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Comparative study of foundry patterns created using conventional methods and additive manufacturing

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Abstract

Pattern is a very vital tool in the foundry industry, and the traditional method of pattern creation using wood or metal working tools is time-consuming, labor-intensive, and prone to quality variations. This study explores additive manufacturing (3d-printing) as an effective alternative to the conventional pattern making process. Two patterns design were fabricated using 3d printing (Fused Deposition Modelling (FDM) technology) and conventional process and they were compared in terms of their dimensional accuracy, lead time, and cost investment. The result showed that the patterns produced using additive manufacturing have higher dimensional accuracy, lower costs and lead-times, suggesting that the integration of additive manufacturing into the foundry industry could substantially improve production efficiency and quality.

Keywords: Additive manufacturing; Pattern; Foundry; Fused deposition modeling; 3D Printing

1. Introduction

3D printing, otherwise referred to as Additive Manufacturing (AM), is a process for making solid objects based on the digitally controlled deposition of successive layers of material from a Computer Aided Design (CAD) model [1-4]. First invented in 1984 by Chuck Hull, who used ultraviolet lights to harden polymers [5], this method began the stereolithography (SLA) process of 3D printing. Today, several methods of 3D printing technologies exist, which includes; Fused Deposition Modeling (FDM), Selective Laser Melting (SLM), and Binder Jetting [6].

Metal casting is a fundamental manufacturing process that involves pouring molten metal into a mold cavity of the desired shape and letting it solidify [7]. There are different foundry processes, each of which differs in its methodology but generally these processes still require one thing "A Pattern". Pattern is the tool used to construct a mold cavity into which molten metal is poured through the sprue [6]. It is generally a replica of the object to be cast. Pattern making is a principal step in the process of casting that involves the use of materials such as wood, metal, or resins [7], [8]. Without patterns, castings cannot be produced and if there happens to be a defect in the pattern, automatically it causes a repetition of the defect in the cast products, emphasizing its importance in the foundry industry. Although pattern makers have the skill to create patterns, traditional methods could bring about variations in quality, cost, and lead time. The accuracy of produced patterns is heavily dependent on the patternmaker's skill and the quality of the machines and tools available to them [7]. In today's manufacturing world, the demand for intricate and precise castings in various industries, including aerospace, automotive, and medical devices is rapidly increasing [9]. Traditional pattern-making methods struggle to meet these demands efficiently. The hypothesis therefore is that with additive manufacturing technology, these challenges can be mitigated, allowing for the direct printing of 3D digital files to create precise patterns.

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Globally AM has been adopted by the foundries to produce sand molds and patterns [10]. The advantages of such adoption include: Faster production rate, near net shape castings, lower production cost, more flexible operations, capability to produce more complex molds and production of sand molds with finer details. [11] demonstrated that the application of FFF printers to fabricate PLA and ABS patterns reduced lead time and cost. However, their study did not directly compare AM-produced patterns with those made using conventional methods. Similarly, various techniques of 3D printing, such as stereolithography, fused deposition modeling, multi-jet modeling, and selective laser sintering, were considered in [12] for the production of polymer patterns. The result showed that 3D printing reduced time and cost for the fabrication process, but the authors complained of reduced accuracy due to polymer shrinkage and other challenges.

[13] focused on the challenges of FDM-printed PLA patterns for sand castings, revealing that while AM techniques like binder jetting can improve lead time and dimensional accuracy, surface friction between PLA patterns and mold walls remains problematic. The scope of their study was also basically confined to the FDM technique and did not include a cost comparison of AM techniques against traditional methods. [14] applied the software EASYCAST for computer-aided sand casting, and it turned out to be effective for simple geometries, though special tools were needed for irregular geometries. The influences of process parameter on silica sand patterns manufactured using selective laser sintering (SLS) were investigated in [15]. The authors evaluated the influences of process parameters such as laser power, scanning speed, overlapping rate, laser beam diameter and powder mixture ratio on the dimension accuracy. The concluded that SLS of silica sands has the characteristics of high flexibility, shorter lead time, and lower cost. Finally, [16] fabricated silica ceramic cores with improved mechanical properties through stereolithography. These studies demonstrate the benefits of AM in foundry applications but also indicate the need for comprehensive comparisons with conventional pattern-making methods, which this study aims to address.

Although so far, 3D printing for patternmaking has been widely adopted in many developed countries, where companies like Hoosier Pattern Inc. [17] have made tremendous improvements in design capabilities and production efficiency, developing nations are still way far behind in adopting this technology rendering these countries' foundries non-competitive on both regional and global markets [6]. By incorporating 3D printing technology, one can try to reduce or eliminate those limitations and inefficiencies that have been in-built with traditional methods. This research compares the application of 3D printing technology in a pattern-making process with conventional techniques with respect to cost, lead time, accuracy, and ability in the production of complex patterns. The findings of this research are thus going to be of immense benefit, demonstrating the substantial benefits of additive manufacturing, while encouraging foundries in developing nations to adopt this advanced technology, thereby rejuvenating their industries and enhancing their competitiveness.

2. Methodology

To provide a detailed illustration of the steps undertaken to achieve the objectives of this project, this section is divided into two main parts: design specifications and methods. The design specifications section elaborates on the rationale behind the chosen pattern designs, explaining the conceptual decisions and considerations that guided their creation. The methods section then offers an in-depth look at the procedures followed in both fabrication approaches to produce the patterns. Tests and comparisons conducted includes; accuracy, cost, lead time, and surface finishing/strength properties.

2.1. Design Specification

The pattern design process started with a rough sketch using basic drawing tools. The first design was a disk-shape pattern with extruded circular thicknesses on its surface. This disk has a total diameter of 110mm and a height of 16.5mm, with the extruded circular surface thicknesses varying from 0.4mm to 4mm. These variations in thickness are there to help us compare the finesse of each fabrication method to producing very fine details.

The letters S, E, and A were then imprinted on the disk's surface, reason being that these kinds of letters that have narrow spaces between them has proven to be a very difficult task to achieve by pattern makers using the traditional method. By using additive manufacturing, an aim was to determine if these letters can be easily and accurately imprinted. To further compare the methods, three different font sizes—12mm, 9mm, and 6mm—with an extruded height of 2.5mm were used for all the letters. The font used was Arial Black. Additionally, curvy and straight-edge incisions of ascending sizes were added at the side of the disk just to add more complexity and test the capabilities of both methods in creating intricate designs.

Finally, a second pattern (draft pattern) was designed. It was rectangular shaped with draft to test out the smallest draft angle that can be obtained from both methods. This pattern features one square surface of 20mm and another of 19.5mm, with a length of 100mm. This variety in design elements allows us to thoroughly evaluate and compare the performance of conventional and additive manufacturing techniques in pattern creation.

2.2. Methods

Following the objectives, the same pattern design was created using (i) conventional method and (ii) additive manufacturing method.

2.2.1. Additive Manufacturing (AM) Method

The following steps were followed to obtain the 3D printed pattern using additive manufacturing (AM);

CAD Model Development

First, the object to be built has to be modeled using a CAD software. Fusion 360 was used in this study to make the CAD model of the pattern to be produced [18]. It was first designed and sketched in 2D format, and later it was reproduced and translated into 3D format using this software. The CAD and 3D drawing of the patterns are shown in Fig. 1.

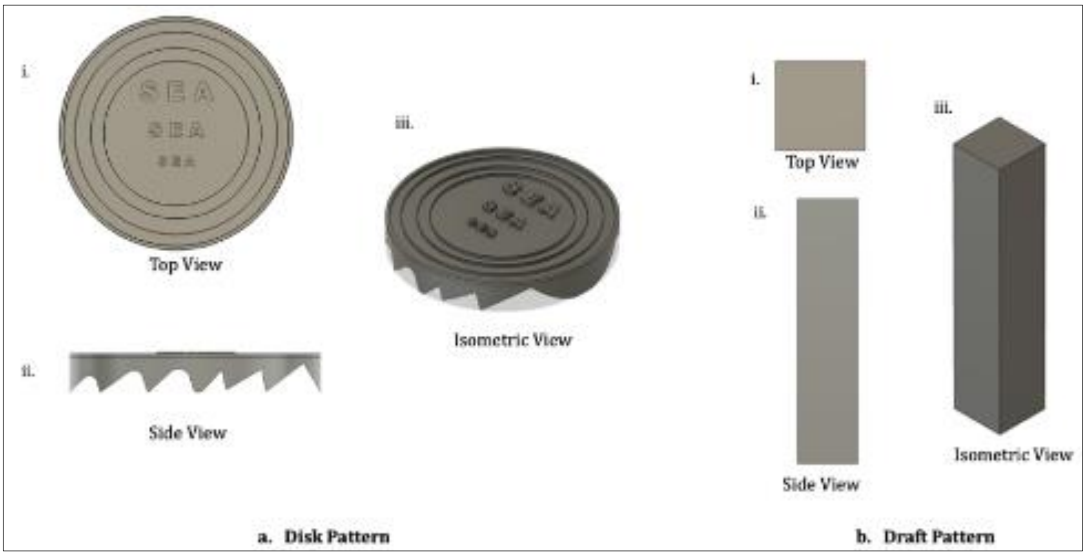

Figure 1 CAD Model of the Pattern Designs. (a) The Disk Pattern. (b) The Draft Pattern. (i) Top view, (ii) Side View and (iii) Isometric View

CAD Conversion to STL Format

From the first step, the 3D digital format of the patterns was obtained. Then the 3D models were exported as a STL file standard of the additive manufacturing industry [19]. This file format contains triangular mesh (polygons) that describes the layout/surface of the three-dimensional model. This file would later be read by the slicer.

CAD Conversion to STL Format

In this step, a pre-processing program prepares the STL file to be built. Several programs are available, and most of them allow the user to adjust the size, location and orientation of the model. This process translates the 3D file into set of instructions for the 3D printer to follow. It basically chops the 3D model into hundreds or even thousands of horizontal layers, telling the 3D printer exactly what to do step by step. The name of the slicer employed was Ultimaker Cura.

With the help of this software, instructions were given to the 3D printer on how the model should be printed and the scale of the model that should be used. The orientation of the model was optimized to the best position it can be printed, support was generated, the infill set to 100% and a layer height of 0.2mm was specified. Layer height represents the thickness of each layer printed while the infill density is the parameter that controls the number of structures present inside the object.

After slicing the STL file, the export from the slicer is a G-code file. The G-code file format (. g-code) is a numerical code programming language, mainly used in computer-aided manufacturing to control automated machine tools like the 3D printer in our case. The 3D printers basically read this code and automatically knows how it would go about printing the model. The g-code file was saved into a memory card.

3D Printing

In this step, the patterns were constructed using the Fused Deposition Modelling (FDM) printing technology, this is because it is the most widely used 3D printing process in the world and is readily available [20]. The printing material used was Poly Lactic Acid (PLA) filament and is also the most common material used with this 3D printing technology as it is cost effective [6].

The G-code file format from the slicer software is read by the 3D printer and it starts printing after the press of a single start button. Most 3D Printers do not need to be monitored after the printing has begun because it is an automatic process and requires no labor at all. The machine will continue to follow the automated G-code instructions as long as there is no software error or the machine doesn't run out of raw material, there should not be an issue during the printing process.

2.2.2. Conventional Method (CM)

The fabrication of the pattern using this method was outsourced to an experienced professional pattern maker. This approach ensured a transparent comparison, as the anticipation was that the most precise and accurate pattern possible through this traditional technique would be obtained.

3. Results and discussion

In the following section, the findings obtained by both methods are presented and analyzed. The patterns obtained via additive manufacturing are shown in Fig. 2. While those obtained through conventional means are shown in Fig. 3.

3.1. Pictorial Result of Produced Patterns

3.1.1. AM Manufactured Patterns

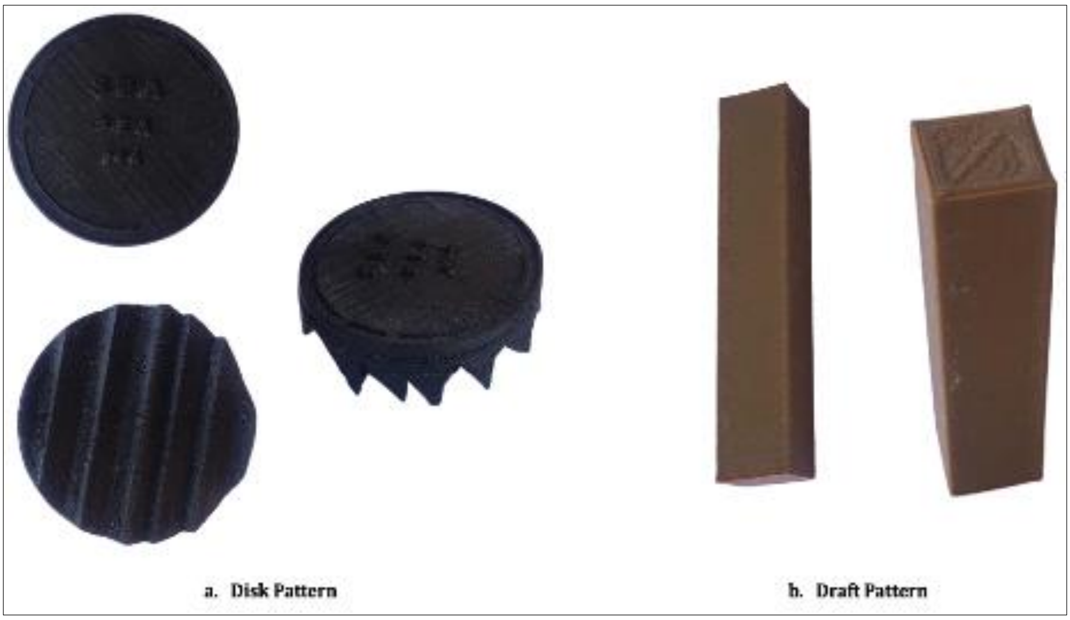

Figure 2 3D-Printed Patterns. (a) Disk Pattern. (b) Draft Pattern

3.1.2. Conventionally Manufactured Patterns

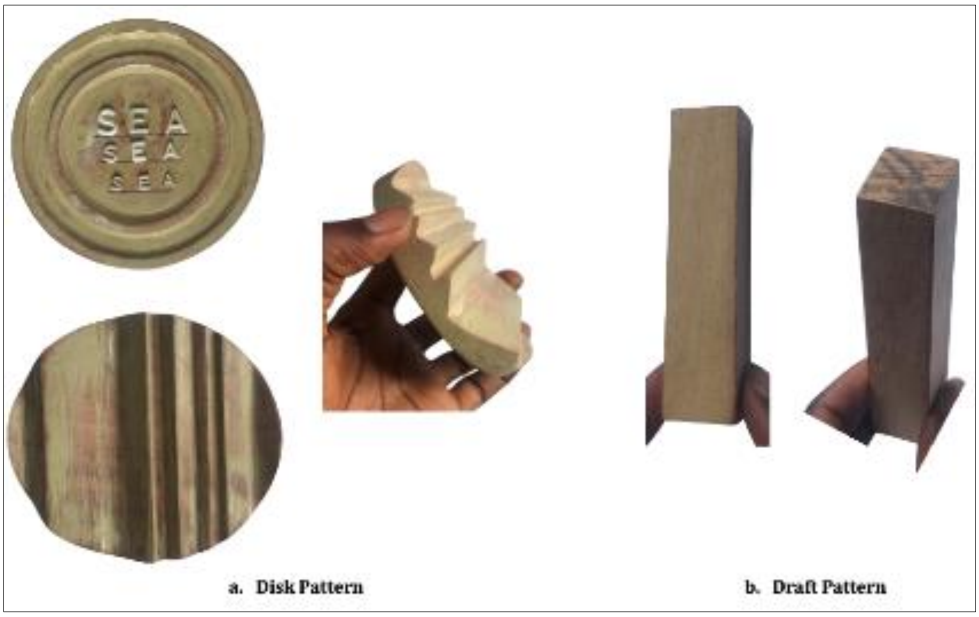

Figure 3 Conventionally Fabricated Pattern. (a) Disk Pattern. (b) Draft Pattern

3.2. Test Result

3.2.1. Dimensional Accuracy

This test was carried out using a Vernier caliper as the measuring tool and all the dimensions are in Millimeters (mm). The percentage error (PE) of every dimension were calculated using Eq. (1) with the Measured Dimension (MD) and Actual Dimension (AD) so as to determine the overall percentage accuracy. Table 1 and 2 shows the accuracy result for the disk and draft pattern respectively.

$$\text{PercentageError(PE)}(\%) = \frac{MD - AD}{\text{AD}} X100 \quad \ldots\ldots\ldots\ldots..(1)$$

Table 1 Dimensional Accuracy Analysis of Disk Pattern

	AD (mm)	**CM Measured Dimension (mm)**	**AM Measured Dimension (mm)**	**CM Method PE (%)**	**AM Method PE (%)**
Total Diameter	110.00	109.00	110.00	0.91	0.00
Height	16.60	15.50	16.30	6.63	1.81
Gap (top - mid text)	10.70	5.00	11.00	53.27	2.80
Gap (mid -bottom text)	9.43	7.00	9.80	25.77	3.92
Text Font Sizes	12.00	13.00	12.00	8.33	0.00
	9.00	8.00	8.80	11.11	2.22
	6.00	6.80	5.80	13.33	3.33
Thicknesses on the Surface	4.00	7.00	4.40	75.00	10.00
	0.80	4.50	1.00	462.50	25.00
	0.60	n/a	n/a	n/a	n/a
	0.40	n/a	n/a	n/a	n/a

Table 2 Dimensional Accuracy Analysis of Draft Pattern

	AD (mm)	CM Measured Dimension (mm)	AM Measured Dimension (mm)	CM Method PE (%)	AM Method PE (%)
Length	100	101	100	1	0
Top Width	20	21	20.5	5	2.5
Bottom Width	19.5	20.8	20	6.67	2.56

Based on the data and result, it is obvious that the Additive manufacturing (AM) methods generally show significantly lower percentage errors across all dimensions compared to conventional manufacturing methods. Percentage error up to 50% was calculated in the conventionally made disk pattern as seen in Fig. 4 which in the case of AM, the max error was about 4%.

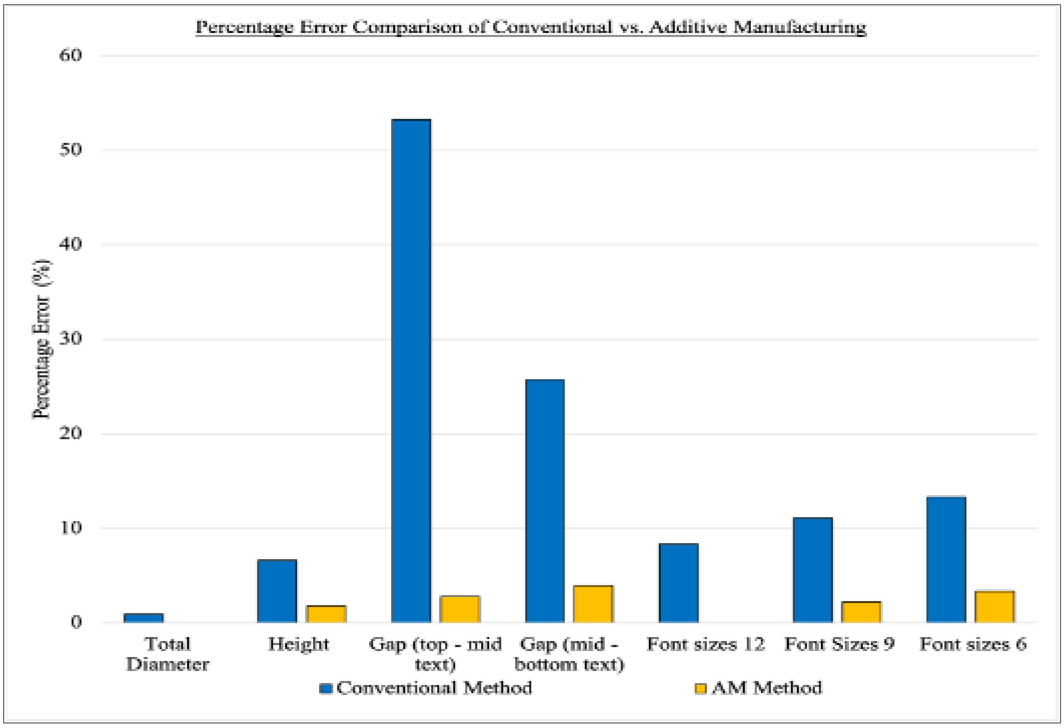

Figure 4 Percentage Error of Disk Pattern

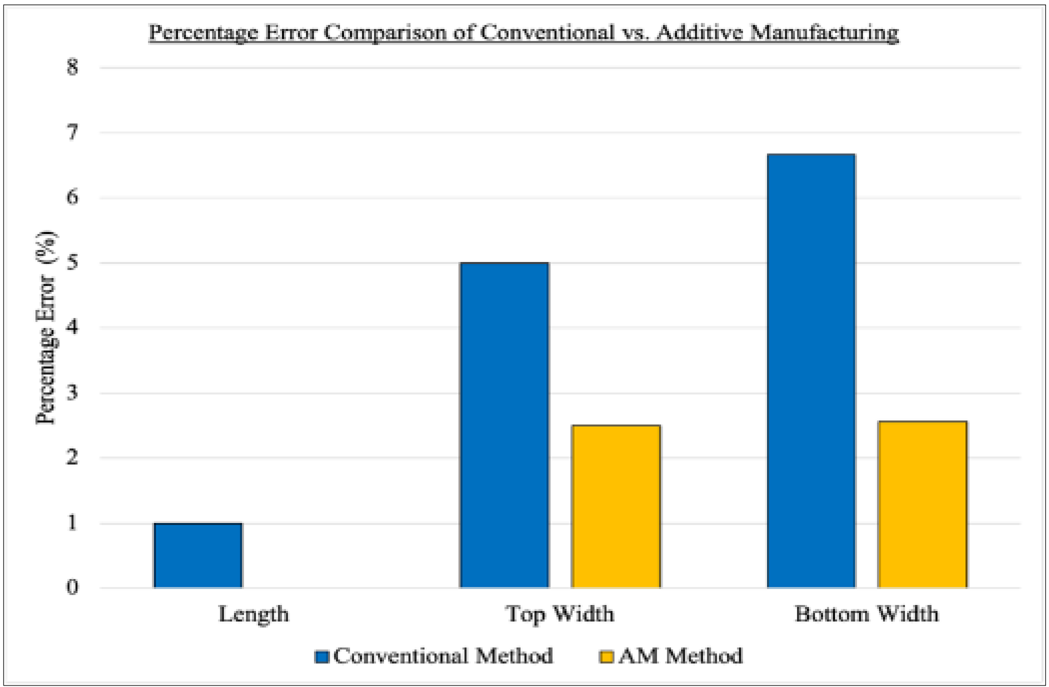

Figure 5 Percentage Error of Draft Pattern

3.2.2. Cost Analysis

The cost for the AM method was collected directly from the slicer software, while the cost for the conventional method was the amount the pattern maker charged us to make the patterns. Table 3 shows the overall cost in Nigerian naira (N) of the patterns from both methods. The cost of producing each pattern design conventionally was higher than with the AM method. The percentage cost difference revealed that the overall cost of producing the patterns conventionally was approximately 44% higher compared to the additive manufacturing (AM) methods.

Table 3 Production Cost Analysis

	Conventional Method (N)	**AM Method (N)**
Disk Pattern	6,500	4,745
Draft Pattern	3,500	1,976
Shipping	2,000	1,500
Documentation (Drawings)	6,000	-
TOTAL	18,000	8,222

Looking at the pie chart in Fig. 6, it is evident that in both methods, the disk pattern incurred the highest expense. Unlike the additive manufacturing method, the pattern maker charged us for documentation and drawing , which he stated were essential for planning the creation of the pattern and this added a substantial cost to the conventional method.

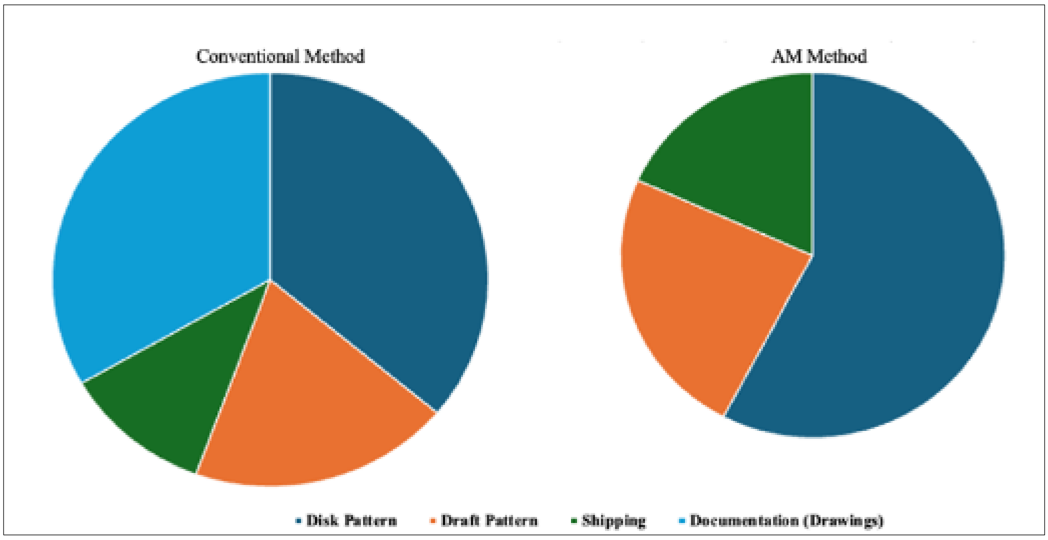

Figure 6 Distribution of Production Cost

3.2.3. Lead Time

The time it took for the pattern to be 3D printed was provided by the slicer software, while the conventional method's time was estimated by the pattern maker. It took the pattern maker 3 weeks from the day of the contract to deliver while the additive manufacturing process only took 3 days from the contract date.

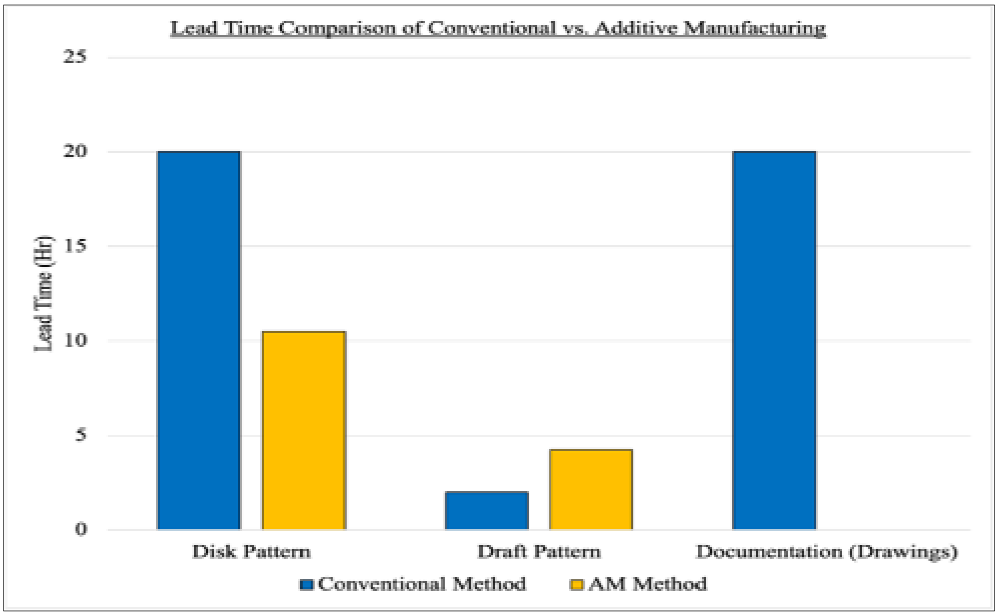

Figure 7 Production Lead Time

Fig. 5 clearly shows the duration each method required to produce the different models/patterns. By calculation, the conventional method overall took about 27 hours and 57 minutes longer than the additive manufacturing method, which translates to roughly 65.64% more time even though the time to make draft pattern conventionally was shorter than with AM.

When considering both the production and delivery times, the total time to produce patterns conventionally was 42 hours and AM method took 14.75 hours. Evident that the additive manufacturing method is significantly faster overall compared to the conventional method.

3.2.4. Surface Finish / Strength Parameter

It was observed that surface of the model produced by additive manufacturing has some sort of texture on it, this is due to the laying of the layers by the 3D printer. This can be advantageous when trying to obtain surface cast finish. Nonetheless, there are two ways to reduce this texture to achieve a better surface finish if it is not required. The first it by reducing the size of the layer thickness or by doing some post-processing after printing. The surface of the model produced by the conventional method was smoother than that of the additive model. In terms of the strength properties, the tensile strength of the PLA material is about 37Mpa, and its flexural Modulus is 4Gpa [21]. While the tensile strength of the wood used was about 60Mpa and its flexural Modulus of 7.9Gpa [22]. However, both of these materials meet the strength requirement of a good pattern.

4. Discussion

By observing the printed main pattern Fig. 2, it was noticed that just two of the thicknesses were visible with the surface circular thicknesses. The 0.4mm and 0.6mm thickness did not come out well but there were signs that the printer attempted to produce them. Not seeing them could be indication that they either broke off while in transit as they are very thin, that there is a potential limitation in achieving fine details with the technology or that the default print settings are not sufficient to meet this particular criterion. On the main pattern produced via conventional means however (Fig. 3), only two of the surface thickness were visible as well but with no trace of the two other smaller thickness. Additionally, the letters "S, E and A" on the AM pattern model with a font size of 6mm, were not very visible, this may suggest that there might be challenges in printing texts with small fonts clearly. The same letters on the conventionally produced pattern were visible. By observation, it was glued to the surface of the pattern. Finally, the straight and curvy cuts on the bottom of the printed pattern came out well compared to those on the traditionally produced pattern. Those on the AM printed pattern were evenly distributed and closer to the looks of the CAD model, demonstrating that additive manufacturing could be effectively implemented for creating highly complex designs.

The test results demonstrate that additive manufacturing (AM) methods significantly outperform conventional manufacturing in terms of dimensional accuracy, cost, lead time, and surface finish. the dimensional accuracy test revealed that AM methods have lower percentage errors than conventional methods. Cost analysis indicated that AM is approximately 44% more cost-effective, primarily because the pattern maker's charges for documentation and drawing substantially increased the cost of conventional methods. In terms of lead time, AM methods were significantly faster, taking only 3 days from contract to delivery, whereas the conventional method took 3 weeks. Furthermore, while the surface finish of conventionally produced models was smoother, AM models showed some texture due to layer deposition, which can be mitigated through post-processing. Both methods met the necessary strength requirements.

5. Conclusion

In conclusion, a common pattern was created using the additive manufacturing technology and the conventional method. A comprehensive comparison of cost, lead time, accuracy and surface finish were carried out between the two methods. The goals of any manufacturing industry are to minimize production cost and time, while simultaneously maximizing the output. The results obtained from the various test performed showed that implementing additive manufacturing into the foundry process is of great advantage. Patterns produced using AM were done in less time, with better dimensional accuracy, and at a lower cost compared to those produced using conventional methods.

The level of accuracy achieved with additive manufacturing could be seen to be twice that of the conventional method. In addition, the cost of pattern production through additive manufacturing was significantly lower, and the time required for fabrication was shorter than the traditional means, suggesting that adopting additive manufacturing in the foundry industry can effectively address the challenges of complexity, cost, and production delays traditionally associated with pattern making.

A limitation of this study is that the human factor in the results of the two methods was not thoroughly considered. Also, the pattern fabrication was outsourced to a single company for each method. No comparison was made between companies, primarily due to the limited options available for outsourcing. This constraint may affect the generalizability of our findings, as variations in expertise and processes between different companies were not accounted for. Therefore, a recommendation is that more research and work should be carried out in order to ascertain the effectiveness of additive manufacturing for pattern creation. Future research could explore the application of different additive manufacturing techniques and materials to further optimize pattern accuracy and strength properties. Lastly, further steps should also be taken to produce castings using AM-manufactured patterns to evaluate their performance in real-world foundry applications.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors of this article have declared that no competing interest exist.

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