Determining When to Use 3D Sand Printing: Quantifying the Role of Complexity

By

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Abstract

The additive manufacturing industry has the potential to transform nearly every sector of our lives and jumpstart the next Industrial Revolution. Engineers and designers have been using 3D printers for more than three decades but mostly to make prototypes quickly and cheaply before they embark on the expensive business of tooling up a factory to produce the real things. In sand casting industries, a growing number of companies have adopted 3D sand printing to produce final casts. Yet recent research suggests that the use of 3D sand printing has barely begun to achieve its potential market. It is not surprising that executives are having difficulty adopting additive manufacturing; the technology has many second - order effects on business operations and economics. One of the most important factors is the lack of awareness of additive manufacturing's applications and values in the sand casting manufacturing process. The lack of awareness is significantly slowing down the adoption rates. This research will help executives to optimize their adoption decision by answering the question of ''At what level of part complexity should sand printing be used instead of the conventional process in molds and cores manufacturing?" Moreover, this thesis defines and analyzes the geometric attributes which influence the parts' complexity. As known in the conventional sand casting process, the high level of complexity leads to higher manufacturing cost. On the other hand, in the additive manufacturing process, the manufacturing cost is fairly constant regardless of the level of complexity. Therefore, 3D sand printing provides a unique advantage that the increasing in geometric complexity of the part has no impact on the molds and cores manufacturing cost or what is known as ''*complexity for free*.'

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Chapter 1 (Introduction)

1.1 Motivation

Foundries in the United States are considering the production of molds and cores using additive manufacturing technology as a new opportunity to expand and transform their business, which is restricted by limited skilled labor. But the lack of understanding of the advantages of additive manufacturing is significantly slowing down the adoption rates. Yet executives do not have enough information to prove the economic feasibility of using additive manufacturing techniques to produce molds and cores [1]. The motivation of this research comes from a sense of responsibility towards the importance of the sand casting industry to the national economy, and to help foundries to make a smooth and accurate decisions using additive manufacturing technology. Although there are many new advanced technologies for metal casting, sand casting remains one of the most widely used casting processes today [2] . Many statistics showed that over 70% of all metal castings are produced via sand casting, and feeds the most vital manufacturing sectors in the country such as oil and gas, aerospace and automotive industries [3].

1.2 Background

1.2.1 Sand Casting

Sand casting is used to make large parts, molten metal is poured into a mold cavity formed out of sand. The sand casting process is one of the expandable-mold methods, and is considered the most widely used casting process. In reality, sand casting utilizes expendable sand molds to form complex metal parts that can be made of nearly any alloy [4][5]. Moreover, sand casting is the most economical method to produce items in metal [3]. Typically, sand casting has a low production rate because the sand mold must be destroyed in order to remove the part, called the casting. The sand mold separates along a parting line and the solidified casting can be removed. The sand casting process is also involves the use of using furnaces, metals, patterns, and cores The metal is melted in the furnace and then ladled and poured into the cavity of the sand mold, which is formed by the pattern.

Sand casting is used to produce a wide variety of metal components with complex geometries [6]. These parts can vary greatly in size and weight, ranging from a couple ounces to several tons. Typical large cast products include components as engine blocks, cylinder heads, transmission housing, pistons, turbine disks, railroad wheels, and ornamental artifacts. Smaller applications include gears, pulleys, crankshafts, connecting rods, and propellers.

1.2.2 Mold Making.

The first step in the sand casting process is to create the mold for the casting [7]. In an expendable mold process this step must be performed for each casting. A sand mold is formed by packing sand into each half of the mold. The sand is packed around the pattern, which is a replica of the external shape of the casting. When the pattern is removed, the cavity that will form the casting remains. Any internal features of the casting that cannot be formed by the pattern are formed by separate cores which are made of sand prior to the formation of the mold. The mold-making includes positioning the pattern, packing the sand, and removing the pattern. The mold-making is affected by the size and the part complexity, the number of cores, and the type of sand mold. If the mold type requires heating or baking time, the mold-making time is substantially increased. Also, lubrication is often applied to the surfaces of the mold cavity in order to facilitate removal of the casting. The use of a lubricant also improves the flow of the metal and can improve the surface finish of the casting. The lubricant that is used is chosen based upon the sand and molten metal temperature. Figure 1 shows a mold and core for one of the study cases that used in this thesis.

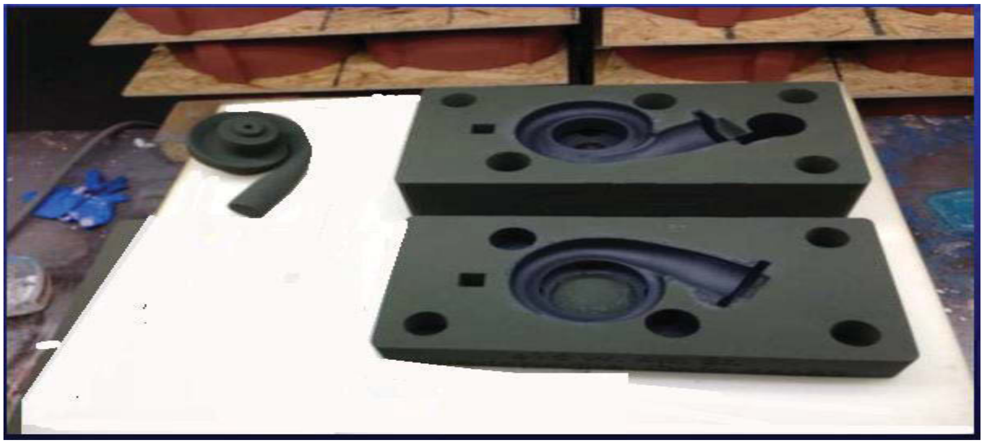


Figure 1: Two pieces mold and core [source: Humtown Products]

1.2.3 Patterns. The cavity in the sand is formed by using a pattern which is an approximate duplicate of the real part, and patterns may be made of wood, plastic, or metal [8]. The cavity is contained in an aggregate housed in a box called the flask. Patterns also may be made from combination of materials to reduce the pattern's wear in some critical regions. Unlike cores, same patterns are used repeatedly to make molds. Therefore, pattern-making specialist are carefully selected the pattern's material to be accommodated with expected production quantity and the level of accuracy that is required.

There are several types of patterns used in foundry practice. In [9] the pattern type categorized as following:

Single or loose pattern

Gated pattern

Match-plate pattern

Cope and drag pattern

Each of these pattern types has advantages and limitations. Hence, the selection of pattern type will generally depend on the requirements associated with a particular casting.

1.2.3. A Loose Pattern. A loose pattern is a copy of the part to be cast also incorporates shrinkage allowance, core print, and other features required by the casting process. Typically, this pattern type is made of wood, but it can also be made of metal of metal, plaster, wax. Loose patterns are frequently used to produce prototype casting or for other low quantity applications because they can usually be fabricated quickly and for low cost [9]. However, because of the large amount of manual effort required to produce the actual casting, loose patterns are not usually suitable for application where large quantities of casting are required. Manual operations include forming the parting surface by hand, hand cutting the gating system, and manually drawing the pattern from the sand. Because of the manual operations, casting dimensions are also likely to vary from casting to casting [9].

1.2.3. B Gated Patterns. A gated pattern is loose pattern that has the gating system included as a prat of the pattern. This eliminates the time and inconsistency associated with hand-cutting the gates and runners [9]. Also, since the gating system is designed and fabricated as a part of the pattern, the consistency of molten martial flow into the casting and feeding of the casting during solidification is improved. Gated patterns are appropriate for pouring small quantities of casting when quick turn around and low cost are important [10]

1.2.3. C Match-Plate Patterns. A match-plate pattern consists of a wood or metal plate with the cope portion of the pattern mounted on one side and drag portion of the pattern mounted don the other side [10]. Hence, the match plate pattern incorporates the parting line into the pattern and also include the gating system as an integral part of pattern. Match-plates may be assembled by tool builder or they may be integrally cat as one piece in sand or plaster molds. Match-plates are suitable for large quantity production. Also they are generally used with some type of molding machine in order to maximize the speed of molding and minimize the cycle time to produce casting [11]. Match-plates also increase the dimensional accuracy of the casting because of the built in registration between the cope and drag portions of the patterns [10]. The size of the casing produce by using a match-plate pattern is limited by the weight of the mold and flask that can be handled by the foundry [9]. Therefore, this type of patterns are best suited for mass production of small castings.

1.2.3. D Cope and Drag Patterns. In a cope and drag pattern, the cope and drags halves of the pattern are each mounted on separate plate. Separate plates enable significant cycle time reduction because allow the cope and drag halves of the mold to be made simultaneously by workers using different molding machine [11]. Additionally, cope and drag patterns are well suited for use with high speed mechanized or automated molding equipment [11]. For these reasons, this pattern type is often the pattern of choice for high volume production applications. and it also good choice for molding medium and large castings on molding machines because each half of the mold is handled separately so weight is greatly reduced . Finally, Separate pattern plates are more costly.

Several materials are used fort master pattern construction. Each has its advantages in different application. According to [9] and [10] the patterns material can be summarized by the following:

Wood: wood are widely used in foundry industry. The most frequently used types of wood include, pine, poplar, mahogany, and cherry [9]. Mounting a wood pattern helps to maintain its shape. All wood patterns should be properly segmented to offset the effects of grain orientation. Each segments should be glued and secured with screws. Nailed pattern construction should be avoided wherever possible. To increase the life of wood pattern, core prints and other areas prone to wear can made of hard maple or birch [10].

Metal: patters are particularly well suited for long production runs. Compared, metal is more abrasion resistant and less subject to wear. Tighter dimensional tolerance can be held in metal tooling compared to wood. Metal patterns can be cast to size with little or no machining.

Plastic: plastic materials are being increasingly used in modern foundry practice. Epoxy resins, which are bonded to reinforcing materials have high strength and proven to be very acceptable as pattern material. Some advantages include n, high compressive strength, good abrasion resistance to chemical attack, high bending Strength, and easy to release from the molding sand. Another advantage of using plastics is that complete patterns and cores boxes can inexpensively duplicated from an existing wood master.

Pattern-making is a very essential step in the conventional sand casing manufacturing process. This process requires an expert designer who works side by side with skillful workers. The cost of producing the patterns depends on the complexity of the part, the required quantity, and specified accuracy. Accordingly, the patterns can be of various design types such as the one-piece patterns, split patterns, and match-plate patterns.

1.2.4 Cores.

Core is a sand shape inserted into the mold to produce the internal features of the part such as holes or internal passages. Cores are placed in the cavity to form holes of the desired shapes. Core's print is the region added to the pattern, core, or mold that is used to locate and support the core within the mold [12].

Traditionally, Cores are made by ramming or blowing the raw sand mixture into a core box. Metal rods are sometimes used to strengthen the core [10]. If the core is made in parts, the parts are glued together after baking and are then briefly re-baked with circulating air at about 4500F (or 2300C) until the core reaches a nut-brown color[10] . Oxidation, condensation, polymerization, and drying develops the desired strength in the core according to its original composition. It is very important that the proper baking time and temperature be used for a given binder and core size. A properly baked core does not produce harmful gases, has adequate strength, and collapses at the right time after the casting is poured.

A core box is a device for molding a core. Core boxes may be made of wood or metal, depending on the number of cores to be produced. A metal box is generally made by casting it from a wood master core box. The added cost of making and finishing a metal box is justified when a wood box would not outlast the job. Metal core boxes are usually made of aluminum and have steel strips inserted in areas that are exposed to excessive wear. Rapid tooling processes may also be used to fabricate a master core box.

Cores are typically made out of sand so that they can be shaken out or blown of the casting rather than requiring the necessary geometry to slide out [13]. As a result, sand cores allow for the fabrication of many complex internal features. Each core is positioned in the mold before the molten metal is poured. In order to keep each core in place, the pattern has recesses called core prints where the core can be anchored in place. However, the core may still shift due to buoyancy in the molten metal. Further support is provided to the cores by chaplets. These are small metal pieces that are fastened between the core and the cavity surface. Chaplets must be made of a metal with a higher melting temperature than that of the metal being cast in order to maintain their structure. After solidification, the chaplets will have been cast inside the casting and the excess material of the chaplets that protrudes must be cut off.

There are various different ways to connect individual core parts to form an entire casting mold: Gluing, screw connections or threaded rods, or fastening with nails. Core locking refers to the connection of two or more cores. Referring to [14] the following methods generally used in cores assembly.

A- Gluing: gluing technology ranging from manual gluing stations to semi-automatic gluing appliances and fully automatic gluing applications.

B- Screwing and nailing: The screwing together of individual cores to make core packages can be carried out manually on stationary units or can be completely automated using robots and screw units. Nailing is another variant of this procedure [14].

C- The Core Lock system: connects multiple individual cores together so that they interlock. To achieve this, one or more locking cores are shot through the core package. This highly flexible enables different core packages to be assembled without glue or fasteners.

1.2.5 Sprues and Runners.

The molten material is poured in the pouring cup, which is part of the gating system that supplies the molten material to the mold cavity [15]. The vertical part of the gating system connected to the pouring cup is the “*sprue”*, and the horizontal portion is called the “*runners”* and finally to the multiple points where it is introduced to the mold cavity called the gates. Additionally, there are extensions to the gating system called vents that provide the path for the built up gases and the displaced air to vent to the atmosphere. The purpose of this is to feed the molten metal to the mold cavity as the molten metal solidifies and shrinks, and thereby prevents voids in the main casting.

1.2.6 Sand Casting Machines And Operations.

In a two-part mold, which is typical of sand castings, the upper half, including the top half of the pattern, flask, and core is the called *“cope* “and the lower half is called “*drag”* [16] . The parting line or the parting surface is the line or the surface that separates the cope and the drag. The drag is first filled partially with sand, and the core print, the cores, and the gating system are placed near the parting line. The cope is then assembled to the drag, and the sand is poured on the cope half, covering the pattern, core and the gating system. The sand is compacted by vibration and mechanical means. Next, the cope is removed from the drag, and the pattern is carefully removed. The object is to remove the pattern without breaking the mold cavity. This is can be achieved by designing a draft, a slight angular offset from the vertical-axes to the vertical surfaces of the pattern. This is usually a minimum of 1° or 1.5 mm (0.060 in), whichever is greater. The rougher the surface of the pattern, the more the draft to be provided. In addition to draft angle design, patterns usually coated with parting agent in order to facilitate their removal from the mold.

1.2.7 Quality Assurance Methods._

From the raw material to final casting products, quality engineers should monitor everything of sand casting. Referring to [17] the following are some general guidelines should be carefully applied:

1. Raw material quality control: Generally, quality in charge should check the chemistry property as new raw material coming. The raw material cover pig iron, strap steel, coal and sand.

2. Production quality control: the working instruction should be confirmed before production. Moreover, Continuous monitoring of production’s processors and parameters. Especially the first sample must be checked carefully.

3. Checking the chemistry again when the products are finished. Also the mechanical property should be measured, such as tensile strength, yield strength, elongation and hardness.

4. To find the inner defect, non-destructive method traditionally be used to check the products, such as ultrasonic testing, and radiography inspection. To find the surface crack, the magnetic particle testing and penetrating testing are also choices.

5. Records for about half years should be save for future use, or to trace every batch.

1.2.8 Design Allowances.

Allowances are usually made in the core, mold, and pattern in order to compensate the dimensional changes that will happen during any step of the sand casting process [18]. The various type of allowances can be summarized by; the contraction allowances, the draft allowances, the shakeout allowances, the finishing or machining allowances, and the distortion allowances.

The cavity is usually made oversized to allow for the metal contraction as it cools down to room temperature. By making the pattern oversized, the contraction can be approximately compensated. These are linear factors and apply in each direction [16]. These shrinkage allowance are only approximate, because the exact allowance is determined by the shape and size of the casting. In addition, different parts of the casting might require a different shrinkage allowance. Moreover, sand castings generally have a rough surface sometimes with surface impurities, and surface variations. A machining allowance is made for this type of defect. Furthermore, distortion can be occurred in thin casting (thin parts can be vary compared to the length of the part) [15] .To account for this distortion, the original pattern should be initially distorted in the opposite direction.

1.4 Sand Casting Major limitations

Pattern, cores and mold making, therefore, are the life blood of the foundry business. Without patterns, foundries cannot make castings. And without new patterns, foundries cannot produce new castings. But there are many constraints for these traditional techniques. Some of these constraints are the minimum wall thickness, sharp corners, undercut might need to be eliminated, draft angle, the level of the part complexity and its costs. For example, the internal geometry of the part might be too complex resulting in an overly expensive core. Or, the part might need to be given a greater draft angle to allow the pattern to pull away from the sand mold cleanly [19]. Because of considerations such as these, a customer usually has to cast a part that is at least slightly different from the design that this customer originally envisioned [19].

1.5 Cost Considerations

1.5.1 Production Cost.

The first relevant cost is the production cost which includes a variety of operations used to cast the part, including core-making, mold-making, pouring, and cleaning [13][20]. The cost of making the cores depends on the volume of the cores and the quantity used to cast the part. The cost of mold manufacturing is not greatly influenced by the complexity of the part’s geometry when automated equipment is being used. However, the inclusion of cores will slightly slow the process and, therefore, increase the cost. Lastly, the cost of pouring the metal and cleaning the final casting are both driven by the weight of the part. It will take longer to pour and to clean a larger and heavier casting.

1.5.2 Tooling Cost.

The second cost is the tooling cost which has two main components - the pattern and the core-boxes [13]. The pattern cost is primarily controlled by the size of the part as well as the part's complexity. Much like the pattern, the complexity and the size of the cores will affect the time needed to manufacture this part of the tooling, and hence the cost.

1.5.3 Cost Distribution.

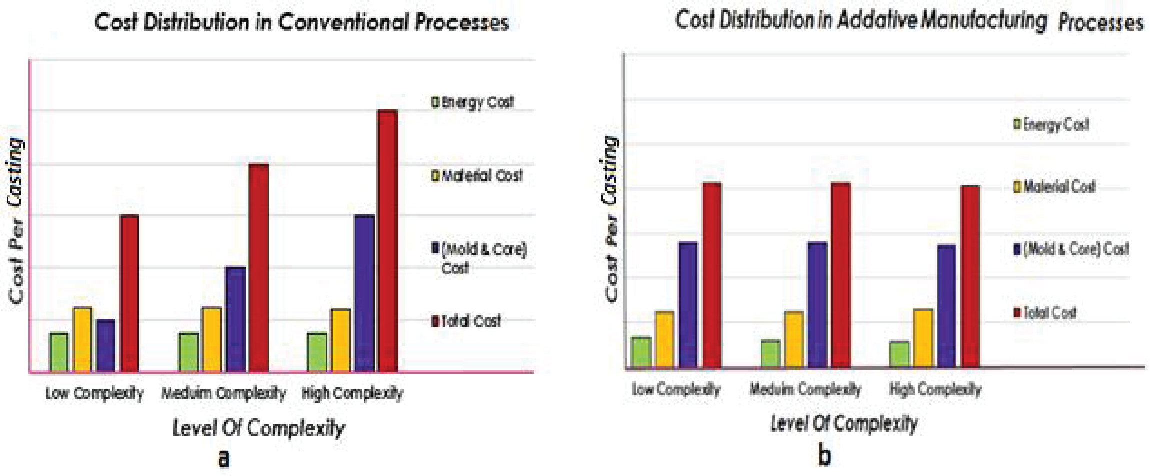


Figure 2: The cost distribution per casting[21]

The data in Figure 2 was collected from [21] that shows the cost distribution in both types of manufacturing with different levels of complexity along the X-Axis. Obviously, the mold-making cost and the core-making cost are the keys factors in determining the total cost. For Example, Figure 2/a shows the cost breakdown for sand casting using conventional manufacturing processes. Both the energy and material cost did not change when the complexity increased. But, the mold-making cost and core-making cost changed when the complexity was increased.

Traditionally, beside the tooling cost there are four type of cost involve in molds and cores manufacturing which are variable with the of level of the part complexity [27]:

- Labor and overhead cost: It can be up to 50%.
- Materials and consumables cost: 15 to 20%
- Energy cost. 10 to 15%.

- Defects and scraps cost. 0 to 15%.

Figure 3 modified from [22] ''The conventional sand casting processes map'' demonstrate the reasons why the energy and material did not change when the complexity increased while the mold-making and core-making cost increased with increasing complexity.

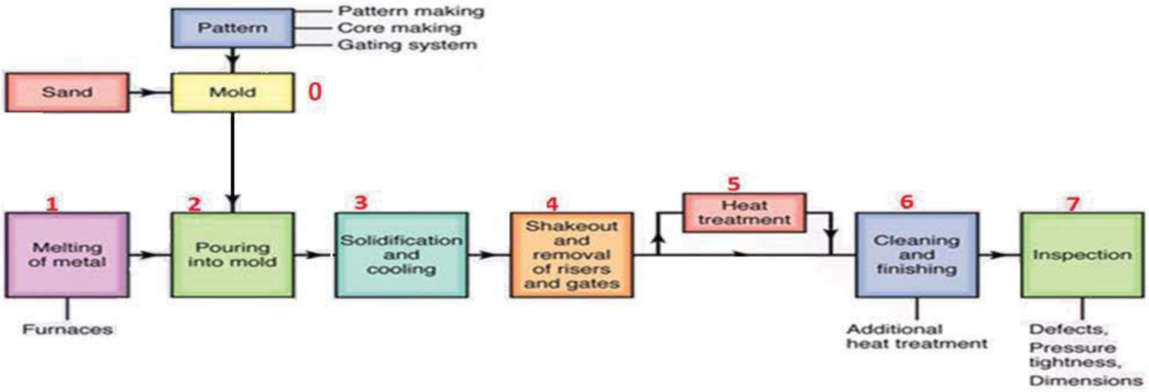


Figure 3:The conventional sand casting process map [22]

The process labeled from 0-7 in Figure 3 shows the typical steps in the conventional sand casting production line. The processes from ''1-7 '' are common steps in both conventional manufacturing and additive manufacturing. Moreover, by taking a closer look at these processes in Figure 3, it is noticeable that the cost in these process will not change with any level of complexity because most of steps '' 1-7'' are an automated process. Also, in steps ''1-7'' the driver cost is summarized by two categories; energy cost and the material cost. For example, In step 1, the same amount of energy and material will be used whether the conventional or additive manufacturing been used at any level of complexity. While the major difference in the cost stand point will be in process ‘’0 ‘’ where the technology and machines used in conventional manufacturing are completely different from those in additive manufacturing, hence the cost is also different.

1.5.4 Carrying and Holding Cost***:*** For a given production volume, The *Work In Progress* (WIP) is proportional to production lead time. The large size pattern and cores are at an operation or in the system, whether in process, in transit, or waiting, the greater the accrued cost of carrying those patterns and cores [23]. The cost advantage of smaller inventories goes beyond dollars. With small inventory, patterns and cores are easier to keep track of so inventory records can be kept more accurate. It easy to count items and see overstocks or pending shortages. Small inventories free up floor space and make it possible to store patterns and cores next to machines and operation where the needed. This eliminates the double handling , and double accounting that occur when patterns or cores are put into stockrooms and then later withdrawn and moved to places where needed. Moreover, patterns and cores are moved directly from the receiving area to operation on the shop floor [23].

1.6 Additive Manufacturing in Sand Casting

The recent innovation in additive manufacturing technology have changed the traditional view of the sand casting process. Today there are 3D printers available which can print a sand mold directly from CAD files in a matter of hours As a results, sand mold and cores can be produced without the need of patterns (Patternless Molds). Consequently, the cost considerations for the printed mold no longer depend on the tooling. In other words, additive manufacturing has a unique advantage of producing highly complex parts independent of the level of the part’s complexity consideration.

Voxeljet and Exone are the leaders in 3D sand printing. Both compete in the industrial segment, use a similar 3-D printing technology, and boast some of the largest print beds in the world [29]. Where these two companies differ boils down to the materials they can print with. Voxeljet only offers 3-D printing in two different types of plastic and one type of sand. ExOne, on the other hand, offers 3-D printing in two different types of sand, five types of metals with seven different finishes, and a soda lime glass that's available in three different finishes [29].

Printed sand molds are appropriate for any ordering quantity and for geometry that is not supportable using traditional sand casting (especially when undercut is required). The surface finish and mechanical properties are consistent with traditional sand castings [24]. Many studies have proved that additive manufacturing can be used to produce metal specimens with similar properties to those created using a conventional process. In sand casting, the mechanical and physical properties such as the surface finish, the hardness, the density, the level of porosity and the strength have important consequences on the final casting’s quality.

A schematic of the binder jetting process is provided in Figure 4 [24]. During binder jetting, a polymer binder is printed onto a bed of powder using a traditional inkjet print head to form one cross-sectional layer of the part After a layer of binder is printed, the powder bed lowers, and fresh powder is spread over the powder bed using a roller. Then, the next layer of the part is patterned onto the powder bed atop the previous layer. In this manner, the object is constructed layer by layer.

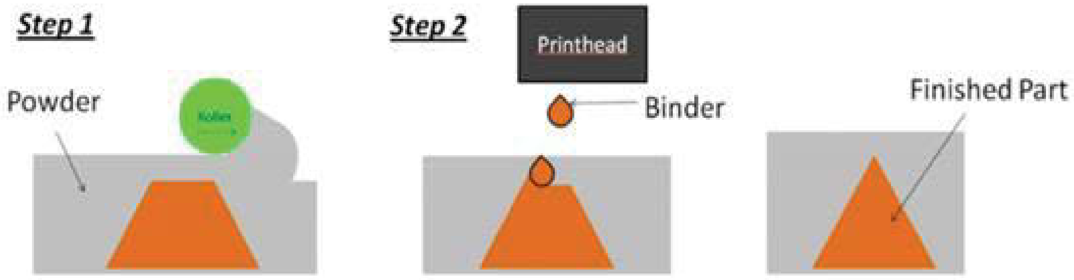


Figure 4: Schematic of binder setting process [24]

Available printers today are printing molds through the process of dispensing foundry-grade resin into range of 0.011 inch thick layers of specially engineered sand according to patterns derived from CAD data and building up layers to produce molds and cores that are dimensionally accurate and uniform. This additive manufacturing process also is fast, reduces lead times, and is flexible [24].

An important asset of the process is that the geometric freedoms offered by additive manufacturing can be leveraged to provide a means for metal casting of complex geometry that are not possible to fabricate via traditional casting means. Without a doubt, additive manufacturing technology will be able to customize and modify mold designs to improve casting performance, reduce weight, or add complexity to castings without the high increase in cost as in the conventional process.

1.7 Geometric Complexity in Previous Work

Shape complexity is been described as qualitative values like low, medium, high and very high. Geometric elements such as internal features, external features and wall thickness result in higher shape complexity [Joshi]. One of the remarkable work in measuring complexity as a quantitative value is done by *Durgesh* Joshi and *Bhallamudi Ravi* .

In Durgesh Joshi and Bhallamudi Ravi paper they have defined shape complexity factor using weighted criteria based on part geometry parameters such as number of cored features, volume and surface area of part, core volume, section thickness and draw distance. The coefficients of the criteria are computed by regression analysis using the actual shape complexity, which is defined as the additional cost of tooling manufacture compared to the machining of a simple shape like a cube, and computed using actual cost data from the tooling manufacturer. The regression was carried out using CAD models and cost data of 40 industrial castings of varying shapes [30].

Another paper named "*Casting cost estimation in an integrated product and process design environment"* has been done by "*R. G. Chougule"* and "*B. Ravi"* demonstrated the relation between the tooling cost and the complexity. Moreover, "*The feature based method uses geometric features"* (such as slot, hole and rib) of the product and tooling as the basis for cost estimation, this paper was done by "*Feng et al. 1996, Ou-Yang and Lin 1997."*

In general, very little work has been reported on cost estimation of sand casting that accounts for over 75% of casting production [21].

Chapter 2(Research Objectives)

2.1 Rationale for the Study

In 2014, America Makes awarded the Youngstown Business Incubator (YBI) a research project to develop a framework for the establishment of a 3D sand printing regional network for the U.S foundry industry [25]. The project title was “Accelerated Adoption Of Additive Manufacturing Technology In The American Foundry Industry.’’ In addition to the Youngstown Business Incubator (YBI) the project included Youngstown State University, the University of Northern Iowa, and the American Foundry Society, ExOne, Jenney Capital Market, and Humtown Patterns corporation. This network will assist foundries in additive manufacturing designs of molds and cores. Also the network will demonstrate the value proposition of additive manufacturing for small and medium size enterprise.

2.2 Hypothesis

As a part of this network, this research tries to help foundries to determine where is the area that the additive manufacturing become more cost effective than the conventional process. As is known, using additive manufacturing needs considerable initial investment which involves capital investment in printers and funding their annual maintenance service contracts. The expected cost of printed molds and cores will be fairly constant regardless of the increase of the complexity level of the part. On the other hand, in conventional molds and cores, the expected cost will be influenced by the tooling costs. Therefore, in conventional molds and cores, the cost will increase gradually or exponentially with increasing the complexity level of the part.

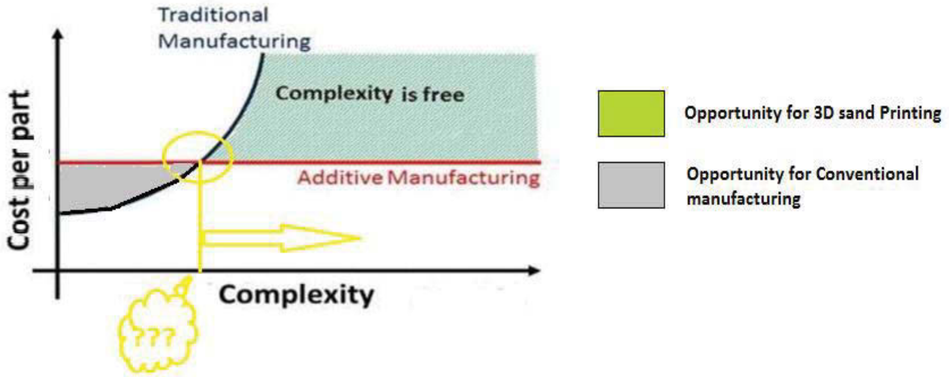


Figure 5: The expected trend of the cost vs complexity [15]

The green area shown in Figure 5 is a great opportunity for additive manufacturing to be economically more cost effective than conventional manufacturing at a certain level of complexity.

2.3 Analysis Goals

This study was performed with two main goals to reach. The first goal was to find a criteria to identify the complexity of any part, and to analyze the geometric attributes that is influence the complexity. The optimal criteria should contain some special characteristic. Some of the desired characteristic is the capability to depict the complexity as a quantitative values, and the ability to accommodate with the unlimited parts and design features. Additionally, the criteria should be practical and easy to use by individuals.

Based on the selected criteria, the second goal is to determine the turning point in Figure 5 where additive manufacturing starts to be more economically feasible to use instead of conventional manufacturing. To achieve the research objectives a careful selection of two study cases was required. The study cases should represent real life situations encountered by foundries. It also requires to work side by side with engineers, cost estimators, and experts in this field

Chapter 3. (Methodology)

To achieve the research objectives. The complexity should be described as a quantities value, and then the cost should be estimated at different complexity values. In order to reach these objectives, a criterion was adopted from [30] to measure the complexity for the two case studies. As a second step, the cost was estimated for these case studies.

3.1 The Role of Complexity

In conventional manufacturing, the part complexity has a direct relation with tooling cost [30]. A higher shape complexity however, leads to higher cost. Parts may require multiple operations, special tools, skillful labors, significant tool wear and lower productivity [34]. Quantitative evaluation and comparison of shape complexity of alternative part designs can therefore be very useful.

3.1.1 Description of the Shape Complexity Factor

In traditional manufacturing, understanding the shape complexity factor provide many cost advantages as discussed in [36]. According to [36] & [21] a high shape complexity affects the manufacturability and generate a higher cost in one or more of the following:

1-Overhead cost

2-Material cost

3-Procces cost

4- Tooling cost

Beside the part shape complexity the overhead cost, material cost and process cost generally depend on order quantity and the part weight [36]. While tooling cost primarily driven from the shape complexity [30]. As much as possible, a high attention should be consider to reduce the shape complexity during the product development. Especially when several designs are available. Therefore, choosing the less complex design leads to a great saving.

3.1.2 Tooling Cost.

Figure 6 Shows the influence of complexity on the tooling cost. The data in Figure 6 about tooling cost and complexity was published in [21]. Referring to the tooling cost analysis which explained by [30], the machining of certain tool is higher for part with greater complexity, and machining can be too expensive based on the parts' complexity. For example, machining a simple shape can be achieved and removed by single and inexpensive cutting tool which can be done at low operating cost. If the same volume is to be removed for a complex shape, it may require CNC machines which leads to higher operating cost [30].

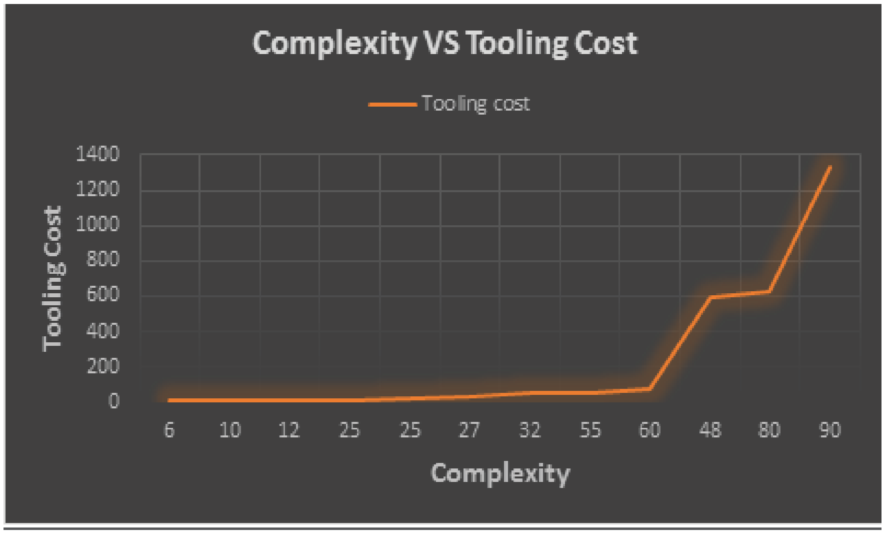


Figure 6:Tooling cost at different level of complexity [21]

In Figure 6, the criteria that used to measure the complexity in Figure 6 is slightly different than the one used in this thesis (see section 3.1.3). The criteria used in this thesis driven from six geometric attributes; the part volume, the surface area, the core volume, number of core, minimum and maximum wall thickness and draw distance. While the criteria used in Figure 6 count for two geometric attributes only; the surface area and the number of cores. However, Figure 6 emphasize on the fact that tooling cost increases with higher shape complexity, and sometime can be too expensive when complex features is required in the design.

The data in Figure 7 was collected from [36]. However, Figure 7 shows that the tooling cost has two main components; the pattern and the core-box. To achieve high accuracy in the final castings a high level of skills is required. High level of accuracy in pattern and core-boxes is important to produce castings which are close to the net shape. The pattern and core-box cost primarily controlled by the size of the part , material for making pattern, required accuracy and part complexity . Therefore, the shape complexity will affect the time to manufacture this part of the tooling and hence the cost [36].

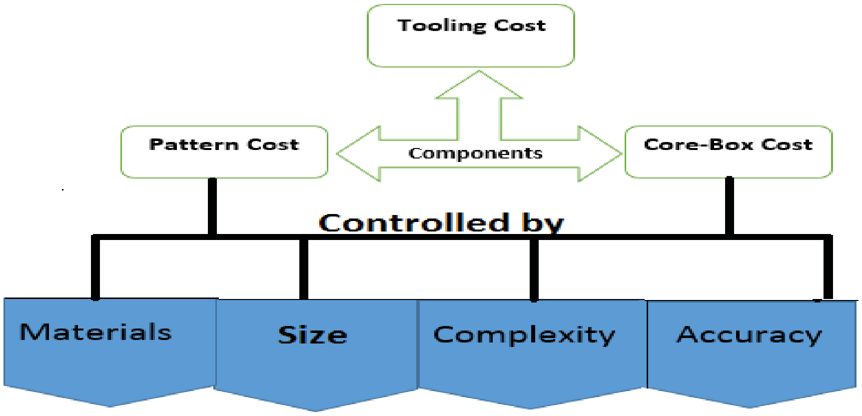


Figure 7: Tooling cost components

According [21] the cost of tooling (pattern, core box, mold, etc.) in the foundries and pattern shops usually amortize over the number of castings produced, and it is a significant proportion of the casting cost, especially when order size is low. In this thesis tooling cost was treated as a fixed initial cost.

3.1.3 Criteria for Shape Complexity

The criteria for measuring the shape complexity used in this thesis was adopted form [30]. This section will define and analyze the shape complexity factories referring [30] ‘’Quantifying the shape complexity of cast parts by Durgesh Joshi and Bhallamudi Ravi The geometric features of part design, which influence the design of tooling, determine the complexity of tooling and therefore its cost. A cast part may require multiple pieces of tooling (separated by the parting surface). The outer shape of the part is obtained by the sand mold prepared using cope and drag patterns placed in a flask. The inner features (holes and undercuts) are obtained by sand cores prepared in core boxes.

Designers and tool makers observed that the tool manufacturing cost depends on the number of cores, volume and surface area of part, core volume, draw distance and variation in section thickness, all of which can be determined from the part CAD model. Accordingly, we will use the following six geometry-driven criteria for shape complexity evaluation. The criteria equations are set up to return a value between 0 and 1; higher values indicate a greater contribution to complexity [30]. The following are the six different attributes for the criteria as they explained in [30]:

- **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

$$\boldsymbol{C_{PR} = 1 - \frac{V_P}{V_b}} \tag{1}$$

Where, V_P is the volume of part and V_b is the volume of its bounding box. (See Figure 8 for more details about $\boldsymbol{V_P}$ & $\boldsymbol{V_b}$**)**

- **Area ratio (C_{A_R}):** 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. More features in tooling geometry increase the surface area of tooling. Higher this surface area more will be the cost of machining and hence higher the complexity. This criterion is defined as:

$$\boldsymbol{C_{AR} = 1 - \frac{A_S}{A_P}} \qquad (2)$$

Where $\boldsymbol{A_S}$ is the surface area of an imaginary sphere with volume equal to that of the part, given by. $\boldsymbol{A_S = (4\,\pi)^{1/3}(3\,V_P)^{2/3}}$ **.** $\boldsymbol{A_P}$ Here and $\boldsymbol{V_P}$ are the surface area and volume of part respectively. (See Figure 8 for more details about $\boldsymbol{A_S}$ & $\boldsymbol{A_P}$**).**

- **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;

$$\boldsymbol{C_{NC} = 1 - \frac{1}{\sqrt{1+N_C}}} \qquad (3)$$

Where **N**C is the number of cored features.

- **Cores 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.

$$C_{CR} = 1 - \frac{\sum V_{C_i}}{V_b} \qquad (4)$$

Where V_{C_i} is the volume of the cores and V_b is the volume of the bounding box (see Figure 8)

- **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 :

$$C_{TR} = 1 - \frac{T_{min}}{T_{Max}} \qquad (5)$$

Where $Tmin$ and $T\ max$ are the minimum and maximum thickness of the part, respectively.

- **Depth ratio (CDR):** 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.

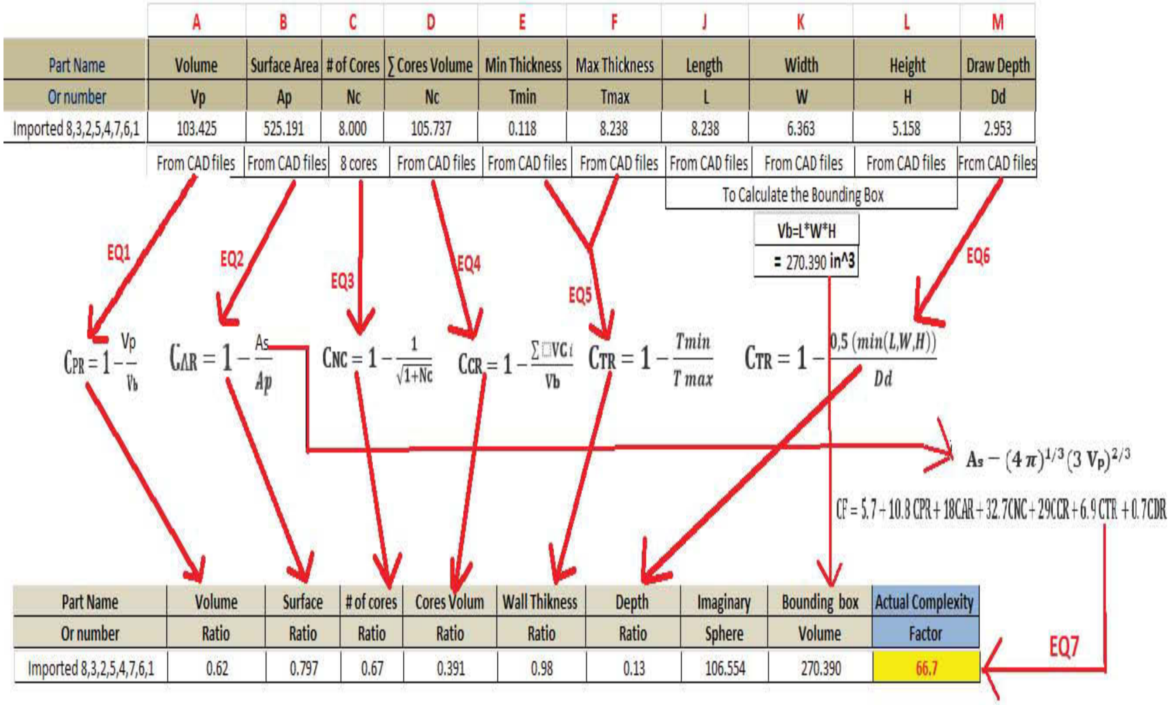
$$C_{DR} = 1 - \frac{0{,}5\ (min(L,W,H))}{D_d} \qquad (6)$$

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

The previous equations are quantitative evaluation of shape complexity of cast parts using geometry driven criteria based on number of cores, part volume ratio, core volume ratio, area ratio, thickness ratio and depth ratio. In [30] Regression analysis was used for 40 industrial parts of varying to determining the coefficients of the shape complexity equation shown below in (7). In [30] the relation has been validated by parts not covered in regression analysis, proving its usefulness for estimation of shape complexity of new parts.

$$CF_{Estimated} = 5.7 + 10.8\ C_{PR} + 18\ C_{AR} + 32.7\ C_{NC} + 29C_{CR} + 6.9\ C_{TR} + 0.7\ C_{DR} \qquad \textbf{(7)}$$

In order to understand how the equation from 1-7 works, the following example will calculate the complexity factor for the given part in Figure 10 (see Chapter 4). This part consist of eight different cores and Figure 8 below shows the details calculation using equations 1-7. The data labeled from (A-M) in Figure 8 was extracted directly from a CAD file.



	A	B	C	D	E	F	J	K	L	M
Part Name	Volume	Surface Area	# of Cores	∑ Cores Volume	Min Thickness	Max Thickness	Length	Width	Height	Draw Depth
Or number	Vp	Ap	Nc	Nc	Tmin	Tmax	L	W	H	Dd
Imported 8,3,2,5,4,7,6,1	103.425	525.191	8.000	105.737	0.118	8.238	8.238	6.363	5.158	2.953
	From CAD files	From CAD files	8 cores	From CAD files	From CAD files	From CAD files	From CAD files	From CAD files	From CAD files	From CAD files

To Calculate the Bounding Box

Vb=L*W*H

= 270.390 in^3

$$C_{PR} = 1 - \frac{V_p}{V_b} \quad C_{AR} = 1 - \frac{A_s}{A_p} \quad C_{NC} = 1 - \frac{1}{\sqrt{1+N_c}} \quad C_{CR} = 1 - \frac{\sum VC_i}{V_b} \quad C_{TR} = 1 - \frac{T_{min}}{T_{max}} \quad C_{TR} = 1 - \frac{0,5\,(min(L,W,H))}{D_d}$$

$$A_s - (4\pi)^{1/3}(3V_p)^{2/3}$$

$$CF = 5.7 - 10.8\,CPR + 18CAR - 32.7CNC + 29CCR + 6.9\,CTR + 0.7CDR$$

Part Name	Volume	Surface	# of cores	Cores Volum	Wall Thikness	Depth	Imaginary	Bounding box	Actual Complexity
Or number	Ratio	Ratio	Ratio	Ratio	Ratio	Ratio	Sphere	Volume	Factor
Imported 8,3,2,5,4,7,6,1	0.62	0.797	0.67	0.391	0.98	0.13	106.554	270.390	66.7

Figure 8: Complexity factor calculation for the part in Figure 10 (see Chapter 4)

3.1.4 Selecting case studies and costing criteria

After evaluating the complexity as a quantitative value which has explained in section 3.1.3, selecting a real life case study is the second step in thesis's methodology. Humtown Products is one of the active members in the regional 3D sand printing network in the U.S foundry industry. Humtown Products was able to share two case studies in order to implement and test the thesis hypothesis. Humtown Products also provided the required inputs and prices per the researchers' requests. This research is looking and studying the cost of making the molds and the cores only. This research did not count for the cost of the metal, cost of pouring, cost cooling and solidification and the cost of inspection. This research as explained in Chapter 1 assumed that these steps can be automated and can be fairly constant with different level of complexity.

Both case studies are conventionally contained multiple cores. The cores produced, inspected and assembled at Humtown Products. If the same molds and cores made via 3D sand printing, the mold and cores will be printed without the need of the patterns or core boxes. Additionally, in 3D sand printing there is no need for core assembly because the cores will be printed as one unit. This is an example of part consolidation.

The costing procedure was including the following steps;

- Measured the part’s complexity based in the criteria from section 3.1.3.
- Inserted one more core each time; then measuring the complexity and estimated both types of costs; the conventional cost and 3D sand cost as Figure 9 shows.

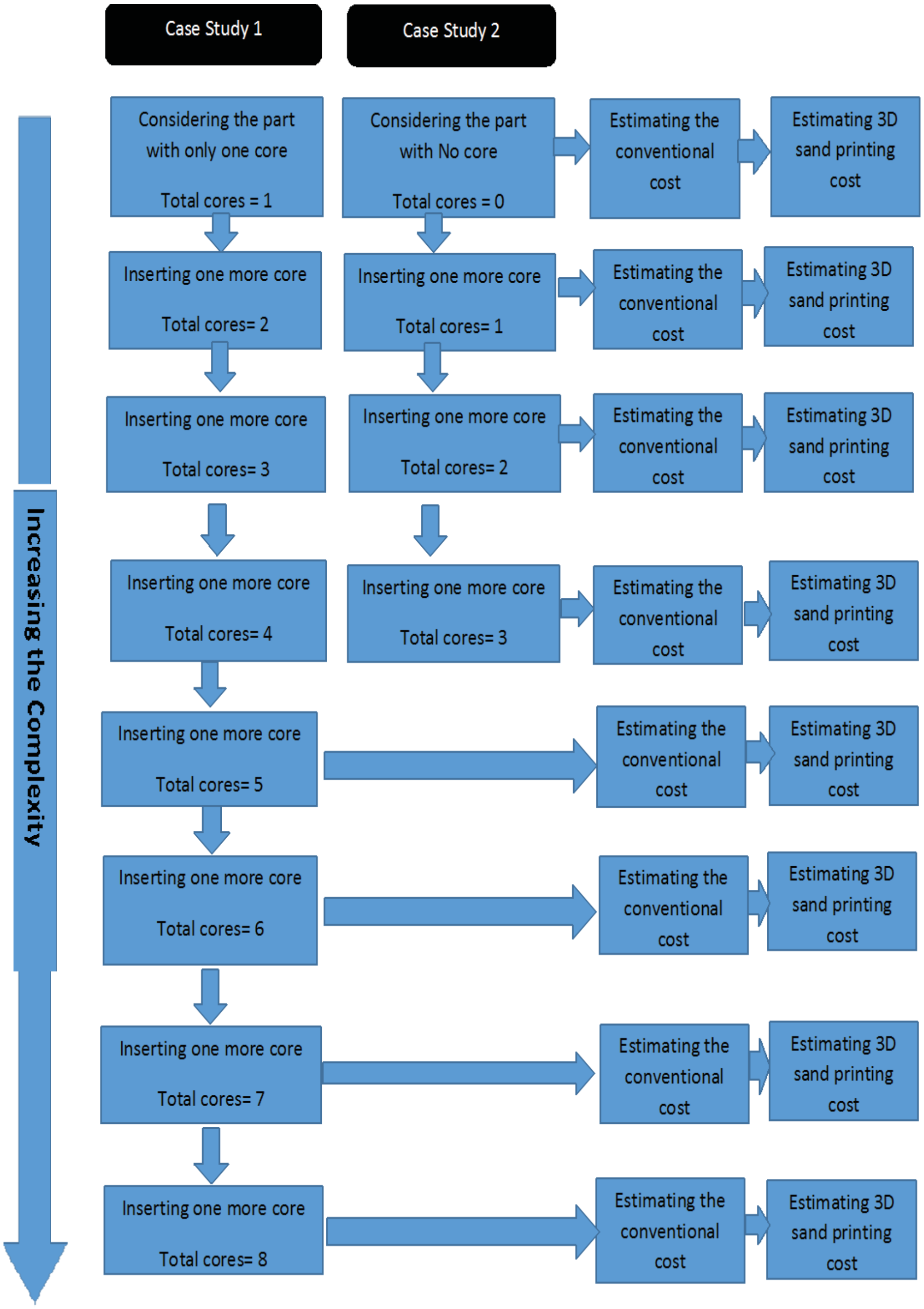


Figure 9: Shows the procedure of increasing the complexity and estimating the cost for case study 1 and 2.

- For all estimated cost, the conventional cost and 3D sand cost was plotted against the measured complexity factors.
- Determined at what points or range of complexity both curves intersected?
- Analyzed the trends for the conventional cost and 3D sand curves cost. And apply some sensitivity analysis.
- Obtaining at what level of complexity the 3D sand printing become more cost effective to use than the conventional manufacturing.

3.1.5 Estimating Conventional Cost & 3D Sand Cost

Estimating the conventional and 3D sand cost was provided by Humtown Product's estimation department. The typical methodology used in 3D sand cost estimation is by measuring the volume of the bounding box for a given mold or core [32]. The volume for the bounding box of the mold or the core determine its cost regardless to the level of the complexity. In other words, the cost of printing a certain bounding box is constant whether printing simple or complex molds or cores.

On the other hand, the methodology used for conventional molds core cost estimation depended on some of the following parameters [32];

- Complexity of the mold and cores.
- Number of the cores.
- Volume of the molds and cores.
- Type of the sand used.

These factors determine the labors and overheads, material and consumables, energy used, and the percentage of defects. Hence determine the total conventional cost. Noting that the tooling cost is assumed to be amortized over volume or to be considered as initial fixed cost [27].

Chapter 4 (The Results)

The results of this study include several types of data analysis. This Chapter is divided into four major sections: (1) Description of the selected case studies. (2) The results of increasing number of cores on the complexity factors and its calculation (3) The impact of increasing part's complexity on the cost of both type of manufacturing; conventional and 3D sand printing (4) Obtaining the level of complexity when 3D sand printing becomes more cost effective. A detailed explanation of the data analysis performed in order to obtain these results is presented in each section. However, all the analysis on the following section considering the molds and cores manufacturing cost only, this research as explained earlier was not considering the cost of the metal, furnaces, finishing, packaging & delivery, etc.

4.1 Description of the Case Studies

4.1.1 Case Study 1:

This case study based on an actual casting with fabricated molds and cores fabricated by Humtown Products. The challenge was which type of manufacturing will be more cost effective. This research calculated the complexity factor of the casting to perform a comparative study between the two types of manufacturing [33]:

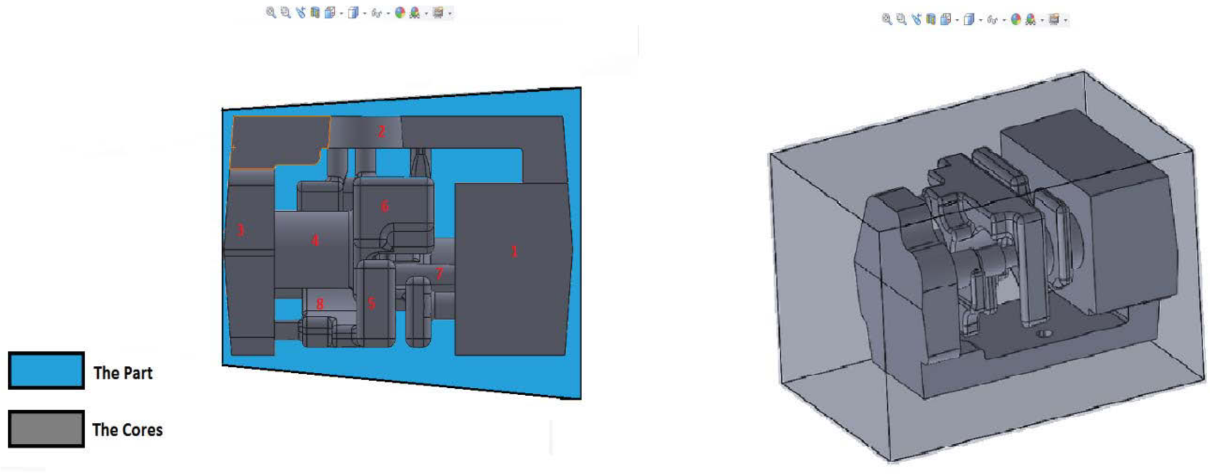
A- Conventional mold and core manufacturing:

- Identical copy of the part was made (the pattern), in order to produce the mold.
- Eight different cores was made and assembled to produce one unit core.
- This assembled core then installed into the mold, and shipped to the customer.

B- 3D sand printing:

- A printed mold was produce directly from CAD files without the need for the pattern.
- The printed cores were produced directly from CAD files (the eight cores here were produced as a one unit)
- The core installed into the mold and shipped to the customer.

Figure 10 shows a modified design for the casting and the eight cores. The modified design achieves two purposes. First, this allows Humtown Products to keep customer data private. Second, this design assist in a logical and useful analysis that will be described in this section.



a) Side view

b) Angular view

Figure 10: Case study 1

Referring to Figure 10/a the light blue color is the gap inside the mold which becomes the actual casting after pouring the metal. In contrast, the gray color represents the cores which are the solid parts inside the mold preventing molten metal from filling holes and hollow shapes inside the actual part.

As mentioned earlier, the second goal for the new design was to measure the cost of producing the molds and the cores at different levels of complexity. Figure 11 shows the steps was performed to measure the complexity at multiple levels. The analysis started by inserting only one core, then added a single core, then repeated this process until all eight cores are added. This process permits a comparative cost study at eight different levels of complexity.

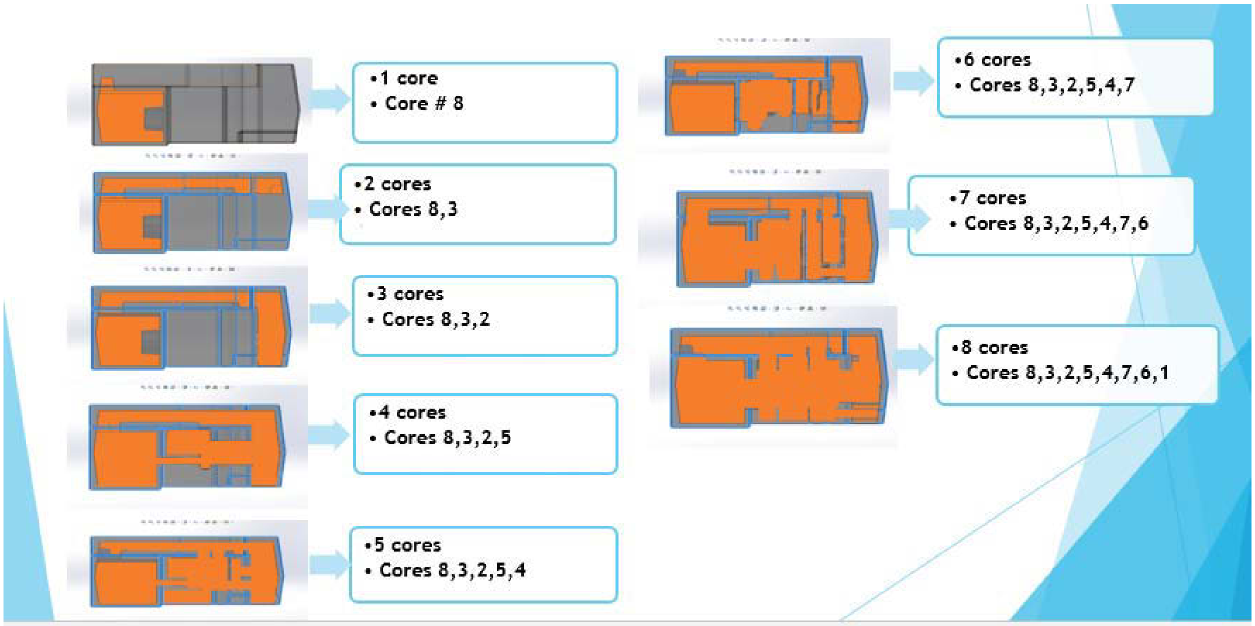


Figure 11:The sequence of inserting more cores (1 Core is the lowest complexity, 8 cores is the highest complexity)

4.1.2 Case Study 2: This is another real situation when Humtown Products had to choose the most cost effective manufacturing approach [33]. In this case study, the design is modified in order to study the impact of increasing the complexity of the cores on the manufacturing cost for both approaches; conventional and 3D sand printing.

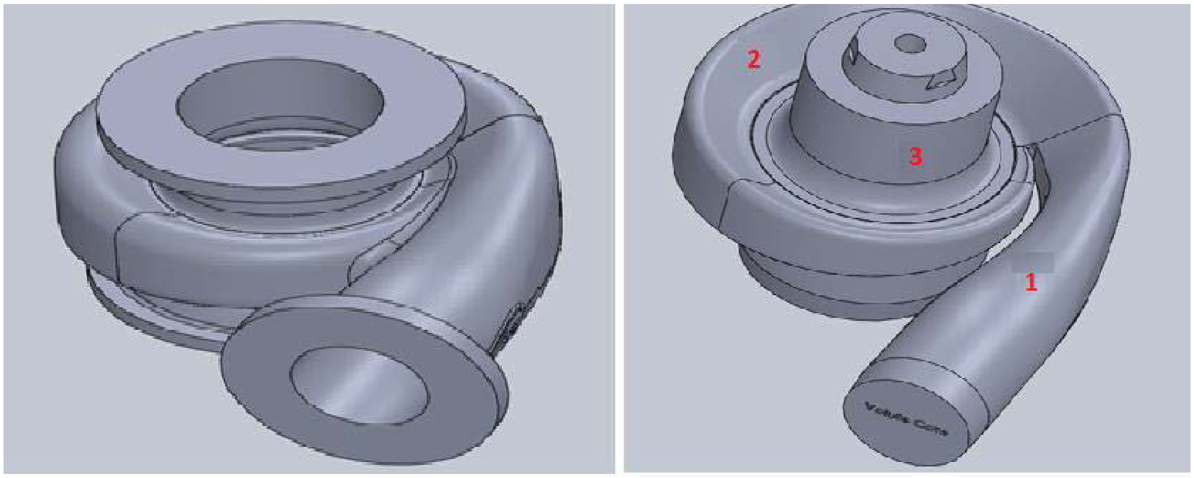
A- Conventional Manufacturing:

- Identical copy of the part was made (the pattern), in order to produce the mold.
- 3 cores was made and assembled to produce one unit core.
- The assembled core then installed into the mold, and shipped to the customer.

B- 3D sand printing:

- Both the molds and the cores were printed directly from the CAD files. The 3 cores in this approach was printed as one unit.
- The molds and the cores was assembled and sent to the costumer.

Figure 12/a Shows the final part, Figure 12/b shows the cores which was needed to produce the final part shown in Figure 12/a. In conventional manufacturing, the cores was made from 3 different cores, and then assembled together as Figure 12/b demonstrates.



a) The final cast

b) The cores (Conventionally 3 cores attached together)

Figure 12: Case study 2

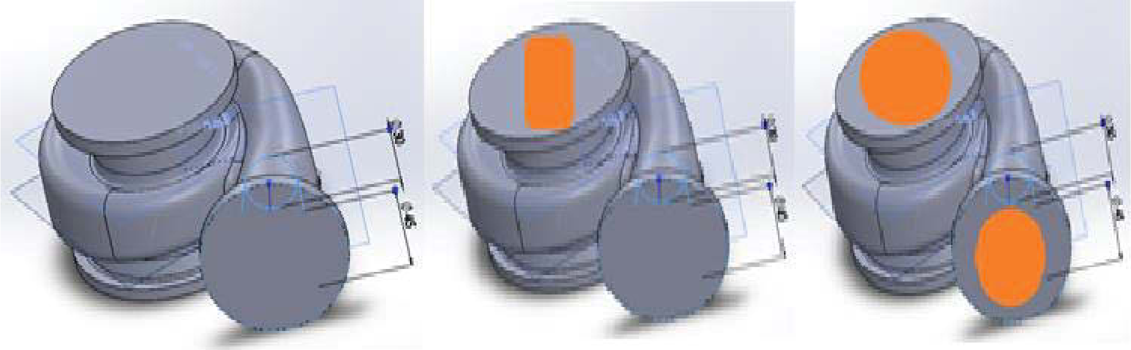
The next step was to modify the actual design. The purpose of these modifications is to study the molds and cores manufacturing cost in both conventional manufacturing & 3D sand printing at different levels of complexity. The following is a summary of those modifications:

A) Consider the part as solid unit without having any core as shown in Figure 13/a. This case expected to be the lowest level of complexity

B) A simple core which is cube shaped was inserted as shown in Figure 13/b. This case indicate higher level of complexity than the one from the previous case that shown Figure 13/a.

C) Two more complex cores which are cylindrical in shape were inserted as shown Figure 13/c. This case is expected to be more complex from the previous case that shown in Figure 13/b.

D) The original case which consist of 3 cores as shown in Figure 12. This case expected to be the most complex design.



a) No core inserted

b) 1 cubic core inserted

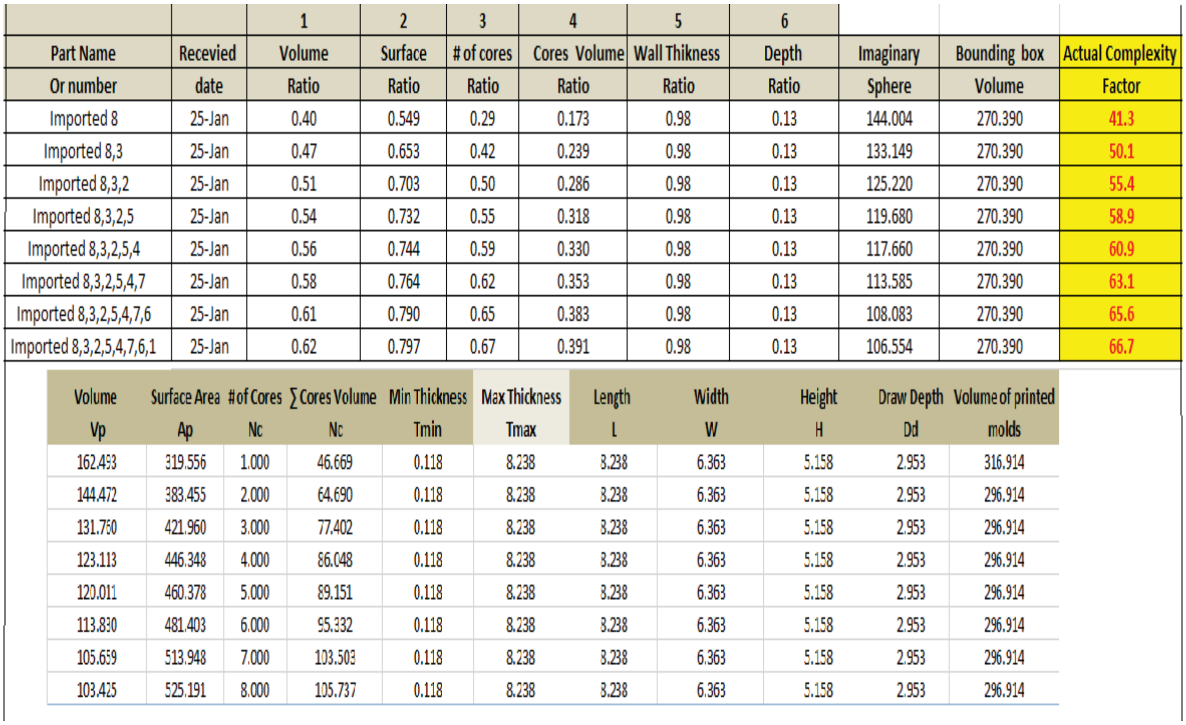
C) 2 cylindrical cores insetred

Figure 13:The modification in the design to reduce the original complexity

4.2 Results of Increasing the Number of the Cores on the Complexity Factors

4.2.1: Case Study 1: Measuring The complexity Factor***:*** As shown in section 4.1.1 up to eight cores were added, this section shows the calculation of the complexity factor for each step in case study 1. Table 1 shows the geometric data was used to measure the complexity factors based on complexity model which was explained in Chapter 3.

Table 1: shows the geomtric data needed to measure the complexity factors.



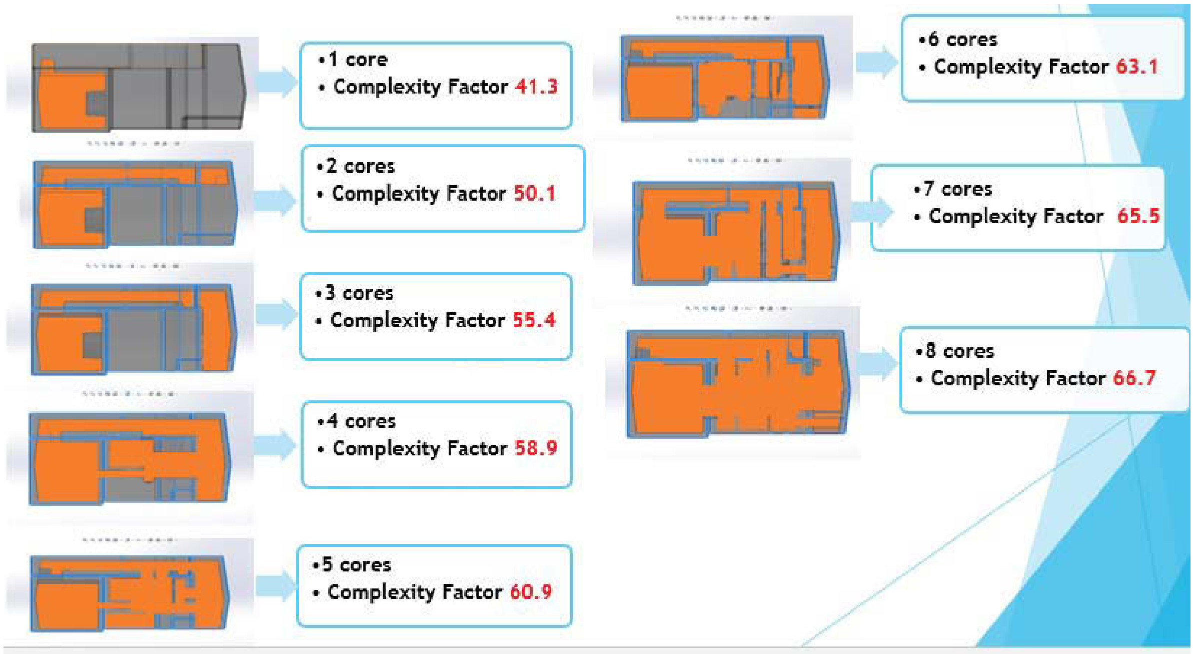
		1	2	3	4	5	6			
Part Name Or number	Recevied date	Volume Ratio	Surface Ratio	# of cores Ratio	Cores Volume Ratio	Wall Thikness Ratio	Depth Ratio	Imaginary Sphere	Bounding box Volume	Actual Complexity Factor
Imported 8	25-Jan	0.40	0.549	0.29	0.173	0.98	0.13	144.004	270.390	41.3
Imported 8,3	25-Jan	0.47	0.653	0.42	0.239	0.98	0.13	133.149	270.390	50.1
Imported 8,3,2	25-Jan	0.51	0.703	0.50	0.286	0.98	0.13	125.220	270.390	55.4
Imported 8,3,2,5	25-Jan	0.54	0.732	0.55	0.318	0.98	0.13	119.680	270.390	58.9
Imported 8,3,2,5,4	25-Jan	0.56	0.744	0.59	0.330	0.98	0.13	117.660	270.390	60.9
Imported 8,3,2,5,4,7	25-Jan	0.58	0.764	0.62	0.353	0.98	0.13	113.585	270.390	63.1
Imported 8,3,2,5,4,7,6	25-Jan	0.61	0.790	0.65	0.383	0.98	0.13	108.083	270.390	65.6
Imported 8,3,2,5,4,7,6,1	25-Jan	0.62	0.797	0.67	0.391	0.98	0.13	106.554	270.390	66.7

Volume Vp	Surface Area Ap	#of Cores Nc	∑Cores Volume Nc	Min Thickness Tmin	Max Thickness Tmax	Length L	Width W	Height H	Draw Depth Dd	Volume of printed molds
162.493	319.556	1.000	46.669	0.118	8.238	3.238	6.363	5.158	2.953	316.914
144.472	383.455	2.000	64.690	0.118	8.238	3.238	6.363	5.158	2.953	296.914
131.760	421.960	3.000	77.402	0.118	8.238	3.238	6.363	5.158	2.953	296.914
123.113	446.348	4.000	86.048	0.118	8.238	3.238	6.363	5.158	2.953	296.914
120.011	460.378	5.000	89.151	0.118	8.238	3.238	6.363	5.158	2.953	296.914
113.830	481.403	6.000	95.332	0.118	8.238	3.238	6.363	5.158	2.953	296.914
105.659	513.948	7.000	103.503	0.118	8.238	3.238	6.363	5.158	2.953	296.914
103.425	525.191	8.000	105.737	0.118	8.238	3.238	6.363	5.158	2.953	296.914

The following data was extracted from CAD file of the part for each case;

- The volume of the part
- Surface area of the part
- The number of the cores
- The volume of the assembled cores
- Minimum and maximum thickness of the part
- Draw distance

These geometric attributes were explained in depth in Chapter 3. The complexity factors were calculated based on Equation 7 from Chapter 3. Figure 14 shows the final complexity value per inserted core.



- 1 core
- Complexity Factor 41.3

- 2 cores
- Complexity Factor 50.1

- 3 cores
- Complexity Factor 55.4

- 4 cores
- Complexity Factor 58.9

- 5 cores
- Complexity Factor 60.9

- 6 cores
- Complexity Factor 63.1

- 7 cores
- Complexity Factor 65.5

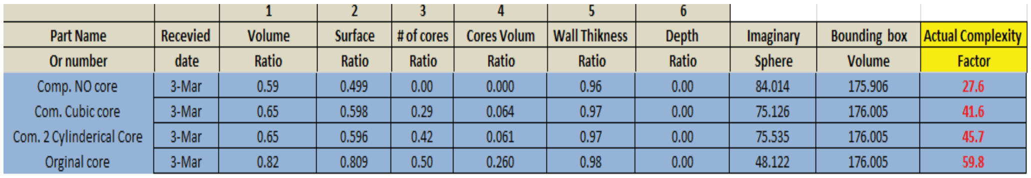
- 8 cores
- Complexity Factor 66.7

Figure 14: Calculated complexity factors based on equation #7 (see Chapter 3)

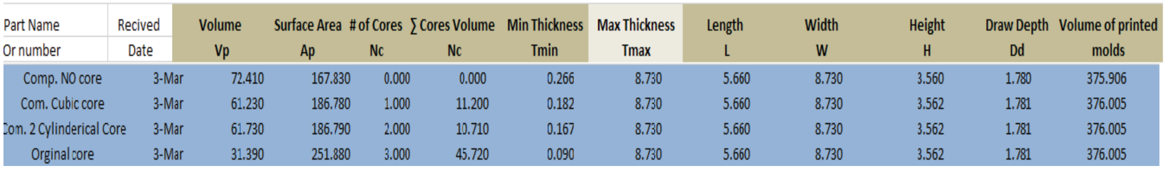
4.2.2: Case Study 2: Measuring the Complexity Factor

In case study 2, the complexity was reduced by inserting 2 cylindrical cores, inserting 1 cubic core, and by eliminating the core. Table 2 shows the data used to calculate the complexity factories for each step of reducing the complexity.

Table 2: Shows the geometric data needed to calculate complexity factors for case study 2.



		1	2	3	4	5	6			
Part Name Or number	Recevied date	Volume Ratio	Surface Ratio	# of cores Ratio	Cores Volum Ratio	Wall Thikness Ratio	Depth Ratio	Imaginary Sphere	Bounding box Volume	Actual Complexity Factor
Comp. NO core	3-Mar	0.59	0.499	0.00	0.000	0.96	0.00	84.014	175.906	27.6
Com. Cubic core	3-Mar	0.65	0.598	0.29	0.064	0.97	0.00	75.126	176.005	41.6
Com. 2 Cylinderical Core	3-Mar	0.65	0.596	0.42	0.061	0.97	0.00	75.535	176.005	45.7
Orginal core	3-Mar	0.82	0.809	0.50	0.260	0.98	0.00	48.122	176.005	59.8



Part Name Or number	Recived Date	Volume Vp	Surface Area Ap	# of Cores Nc	∑ Cores Volume Nc	Min Thickness Tmin	Max Thickness Tmax	Length L	Width W	Height H	Draw Depth Dd	Volume of printed molds
Comp. NO core	3-Mar	72.410	167.830	0.000	0.000	0.266	8.730	5.660	8.730	3.560	1.780	375.906
Com. Cubic core	3-Mar	61.230	186.780	1.000	11.200	0.182	8.730	5.660	8.730	3.562	1.781	376.005
Com. 2 Cylinderical Core	3-Mar	61.730	186.790	2.000	10.710	0.167	8.730	5.660	8.730	3.562	1.781	376.005
Orginal core	3-Mar	31.390	251.880	3.000	45.720	0.090	8.730	5.660	8.730	3.562	1.781	376.005

Figure 15 shows the calculated complexity factors for case study 2. As expected reducing number of cores and its geometry leads to a lower complexity factors.

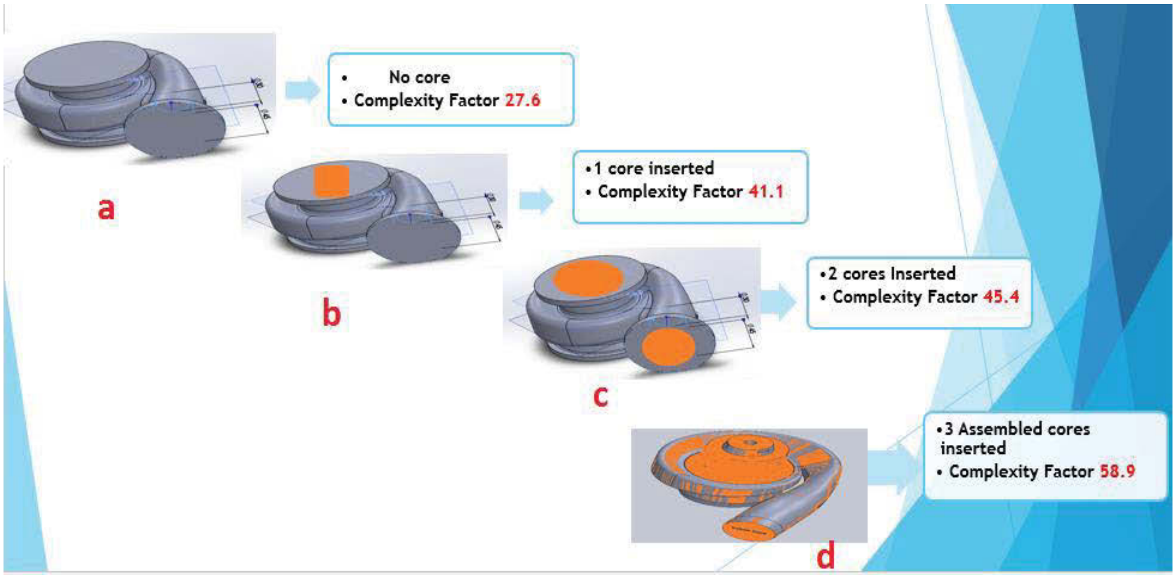


Figure 15: Shows the calculated complexity factors for case study 2 based on equation # 7(see Chapter 3)

Figure 15/a shows the lowest complexity score which is 27.6 % when no cores was involved. The complexity score was raised to 58.4 % when three cores were inserted as shown in Figure 15/d.

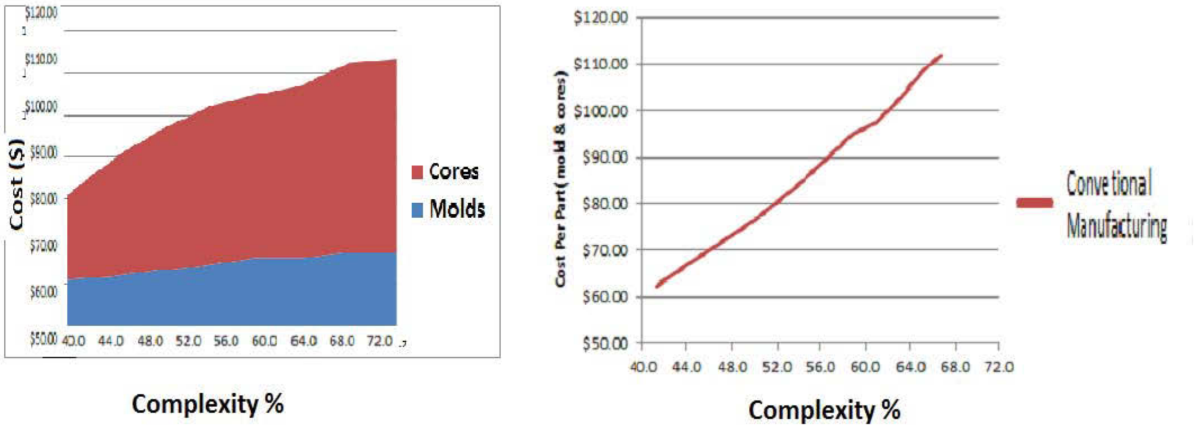
4.3 The impact of increasing part's complexity on the cost of both types of manufacturing; conventional and 3D sand printing.

This section focus on the correlation between the cost and complexity. However, in Chapter 1 and 2 a deep explanation has showed the expected relation between the complexity and the cost. Moreover, this section will show the analysis results and the differences in the estimated cost in both types of manufacturing; the conventional & 3D sand printing.

4.3.1 Case study 1: Cost vs complexity.

Figure 16/b shows the cost at different levels of complexity when conventional manufacturing was used. An important observation about Figure 15 is the cost started at lower values and increased gradually with increasing complexity. Additionally, Figure 16/a cost of the molds and the cost of cores individually. Figure 16/b shows that the cost of the cores increase greatly with higher levels of complexity.

Part Name Or number	Cost of conventional Molds	Cost of convetional cores	Conventional Set	Actual Complexity Factor
Imported 8	22.184	$40.15	$62	41.3
Imported 8,3	23.753	$55.65	$76	50.1
Imported 8,3,2	26.722	$66.58	$87	55.4
Imported 8,3,2,5	29.691	$74.02	$95	58.9
Imported 8,3,2,5,4	32.661	$76.69	$97	60.9
Imported 8,3,2,5,4,7	32.661	$82.01	$103	63.1
Imported 8,3,2,5,4,7,6	35.630	$89.04	$110	65.6
Imported 8,3,2,5,4,7,6,1	35.630	$90.96	$112	66.7



a

b

Figure 16: Cost vs complexity when the conventional manufacturing was used.

Figure 17/b shows the cost at different level of complexity when 3D sand printing was used. The major observation about Figure 17 is that the cost started at higher value than the one from conventional manufacturing, and stayed fairly steady with increasing complexity. Figure 17/b shows that the cost of molds is constant among all different levels of complexity because the 3d printing cost depend on the printed volume, and the printed volume for mold in case study 1 was constant.

Part Name	Volume of printed	Cost of printed	Volume of printed	Cost of Printed	Printed	Actual Complexity
Or number	Molds	Molds	Cores (bounding box Volume)	Cores	Set	Factor (%)
Imported 8	296.914	50.475	61.257	10.41366208	$70.63	41.3
Imported 8,3	296.914	50.475	186.782	31.75298084	$82.23	50.1
Imported 8,3,2	296.914	50.475	202.464	34.41893985	$84.89	55.4
Imported 8,3,2,5	296.914	50.475	202.464	34.41893985	$84.89	58.9
Imported 8,3,2,5,4	296.914	50.475	202.464	34.41893985	$84.89	60.9
Imported 8,3,2,5,4,7	296.914	50.475	202.464	34.41893985	$84.89	63.1
Imported 8,3,2,5,4,7,6	296.914	50.475	202.464	34.41893985	$84.89	65.6
Imported 8,3,2,5,4,7,6,1	296.914	50.475	202.464	34.41893985	$84.89	66.7

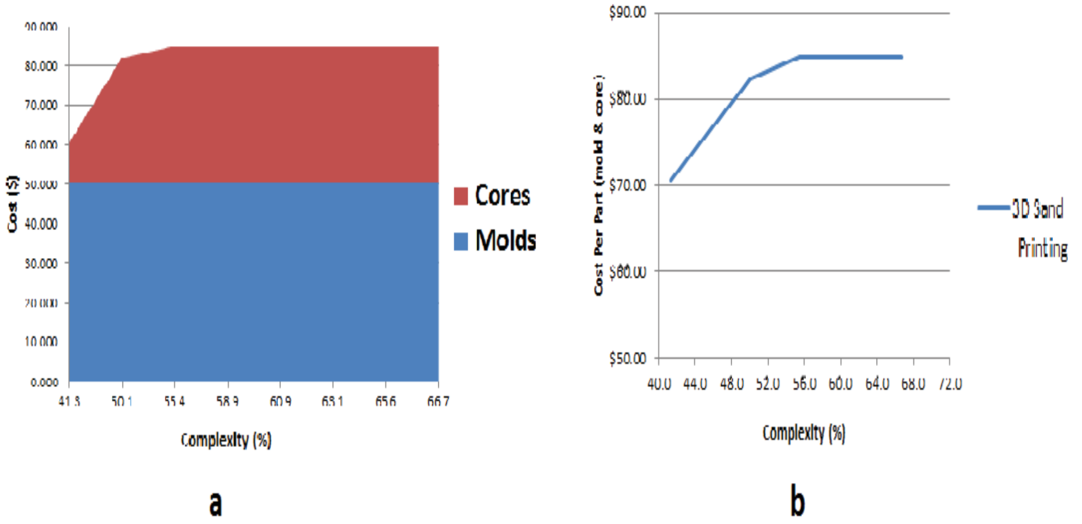


Figure 17: Cost vs complexity when 3D sand printing was used

4.3.2 Case study 2: Cost vs complexity.

In addition to case study 1, a similar analysis was applied on case study 2 in order to have better understanding of the relationship between the cost and complexity in molds and cores manufacturing. Figure 18 and 19 are the cost vs complexity charts for case study 2.

Figure 18/b and 19/b show the same trend observed in case study 1, in conventional manufacturing the cost started at low values with low complexity level. The cost increased with increasing complexity. On the other hand, in 3D sand printing the cost started at higher value than the conventional one, but with increasing complexity the rate of increase in was less than the cost for conventional mold and core fabrication.

Moreover, in Figure 18/a the molds and the cores cost increased with increasing complexity. But, the cores cost incresaed in higer rate as we obserivered in case sudy 1. While, the molds cost shown in Figure 19/a has constant cost because the printed vloume was constant at all levels of complexity .

Part Name Or number	Cost of conventional Molds	Cost of convetional cores	Conventional Set	Actual Complexity Factor
Comp. NO core	26.313	$0.00	$26	27.6
Com. Cubic core	26.320	$10.00	$36	41.6
Com. Cylinderical Core	26.320	$20.00	$46	45.7
Orginal core	61.000	62.000	$123	59.8

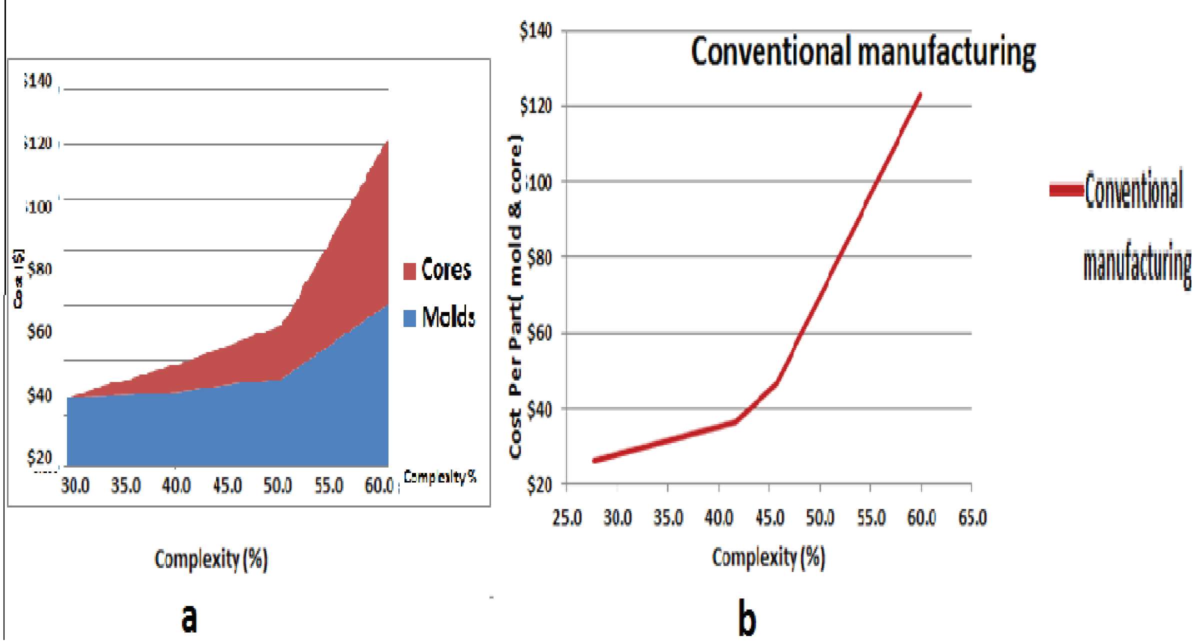
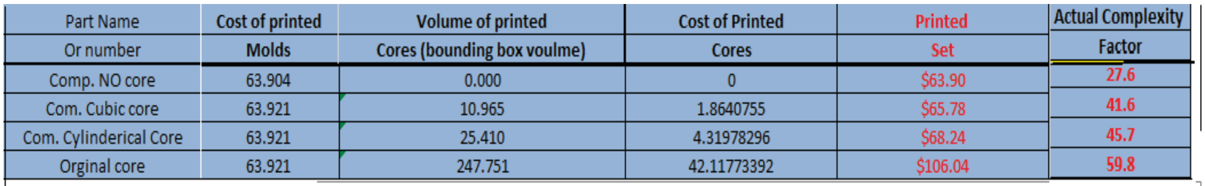


Figure 18: Cost vs complexity when conventional manufacturing was used for case study 2



Part Name Or number	Cost of printed Molds	Volume of printed Cores (bounding box voulme)	Cost of Printed Cores	Printed Set	Actual Complexity Factor
Comp. NO core	63.904	0.000	0	$63.90	27.6
Com. Cubic core	63.921	10.965	1.8640755	$65.78	41.6
Com. Cylinderical Core	63.921	25.410	4.31978296	$68.24	45.7
Orginal core	63.921	247.751	42.11773392	$106.04	59.8

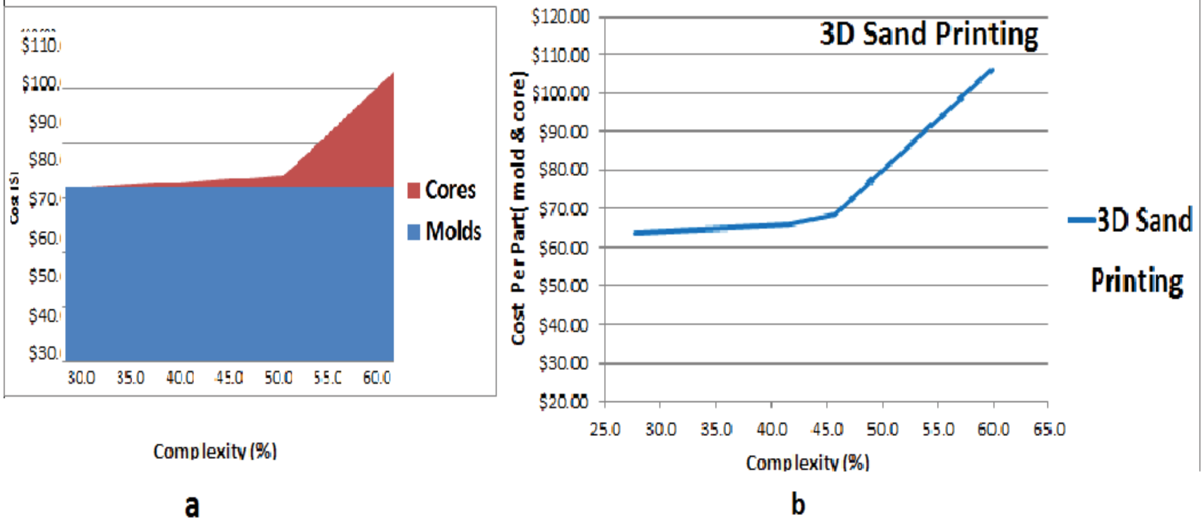
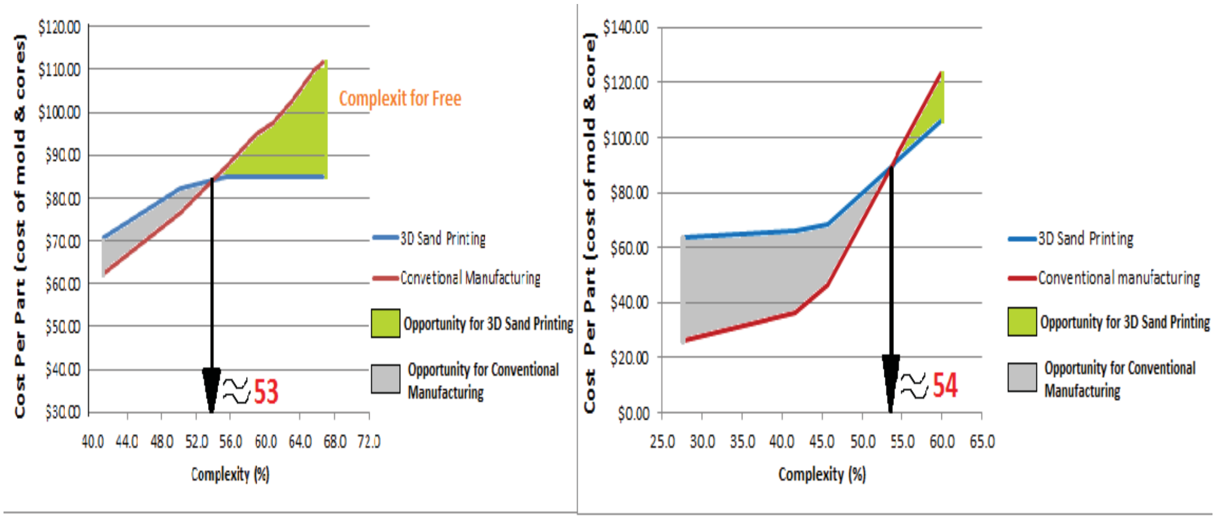


Figure 19:Cost vs complexity when 3D sand printing was used for case study 1

4.4 Obtaining at what level of complexity 3D sand printing become more cost effective?

The main objective of this thesis as mentioned in Chapter 2 is to help founders to decide what is more cost effective to use in molds and cores manufacturing; conventional manufacturing or 3D sand printing. Based on complexity calculation shown in Chapter 3, the hypothesis of this research expected to have a complexity level where 3D sand printing become Cheaper to use than the conventional manufacturing (see Figure 6). This section shows the results of applying the state of hypothesis.

Figure 20 shows the cost vs complexity chart for case studies 1 & 2 when both conventional manufacturing cost and 3D sand printing cost are plotted in one chart.



a) Case Study 1

b) Case Study 2

Figure 20: Cost vs complexity for both types of manufacturing

The results shown in Figure 20 can be explained as the following:

- Case study 1 shows what is called complexity for free (the green area). After a certain level of complexity (in case study 1 approximately at 53%) the cost remain constant regardless to the part's complexity within the printed volume.

- The expected trends for the costs was appeared which means 3D sand printing within today prices and technology is very competitive with complex part.

For parts with complexity factor of 52-55 % or greater, 3D sand printing become better choice in molds and core manufacturing

Chapter 5 (The Discussion)

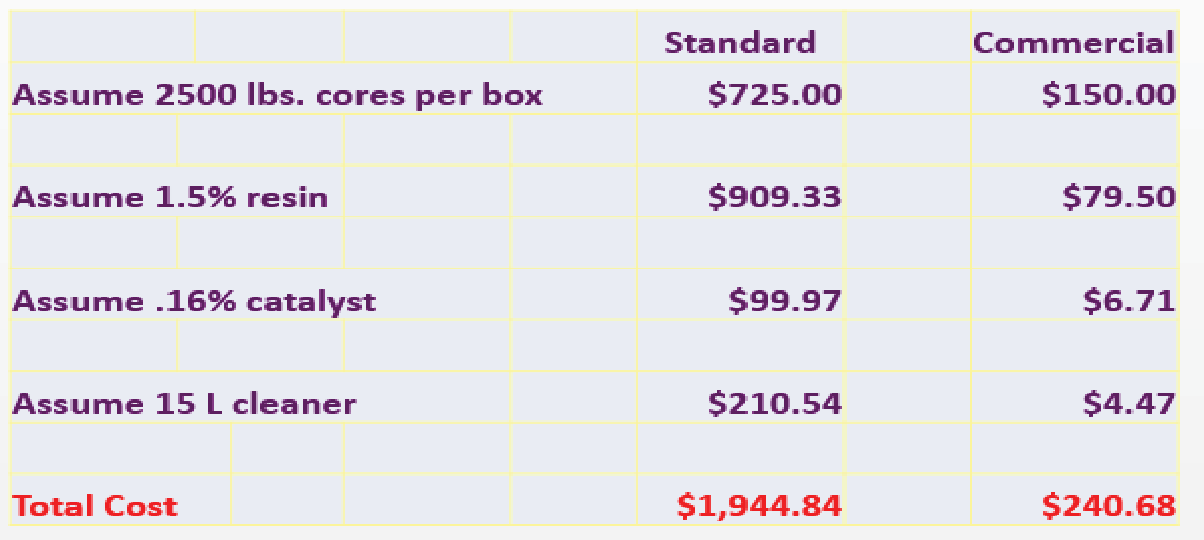
Chapter 4 showed that 3D sand printing is more cost effective than conventional mold and core fabrication at higher levels of complexity. 3D sand printer manufactures such Exone and Voxeljet are promising their customers a new generation of 3D sand printers which are expected to be faster and have a larger work envelope. This Chapter will discuss three major aspects. (1) The expected future drop in the printer's prices and the sand printing materials which influence the manufacturing cost. (2) Production time. (3) The freedom and the capability to design in acceptable cost.

5.1 Sensitivity analysis of Operating at cheaper or higher 3D sand manufacturing cost

This section will examine the changes on Figure 20 (in Chapter 4) if the 3D sand printing manufacturing cost decreased and increased by 20 %. The expected drops will come primarily from two cost components; the printer's prices and the sand printing materials prices. For example, according to study done by Metal Casting Center at University of Northern Iowa, there are many commercial sand printing materials are available in the market in very competitive prices.

Table 3 shows the prices of the standard printing material and the commercial printing material as published [37]. Table 3 indicate that many sand printing material manufacturer and developer started to produce a cheaper sand printing material within the accepted quilt.

Table 3: Standard and commercial printing material prices [37]



	Standard	Commercial
Assume 2500 lbs. cores per box	$725.00	$150.00
Assume 1.5% resin	$909.33	$79.50
Assume .16% catalyst	$99.97	$6.71
Assume 15 L cleaner	$210.54	$4.47
Total Cost	$1,944.84	$240.68

According to [38] the printing material cost weighting around 33% of the total 3D printing manufacturing cost, Figure 21 below shows the printing material percentage among other cost components.

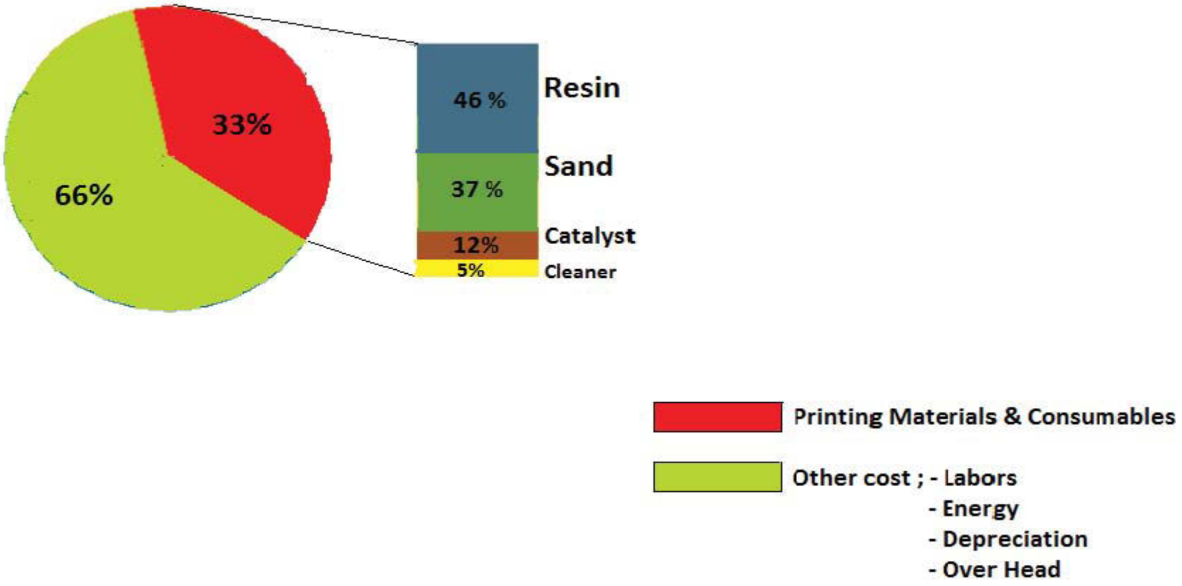


Figure 21: Printing Material cost among other costs components in 3D sand printing[37][38].

Using the information that is shown in Table 3 and Figure 21, if the commercial material used in our cost model the drop in the total prices will be estimated as the following:

- The reduction in the material cost ➔$\frac{1944-240}{1944}$ = 87% reduction in the material prices.
- The reduction in total cost ➔87% X 33%= **28%** expected reduction in total price when commercial material used.

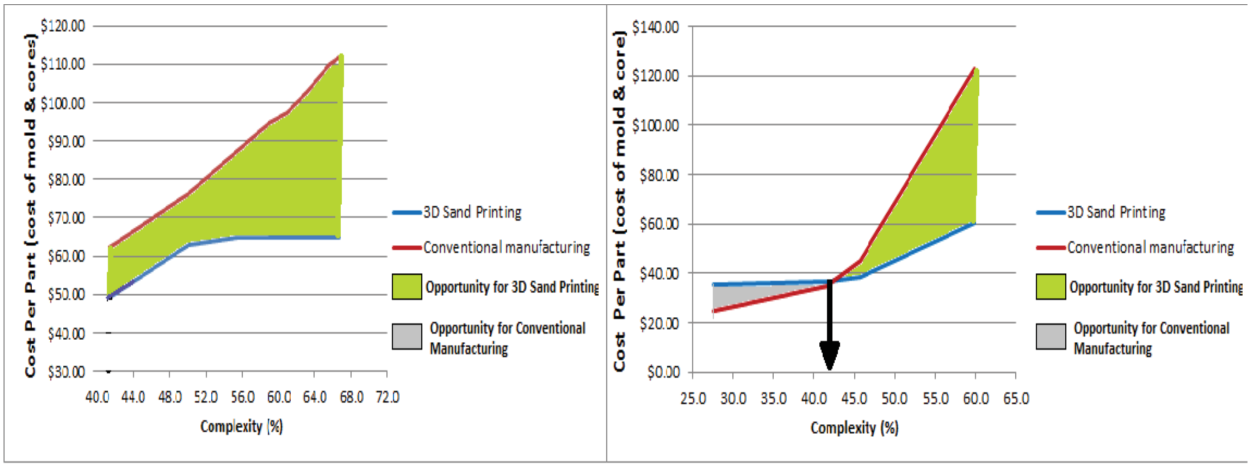
However, in Chapter 4, Figure 20 showed that the complexity range of 52-55% is the turning point for both types of manufacturing where 3D sand printing became more economic to use than the conventional manufacturing.

Figure 22 in this section shows the new results when the cost assumed to be dropped by 20 %. The following consideration was assumed to obtain the results that is shown in Figure 22:

- 3D sand printing cost dropped by 20%.
- Conventional manufacturing cost remained at the same estimated cost.
- There were no changes to the geometric features of the castings meaning that the casting complexity remained the same.

The overall observation in Figure 22 is that the green area has greatly increased. The green area represents the opportunity for 3d sand printing to be a better economic choice.

In case study 1, 3D sand printing manufacturing cost was cheaper at all levels of complexity. At 40% complexity the 3D cost was slightly cheaper than conventional manufacturing, and with high level of complexity the 3D sand became considerably more cost effective.



a) Case Study 1 **b) Case Study 2**

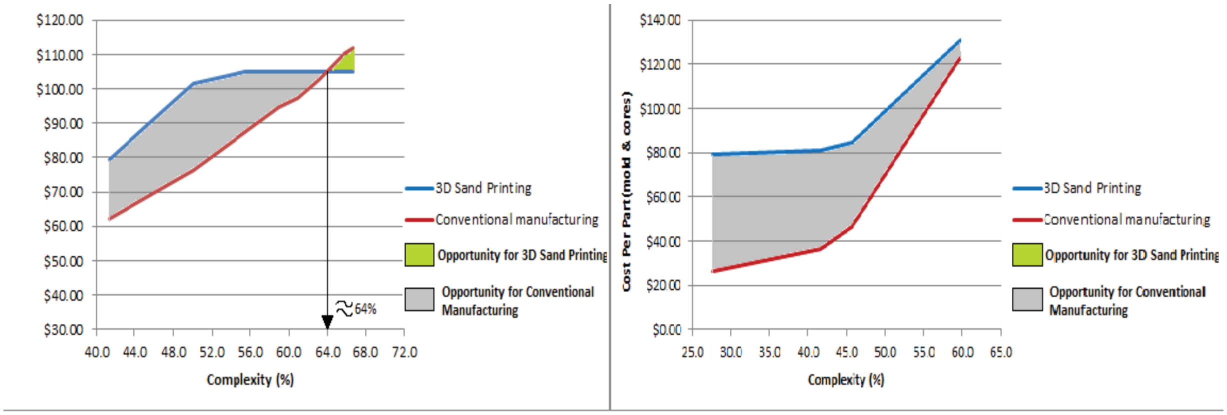
Figure 22: Cost vs complexity for both type of manufacturing when the pricess dropped by 20%.

In case study 2, the intersection point between 3D sand cost and conventional manufacturing cost was shifted to lower level. And the green area has also greatly increased compared with the original cost in Figure 20(in Chapter 4).

Therefore, 3D sand printing seems to be an optimal option to use at all level of complexity in near future, especially if the 3D sand printer manufacturing companies able to provide cheaper printers

On the other hand, Figure 23 shows the new results when the cost assumed to be increased by 20 %. The following consideration was also assumed to obtain the results that is shown in Figure 23:

- 3D sand printing cost increased by 20%.
- Conventional manufacturing cost remained at the same estimated cost.
- There were no changes to the geometric features of the castings meaning that the casting complexity remained the same.



a) Case Study 1 **b) Case Study 2**

Figure 23: cost vs complexity for both types of manufacturing when the cost increased by 20 %

Figure 23 shows that in case study 2 there is no economic feasibility to used 3D sand printing if the molds and cores manufacturing cost increased by 20 % of the current prices. Similarly, in case study 1, the green area was greatly reduced when the cost increased by 20%.

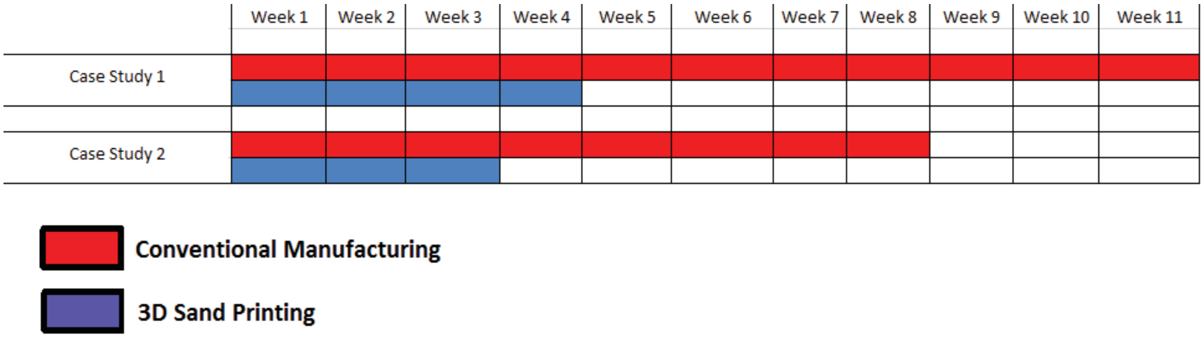
5.2 The impact of tooling cost on complexity vs cost curves.

Chapter 3 have mentioned that the tooling cost in this study was treated as fixed initial cost. However, the tooling cost is very difficult to be accurately estimated. Tooling cost usually amortize over predicted production volume. Therefore, the tooling cost as mentioned earlier was considered as a fixed initial cost, and the cost was estimated in this study for the volume of 1 set of mold and core. According to Humtown Products, for case study 1, the total tooling cost for the 8-cores was estimated to be $50,000. And for case study 2, the estimated tooling cost was $ 13,000. In other words, if the tooling cost was consider for this analysis over volume of one, then the conventional manufacturing approach will be sustainably expensive.

5.3 Manufacturing time

In conventional manufacturing processes, considerable time consumed on molds and cores manufacturing especially when new tools are involved [33]. According to Humtown Products the time saving on case studies 1 & 2 was impressive and provided untimed satisfaction to the customers. The data in Table 3 was provided by Humtown Products sales manager, Table 3 shows the manufacturing time required in both types of manufacturing. The estimated time shown in Table 3 is from costumer purchase order to delivery.

Table 4: Shows the manufacturing time was needed for case study 1 and 2.



	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11
Case Study 1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	🟦	🟦	🟦	🟦							
Case Study 2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
	🟦	🟦	🟦								

🟥 **Conventional Manufacturing**

🟦 **3D Sand Printing**

Table 4 shows that in case study 1 the manufacturing time reduced from 11 months to 4 months only when 3D sand printing was used. Basically, in conventional manufacturing, tremendous time spend on tooling design, tooling manufacturing, and applying the allowances that explained in Chapter 1.

In case study 1, according to Humtown Products, 7 weeks were spent on tooling which included purchasing the proper tooling material, tooling design, tooling manufacturing, customer approvals. However, the patterns and cores manufacturing, and the other typical process such as sand preparation and designing gating systems took around 4 weeks. On the other hand, when 3D sand printing was used, most of the time spent on designing the molds and the cores based on customer 3D model and designing the proper gating systems.

Similarly, case study 2 the manufacturing time was reduced from 8 months to 3 weeks when 3D sand printing was used. By eliminating the need for tools, 3D sand printing consider an effective tool to produce molds and manufacturing in short time.

5.4 Design capability

This research has proven the economic feasibility for 3D sand printing uses for parts with high level of complexity (between 52-55 or greater). 3D sand printing provides a large room for designer to design for weight reduction and design for better functionality without increasing the manufacturing cost [35]. However, according to [35] some complex designs are unable to be conventionally manufactured, but now these designs can be achieved by using 3D sand printing. Examples include:

- No draft angle or the draft angle is negative.
- When deep undercut is exists.

Chapter 6 (Conclusion & Future Work)

6.1 Conclusion

The work described in this thesis mainly discussed the relationship between the manufacturing cost and the part's complexity in molds and cores manufacturing in sand casting process. The part shape complexity used as a tool to compare the estimated manufacturing cost in both types of manufacturing; 3D sand printing and conventional manufacturing.

Quantitative evaluation of shape complexity of cast parts has been adopted and used to measure the complexity factors for two case sides. The adopted complexity criteria had used six geometric feature in order to measure the complexity factor. These geometric attributes that include; part volume ratio, area ratio, core volume ratio, number of cores ratio, thickness ratio and depth ratio.

After measuring the complexity for the two case studies at different levels of shape complexity, the conventional and 3D sand printing cost were estimated. Cost analysis and sensitivity analysis was applied. The following is a conclusion of the results:

- The results showed there is a considerable economic opportunity for 3D sand printing to be used at high levels of complexity. In today prices, the results showed that the economic feasibility of 3D sand printing starts at level of complexity 53-54 % or more.
- When 3D sand printing cost decreased by 20%:

A- For case study 1 the economic feasibility has greatly improved. The results showed 3D sand printing can be a better economic choice at lower levels of complexity; the turning point has shifted from 53% complexity to less the 40% complexity.

B- Similar to case study 1, the results in case study 2 showed 3D sand printing can be a better economic choice at lower levels of complexity; the turning point has shifted from 54% complexity to less the 43% complexity.

3D sand printing seems to be an optimal option to use at all level of complexity in near future, if the 3D sand printer manufacturing companies able to provide cheaper printers with low operation and material cost.

- The estimated cost in conventional manufacturing depend on the part complexity. While the estimated cost in 3D sand printing manufacturing depend on the volume of the bounding box of the part.
- Using 3D sand printing results of tremendous reduction in the time required to produce sand molds and cores. By eliminated the tooling needs, 3D sand printing reduced the manufacturing time in case study 1 from 11 weeks to 4 weeks, and for case study 2, from 8 weeks to 3 weeks only.
- Some complex designs are unable to be conventionally manufactured, but now these designs can be achieved by using 3D sand printing. Examples include:

  A- No draft angle or the draft angle is negative.

  C- When deep undercut is exists.

- 3D sand printing has unique economic advantage that the increasing in geometric complexity of the part has a little or no impact on the molds and cores manufacturing cost.

6.2 Future Work

Firstly, the type of analysis provided by this thesis is mainly dependent on the current prices of the material, energy, and the available printers. And any major change of these prices the study should be updated accordingly. For example, experts expect to have drop in the prices of the future sand printer. And as showed in Chapter 5, the drop of the prices have a high impact on the results.

Secondly, to make the thesis results useable by foundry, an excellent extend to this thesis is by programming a software. The envisioned software is to include the equation mentioned in Chapter 4, this software should be able to measure the complexity when the end-user plug in the six geometric attributes that explained in Chapter 3 & 4. However, the software also should include pricing criteria to compare the prices in both types of manufacturing. The pricing methodology can be easily driven from physical measurement such as of the printed volume, the mold volume, the cores volume and some others.

Thirdly, this thesis assumed that the 3D sand molds and cores printing provided a consistent surface finish and mechanical properties with traditional molds and cores manufacturing. However, a good extension to this thesis is to add one more factor which is the quality of the produced molds and cores. Thus, can be achieved by testing the physical and mechanical properties such as surface roughness, density, porosity, microstructure, hardness, compression strength. This work will give additional evaluation for both types of manufacturing beside the estimated cost.

Fourthly, linear programming can be used to find the optimum solution when more factors to be added such as the quality, time, beside the cost and complexity. Also, this type of analysis can be applied to other industrial process such as forging, machining, assembly, finishing, etc. noting that the complexity equation should be driven from each process cost component.

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