>
<tr>
<td>Production Week per year</td>
<td>50 week</td>
</tr>
<tr>
<td>Utilization Rate</td>
<td>57%</td>
</tr>
<tr>
<td>Labor</td>
<td>30 $/hr</td>
</tr>
<tr>
<td>Process Yield</td>
<td>95%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th>per piece</th>
<th>per year</th>
<th>percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Machine Cost</td>
<td>$144.46</td>
<td>$722,289</td>
<td>26.90%</td>
</tr>
<tr>
<td>Auxiliary Cost</td>
<td>$205.19</td>
<td>$1,025,930</td>
<td>38.21%</td>
</tr>
<tr>
<td>Material Cost</td>
<td>$160.18</td>
<td>$800,877</td>
<td>29.80%</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$7.66</td>
<td>$38,279</td>
<td>1.43%</td>
</tr>
<tr>
<td>Labor Cost</td>
<td>$19.48</td>
<td>$97,402</td>
<td>3.63%</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$536.96</td>
<td>$2,684,778</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

**Application Specification**

- **Bounding Box Dimension x**: 127 mm
- **Bounding Box Dimension y**: 76 mm
- **Height z**: 52 mm
- **Bounding Box Volume**: 501904 mm³
- **Part Volume**: 96706 mm³
- **Support Structure Rate**: 20%
- **Total Volume**: 116047 mm³
- **Number of layers**: 2600
- **Number of parts per build**: 3
- **Total Material Mass**: 7,933.40 kg
- **Total Material Cost**: 800,876.57 $

**SLM Machine**

- **Machine**: EOSINT M280
- **Machine Purchase Cost**: 444,486 $
- **Machine Lifespan**: 8 years
- **Annual Production Time**: 5,000.00 hr
- **Workspace Dimension x**: 250 mm³
- **Workspace Dimension y**: 250 mm³
- **Workspace Dimension z**: 325 mm³
- **Laser Power**: 200 W
- **Layer Thickness**: 0.02 mm
- **Number of layers**: 2600
- **Number of parts per build**: 3
- **Total Material Mass**: 7,933.40 kg
- **Total Material Cost**: 800,876.57 $

**Mfg Auxillary Cost**

- **Machine consumables**: 1,299 $
- **Consumables**: 1,299 $
- **Maintenance Cost**: 28,223 $/year
- **Wire erosion machine**: 14089.9 $/year
- **Yearly Rent Rate**: 139 $/m²
- **Building Area**: 247 m²

**Energy Cost**

- **Specific Energy Consumption**: 357.05 MJ/kg
- **Total Energy Cost**: 38,278.78 $
- **Labor Cost**: 30.00 $/hr
- **Total Labor Cost**: 97,402.50 $

**Material Input**

- **Raw Material**: Stainless Steel 17-4 PH
- **Density of Material**: 7.80E-06 kg/mm³
- **Cost per kg**: 100.95 $
- **Powder Recycle Rate**: 80%

**Process Time**

- **Tbuild = 0.449679+0.004498*NL +0.096723*Ni+0.000194*Vtot**
- **Pre-processing**: 1.25 hr
- **Build Time**: 34.95 hr
- **Post-processing**: 0.6 hr

**Energy Consumption**

- **Minimum Energy Rate per Volume**: 1.96 MJ/cm³
- **Maximum Energy Rate per Volume**: 3.61 MJ/cm³
- **Energy Rate**: 0.0225 $/MJ
- **Single Build**: 337.68 MJ/kg
- **Full Build**: 239.99 MJ/kg
Appendix B: Spreadsheet based cost estimation model for Subtractive Manufacturing (SM) process

<table>
<thead>
<tr>
<th>Production</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Volume</td>
<td>5000 parts</td>
</tr>
<tr>
<td>Total Production Volume</td>
<td>5264 parts</td>
</tr>
<tr>
<td>Production Hours per week</td>
<td>100 hr</td>
</tr>
<tr>
<td>Production Week per year</td>
<td>50 week</td>
</tr>
<tr>
<td>Utilization Rate</td>
<td>57%</td>
</tr>
<tr>
<td>Labor</td>
<td>30 $/hr</td>
</tr>
<tr>
<td>Process Yield</td>
<td>95%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th>per piece</th>
<th>per year</th>
<th>percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Machine Cost</td>
<td>$62.50</td>
<td>$312,500</td>
<td>15.98%</td>
</tr>
<tr>
<td>Auxiliary Cost</td>
<td>$91.40</td>
<td>$456,977</td>
<td>23.36%</td>
</tr>
<tr>
<td>Material Cost</td>
<td>$178.57</td>
<td>$892,872</td>
<td>45.65%</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$1.05</td>
<td>$5,255</td>
<td>0.27%</td>
</tr>
<tr>
<td>Labor Cost</td>
<td>$57.64</td>
<td>$288,221</td>
<td>14.74%</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$391.16</td>
<td>$1,955,825</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Application Specification

| Bounding Box Dimension x | 127 mm |
| Height z | 52 mm |
| Bounding Box Volume | 501904 mm³ |
| Part Volume | 96706 mm³ |
| Buy-to-Fly Ratio | 5.19 |
| Number of tools needed | 10 |
| Number of machining surfaces | 25 |
| Number of Machines | 5 |
| Production overview |
| Annual Production Time | 5,000.00 hr |
| CNC Machine |
| Machine | CNC Milling |
| Machine purchase cost | 250000 $ |
| Machine Lifespan | 8 year |
| Material Removal Rate | 1,800,000 cm³/min |
| Part reloading time | 0.01 hr |
| Post Processing Time | 0.60 hr |
| Tool change time | 0.0083 hr |
| Process Time |
| Specific Energy Consumption | 14.5 J/mm³ |
| Energy Rate | 0.0225 $/MJ |

Material Input

| Raw Material | Titanium |
| Density of Material | 4.51E-06 kg/mm³ |
| Cost per kg | 75 $/kg |

<table>
<thead>
<tr>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy Consumption</td>
</tr>
<tr>
<td>Energy Rate</td>
</tr>
<tr>
<td>1MJ = 0.276 kWh</td>
</tr>
<tr>
<td>Total Labor Cost</td>
</tr>
</tbody>
</table>
Appendix C: Commercial metal PBF systems around the world (Wohlers & Caffrey, 2015)

Currency exchange rate: $ 1 = € 0.93; $ 1 = £ 0.78; $1 = ¥ 109.17 (April 2017)

<table>
<thead>
<tr>
<th>Country</th>
<th>Company</th>
<th>Model Name</th>
<th>Build Volume, mm(inches)</th>
<th>Material</th>
<th>Approx. Price x 1,000 Equivalent to USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Beijing Long Yuan</td>
<td>DiMetal 100</td>
<td>120 x 120 x 150 (4.7 x 4.7 x 5.9)</td>
<td>316L stainless steel, cobalt-chrome</td>
<td>$200</td>
</tr>
<tr>
<td></td>
<td>Hunan Farsoon</td>
<td>FS271 M</td>
<td>275 x 275 x 320 (10.8 x 10.8 x 12.6)</td>
<td>316L stainless steel; cobalt-chrome, aluminum, titanium alloys</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Wuhan Huake 3D</td>
<td>HK M250</td>
<td>250 x 250 x 250 (9.8 x 9.8 x 9.8)</td>
<td>stainless steel and many other metals</td>
<td>$328</td>
</tr>
<tr>
<td></td>
<td>Xi'an Bright Laser</td>
<td>BLT-S200</td>
<td>105 x 105 x 200 (4.1 x 4.1 x 7.9)</td>
<td>titanium alloys, nickel base alloys, aluminum alloys, stainless steel, tool steel, cobaltchrome</td>
<td>$200 base price</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BLT-S300</td>
<td>250 x 250 x 400 (9.8 x 9.8 x 15.7)</td>
<td>same as above</td>
<td>$490 base price</td>
</tr>
<tr>
<td>England</td>
<td>Renishaw</td>
<td>AM250</td>
<td>250 x 250 x 300 (9.8 x 9.8 x 11.8)</td>
<td>stainless steel, tool steels, aluminum, titanium, cobalt-chrome, nickel alloys</td>
<td>$375</td>
</tr>
<tr>
<td></td>
<td>AM250 +</td>
<td></td>
<td>250 x 250 x 350 (9.8 x 9.8 x 13.8)</td>
<td>same as above</td>
<td>$461</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EVO Project</td>
<td>250 x 250 x 350 (9.8 x 9.8 x 13.8)</td>
<td>Ti64, Inconel, Aluminum</td>
<td>-</td>
</tr>
<tr>
<td>Germany</td>
<td>Concept Laser</td>
<td>Mlab cusing</td>
<td>90 x 90 x 80 (3.5 x 3.5 x 3.2) or 70 x 70 x 80 (2.8 x 2.8 x 3.2) or 50 x 50 x 80</td>
<td>stainless steel, CoCr alloy, bronze alloy, precious metals including silver and gold</td>
<td>$177</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mlab cusing R</td>
<td>90 x 90 x 80 (3.5 x 3.5 x 3.2) or 70 x 70 x 80 (2.8 x 2.8 x 3.2) or 50 x 50 x 80 (2 x 2 x 3.2)</td>
<td>same as above plus titanium alloys, pure titanium</td>
<td>$199</td>
</tr>
<tr>
<td></td>
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<td>M1 cusing</td>
<td>250 x 250 x 250 (9.8 x 9.8 x 9.8)</td>
<td>stainless steel, tool steels, CoCr alloys, nickel-based alloys</td>
<td>$389</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M2 cusing (200W)</td>
<td>250 x 250 x 280 (9.8 x 9.8 x 11)</td>
<td>stainless steel, tool steels, CoCr alloys, nickel-based alloys, aluminum alloys, titanium alloys, pure titanium</td>
<td>$485</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M2 cusing (400W)</td>
<td>250 x 250 x 280 (9.8 x 9.8 x 11)</td>
<td>same as above</td>
<td>$517</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M2 cusing</td>
<td>250 x 250 x 280 (9.8 x 9.8 x 11)</td>
<td>same as above</td>
<td>$582</td>
</tr>
<tr>
<td>Model</td>
<td>Price</td>
<td></td>
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<tr>
<td><strong>Multilaser (2 x 200W)</strong></td>
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<tr>
<td>M2 X line 1000R</td>
<td>aluminum alloys, titanium alloys, nickel-based alloys $1,510</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>M2 X line 2000R</td>
<td>same as above $1,701</td>
<td></td>
<td></td>
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<tr>
<td><strong>EOS</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EOS PRECIOUS M 080</td>
<td>precious metal alloys $216 base price</td>
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<tr>
<td>EOSIN T M 280</td>
<td>co-balt-chrome, titanium, stainless and tool steel, Inconel, aluminum $448 base price</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EOS M 290</td>
<td>same as above $518 base price</td>
<td></td>
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<tr>
<td>EOS M 400</td>
<td>Inconel, aluminum $1,350 base price</td>
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<tr>
<td><strong>Realizer</strong></td>
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<tr>
<td>SLM SLM 50</td>
<td>316 L stainless steel, cobalt-chrome, jewelry gold, dental gold alloys, platinum, palladium alloys $130</td>
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<tr>
<td>SLM 100</td>
<td>H13 tool steel, titanium, titanium V4, aluminum, cobalt-chrome, 316 L stainless steel, Inconel, gold, ceramic materials under development $211</td>
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<tr>
<td>SLM 125</td>
<td>H13 tool steel, titanium, titanium V4, aluminum, cobalt-chrome, 316 L stainless steel, Inconel, gold, ceramic materials under development $297</td>
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<tr>
<td>SLM 250</td>
<td>H13 tool steel, titanium, titanium V4, aluminum, cobalt-chrome, 316 L stainless steel, Inconel $421</td>
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<tr>
<td>SLM 300</td>
<td>aluminum alloys, steel, others $518</td>
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<tr>
<td><strong>SLM Solutions</strong></td>
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<tr>
<td>SLM 125HL</td>
<td>316L stainless steel, 17-4PH, H13 tool steel, Al-Si-12, Al-Si-10, AlSi7Mg, titanium, Ti-6Al-4V, Ti-6Al-7Nb, Hastaloy X, cobaltchrome, Inconel 718 and 625 $211 base price</td>
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<tr>
<td>SLM 280HL</td>
<td>same as above $486 base price</td>
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<tr>
<td>SLM 500HL</td>
<td>same as above $756 base price</td>
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<tr>
<td>Country</td>
<td>Manufacturer</td>
<td>Model</td>
<td>Dimensions</td>
<td>Materials</td>
<td>Price</td>
</tr>
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<td>----------</td>
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</tr>
<tr>
<td>Italy</td>
<td>Sisma Spa</td>
<td>Mysint1 00</td>
<td>100 dia. x 100 (3.9 dia. x 3.9)</td>
<td>stainless steel, CoCr alloy, bronze alloy, precious metals</td>
<td>$178</td>
</tr>
<tr>
<td>Japan</td>
<td>Matsuura</td>
<td>Lumex Avance-25</td>
<td>250 x 250 x 100 (9.8 x 9.8 x 3.9)</td>
<td>steel, stainless steel, titanium</td>
<td>$864</td>
</tr>
<tr>
<td></td>
<td>OPM Laborator y Co., Ltd.</td>
<td>OPM25 0L</td>
<td>250 x 250 x 250 (9.8 x 9.8 x 9.8)</td>
<td>steel, stainless steel, titanium</td>
<td>$595</td>
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<tr>
<td>Sweden</td>
<td>Arcam</td>
<td>A2X</td>
<td>200 x 200 x 380 (7.9 x 7.9 x 15)</td>
<td>titanium, Inconel, cobalt-chrome, high-end alloys</td>
<td>$756</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q10</td>
<td>200 x 200 x 180 (7.9 x 7.9 x 7.1)</td>
<td>titanium, cobalt-chrome</td>
<td>$610</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q20</td>
<td>350 dia. x 380 (13.8 dia. x 15)</td>
<td>titanium</td>
<td>$864</td>
</tr>
<tr>
<td>U.S.</td>
<td>3D Systems</td>
<td>ProX 100 Dental</td>
<td>100 x 100 x 80 (3.9 x 3.9 x 3.1)</td>
<td>certified Ni-free cobaltchromium materials</td>
<td>$224</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ProX 100</td>
<td>100 x 100 x 80 (3.9 x 3.9 x 3.1)</td>
<td>stainless steels, tool steels, non-ferrous alloys, superalloys and others</td>
<td>$226</td>
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<tr>
<td></td>
<td></td>
<td>ProX 200</td>
<td>140 x 140 x 100 (5.5 x 5.5 x 3.9)</td>
<td>same as above</td>
<td>$422</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ProX 300</td>
<td>250 x 250 x 300 (9.8 x 9.8 x 11.8)</td>
<td>same as above</td>
<td>$684</td>
</tr>
</tbody>
</table>