A Study of Mixed Manufacturing Methods in Sand Casting Using 3D Sand Printing and FDM Pattern-making Based on Cost and Time

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Abstract

Sand casting has long been known to be an effective manufacturing method for metal casting and especially for parts of large dimensions and low production volume. But, for increasing complexity, the conventional sand casting process does have its limitations; one of them mainly being the high cost of tooling to create molds and cores. With the advent of additive manufacturing (AM), these limitations can be overcome by the use of a 3D sand printer which offers the unique advantage of geometric freedom. Previous research shows the cost benefits of 3D sand printing molds and cores when compared to traditional mold and core making methods. The line of research presented in this thesis introduces the idea of additive manufacturing at different stages of the sand casting process and investigates the decision-making process as well as the cost-based effects. This will enable foundries and manufacturers to integrate the use of AM machines more smoothly into their production process without the need for completely re-engineering the existing production system. A critical part of this thesis is the tooling cost estimation using a casting cost model that is significantly accurate to industry standard quotes. Based on these considerations, this thesis outlines three approaches for achieving this goal apart from traditional mold and core making methods. The first approach integrates 3D Printing at the pattern making level where the patterns and core-boxes are “printed” on an FDM printer. This eliminates the tooling costs associated with a traditional sand casting method. The second approach integrates 3D Printing at the core-making level by “mixing” traditional mold-making process and 3D sand printing process for core-making. The third approach, the 3D sand printer is used to create both the molds and the cores, thereby eliminating the need for traditional methods. An initial hypothesis is created which states that, for a given production volume, with increased complexity of the casting, additively manufacturing only the cores and conventionally manufacturing the molds is cost-feasible when compared to traditional manufacturing or 3D sand printing. It is finally concluded that the initial hypothesis is valid when part geometries are highly complex and production volumes range between medium to high. It is also concluded that a decision making tool based on the methodology provided can help determine a specific mixed manufacturing method for the manufacturer.

Acknowledgements

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Humtown Products and their Sales Manager Brandon Lamoncha deserve a separate mention. Brandon's inputs and suggestions have provided me with an in-depth perspective on the costs associated with tooling manufacturing. Also, special thanks to Ashley Martof for providing the costing data on the Fortus 900 machine.

I thank my friends who are the closest to family I have here in the United States. They have seen me through my ups and downs and were always ready to help me. And finally I am extremely grateful to my parents Jyothi Gullapalli and Surya Kumar Gullapalli, who live in India, and have shown unflinching support even when I doubted my own capabilities. Their words of advice and encouragement have empowered me to constantly improve myself.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

In 2013, a total of 103.2 million metric tons of metal castings were produced globally, which was a 3.4% increase when compared to 2012.[1] The United States metal casting industry is made up of 1961 facilities and the industry capacity is 15.3 million tons.[1] The total industry sales are expected to reach $30.6 billion in 2018.[1] Also, the U.S. is second in the world in casting shipments based on tonnage with China in first place and India in third. To increase their competitiveness, it is imperative for foundries to take advantage of new technologies like AM and eradicate the technological barriers that exist within. Implementing additive technologies requires a re-thinking of existing modeling, simulation and process control systems. But the pre-requisites of implementation imply that the organization/ foundry are aware of the benefits this technology provides. A reduction in knowledge gap keeps the organization in sync with rapid advancements in the industry and also plays a key role in faster adoption. The challenging part of adopting AM is changing the traditional mindsets in organizations. [2] This thesis is an attempt to reduce a similar knowledge gap between traditional sand casting practices and AM. The motivation for this thesis is to work within the confines of the current foundry processes and determine a way to bring AM into these existing processes in a less intrusive way.

The foundation of this thesis depends on having a good fundamental understanding of the metal casting process and the AM process. Hence, the aim of the next two chapters is to provide an in-depth understanding of metal casting, specifically the sand casting process, and also the adoption of AM in the casting sector. The final chapter also discusses existing cost models and methods to calculate the complexity of a 3D CAD model.

1.1 Metal casting

Metal casting is a production process which involves molten metal being poured into a mold made of sand, metal or ceramic to form geometrical shapes. The global production output in 2014 is more than 105 million metric tons. [3]. Metal casting inherently lends itself to the formation of parts which are intricate, rigid and frequently unobtainable by other fabrication processes. [4]

A casting can be defined as a metal geometric shape obtained by allowing molten metal to solidify in a mold cavity. This method provides inherent advantages, which makes casting preferable over other shaping process. [5] Some advantages are:

1. Externally and internally intricate shapes can be formed which results in the minimization or elimination of other operations such as machining, forging or welding.

2. This process is highly adaptable for mass production. An example of such a requirement is in the automotive sector.
3. It is possible to cast objects in a single piece which otherwise would require construction in several pieces.
4. It is economically feasible and easy to cast heavy and extremely large metal objects. Parts weighing up to 200 tons in hydroelectric plants are a primary example.

Recent advancements in metal casting have greatly improved the quality of castings. Based on proper selection of materials, correct heat treatment, and careful foundry control, castings of uniform high quality can be manufactured commercially. Also, through increased cooperation between the designer and foundry, stronger castings can be obtained without being penalized by high production costs which are usually a by-product of poor material selection or faulty design. [4]

1.2 Sand Casting

1.2.1 Process components

There are a number of casting methods, which differ in the technique and the equipment used, but all of which require the following systems: [5]

1. Patternmaking (including core boxes)

A pattern is used to create the mold shape and is the actual shape of the metal part that needs to be created. A core-box is used for the creation of cores which form the interior geometries of the casting.

Traditional pattern-making requires precise skills in woodworking and also knowledge of metal casting. Metallurgical concepts like shrinkage rates and solidification for different metals become important for the pattern-maker when preparing the pattern. Patterns are needed to make molds which, in turn, are made by packing molding sand (in the case of sand casting) around the pattern.

There are two kinds of patternmaking: one that happens in foundries and one that happens in pattern shops. Most foundries are concerned with modifying existing patterns and preparing them for molding while most pattern shops produce new patterns and cores. The pattern shops operate as a separate business from the foundry.

Manually building a pattern requires the skill of a pattern maker who can read two dimensional drawings and create a three dimensional part. A variety of different pieces are glued or fastened together to construct the shape of the pattern. A certain amount of draft is added to the pattern which makes the process of removal from the sand mold easier. This also ensures that extra metal is casted intentionally which can be removed via machining. A key factor in pattern designing is that the pattern must be able to withstand the repeated ramming of the molding process in the foundry.

The patternmaker is also in-charge of deciding the shape and number of cores required and also the design and build of the core-boxes. Hence, the skill of an excellent patternmaker is the ability to visualize the negative shape of the part and then realize how the internal geometry would look like. Hence, a high level of expertise is expected of a patter-maker who, for example, might be working in a foundry which does a lot of automotive or aircraft engine work, where the complexity of the cast part would be high. Another patternmaker working at a foundry which produces frames may not be as experienced with core-box fabrication.

2. Core-making

Cores are usually made of sand and then placed inside a mold cavity to form the interior surface of the castings. Thus the void between the core and the mold-cavity forms the actual shape of the casting. These cores can be made of metal, plaster or core sand. But to achieve the utmost intricacy in castings, the primary requirement is that after pouring and cooling of the metal, the cores have to be collapsible.

Cores provide the casting process with the ability to make the most intricate shapes, eliminate a lot of machining, and produce shapes which would be impossible to machine. In addition, cores serve a number of other purposes:[5]

- Complete molds may be assembled of core mold forms. This practice is useful when the intricacy of the casting makes it impractical to use a mold.
- Cores can be used to form a part of the mold.
- Cores strengthen or improve a mold surface
- Cores can be used as a part of the gating system
- Ram-up cores are used for several purposes. These cores are located on the pattern and rammed up along with the molding sand, the core then forming a part of the mold face.

A core sand mixture consists of sand grains and organic binders which provide green strength, cured strength and collapsibility. These mixtures are then molded into cores by using a mixture of manual labor and machines like jolt machines, shell-core machines and core-blowers.

3. Molding

Molding requires specialized equipment and the form is achieved in one of several ways:[5]

- By compaction of the aggregate around the pattern
- By free flow of dry aggregate around the pattern using shell molding techniques

- By free flow of slurry or liquid aggregate around the pattern.

Green sand molding is done by compacting aggregate around a pattern by ramming, squeezing, jolting, vibration or a combination of these. This work is carried out as bench molding, machine molding, and floor and pit molding.

4. Melting and pouring

   There are many different kinds of furnaces used for melting pig iron and make it ready for pouring. But the most common ones are cupolas, open hearths, air furnaces, electric arc furnaces, and crucible furnaces.

   Once the metal has been melted and is ready for pouring, steps have to be taken to ensure proper pouring which will result in a sound casting. Although it may seem relatively simple, many factors go into achieving a good quality cast. The solidification characteristics of metals and alloys must be accounted for while designing the gating system which is an integral part of the pouring process.

5. Cleaning

   The series of operation in a cleaning department are as follows:[5]

   a. Removal of gates and risers- rough cleaning
   b. Surface cleaning, exterior and interior of casting
   c. Trimming- the removal of fins, wires, and protuberances at the gate and riser locations

d. Finishing- final surface cleaning, giving the casting its outward appearance.
e. Inspection

1.2.2 Tooling costs

Tooling is essentially the creation of patterns and core-boxes. The tooling costs are generally a result of the sand casting tool design and fabrication process. The part design is communicated via a 3D model or a set of 2D drawings or any other means which can convey the design intent.

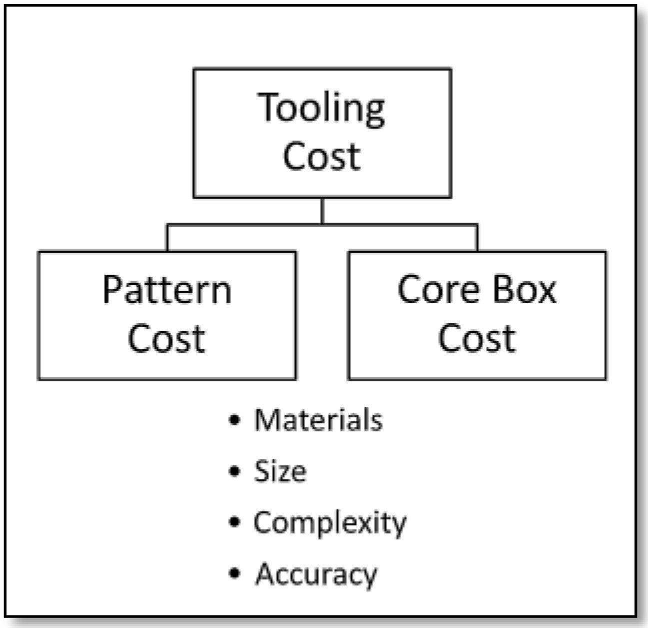


Figure 1 Tooling cost components

Given this initial part design and a general understanding of the cost, lead time, accuracy and production volume, the tool builder must decide on the best approach for constructing the tooling. Some of the primary considerations for tool building are: [6]

- Functionality of the casting
- How to best achieve the specified external and internal shape of the casting
- How molten metal will flow during filling and feed during solidification of the casting
- How the casting will shrink during solidification and cooling to room temperature
- Where the parting line should be located to best facilitate foundry operations
- Where and how much draft should be applied
- Where and how much extra material should be provided for machining
- What type of pattern should be used
- What fabrication process should be used to construct the pattern
- What pattern material should be used

Rapid Tooling is the process of creating tools quickly and with minimum direct labor. Tool-making approaches that apply additive, subtractive, and pattern-based processes come under rapid-tooling. Hence it can be considered a much more modern approach to the creation of tooling. There are two kinds of rapid tooling: [7]

- Indirect Tooling - Where molds are produced by the creation of a pattern first. Using SLA, FDM and LOM techniques in additive manufacturing master patterns can be created to fabricate a silicone rubber mold, which can then be used for making multiple hard patterns from poly eurathene and epoxy rubber. [8]

- Direct Tooling – Where additive processes build the actual tooling. This includes epoxy patterns in SLA systems, ABS plastic patterns in an FDM system or paper patterns in a LOM system. [8]

In this thesis, the tooling costs associated with direct tooling approaches using an FDM based system to create patterns will be analyzed. Also tool-less manufacturing using the binder jetting technology to directly 3D print the molds and cores shall be analyzed.

The tooling cost estimates received from the industry were a singular number and a break-down of individual components was unavailable. Hence, an attempt has been made to show the tooling costs in finer detail. The following components have been determined to have the most effect on the total tooling cost:

- Tool design labor costs
- Tool manufacturing labor costs
- Re-working costs
- Additional costs such as materials, reworking, maintenance and energy costs

Since the tool design and manufacture is a highly laborious process in the traditional foundry environment, labor costs have been calculated based on the hourly rate paid to the workers.

Two mechanical engineers and two tool and die makers are assumed to be working on this project. The tool design labor cost is assumed to be $45.0 per hour based on the 2015 Median Pay for experienced mechanical engineers. [9] Similarly, the manufacturing labor cost is assumed to be $30.0 per hour based on the hourly mean wage for experienced tool and die makers in the aerospace manufacturing industry. [10]

1.2.3 Reworking costs

The majority of the reworking costs occur due to the presence of casting defects in the sand casting process. [11] Casting defects usually manifest in the foundry as reworking costs or casting scrap costs.

With the combination of a 3D CAD model, simulation techniques and rapid tooling methods these reworking costs can be avoided and in some cases eliminated. [6]

This thesis incorporates the cost of reworking into the final tooling costs based on data obtained from Humtown Products. For the conventional mold and core making processes, the rework costs have been included in the tooling costs. Also, for the methods involving 3D sand printing, Humtown suggests that a mold and core design is reworked for a maximum of two times if at all required.

1.3 Additive Manufacturing

Additive manufacturing is the technical term used to describe what used to be rapid prototyping and what is now popularly known as 3D Printing. The term rapid prototyping was used to describe a process used to create prototypes or representation of parts that would be the basis for further models, eventually leading to the final product which would then be commercialized. [12]. In a product development and manufacturing context, rapid prototyping describes process used to create quick physical prototypes directly from digital CAD data with less focus on the quality of the prototype and more focus on the visual aesthetic.

Due to the recent technological advancements made in this field, the term "rapid prototyping" failed to encapsulate the emerging new processes and the increase in quality of output. A new term was needed to describe these processes which capable of producing directly manufacturable parts with high quality. Rapid prototyping also fails to describe the underlying principle of such technologies, which are based on an additive approach. Due to these reasons, the new term "Additive Manufacturing" was proposed by ASTM International. [12]

The basic principle behind AM is that a 3D CAD model can be fabricated directly without the requirement of any kind of process planning. Where other manufacturing processes require a detailed analysis of the part geometry to determine how the individual features can be manufactured and then fit into an assembly to create the final product, an AM based technology simply requires a basic understanding of the AM machine and materials needed to create the part.

The official ASTM definition of additive manufacturing is as follows, "*Standard Terminology for Additive Manufacturing Technologies defines Additive Manufacturing as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication."[13]*

As estimated in 2015, the total value of the AM industry including all products and services were $5.165 billion. Also in 2015, Israel is responsible for 41.1% of total industrial AM systems and the US shares 16.7% of the same total. [2] These systems are categorized into seven types based on the various processes. [14]

1. Binder Jetting
2. Direct Energy Deposition
3. Material Extrusion
4. Material Jetting
5. Powder Bed Fusion
6. Sheet Lamination
7. Vat Photo polymerization

Each of the process has different weakness and strengths which are based on characteristics such as: [2]

- Materials that can be utilized
- Build speed
- Surface finish quality and dimensional accuracy of produced parts
- Material properties
- Machine and material costs

Hence, these properties or characteristics also determine which market each process may be suited for. These markets are divided into:

- Prototyping

  The earliest use of additively manufactured parts was for the strict purposes of prototyping. The primary use cases were either as visual aids or as presentation models to explain a specific concept in detail. Further as the material properties improved and newer compact machines were introduced into the market, additively manufactured parts became integral to the iterative product design process.
- Tooling

  This application for AM parts will be discussed in detail in Section 1.4.1 as it is significant to the overall thesis.
- Direct part manufacturing

The application of AM for the creation of direct end-use parts is probably the fastest growing market since 2010. Whereas rapid prototyping and tooling are a step in the overall manufacturing production process, direct part manufacturing essentially simplifies a particular manufacturing process to a single step. This can be termed as the holy grail of AM.

- Maintenance and repair

  For damaged parts, which have a long lead time, additive manufacturing has been increasingly seen as a way to repair them at a faster rate. Also parts made in the additive way provide a metallurgical bond with the base material, which reduces the heat affected zone in the nearby material. This feature is useful for parts that have a high sensitivity to heat distortion. [15]

1.3.1 Additive manufacturing for pattern making: FDM Pattern-making

Although we are aware of sand printing offering great cost and quality advantages for casting parts, there are significant benefits to creating patterns using a 3D printer. Until 2011, the rapid prototyping technique for producing prototypes of models rather than direct-to-use parts was seen as expensive and of low accuracy. [16] But it was also known that rapid prototyping technique can produce high complex functional parts directly from CAD data. This simplifies the process of pattern-making and also reduces redesign costs associated with re-working of a pattern.

As discussed previously, traditional pattern making costs are much more expensive than the actual costs of pouring in a casting run. Also, the lead time to create the tooling for castings is usually in weeks. But using an AM technique like Fused Deposition Modeling for creating patterns this lead time can be reduced to days at just a fraction of the traditional pattern-making cost. [17].

The available literature on the energy consumption and advantages of using a 3D Printer for creating patterns which can be used in sand casting give us general insights but do not provide specific data. [18]

Several case studies are available on the websites of Stratasys and 3D Systems which have machines capable of printing patterns for sand casting. Based on these case studies, it has been determined that FDM is a great fit when: [19] [20]

- Casting production volumes are less than 5000
- The pattern dimensions are less than the build envelope of the FDM systems
- The casting designs are moderate to highly complex
- All surfaces are accessible for smoothing, sealing or coating

The benefits of using an FDM system for pattern-making are:

- Average lead time reduction of 30% to 70%
- Average cost reduction of 60% to 80%

- Part geometry and gate/runner system can be redesigned to take advantage of FDM
- Production of patterns can be automated and hence burden on pattern-shop can be reduced. Also pattern production can be made in-house.
- As shown in the figure below, the traditional process of sand casting requires almost no change in the process, except for the addition of an FDM system to the pattern-making process.

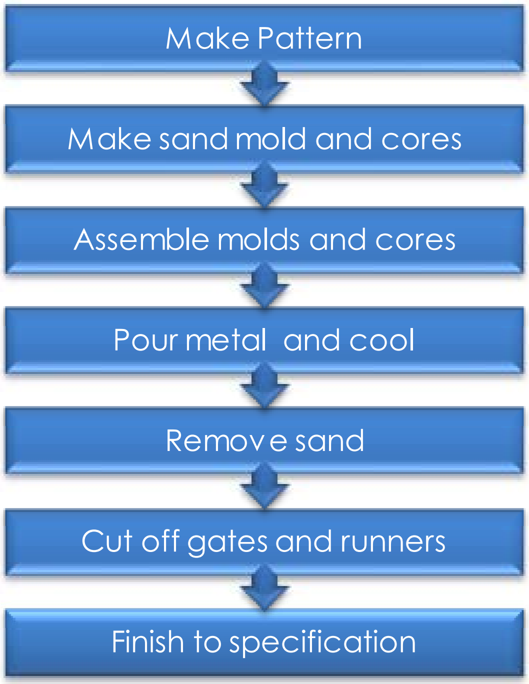


Figure 2: Traditional sand casting process

A Fortus 900mc 3D Printer is used to analyze the cost of 3D printing the patterns using a Poly-Carbonate material both supplied by Stratasys.

1.3.2 Additive manufacturing for mold and core making: Binder Jetting

AM enables the direct production of molds without the need of a pattern. Specifically the binder jetting process is used to fabricate these molds and cores which can then be assembled to create the final mold and core assembly. [21]

The binder jetting process prints a binder into a powder bed to fabricate a part. Hence, only a small portion of the part material is delivered through the print head and the rest consists of powder in the powder bed. The binder droplets form spherical agglomerates of binder liquid and powder particles and provide bonding to the previous layer. Once a layer is printed, the powder bed is lowered and a new layer of powder is spread onto it. [22]

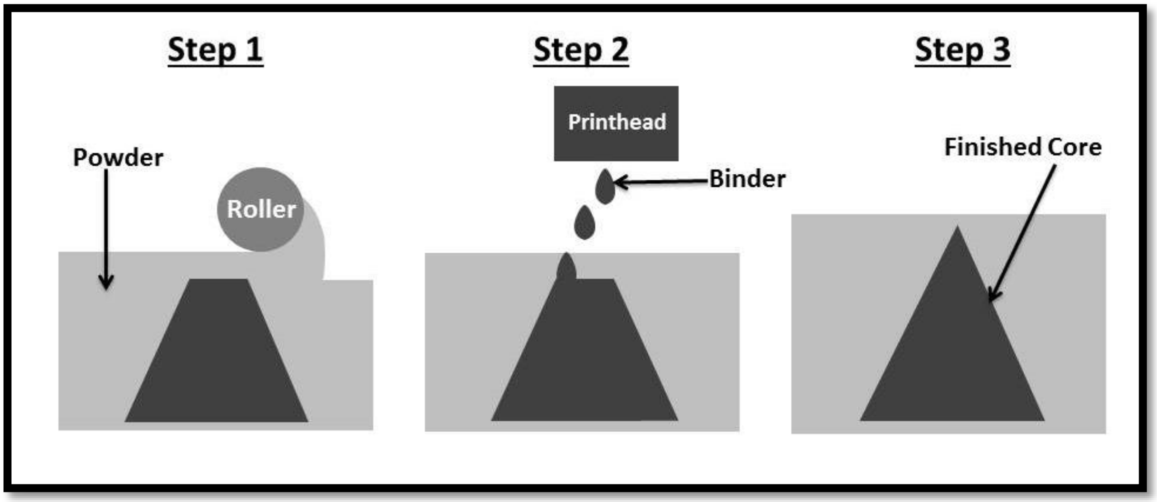


Figure 3: A typical binder jetting process

Due to the fact that binder jetting processes can be economically scaled by simply increasing the number of printer nozzles, it is scalable and also has a high deposition speed. [23]

Materials

The commercially available powder from 3D Systems is plaster based and the binder is water based [24]. Since these printed parts are typically weak, infiltrants like ColorBond, which is acrylate based, StrengthMax, and SaltWaterCure are used to strengthen them.

On the other hand, Voxeljet supplies a poly-methyl methacrylate (PMMA) powder and uses a liquid binder that reacts to room temperature. They recommend that parts remain in the powder bed for several hours so that the binder is completely cured. [25]. Voxeljet also offers silica sand with inorganic binder for smoother process integration into existing foundries.

ExOne supplies a silica sand and two part binder, where one part is coated onto the layer and the other part is printed onto the layer, which causes a polymerization reaction binding the sand particles together. [26] ExOne claims to use only standard foundry materials which ensure easy integration into existing manufacturing practices.

By using a binder jetting system, the process of pattern-making can be totally eliminated, and the molds and cores can be created directly from their design files. Removal of the pattern-making process can bring the cost of tooling significantly (which will be shown through this thesis).

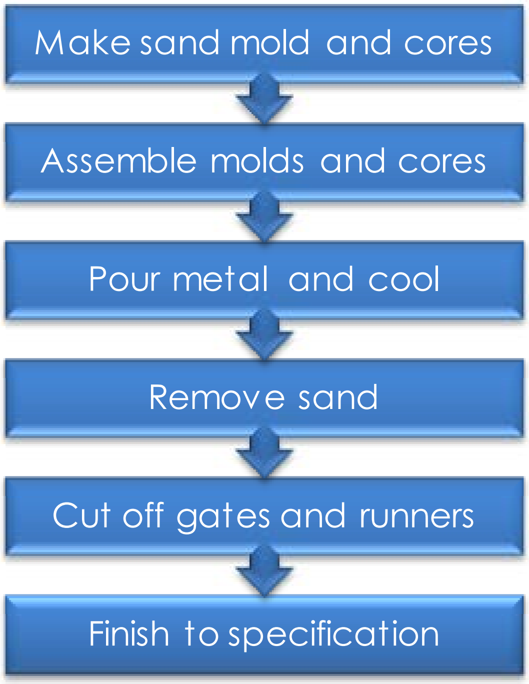


Figure 4: 3D Sand Printing process using a binder jetting system

An S-Max 3D Sand Printer manufactured by ExOne is used by the foundry to create the molds and cores. Hence the costs and build times

1.4 Implementation and Adoption of AM for mold and core making

Depending on which stage AM can be implemented in the Sand Casting Process particularly in the mold and core creation, this thesis defines two additional mixed manufacturing methods apart from the traditional mold and core making method, and the purely additive method of creating molds and cores.

It is also assumed that the adoption of 3D sand printing or FDM pattern-making will have minimal or no influence on the cost per casting in post-fabrication operations including pour, shakeout and secondary operations such as heat treatment, machining and inspections. Hence, these costs shall not be considered in the cost and time study of this thesis. However, it should be noted that consolidation of number of required cores (through 3D sand printing) could eliminate flash which tend to add additional finishing and inspection operations.

The following four definitions are inherent to this thesis and describe each process from the creation of tooling to the final mold and core assembly.

1.4.1 Traditional Manufacturing (TM)

Traditional Manufacturing is defined as the traditional process of mold and core making. This includes the creation of the patterns and core-boxes, creation of molds and cores using traditional foundry techniques, and finally assembly of the molds and cores.

1.4.2 3D Sand Printing of molds and cores (3DSP)

3D sand printing is defined as the process of 3D printing the molds and the cores using a binder-jetting process. These molds and cores are directly printed from their respective design files and therefore the creation of patterns becomes unnecessary. This also eliminates any tooling costs incurred due to the creation of patterns. The cost benefits of this method have already been discussed in [27]

1.4.3 3D Sand Printed Cores (3DSPC)

For the purposes of this thesis, 3D sand printed cores imply the use of traditional techniques to create the mold and a binder-jetting system to fabricate the cores.

There are certain advantages to 3D printing cores such as: [28]

- At the design stage, complex geometries can be created without worrying about manufacturing limitations. Mold parting design, draft angles and core locks are no longer necessary.
- In the CAM-tool manufacturing stage, core-boxes and assembly jigs are not required.
- At the sample testing phase, no additional adjustments are necessary and dependence on binders eliminates the need for core drying and finishing.
- Tool maintenance and storage costs, and tool insurance costs are eliminated.
- Possible elimination of assembly depending on the design.
- Tool wear is non-existent and machine operation is highly user friendly.

1.4.3 FDM based pattern-making (FDMP)

This is defined the creation of patterns using the Fused Deposition Modeling technique described in Section 1.3.1 and the traditional method of creating molds and cores described in 1.2.1 which finally results in a mold and core assembly.

The distinct advantage of FDM pattern-making is the fact that a set of patterns can be grouped together and printed in a single build. This parallel processing of parts implies that the lead time for tooling is drastically reduced and the tooling costs are extremely low.

1.5 Complexity Measurement for CAD models

The cost for traditionally manufacturing a part is a function of its complexity and its manufacturability, when compared to AM which is not bound by the complexity of the part. [29][27] Hence to compare a traditional and an AM process it becomes significant to define how we measure complexity.

There is very limited research on this subject, especially since the complexity of a part changes based on which manufacturing process is used. Based on available literature, two estimation methods have been discussed, which have been proven to be good indicators of complexity.

1.5.1 Shape complexity estimation for cast parts

For this thesis, the complexity of the various case studies described in Section 2.1 are calculated based on a formula developed using regression analysis and detailed in the paper titled "Quantifying the shape complexity of cast parts" by Durgesh Joshi and Bhallamudi Ravi. [29]

Although there is plenty of research on the determination of shape complexity factor, most of it has been for specific manufacturing processes such as axis-symmetric forged parts, or for extrusion based manufacturing processes. [30] Also, initial shape complexity factors did not take into account the tooling cost which can be a great indicator of complexity. Hence, a quantitative evaluation of shape complexity was developed by Ravi and Chougale which indirectly considered the tooling cost based on geometric features of the part. The logic behind this decision is that the geometric features influence, design of the tooling, complexity and as a result the cost of the tooling.

After interacting with toolmakers and designers, the researchers concluded that the tool manufacturing cost depended on number of cores, volume and surface area of part, core volume, draw distance and variation in section thickness. These parameters can easily be determined from a given CAD model. Based on these features, the geometric criteria were determined as follows:

Part Volume Ratio (C_{PR}):

This is the ratio of volume of part to the volume of bounding box. The bounding box is given by the maximum length, width, and height of the part geometry. When the volume of part is close to its bounding box, less material removal is required, resulting in lower machining cost. Higher difference in these volumes leads to a higher manufacturing cost. This criterion is defined as:

$$C_{PR} = 1 - \frac{V_p}{V_b}$$

Here, V_p is the part volume and V_b is the bounding box volume of the part.

Area Ratio (C_{AR}):

This is the ratio of surface area of an equivalent sphere (with the same volume as that of the part) to the surface area of the part. This ratio is based on the fact that sphere has minimum surface area as compared to any other geometry.

$$C_{AR} = 1 - \frac{A_s}{A_p}$$

Where, As is the surface area of the imaginary sphere with a volume equal to that of the part, given by: $A_s = (4\pi)^{1/3}(3V_p)^{2/3}$. A_p and V_p are surface area and volume of the part.

Number of Cores (C_{NC}):

Cores are required for hollow portions of the part and regions that hinder pattern withdrawal during molding. Each core requires a separate tooling; hence more the number of cored features higher will be the tooling cost. The criterion for number of cores is defined as follows, considering that rate of increase in shape complexity gradually decrease with an increase in the number of cored features:

$$C_{NC} = 1 - \frac{1}{\sqrt{(1 + N_c}}$$

Where N_c is the number of cored features

Core Volume Ratio (C_{CR}):

Larger cores require larger size and incur higher tooling cost. Hence the ratio of core volume to bounding box volume is included as another measure of complexity.

$$C_{CR} = \frac{\sum_i V_{c_i}}{V_b}$$

Where, $V_{c_i}$is the volume of the i^{th} core and V_b is the volume of the parts bounding box.

Thickness Ratio (C_{TR}):

This is the ratio of minimum and maximum thickness of the part. A tooling with thin section will be more complex and is more difficult to machine as compared to one with more thick sections. This criterion is defined as:

$$C_{TR} = 1 - \frac{T_{min}}{T_{max}}$$

Where, T_{min} and T_{max} are minimum and maximum thickness of the parts respectively.

Depth Ratio (C_{DR}):

The draw distance, which is maximum depth of the tooling, affects the tooling manufacturing time and hence its cost. The actual draw distance is compared to the minimum possible draw distance, which is half the minimum dimension of the part. The criterion designed such that parts with higher depth ratio will indicate higher complexity.

$$C_{DR} = 1 - \frac{0.5(\min(L, W, H))}{D_d}$$

Where, L,W and H are the length, width and height of the part respectively and D_d is the draw distance of the tooling.

The final shape complexity obtained using regression analysis is:

$$CF_{estimated} = 5.7 + 10.8C_{PR} + 18C_{AR} + 32.7C_{NC} + 29.0C_{CR} + 6.9C_{TR} + 0.7C_{DR} \quad \rightarrow \textit{Eq. 1}$$

This equation has been validated by determining the actual Complexity factor (CF_{actual}) which is the ratio of additional cost of machining to the cost of machining a cube of differential volume.

1.5.2 Shape complexity estimation using layer-by-layer technique

The thesis, authored by Dr. Martin Baumers, discusses the economic aspects of AM usage through the effect of its nature on economic and environmental performance measurement. Also, the ability of AM processes to efficiently create parts is discussed. One component of this thesis is to quantify the shape complexity of an object. [31]

The direct link between the complexity of a design and its traditional manufacturing cost demands that there is an economic benefit to reduce the complexity of the part/design. But using AM, it is effectively possible to obtain this complexity for free, eliminating the need to simplify a particular design and as a result reducing the effect of complexity of design on the manufacturing cost. [32]

However, a weak connection between part geometry and laser scan time has been demonstrated when the part volume and part height are left unchanged in an AM process. [33] There is a possibility that this can be linked to the complexity and hence “complexity is free” may as well be an ideal scenario.

In this thesis, shape complexity is viewed as a subjective experience. The author analyses a paper by Psarra and Grajewski which measures the complexity of two-dimensional shapes. They define these 2D shapes as “configurations consisting of edges and corners defining a continuous perimeter line.”[34]

According to their analysis, the shape complexity is inversely related to the degree of convexity of the perimeter shapes. Full convexity is the property that every point in the perimeter can be connected to every other point without crossing the perimeter of the shape as opaque walls. Hence, all points are visible from every location in a convex shape.

Based on this definition, three measures are defined by Psarra and Grajewski for shape complexity:

- Mean Connectivity Value (MCV) describes the mean proportion of perimeters cells visible from each location. Fully convex shapes have MCV = 1 and MCV = 0 is impossible for closed perimeters.
- The next measure is the standard deviation of the connectivity values present in the cells of the perimeter.
- The final measure is derived from the rate of fluctuation found in connectivity when travelling along the perimeter of the shape. This characteristic is captured by recording the horizontal distance between the intersections of the graph of connectivity with the MCV line. Psarra and Grajewski then measure the standard deviation of this distance to arrive at a measure that describes the degree of fragmentation, repetitiveness or rhythm present in the shape.

This forms a relatively simple and pragmatic way to quantify the shape complexity of engineering designs. But it is only valid for two-dimensional surfaces. Baumers' thesis utilizes this concept to calculate the complexity of the different layers in a sliced three-dimensional part.

1.6 Research Objectives

1.6.1 Rationale for the study

Historically, sand casting has been a very popular method producing the greatest tonnage of castings used in any country. Any developments in the foundries have only been to improve process parameters through the use of high quality materials or to increase production capacity through automation. AM revolutionizes these foundries by bringing in a layer-by-layer method of creating cast parts.

Hence in order to assist foundries in adopting AM for mold and core making, the Youngstown Business Incubator (YBI) was awarded a research project by America Makes in 2014 to develop a framework for establishing a 3D sand printing regional network for the US foundry industry titled "Accelerated Adoption Of Additive Manufacturing Technology In The American Foundry Industry" [35]. Apart from YBI, Youngstown State University, the University of Northern Iowa, the American Foundry Society, ExOne, Jenney Capital Market, and Humtown Patterns Corporation have vested interest in this project.

1.6.2 Hypothesis

This thesis is built upon the paper titled "Quantifying the Role of Part Design Complexity in using 3D Sand Printing for Molds and Cores". The paper evaluates when to use the ever evolving AM sector versus the traditional pattern making. This was done by examining the cost of molds and cores as a function of part design complexity quantified by a complexity factor for two case studies. The complexity of each case study was varied systematically by changing the geometry and the number of cores. The tooling and fabrication costs were estimated for both 3D sand printing and traditional pattern-making. Once the breakeven points were identified, it was shown that 3D sand printing is cost-effective for castings with complexity factor values greater than that of breakeven points.

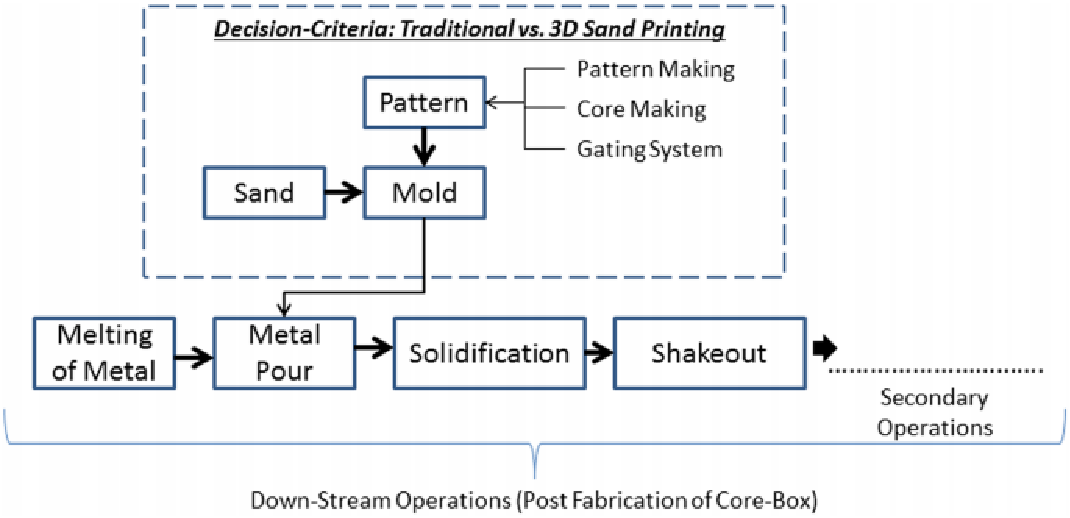


Figure 5: Decision criteria for 3D Sand Printing

One particular idea, mentioned in the future work section of the paper discussed above, was to examine the combinations of traditional pattern-making and 3d sand printing. In other words, until now, 3D sand printing and traditional pattern-making were treated as separate use-cases i.e. the analysis was limited to entirely 3d printing the molds and cores or entirely manufacturing the molds and cores in the traditional way. But a potential way to integrate AM into the foundry industry would be to analyze the benefits of mixing different methods.

Mixing different methods can mean either replacing the traditional pattern-making process with a 3d printing process where the patterns are fabricated using an FDM printer or replacing the traditional core-making process with a 3d printed core process.

To elaborate further, the first method analyses the effects of integrating an FDM printer for pattern-making in the traditional mold-making process [Section 1.4.4]. The second use-case analyses the effects of integrating a 3D sand printer specifically for manufacturing cores. [Section 1.4.3]

Based on these observations, an initial hypothesis is formed which is stated as follows:

"For a given production volume, with increased complexity of the casting, additively manufacturing only the cores and conventionally manufacturing the molds is cost-feasible when compared to traditional manufacturing or 3D sand printing."

This thesis will go on to show that fabricating patterns on an FDM printer eliminates the cost of tooling incurred during a traditional sand casting process and also fabricating cores using a 3D sand printer in the traditional sand casting process eliminates the need for using core-boxes which reduces the costs further.

It is assumed that part design complexity will have minimal or no influence on the cost per casting in post-fabrication operations including pour, shakeout and secondary operations such as heat treatment, machining and inspections.

1.6.3 Analysis Goals

Ultimately, the goals of the thesis are as follows

1. Establish a cost estimation method for tooling design and manufacture cost which can eliminate the dependence on an online tool or a historically generated quote from a foundry.
2. Determine the costs for molds and cores for different families of castings and draw conclusions from the cost per part vs. shape complexity using four different methods of manufacturing at production volumes of 1, 30, 100, and 1000:
    a. Traditional Manufacturing of molds and cores
    b. 3D Sand Printing of both molds and cores

    c. 3D Sand Printing cores and traditionally manufactured molds
    d. 3D Printing the patterns using an FDM printer
3. Determine the lead times taken for each process from pattern creation stage to the final mold and core assembly
4. Create an application which enables manufacturers to utilize the conclusions drawn from this thesis and help make decisions on which manufacturing method will best suit their needs. This application will be created using MS Excel and VBA.

Chapter 2 Methodology

This chapter will describe the methodologies and tools used to achieve the stated research objectives. The first section describes the five case studies utilized for the analysis and the unique features of each case study. Section 2.1 describes the case studies used in this thesis. In section 2.2 the shape complexity calculations used to calculate the shape complexity factor for each case study is shown. Section 2.3 describes the associated costs of manufacturing taken into consideration for these various case studies. Finally the last section looks at how the entire data can be collated to determine the cost per part and an estimation tool can be created in excel.

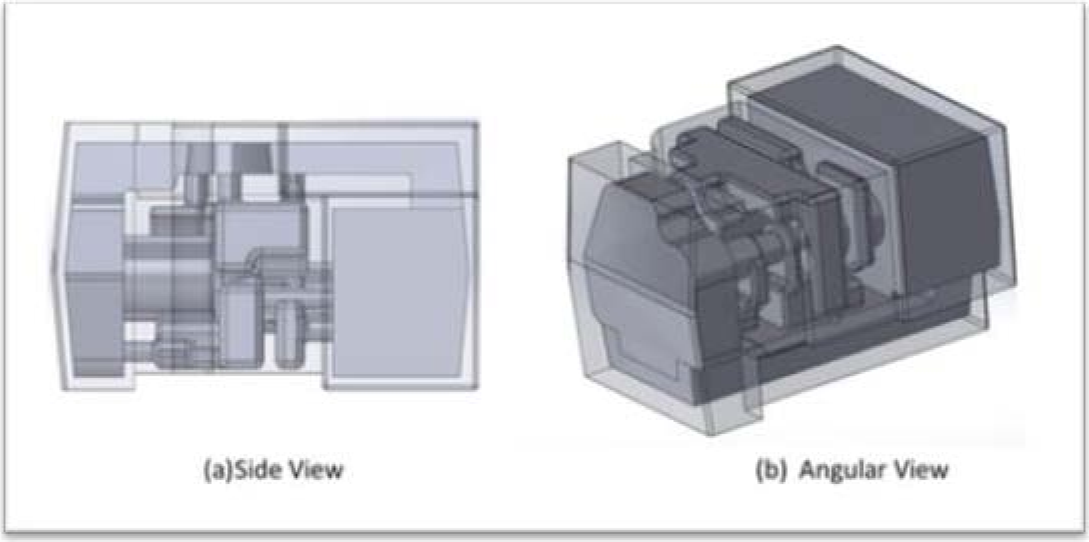
2.1 Description of Case Studies

These case studies were created with an attempt to study the variation of cost with an increase in complexity. Each case study is sub-divided into sub-cases by increasing the complexity in increments for each sub-case. [27]

Case Study 1: Train Air Brake

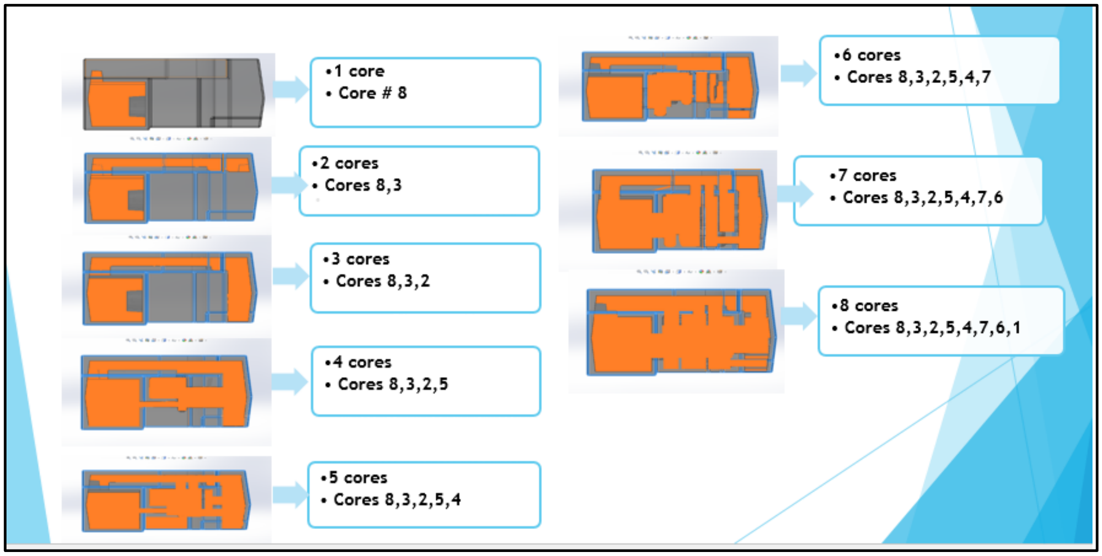
This case study is provided by Humtown Products for the purpose of this thesis and contains the mold and core design package needed to cast a Train Air Brake.

The design package consists of 1 mold design and 8 core designs. Hence a total of 9 sub-cases are created by beginning the first sub-case with one mold and incrementally adding one extra core.


(a)Side View

(b) Angular View

Figure 6: Train Air Brake Side and Angular View


- 1 core
- Core # 8

- 2 cores
- Cores 8,3

- 3 cores
- Cores 8,3,2

- 4 cores
- Cores 8,3,2,5

- 5 cores
- Cores 8,3,2,5,4

- 6 cores
- Cores 8,3,2,5,4,7

- 7 cores
- Cores 8,3,2,5,4,7,6

- 8 cores
- Cores 8,3,2,5,4,7,6,1

Figure 7: Train Air Brake Stage-wise Core Increase

Case Study 2: Turbo Charger

This case study, also provided by Humtown Products consists of a mold and core design to obtain a casted part of a Turbocharger.

In this model, as in the previous case study, the complexity is changed by varying the number of cores. Hence we create 4 sub-cases, where each sub-case has an additional core.

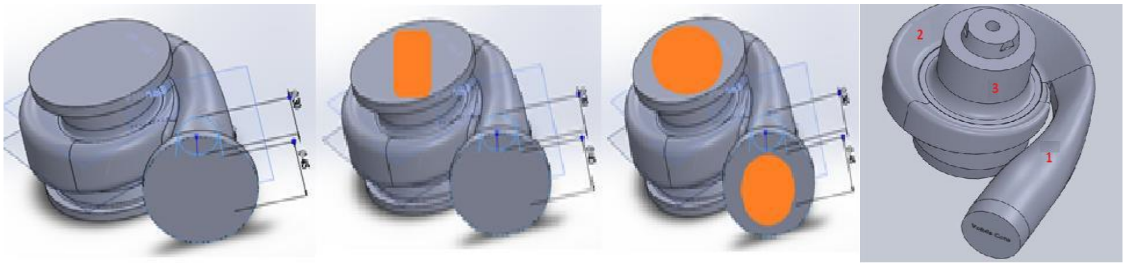


Figure 8: Turbocharger Stage-wise Core Increase

2.2 Complexity Calculations

The shape complexities of these five case studies are calculated using the methodology outlined in Section 1.7.1. Provided below are the shape complexity factors for the five case studies including their respective sub-cases.

Table 1: Complexity factor calculation for each case study and their sub-cases

Part Name	Volume Ratio	Surface Ratio	Number of Cores Ratio	Cores Volume Ratio	Wall Thickness Ratio	Depth Ratio	Imaginary Sphere Volume	Bounding Box Volume	Actual Complexity Factor
Imported No core	0.23	0.26	0.00	0.00	0.98	0.13	170.40	270.39	*19.66*
Imported 8	0.40	0.55	0.29	0.17	0.98	0.13	144.00	270.39	*41.35*
Imported 8,3	0.47	0.65	0.42	0.24	0.98	0.13	133.15	270.39	*50.10*
Imported 8,3,2	0.51	0.70	0.50	0.29	0.98	0.13	125.22	270.39	*55.41*
Imported 8,3,2,5	0.54	0.73	0.55	0.32	0.98	0.13	119.68	270.39	*58.93*
Imported 8,3,2,5,4	0.56	0.74	0.59	0.33	0.98	0.13	117.66	270.39	*60.88*
Imported 8,3,2,5,4,7	0.58	0.76	0.62	0.35	0.98	0.13	113.58	270.39	*63.14*
Imported 8,3,2,5,4,7,6	0.61	0.79	0.65	0.38	0.98	0.13	108.08	270.39	*65.60*
Imported 8,3,2,5,4,7,6,1	0.62	0.80	0.67	0.39	0.98	0.13	106.55	270.39	*66.72*
Comp. NO core	0.59	0.50	0.00	0.00	0.96	0.00	84.01	176.00	*27.64*
Com. Cubic core	0.65	0.60	0.29	0.06	0.97	0.00	75.13	176.00	*41.62*
Com. Cylinderical Core	0.65	0.60	0.42	0.06	0.97	0.00	75.53	176.00	*45.73*
Orginal core	0.82	0.81	0.50	0.26	0.98	0.00	48.12	176.00	*59.81*
Iron Housing	0.60	0.81	0.71	0.31	0.98	0.97	6016.81	109582.48	*66.29*
Steel Structure	0.66	0.82	0.67	0.24	1.00	0.97	2336.12	31533.38	*63.93*

2.3 Tooling Cost Estimation

The tooling cost quotes received from Humtown Products are compared with two different methods of tooling cost estimation. As discussed in earlier sections, tooling cost estimates can vary extensively from foundry to foundry. These foundries often base their estimates on historical data and experience. Hence a reliable way of calculating these costs would prove useful in providing more accurate estimates for the customer.

Only the reworking costs, tool design and manufacturing costs are incorporated into the data since, the online cost estimator provides the tool manufacture cost and the integrated

2.3.1 Industry Quote

The breakdown of the industry quote is listed in Section 1.2.2. Based on these quotes, the tool design and manufacture costs are isolated and detailed in the table below.

Table 2: Foundry Tooling Quote for Two Case Studies

	Part Name or Number	Rework Cost	Tooling creation time: Tooling design+ tooling manufacture (hours)	Tool Design Labor	Tool Manufacture Labor	Quoted Tooling: Design + Manufacture Labor costs	Tooling Material, Maintenance and Energy, overhead expenses	Total Quoted Tooling
Case Study I	Imported No Core	200	34.10	2148.30	613.80	2962.10	12037.90	15200
	Imported 8	200	83.10	5235.30	1495.80	6931.10	10068.90	17200
	Imported 8,3	300	83.10	5235.30	1495.80	7031.10	11968.90	19300
	Imported 8,3,2	300	96.10	6054.30	1729.80	8084.10	11915.90	20300
	Imported 8,3,2,5	400	96.10	6054.30	1729.80	8184.10	12815.90	21400
	Imported 8,3,2,5,4	400	108.10	6810.30	1945.80	9156.10	12843.90	22400
	Imported 8,3,2,5,4,7	500	121.10	7629.30	2179.80	10309.10	12690.90	23500
	Imported 8,3,2,5,4,7,6	600	133.10	8385.30	2395.80	11381.10	12618.90	24600
	Imported 8,3,2,5,4,7,6,1	600	133.10	8385.30	2395.80	11381.10	13618.90	25600
Case Study II	Comp. NO core	300	34.10	2148.30	613.80	3062.10	5937.90	9300
	Com. Cubic core	400	47.10	2967.30	847.80	4215.10	6784.90	11400
	Com. Cylinderical Core	500	55.30	3483.90	995.40	4979.30	7020.70	12500
	Orginal core	600	61.10	3849.30	1099.80	5549.10	6450.90	12600

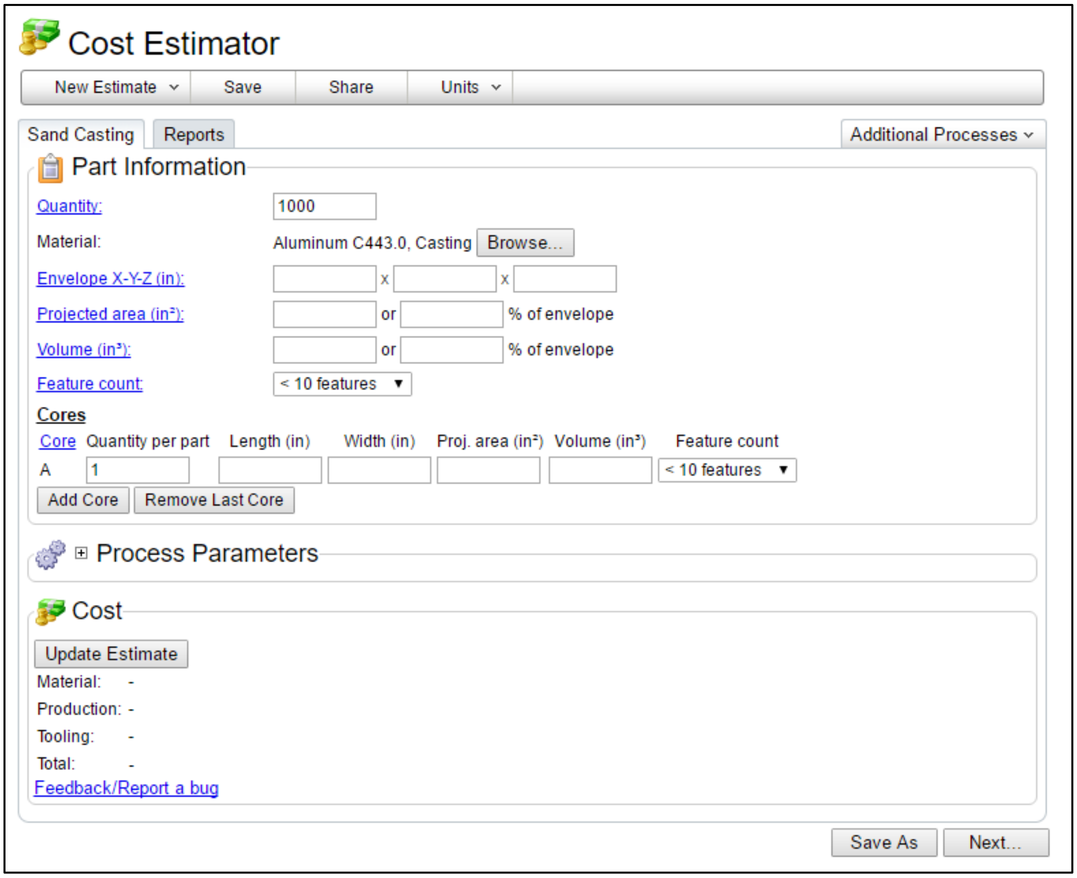
The tooling creation time between design and manufacturing is split in the ratio 0.7 to 0.3 assuming that 70% of the time is spent in designing the part and 30% of the time is spent manufacturing.

2.3.2 Using Online Estimator

The online cost estimator [36] utilizes a feature based calculator to determine the tooling, material and production cost for a sand casted part. The cost estimator utilizes data based on industry averages and typical manufacturing processes and the actual costs may vary based on equipment, specific manufacturer and market conditions.

Hence, comparing these costs with an actual foundry quote would provide a basis for further utilizing this tool.

As shown in Figure 9, the production quantity, material of the cast part, the envelope (or the bounding box) of the part, volume and number of cores are the inputs required.



Cost Estimator

Part Information

Quantity: 1000
Material: Aluminum C443.0, Casting
Envelope X-Y-Z (in): x x
Projected area (in^2): or % of envelope
Volume (in^3): or % of envelope
Feature count: < 10 features

Cores

Core	Quantity per part	Length (in)	Width (in)	Proj. area (in^2)	Volume (in^3)	Feature count
A	1					< 10 features

Process Parameters

Cost

Material: -
Production: -
Tooling: -
Total: -

Figure 9: Sand Casting Cost Estimator

The results are given in the table below.

Table 3: Cost Estimator Results for Both Case Studies

	Part Name or Number	Online Estimated Tooling Cost : Tool Manufacture	Online Estimated Tooling Cost : Tool Manufacture+Tool labor
Case Study I	**Imported No Core**	1380.00	3528.30
	Imported 8	1722.00	6957.30
	Imported 8,3	2101.00	7336.30
	Imported 8,3,2	2857.00	8911.30
	Imported 8,3,2,5	3339.00	9393.30
	Imported 8,3,2,5,4	3914.00	10724.30
	Imported 8,3,2,5,4,7	4574.00	12203.30
	Imported 8,3,2,5,4,7,6	5091.00	13476.30
	Imported 8,3,2,5,4,7,6,1	5646.00	14031.30
Case Study II	**Comp. NO core**	2206.00	4354.30
	Com. Cubic core	2312.00	5279.30
	Com. Cylinderical Core	2523.00	6006.90
	Orginal core	2878.00	6727.30

The tool design labor cost estimated in Section 2.3.1 has been incorporated into this model to normalize the data for comparison.

2.3.3 Casting Cost Estimation in an integrated product design environment

This cost estimation model is based on the paper titled *"Casting cost estimation in an integrated product and process design environment"*[37]. This estimation is driven by the solid model of the part and its attributes and is useful for cost reduction in the early stages of design.

This costing model attempts to provide a module to calculate tooling costs based on product geometry, tooling material and order quantity. A parametric methodology is used to generate accurate tooling costs.

According to this paper, the tooling costs are calculated as follows:

$C_{rel\_tool\_cost} = \exp(0.629 * V_{cast} + 0.048 * C_{ac} + 0.023 * C_{s} + 0.739$

$C_{tooling} = c_{index} * C_{rel\_tool\_cost} \, / \, Q$

Where,

$C_{rel\_tool\_cost}$ = Relative tooling cost for cast iron tooling

$C_{tooling}$ = Amortized cost of tooling

C_{index} = Tooling cost index that varies with manufacturer, currency and time

V_{cast} = Casting volume in m^3

C_{ac} = Accuracy index on 1-100 scale, assumed as 90 for this thesis

C_{s} = Casting shape complexity

Q = Order quantity

Again, the resulting tooling cost has been normalized by adding the tool design labor cost and given below.

Table 4: Tooling Cost Calculation using Casting Cost Model

	Part Name or Number	Casting Volume	Complexioty	Accuracy index (Cac)	Volume of Cast (in m3)	Production Volume (Q)	Actual relative tooling cost ($)	Relative Tooling Cost Crel_tool_cost($)	Individual cost index	Cost Index	Estimated Tooling Cost based on Integrated model ($)	Integrated Casting Cost Estimation model including tool design labor
Case Study I	Imported No Core	209.16	19.66	90	0.0034	1000	1.38	3542.64	0.39	0.36	1274.26	3422.56
	Imported 8	162.49	41.35	90	0.0027	1000	1.722	5830.71	0.30	0.36	2097.25	7332.55
	Imported 8,3	144.47	50.10	90	0.0024	1000	2.101	7130.35	0.29	0.36	2564.72	7800.02
	Imported 8,3,2	131.76	55.41	90	0.0022	1000	2.857	8055.36	0.35	0.36	2897.44	8951.74
	Imported 8,3,2,5	123.11	58.93	90	0.0020	1000	3.339	8732.70	0.38	0.36	3141.07	9195.37
	Imported 8,3,2,5,4	120.01	60.88	90	0.0020	1000	3.914	9134.43	0.43	0.36	3285.57	10095.87
	Imported 8,3,2,5,4,7	113.83	63.14	90	0.0019	1000	4.574	9619.72	0.48	0.36	3460.12	11089.42
	Imported 8,3,2,5,4,7,6	105.66	65.60	90	0.0017	1000	5.091	10179.45	0.50	0.36	3661.45	12046.75
	Imported 8,3,2,5,4,7,6,1	103.43	66.72	90	0.0017	1000	5.998	10445.67	0.57	0.36	3757.21	12142.51
Case Study II	Comp. NO core	72.41	27.64	90	0.0012	1000	0.978	4250.17	0.23	0.36	1528.75	3677.05
	Com. Cubic core	61.23	41.62	90	0.0010	1000	1.326	5860.91	0.23	0.36	2108.11	5075.41
	Com. Cylinderical Core	61.73	45.73	90	0.0010	1000	1.76	6441.99	0.27	0.36	2317.13	5801.03
	Orginal core	31.39	59.81	90	0.0005	1000	2.24	8904.51	0.25	0.36	3202.87	7052.17
								Average:	0.36			

2.4 Cost Studies

This study estimates the costs for four different methods of manufacturing molds described in Section 1.4 and cores starting with the creation of the patterns to the assembly of molds and cores in order to find the cost per part at various complexities. The break-even points at which two methods become equally feasible are also analyzed through which conclusions can be drawn.

Also, the cost per part for each process has been determined for each sub-case and also at various production volumes (Q) of 10, 30, 100, and 1000 units. The notation used for denoting the costs consists of a subscript and a superscript.

The subscripts always refer to either to the various components of the total cost such as mold cost, core cost, tooling cost etc. For example: C_M is the cost of mold-making (M).

The superscripts always refer to each manufacturing method. For example: C^{TM} is the cost of traditional manufacturing (TM).

2.4.1 Traditional Manufacturing (TM)

The TM costs are calculated based on the tooling, mold and core cost estimates received from Humtown Products. The tooling costs provided were isolated to as much fine detail as possible and incorporated into the Cost per Part (C_P) calculations.

Among the several cost factors in sand casting, the two major components are tooling and fabrication costs which involve a variety of operations to produce the molds and cores. In previous research, the tooling making costs were generated using an online estimator for sand casting process. [27] But this estimator provides just the cost of manufacturing the tooling and does not consider the rework costs, the tool design or even the tooling material costs which are essential components of a tooling cost. Hence, estimates for each sub-case were obtained from Humtown Products and were incorporated to provide an accurate and finer analysis.

Tooling Costs:

Since tooling cost is determined for a set production volume, the tooling cost per part is determined as follows:

$C_{TP} = (C_T)/Q$ → ***Eq. 2***

$C_T = C_{tm} + C_{ac} + C_{td}$ → ***Eq. 3***

Where,

C_{TP} is the tooling cost per part

C_T is the total tooling cost for a given production volume

Q is the production volume required

C_{tm} is the cost associated with tool manufacturing

C_{td} is the cost associated with tool design

C_{ac} is the additional cost of energy, labor, overhead and material procurement

Mold and Core-making Costs:

$C_{MC}^{TM} = (C_M^{TM} + C_C^{TM}) * Q$ → ***Eq. 4***

Where,

C_M^{TM} is the mold making cost per part for a TM process

C_C^{TM} is the core making cost per part for a TM process

C_{MC}^{TM} is the total cost of mold and core making for a given production volume Q

Cost per part calculation (C_P):

$C_P^{TM} = (C_{MC}^{TM})/Q + C_{TP}$ → ***Eq. 5***

Where,

C_P^{TM} is the cost per part for a TM process

2.4.2 3D Sand Printing (3DSP)

The data for cost of 3D sand printing has been obtained from [27], which utilizes the same methodology described in Section 2.1.

For both mold and cores, the fabrication costs are estimated using the industry quotation methods based on the size of casting, number of cores etc. [27]

$C_{MC}^{3DSP} = (V_a + V_{b,m} + V_{b,c}) * C_{bj}$ → ***Eq. 6***

Where,

C_{MC}^{3DSP} is the cost of mold and core making

$V_{b,m}$ is the volume of the bounding box of the mold

V_a is the volume of the additional sand required around the part

$V_{b,c}$ is the bounding box of the cores

C_{bj} is the volumetric cost of binder jetting process including consumables, labor, energy, depreciation and overhead

For this thesis, the C_{bj} is taken as \$0.17 per cm^3 which is the estimated cost used in previous research as well. [27]

The total cost of mold making for a production volume Q is $C_M^{3DSP} *Q$

The total cost of core making for a production volume Q is $C_C^{3DSP} *Q$

The tooling costs associated with 3D sand printing is zero since there is no creation of patterns or core-boxes.

Therefore the cost per unit production volume (or cost per part) is

$C_P^{3DSP} = ((C_M^{3DSP} *Q) + (C_C^{3DSP} *Q))/Q$ or

$C_P^{3DSP} = C_M^{3DSP} + C_C^{3DSP}$ → ***Eq. 7***

This result shows that the 3DSP cost per part is independent of the production volume.

2.4.3 3D Sand Printed Core (3DSPC)

A combination of equations is used to calculate the cost of a 3DSPC process.

The cost components of a 3DSPC process are:

- Tooling cost for mold-making CM is obtained from the first use-case of each case study which consists of no cores, $(C_{TP})_{no\text{-}cores}$

  [insert cost for no cores CS1 and CS2]

- Mold making cost using traditional techniques, $C_M^{TM} * Q$
- Core making using the binder jetting process, $C_C^{3DSP} * Q$

There is no additional cost of tooling for core making, since core-boxes are eliminated by the use of a binder jetting system.

Hence, the total cost per part for 3DSPC is calculated as:

$$C_P^{3DSPC} = (C_{TP})_{no\text{-}cores} + ((C_M^{TM} *Q) + (C_C^{3DSP} * Q)) / Q$$

Or

$$C_P^{3DSPC} = (C_{TP})_{no\text{-}cores} + C_M^{TM} + C_C^{3DSP} \qquad \rightarrow \textbf{\textit{Eq. 8}}$$

2.4.4 FDM Pattern-making (FDMP)

The following are the cost components required to calculate the cost per part for FDM based pattern-making:

- Cost of printing patterns in an FDM printer, C_{FDMP}

  The cost of printing FDM patterns is

- Cost of traditional mold making, C_M^{TM}
- Cost of traditional core making, C_C^{TM}

Therefore, the cost per part is calculated as follows:

$$C_P^{FDMP} = (C_{FDMP} / Q) + C_M^{TM} + C_C^{TM} \quad \rightarrow \textbf{\textit{Eq. 9}}$$

2.5 Time Studies

The lead time calculation is done based on industry estimates for traditional manufacturing techniques and build rates per hour for any AM processes used in the thesis. The following components are defined to calculate the final lead times for the four methods described in Section 1.4:

- Lead time for tool design (T_{td}) and tool manufacturing (T_{tm}) to create the patterns and core-boxes based on quotes obtained from Humtown Products
- Time to create the molds (T_m^{TM}) and cores (T_c^{TM}) from setup of tooling to the final assembly, also obtained from industry
- Build time for molds (T_m^{3DSP}) and cores (T_c^{3DSP}) on an S-max printer, based on build volume of the machine and also the build rate provided by the machine supplier
- Pre (T_{pre}) and post (T_{post}) processing times for S-max printers
- Build time for patterns for a Fortus 900mc printer T_{FDMP}

Utilizing two or more machines would ideally reduce the lead time due to parallel processing but would also require more capital investment for the foundry. Hence for the purposes of this thesis, it is assumed that only one 3D sand printer and only one FDM printer are available for the foundry.

2.5.1 Traditional Manufacturing (TM)

The total lead time to create a mold and core assembly is the sum of the time to create tooling (from design to manufacturing) and the time to create the mold and cores conventionally.

The quote from Humtown provides the total time for tooling including the times for purchase of tooling material, tool design, tool manufacture and the customer approvals. The tool design and manufacturing time have been isolated from these numbers by taking into account the fact that it takes 1 day to purchase the material and 5 days for customer approvals.

Therefore,

$$T_{lead}^{TM} = T_{tm} + T_{td} + (T_m^{TM} + T_c^{TM})/8 \qquad \rightarrow \textit{Eq. 10}$$

T_{lead}^{TM} is the total lead time for manufacture

$T_m^{TM} + T_c^{TM}$ is the time to create the molds traditionally + time to create the cores traditionally

$T_{tm} + T_{td}$ is the total time to design and manufacture the tooling

2.5.2 3D Sand Printing (3DSP)

For 3DSP, the lead time is calculated (in days) as follows:

$$T_{lead}^{3DSP} = (T_m^{3DSP} + T_c^{3DSP} + T_{pre} + T_{post})/24 \qquad \rightarrow \textit{Eq. 12}$$

The build times for molds and cores are calculated based on the total build height after parts are nested in the machine and the height build rate specified for an S-Max printer.

$$T^{3DSP} = h_{build} \,/\, r_{build} \qquad \rightarrow \textit{Eq. 13}$$

Where,

h_{build} is the build height after part nesting measured in inches

r_{build} is the height built rate for S-max which is estimated to be around 1 in/hr

2.5.3 3D Sand Printed Cores (3DSPC)

For a 3DSPC method, the total lead time (in days) is a combination of time for creation of mold and the times to 3D print the cores on an S-max.

$$T_{lead}^{3DSPC} = (T_m^{TM}/8) + T_{td} + (T_c^{3DSP} + T_{pre} + T_{post})/24 \qquad \rightarrow \textit{Eq. 14}$$

2.5.4 FDM Pattern-making (FDMP)

The total lead time (in days) for a FDMP method is a combination of the time to build the patterns in a Fortus 900 and the time to traditionally create the molds and cores.

$$T_{lead}^{FDMP} = (T_m^{TM} + T_c^{TM})/8 + (T_{FDMP}/24) \qquad \rightarrow \textit{Eq. 15}$$

T_{FDMP} is the build time to the patterns in a Fortus 900 FDM printer. For each case study, it is assumed that the mold and all cores are printed together in one build. This build optimization saves time and cost and it's a more sensible way of creating patterns than fabricating each mold and core separately.

2.6 Application for complexity calculation

Based on the data accumulated, creation of a tool which would estimate the complexity factor, build times and associated costs would greatly serve the purpose of automating all the calculations shown above.

Since Microsoft Excel has been used to store the data generated from the methodologies discussed above, a tool built inside Excel is a logical choice. Hence, Visual Basic Applications (VBA) has been used to create a user interface which can be used to enter the inputs line by line and subsequently generate the complexity factors.

The following are the features that have been identified as initial inputs for the tool:

- Part Name
- Part Volume
- Surface Area
- Number of Cores
- Volume of All Cores

- Minimum thickness of the part
- Maximum thickness of the part
- Length
- Width
- Height

The user interface is created in VBA using textboxes and data fields. Three action buttons ("OK", "Clear" and "Cancel") are provided for control as shown in the figure below.

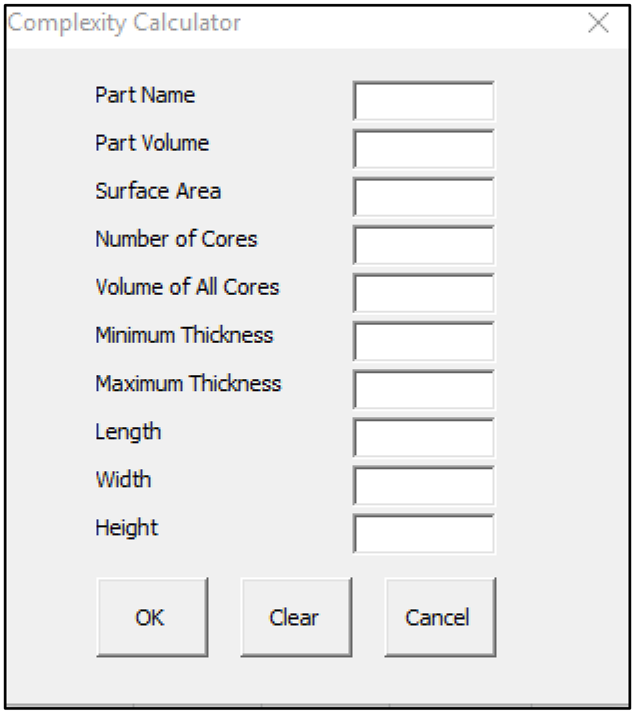
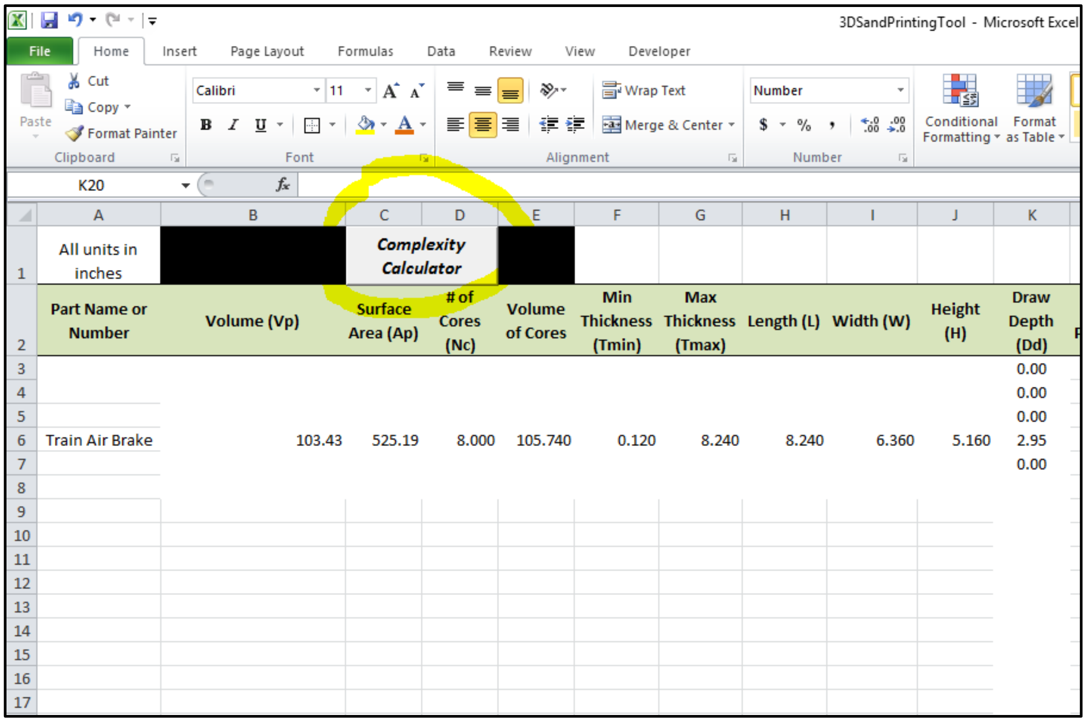


Figure 10: Complexity Calculator User Interface

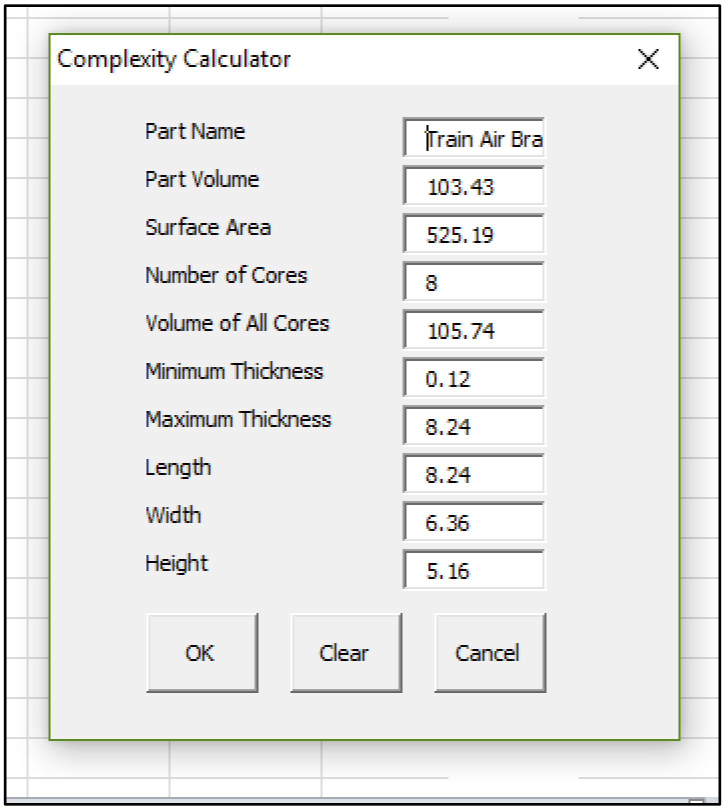
In Figure 11, the highlighted portion is a click button titled "Complexity Calculator". This button acts as a macro and upon clicking; it connects to the user interface show in Figure 10.



	A	B	C	D	E	F	G	H	I	J	K
1	All units in inches	[redacted]	*Complexity Calculator*		[redacted]						
2	Part Name or Number	Volume (Vp)	Surface Area (Ap)	# of Cores (Nc)	Volume of Cores	Min Thickness (Tmin)	Max Thickness (Tmax)	Length (L)	Width (W)	Height (H)	Draw Depth (Dd)
3											0.00
4											0.00
5											0.00
6	Train Air Brake	103.43	525.19	8.000	105.740	0.120	8.240	8.240	6.360	5.160	2.95
7											0.00
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											

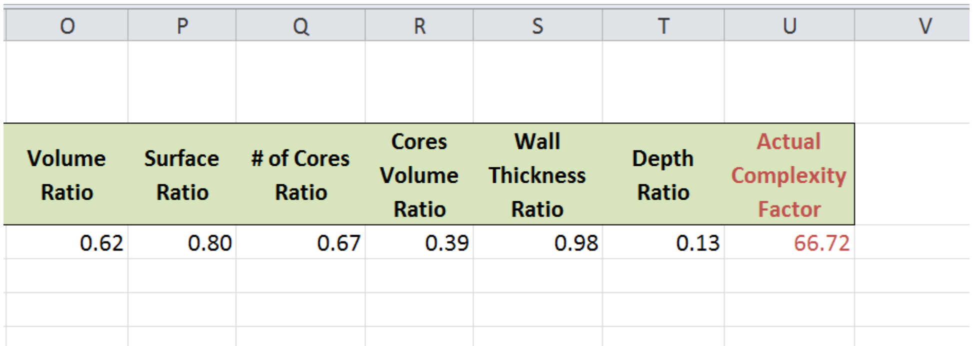
Figure 11: Macro Button for Complexity Calculator

Once the values have been entered and the user presses the OK button (as shown in figure 12), the complexity number is calculated in the excel sheet and displayed in the far right column (shown in Figure 13).



Part Name	Train Air Bra
Part Volume	103.43
Surface Area	525.19
Number of Cores	8
Volume of All Cores	105.74
Minimum Thickness	0.12
Maximum Thickness	8.24
Length	8.24
Width	6.36
Height	5.16

Figure 12: Example Calculation for Train Air Brake with 8 Cores



Volume Ratio	Surface Ratio	# of Cores Ratio	Cores Volume Ratio	Wall Thickness Ratio	Depth Ratio	Actual Complexity Factor
0.62	0.80	0.67	0.39	0.98	0.13	66.72

Figure 13: Final Output in MS-Excel

Chapter 3 Results, Analysis and Discussion

Based on the formulas and equations defined in Chapter 2, the various costs and times are calculated for the sub-cases in each case study.

To understand the variation of costs with respect to complexity, the production cost per part with respect to an increasing change in complexity factor is analyzed for the four manufacturing methods (TM, 3DSP, 3DSPC, and FDMP). Also, the same cost variations vs. complexity factor are analyzed based on changing production volumes (1, 30, 100, and 1000) as well.

3.1 Tooling Costs

Table 5: Tooling Cost Comparison Between Three Estimates

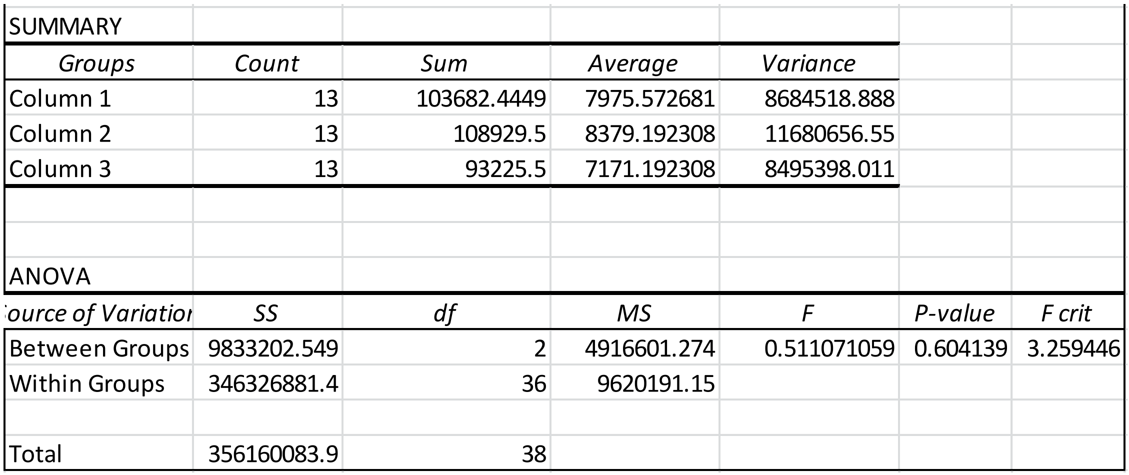
	Part Name or Number	Integrated Casting Cost Estimation model including tool design labor	Online Estimated Tooling Cost : Tool Manufacture+Tool labor	Quoted Tooling: Design + Manufacture Labor costs
Case Study I	**Imported No Core**	3422.56	3528.3	2962.1
	Imported 8	7332.55	6957.3	6931.1
	Imported 8,3	7800.02	7336.3	7031.1
	Imported 8,3,2	8951.74	8911.3	8084.1
	Imported 8,3,2,5	9195.37	9393.3	8184.1
	Imported 8,3,2,5,4	10095.87	10724.3	9156.1
	Imported 8,3,2,5,4,7	11089.42	12203.3	10309.1
	Imported 8,3,2,5,4,7,6	12046.75	13476.3	11381.1
	Imported 8,3,2,5,4,7,6,1	12142.51	14031.3	11381.1
Case Study II	**Comp. NO core**	3677.05	4354.3	3062.1
	Com. Cubic core	5075.41	5279.3	4215.1
	Com. Cylinderical Core	5801.03	6006.9	4979.3
	Orginal core	7052.17	6727.3	5549.1

The tooling costs estimated in Section 2.3 are now compared using a single factor ANOVA (using excel data analysis) to determine if they are statistically significant to each other. An alpha (α) of 0.05 is assumed.

The null hypothesis states that, there is no difference between any of the tooling cost means is zero.

The alternative hypothesis states that, there are significant differences between the three tooling costs.

Table 6: Single Factor ANOVA



SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	13	103682.4449	7975.572681	8684518.888		
Column 2	13	108929.5	8379.192308	11680656.55		
Column 3	13	93225.5	7171.192308	8495398.011		
ANOVA						
ource of Variatio	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9833202.549	2	4916601.274	0.511071059	0.604139	3.259446
Within Groups	346326881.4	36	9620191.15			
Total	356160083.9	38				

The p-value obtained is 0.604 which is greater than 0.05. Hence, we fail to reject the null hypothesis and reach a conclusion that the three tooling costs have no significant differences between them. Therefore, the thesis is at liberty to use any of the tooling costs calculated and for the purposes of this thesis use the industry quote.

3.2 Cost Studies

3.2.1 Cost per Part vs. Complexity Factor at each production volume

The graphs below show the effect of increasing complexity on a manufacturing method. The cost per part vs. complexity is plotted for each case study and every graph considers a different production volume.

Case Study 1: Train Air Brake

For a unit production volume, the 3DSP costs remain the lowest ($159.00-$212.00) since the need for patterns is eliminated (bringing down the tooling cost to zero). The cost per part for FDMP is in the range of $595.0 – $686.00 which is higher than 3DSP but significantly lower than TM or 3DSPC for any value of complexity.

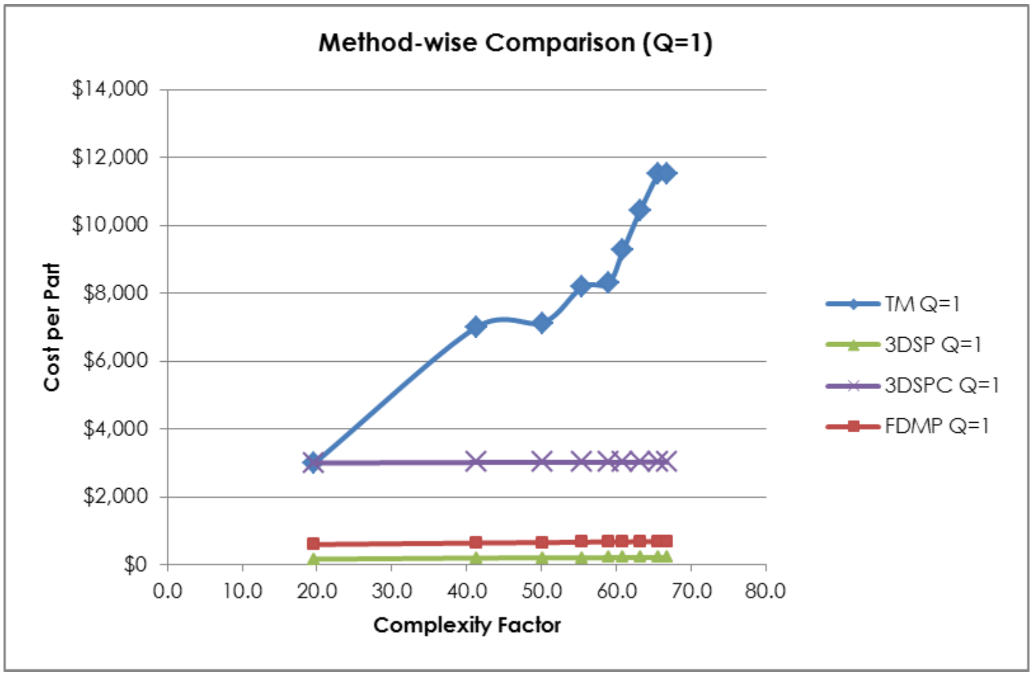


Figure 14: Train Air Brake- Cost per Part vs. Complexity at Q=1

For low production volumes (30+), two break-even points can be observed. The first break-even point is between TM and 3DSP at a complexity of 58.9 and cost per part of $206.00. Hence, below the breakeven point, the TM method is more cost feasible and 3DSP is more feasible above it.

The second breakeven point is between 3DSPC and FDMP methods. Here we observe a break-even point of 32.5 and $70.8. Below the break-even point it is feasible to 3D print the patterns and beyond the breakeven point, a core printing approach makes more economics sense.

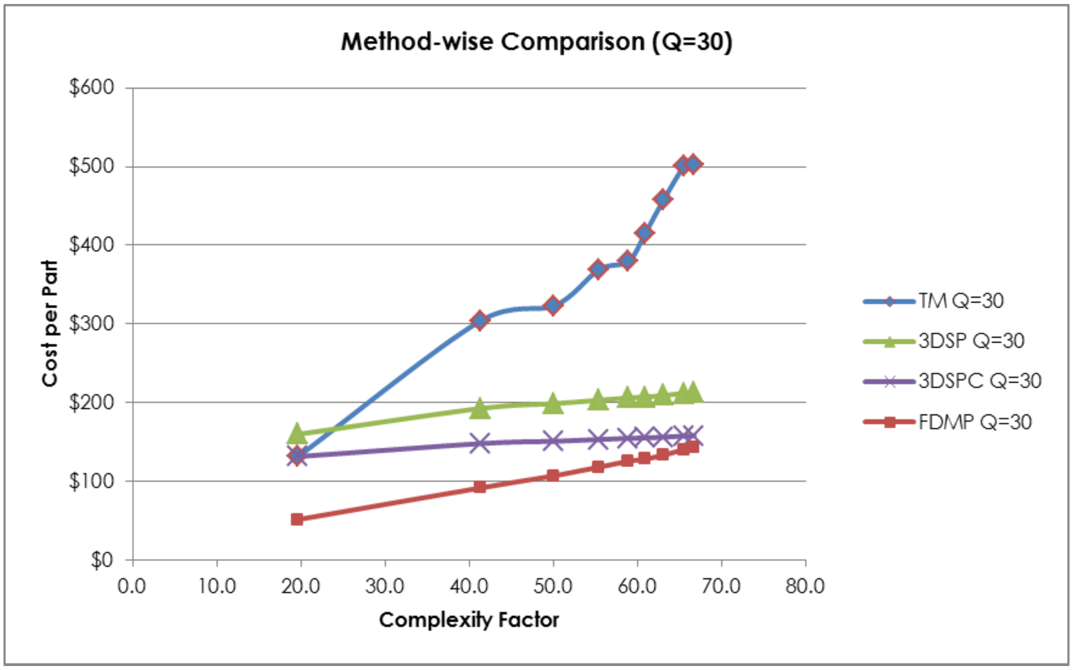


Figure 15: Train Air Brake- Cost per Part vs. Complexity at Q=30

For medium production volumes, the 3DSPC costs are the lowest compared to any other method for any level of complexity. This can be attributed to the low cost of 3D sand printing of cores. The highest cost per part is for a 3DSP process and can be attributed to the cost per part of 3d sand printing.

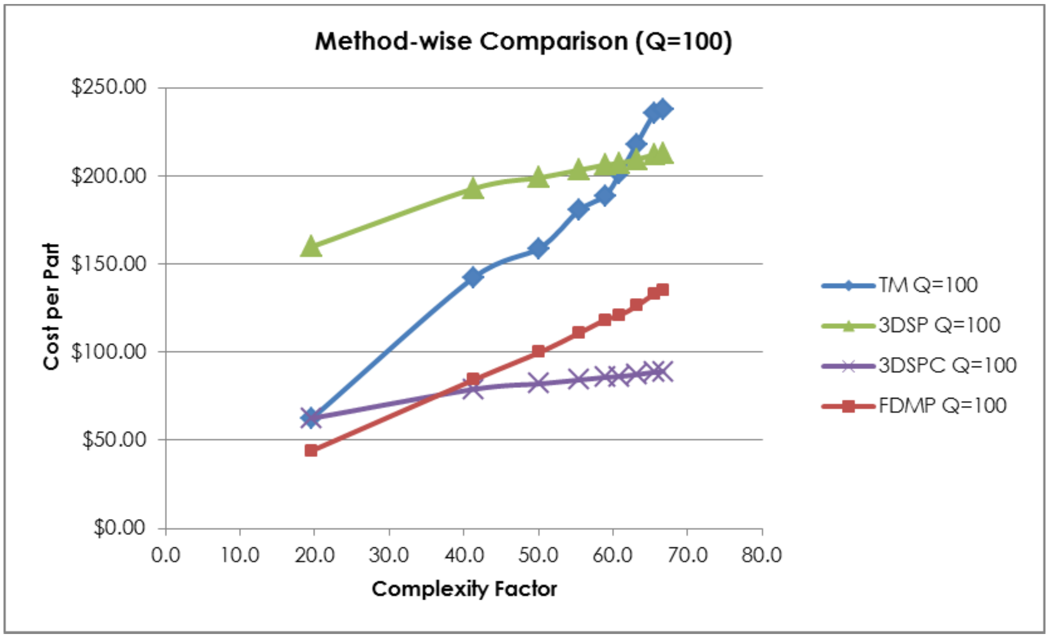


Figure 16: Train Air Brake- Cost per Part vs. Complexity at Q=100

For high production volumes (1000+), the 3DSPC method is the most feasible beyond a complexity of 19.4 and cost of $44.00. The cost curves for TM and FDMP almost intersect since both have a tooling cost associated with them and these tooling costs becoming negligible for high production volumes.

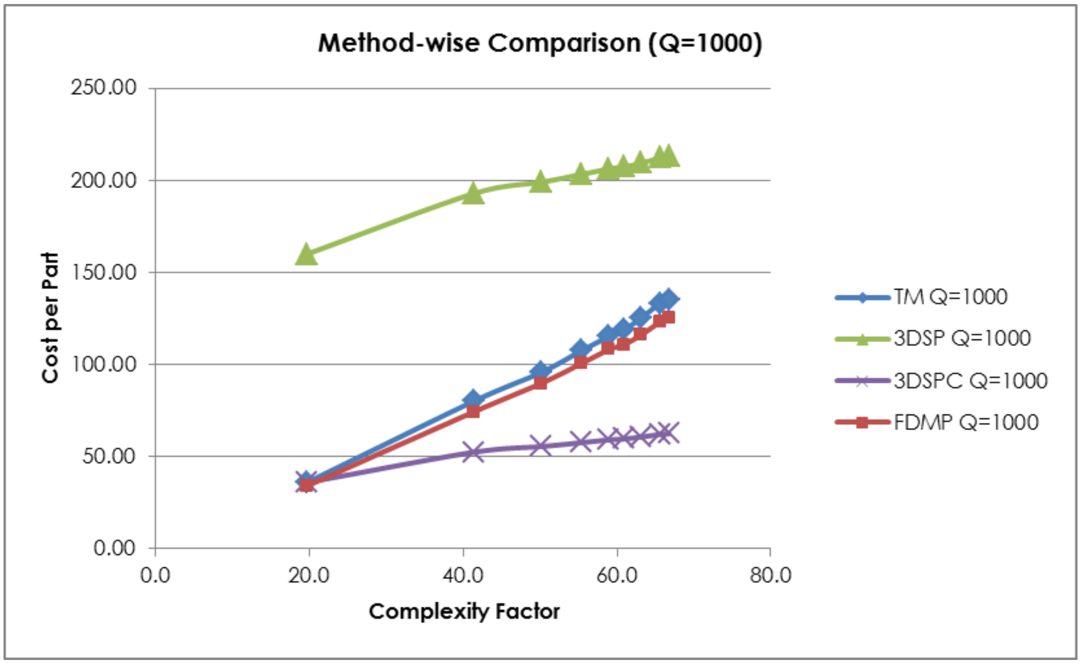


Figure 17: Train Air Brake- Cost per Part vs. Complexity at Q=1000

Case Study 2: Turbo Charger

As in case study 1, a similar set of trends can be observed for case study 2.

For a unit production volume, the 3DSP costs remain the lowest ($127.00-$160.00) since the need for patterns is eliminated (bringing down the tooling cost to zero). The cost per part for FDMP is in the range of $543.0 – $605.00 which is higher than 3DSP but significantly lower than TM or 3DSPC for any value of complexity.

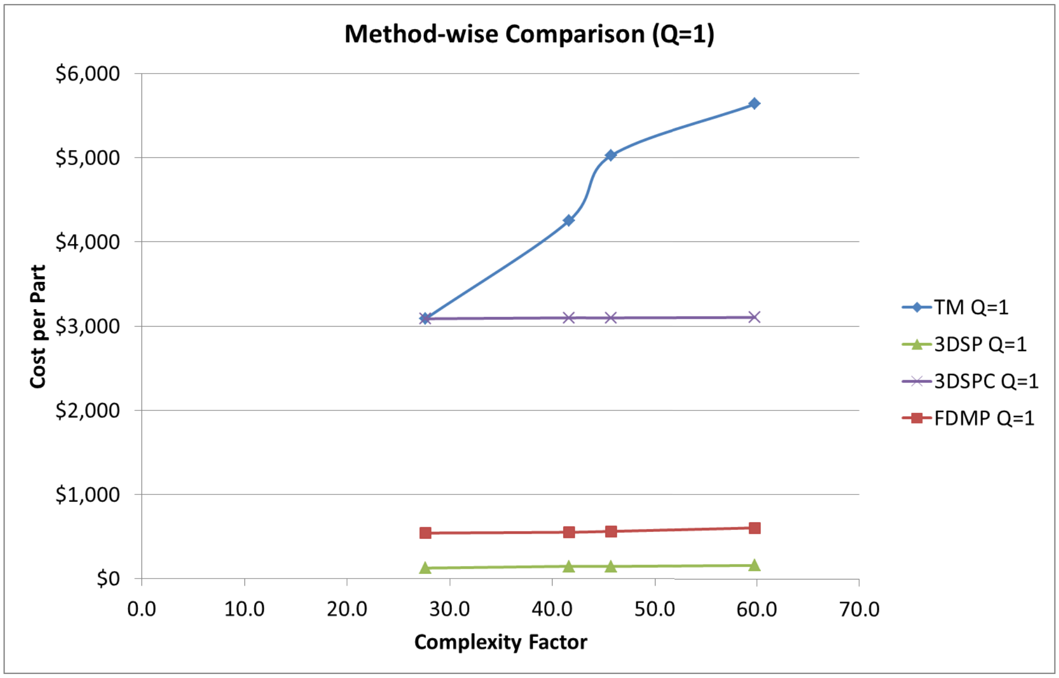


Figure 18: Turbocharger- Cost per Part vs. Complexity at Q=1

For low production volumes (30+), again two break-even points can be observed. The first break-even point is at (55.4, $161.00), above which a 3DSP process is more feasible.

The second breakeven point (52, $72.00), is between 3DSPC and FDMP methods. Below the break-even point it is feasible to 3D print the cores and beyond the breakeven point, a 3D printed pattern making approach makes more economics sense.

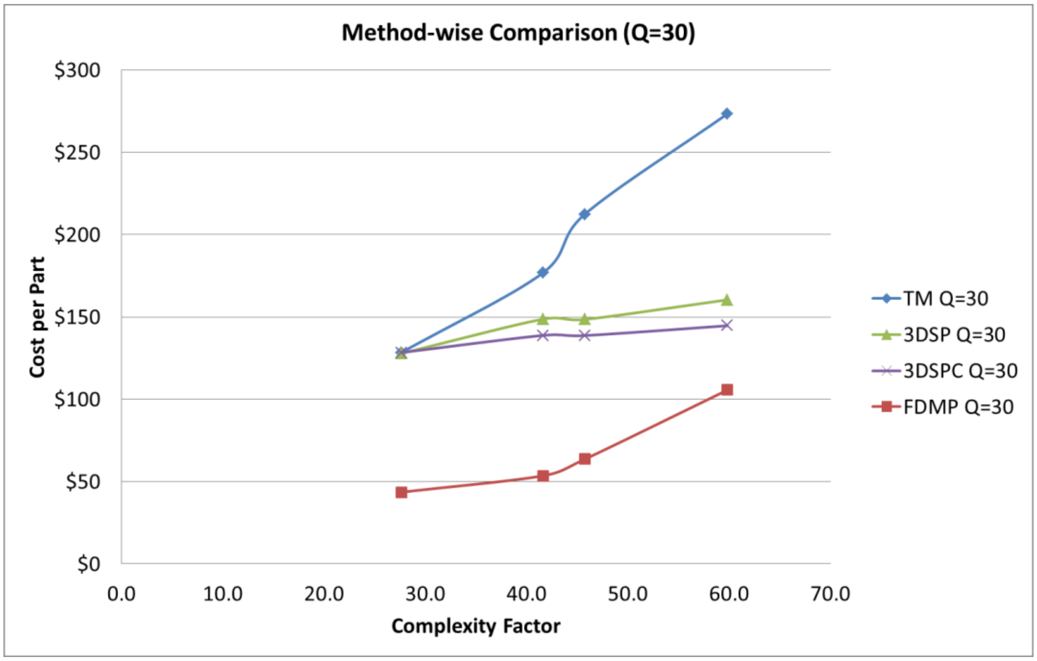


Figure 19: Turbocharger- Cost per Part vs. Complexity at Q=30

For medium production volumes, break even points are observed at [19.7, $36.60] and [44.6, $48.5]. The first breakeven point suggests that for parts with complexity below 19.7, the TM process would be cost economical. The second breakeven point suggests that beyond a complexity value of 44, a 3DSPC method will yield more cost benefits.

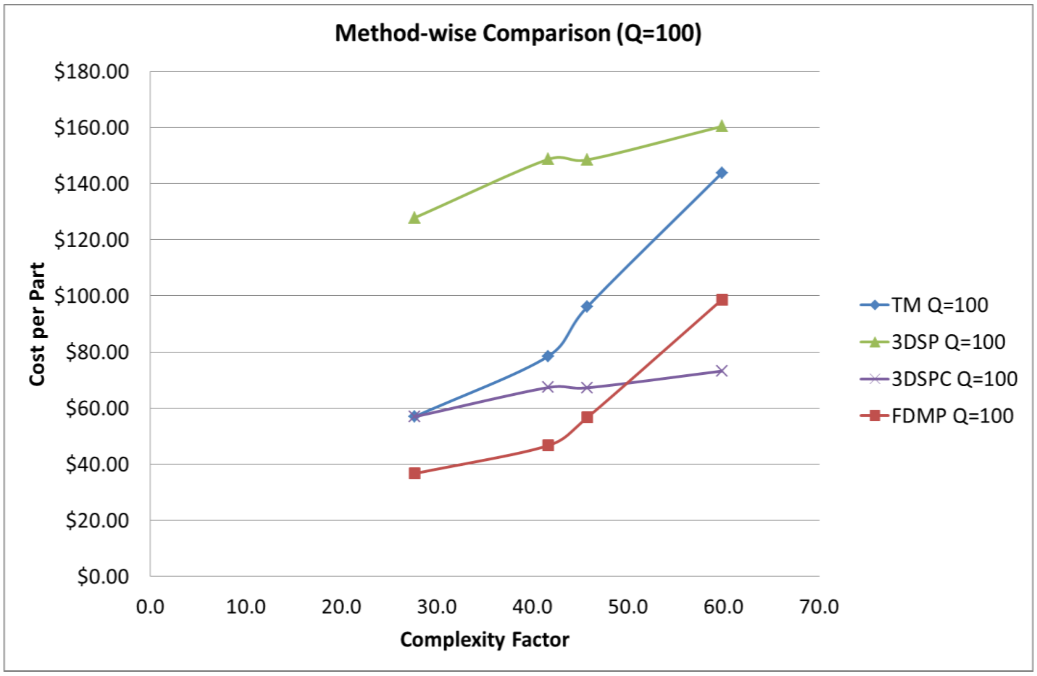


Figure 20: Turbocharger- Cost per Part vs. Complexity at Q=100

For high production volumes (1000+), the TM and FDMP curves intersect showing that the cost for these two processes are essentially equal at high production volumes. A breakeven point is also observed at [44, $38.00] between FDMP and 3DSPC. Interestingly below the breakeven point, the cost per part for TM, FDMP and 3DSPC are almost equal. Hence beyond this breakeven point, a 3DSPC method is cost feasible.

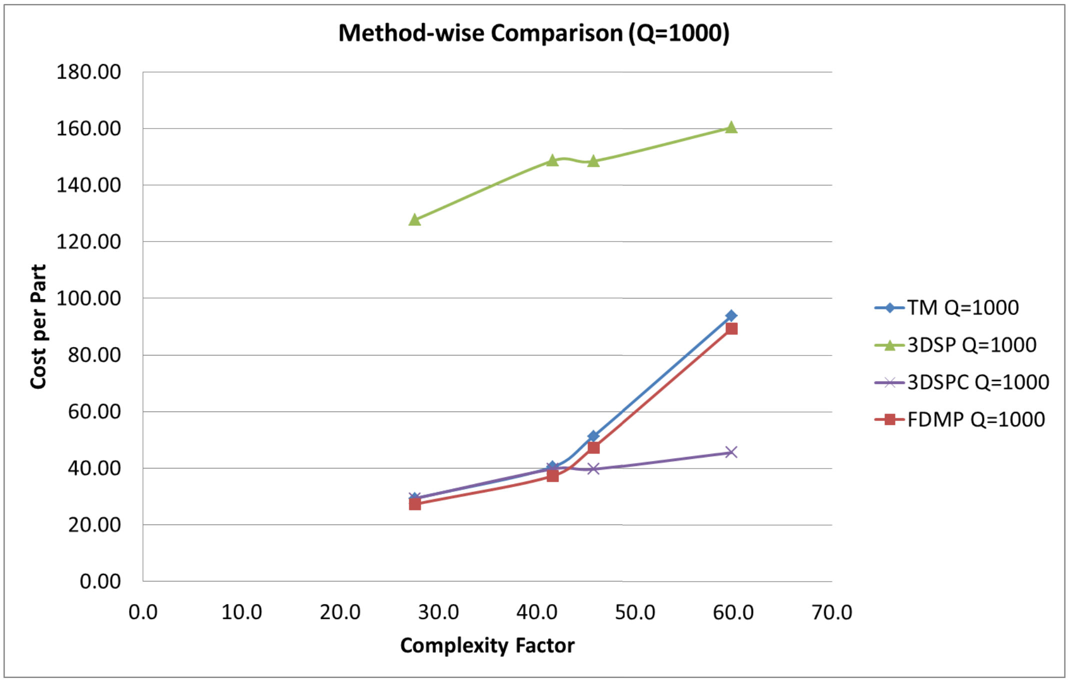


Figure 21: Turbocharger- Cost per Part vs. Complexity at Q=1000

3.3 Time Studies

3.3.1 Lead Time to Manufacture vs. Manufacturing Method

The lead time to manufacture the two case studies is defined from the creation of the pattern and core-box (if required) to the final mold and core-assembly. These lead times also include the pre and post processing times required for removing and cleaning the molds and cores.

Case Study 1: Train Air Brake

Figure 25 shows that **for unit volume production**, 3DSP provides the fastest lead times (less than 2 days) up to a breakeven point of [65.6, 2.37 days] after which an FDMP based approach would provide faster lead times. The TM method has the longest lead times for any sub-case at any level of complexity. This is entirely attributed to the time taken to design tooling for the molds and cores.

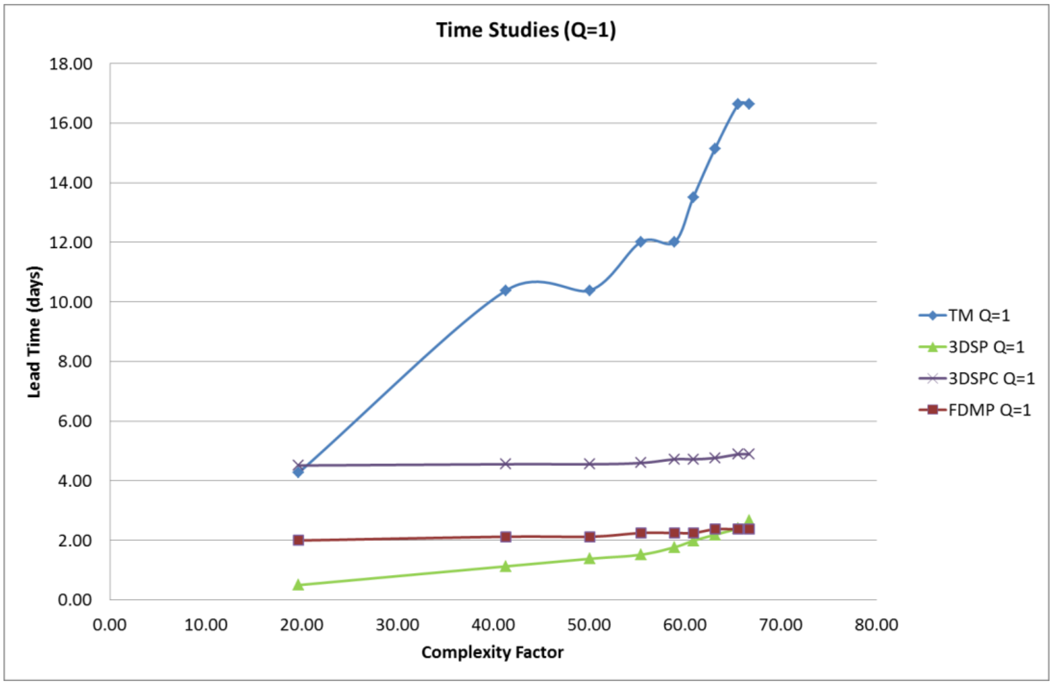


Figure 22: Train Air Brake- Lead Time vs. Complexity at Q=1

For small production volume (30+), 3DSP takes the longest lead time (15 days for the lowest complexity and 90 days for the highest complex part). A breakeven point is observed at [40, 12 days] beyond which the FDMP method provides faster lead times.

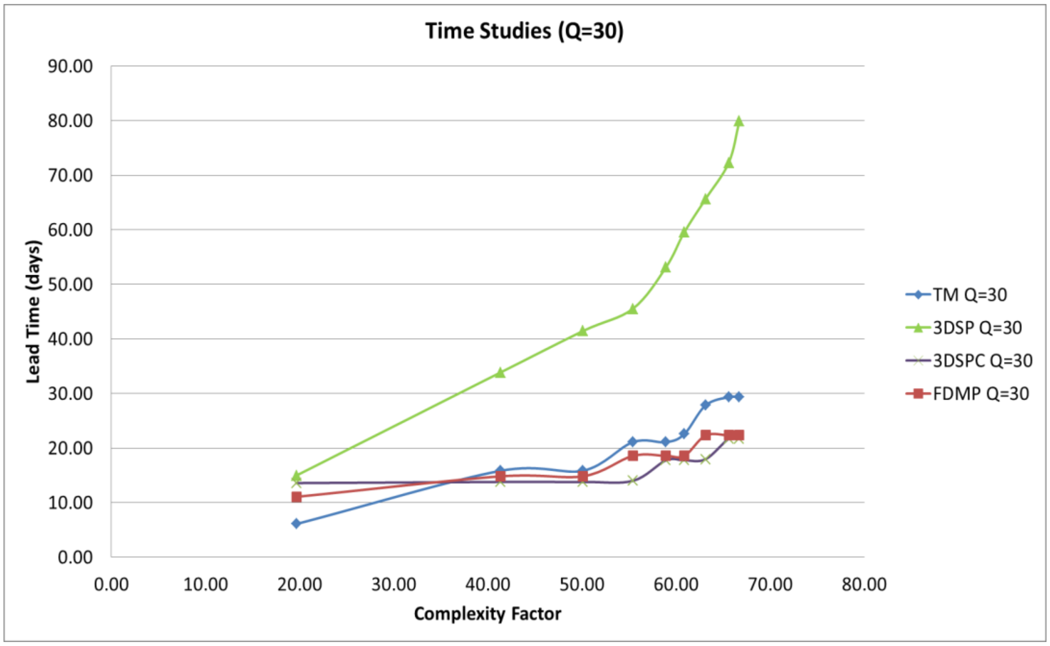


Figure 23: Train Air Brake- Lead Time vs. Complexity at Q=30

For medium to high production volumes (100+), the TM method has the fastest lead times since the binder jetting technology have a limited build volume and speed. It is also observed that FDMP and TM have comparable lead times and as the complexity increases the gap between their lead times reduces. Also the breakevenpoint between 3DSPC and FDMP [27, 38.30 days] shows that, beyond a complexity of 27, FDMP is capable of achieving faster lead times when compared to 3DSP or 3DSPC.

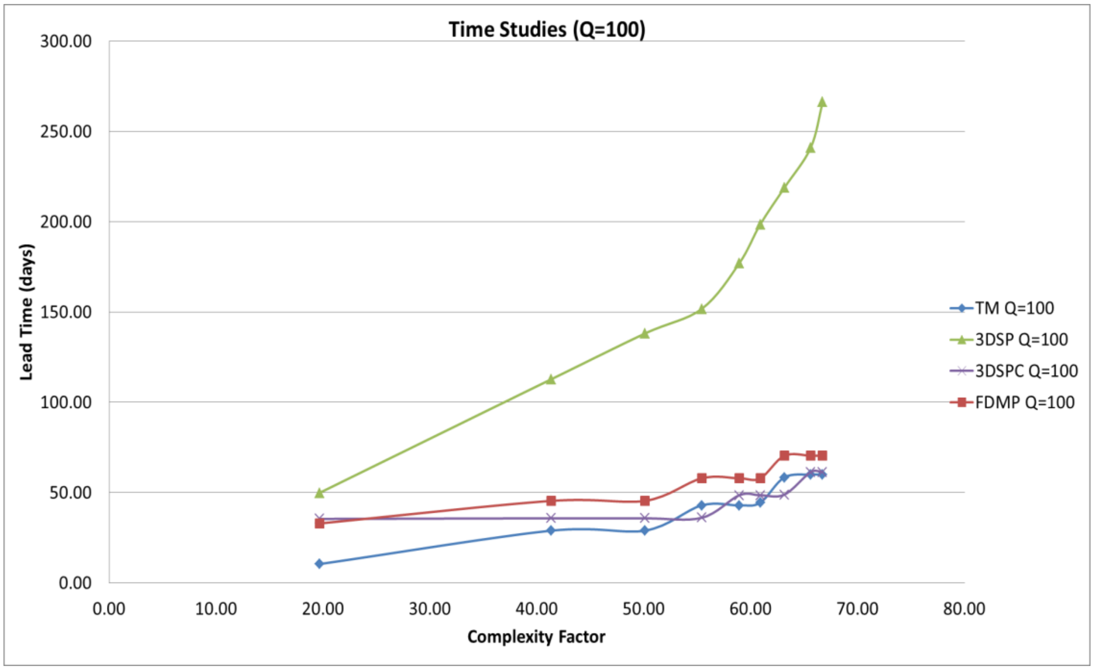


Figure 24: Train Air Brake- Lead Time vs. Complexity at Q=100

Case Study 2: Turbo Charger

Again, similar trends are noticed for case study 2.

For unit production volumes, 3DSP provides the fastest lead times regardless of complexity. The TM method has the longest lead times beyond the breakeven point [27.64 and 4.3 days].

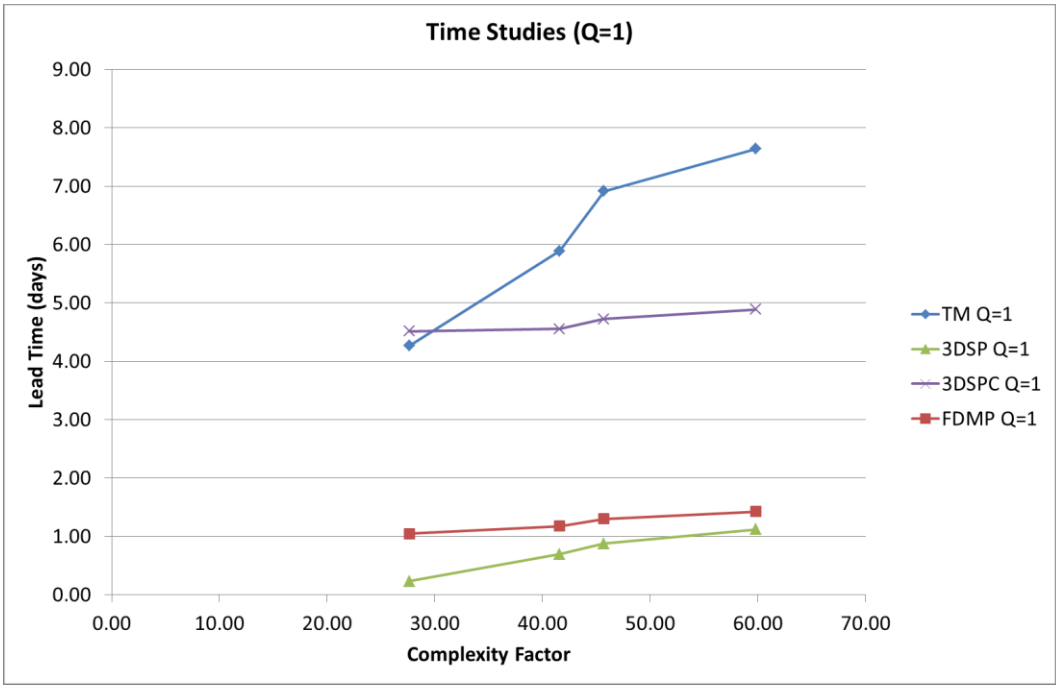


Figure 25: Turbocharger- Lead Time vs. Complexity at Q=1

For small production volume (30+), the time curves for 3DSP and 3DSPC are around 10-12 days apart. This means both the methods have lead times that are close to each other. A breakeven point is observed at [32, 12.5 days], between FDMP and 3DSP, beyond which the FDMP method provides faster lead times. The TM method has the fastest lead times beyond the breakeven point [22.5, 6 days] between TM and 3DSP.

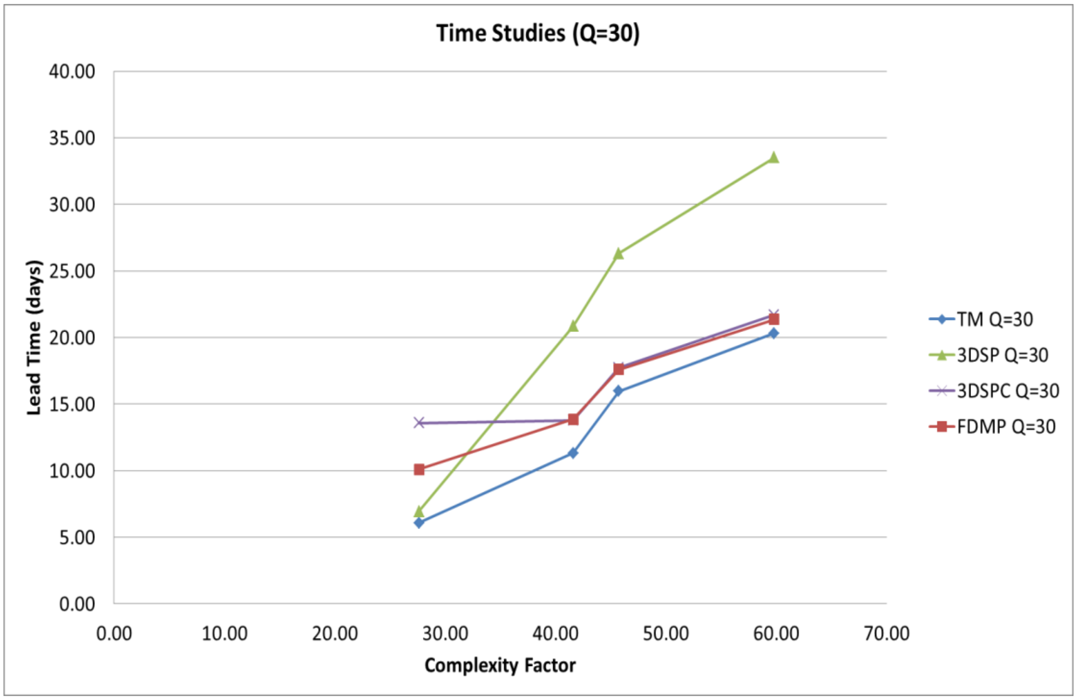


Figure 26: Turbocharger- Lead Time vs. Complexity at Q=30

For medium to high production volumes (100+), again the TM method has the fastest lead times among all four processes. However unlike the previous case study, here it is observed that FDMP and TM have a large difference between their lead times. Also the breakevenpoint between 3DSPC and FDMP [34, 37.60 days] shows that, beyond a complexity of 34, FDMP is capable of achieving faster lead times when compared to 3DSP or 3DSPC.

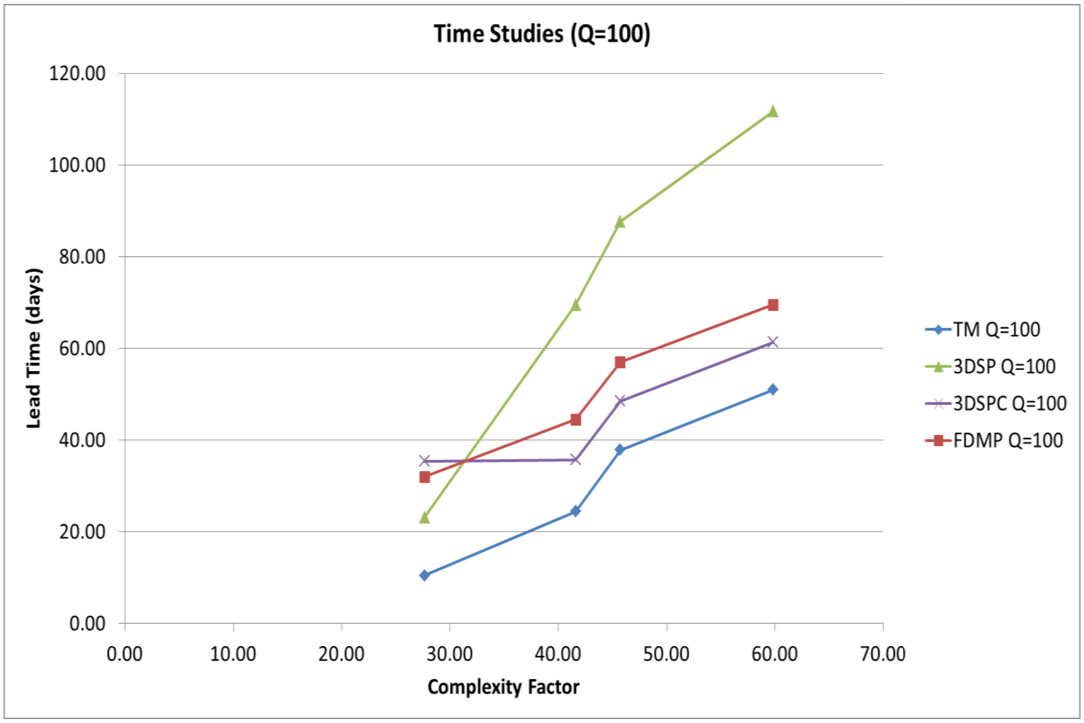


Figure 27: Turbocharger- Lead Time vs. Complexity at Q=100

Chapter 4 Conclusions and future work

The purpose of this thesis was to examine the adoption of a 3D sand printing system or an FDM system at various stages of the sand casting process on the costs and times of the two case studies. This was done by adopting an FDM printer (Fortus 900) at the pattern-making stage creating a method defined as FDMP (Fused Deposition Modeling of Patterns). Secondly, a 3D sand printer has been adopted at the mold and core-making stage by the use of a 3D sand printer (ExOne S-max). This is defined as the 3DSP (3D Sand Printing) method. Thirdly, a 3D sand printer has been adapted only at the core-making stage, which has been defined as the 3DSPC (3D Sand Printed Cores) method. The cost per part vs. complexity graphs were generated for each method and compared on the basis of production volume.

Among the major cost components presented in this thesis, the most significant one has been the tooling costs. Foundries have mostly provided tooling cost estimates based on their foundry experience or historical data. This is a disadvantage for a customer who requires a low production volume of castings. This problem has now been overcome by the use of a casting cost estimation model described in Section 2.3.3 and has been proven to be significantly accurate based on a Single Factor ANOVA.

In both case studies, it is observed that for a unit production volume the 3DSP method is the most cost feasible option and also provides the fastest lead times for any level of complexity. In other words, 3D sand printing the molds and cores is economical both cost-wise and time-wise. The FDMP method is second to 3DSP for parts with low complexity, but beyond a complexity factor of 66 for case study 1 it is observed to provide faster lead times.

For short production runs of 10 to 30, the FDMP method has the least cost per part for a large range of complexities. This implies that, printing the patterns on an FDM printer is economically feasible for low volume production. But for case study 1 (train air brake), the graphs for lead times show that FDMP is faster for complexities beyond 40. Hence, if the requirement is a set of 10 train air brake castings and the complexity factor is above 40, it is recommended to opt for an FDMP method.

For medium production volumes (100+), 3DSP is clearly neither time nor cost effective for both case studies. It is also noticed that the TM method is the most time-effective but definitely not cost effective at higher complexities when compared to 3DSPC and FDMP. Therefore, if time is of critical importance then the TM method should be the preferred method for casting parts.

For large production volumes (1000+), both the case studies clearly agree on TM method providing the fastest lead times. For case study 1, 3DSPC method has the lowest cost per part beyond a complexity factor of 20 but has a larger lead time in comparison to TM.

Hence, it is observed that based on the requirement of the manufacturer, a specific method of manufacturing can be recommended to the manufacturer based on the complexity of the final part and also its production volume.

The app for calculating complexity can be further expanded to include generation of tooling cost using the casting cost estimation method and also the final mold and core making costs for any method of mixed manufacturing. Furthermore, the same app can be used as a decision making tools by manufacturers with limited knowledge of 3D printing processes.

There are other 3D sand printers available in the market supplied by Voxeljet and Viridis3D which supposedly offer faster build rates with more versatile materials. The cost and time economics of using these printers can be a possible avenue for exploration.

In Section 1.5.2, the idea of calculating complexity for every layer of a spliced 3D object has been discussed. This algorithm can be potentially applied to study the energy consumption of various 3D sand printers at each layer.

It is also known that FDM based parts have a significant distortion which may alter the dimensions of the sand molds and cores. The effect of this pattern distortion on the final casting is definitely worth looking at.

This study also assumes that 3D sand printing provides an equal surface finish when compared to traditional mold and core making processes. Therefore, testing the physical and mechanical properties could provide additional decision making criteria for choosing a manufacturing method.

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