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Study of Additive Manufacturing Application to Geothermal Technologies

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ABSTRACT

Geothermal reservoir characterization, field construction, and reservoir operations are very technology intensive activities that contribute significantly to the cost of delivering electricity produced from geothermal resources. Many geothermal technologies, such as downhole tools and drilling equipment, have unusual material, design, and manufacturing considerations dictated by the harsh geothermal environment and extreme aspect ratios required for deployment in a borehole. An additional challenge that faces geothermal applications is the low tool production volume needed to support the industry. Whereas tens of thousands of Oil & Gas wells are drilled and completed in the U.S. annually, there are typically only tens of geothermal wells that are drilled and completed. If a tool typically used in Oil & Gas applications cannot be directly used for geothermal, then the cost associated with making the tool suitable for geothermal is often prohibitive. There is therefore a much smaller inventory of technologies available to the geothermal industry as compared to Oil & Gas and the level of efficiency and sophistication associated with field practice suffers accordingly. A number of advanced manufacturing methods, such as additive manufacturing, have received increased R&D as well as commercial attention in recent years because of their ability to rapidly prototype complex parts. Additive manufacturing in particular provides an opportunity to increase the technology available to the geothermal industry by either reducing fabrication costs associated with complex components or enabling economic production of low volume parts where specialized tooling is often required. Additional potential benefits of additive manufacturing include increased design freedom to make higher performing parts that cannot be made conventionally, the ability to integrate components into assemblies without joining operations, and the ability to economically fabricate variations on design in cases, such as casting molds, where there are large up-front costs associated with tooling. We have recently completed a study that investigated technology needs, representative use cases, manufacturability, and a techno-economic framework for comparing conventional to additive manufacturing methods for geothermal applications. This paper will provide an overview of this recent effort, describe the different elements of the assessment, and summarize the key takeaways related to both the feasibility of using additive manufacturing for geothermal technology applications as well as the potential benefits and impacts.

1. INTRODUCTION

Geothermal reservoir characterization, field construction, and reservoir operations are very technology intensive activities that contribute significantly to the cost of delivering electricity produced from geothermal resources. Many of the activities and technologies associated with geothermal field development and production are identical or similar to those needed for Oil & Gas (O&G). However, because of distinctive conditions in geothermal plays such as high temperature (>200°C), corrosive brines, and hard/abrasive lithologies, many O&G tools are not available for use in geothermal applications. Some of these technologies are likely to be essential for future geothermal applications such as Enhanced Geothermal Systems (EGS). Directional drilling, for example, is likely to be needed for optimization of EGS energy recovery by favorably orienting wells in relation to the fracture planes produced during EGS stimulation (Lowry et al, 2015). Directional drilling technology in combination with hydraulic fracturing has similarly enabled the revolution in unconventional O&G production. Between 2014 and 2018 approximately 40,000 horizontal wells were drilled in the United States (U.S. EIA, 2019). To the authors' knowledge, no deep horizontal wells have been drilled for geothermal energy extraction. While this is largely related to the expense of drilling horizontal wells and the absence of need for such wells in hydrothermal applications, as mentioned previously, this capability will be needed for successful implementation of EGS. Current commercial directional drilling technology is not suitable for use at relevant geothermal applications temperatures. DOE GTO recognizes this need and has previously funded projects to develop high temperature directional drilling systems for the geothermal environment (Dick et al, 2012).

This transition of technologies from O&G to the geothermal industry is needed if geothermal well construction and field development is to see the same improvements in operational practice and reductions in cost experienced by O&G over the last decade. Another key to lowering the cost of reservoir construction in O&G has been continuous improvement of directional drilling, completions and fracking technologies (Godec et al, 2007). The unique conditions of EGS is likely to require similar evolution and refinement of technology in order to realize the same efficiency improvements. Challenges that impede the transition of O&G technologies to the geothermal industry include materials able to handle the geothermal wellbore environment, high-temperature electronics, and low tool production volumes or customization that result in high manufacturing cost. This last challenge, in combination with the need to close the technology gap between O&G and the geothermal industry, highlights the need to evaluate methods for improving manufacturing capabilities and addressing economic barriers associated with technology production.

A number of advanced manufacturing methods, such as additive manufacturing (AM), have received increased R&D as well as commercial attention in recent years because of their ability to rapidly prototype complex parts (Sireesha et al, 2018 and Vendra et al, 2018). The AM industry is now supporting the automotive, aerospace, and clean energy industries with high-grade metal and alloy printing capabilities. It provides an opportunity to increase the technology available to the geothermal industry by either reducing fabrication costs associated with complex components or enabling economic production of low volume parts where specialized tooling is often required. Additional potential benefits of additive manufacturing include increased design freedom to make higher performing parts that cannot be made conventionally, the ability to integrate components into assemblies without joining operations, and the ability to economically fabricate variations on design in cases, such as casting molds, where there are large up-front costs associated with tooling. We have recently completed a study that investigated technology needs, representative use cases, manufacturability, and a techno-economic framework for comparing conventional to additive manufacturing methods for geothermal applications. This paper will provide an overview of this recent effort, describe the different elements of the assessment, and summarize the key takeaways related to both the feasibility of using additive manufacturing for geothermal technology applications as well as the potential benefits and impacts.

2. STUDY METHODOLOGY

The approach taken in this study to evaluate the feasibility and potential impacts of additive manufacturing (AM) to geothermal applications was both qualitative and quantitative. Qualitative evaluation involved activities such as: interviewing AM subject matter experts for their perspective on the advantages and disadvantages of AM compared to conventional manufacturing (CM); interviewing O&G and geothermal industry OEMs to identify key manufacturing considerations related to their technologies; convening a workshop with industry stakeholders and AM experts at Oak Ridge National Laboratory (ORNL) to explore challenges, needs and potential impacts of AM for downhole tool fabrication; and performing in-depth face-to-face design analyses of geothermal tools developed by Sandia National Laboratory (SNL) researchers with ORNL AM experts. The qualitative analyses will not be the primary focus of this paper.

Quantitative efforts to evaluate potential impacts of AM for geothermal applications involved the identification and analysis of 17 representative parts selected from geothermal logging and drilling tools. A detailed assessment of the manufacturability of the parts was first performed by Senvol, a company that specializes in helping industry implement additive manufacturing. Senvol provided detailed descriptions of how the parts might be fabricated using AM, including the preferred AM systems and materials, and also provided detailed step-by-step descriptions of how the parts would be manufactured by CM. ORNL in parallel developed a set of calculators that can be used to estimate the cost and production time for fabricating parts using both CM and AM. The accuracy of the calculators was evaluated against a set of cost quotes from various sources and time estimates from subject matter experts. The calculators were then used in conjunction with the manufacturability assessment to perform techno-economic analysis (TEA) of the primary driving factors and benefits of conventional and additive manufacturing methods based on part design, geometry, and complexity. It is believed that this TEA and study provides a more rigorous approach for evaluating the potential benefits of AM as an alternative to CM. A comprehensive summary of the study and its findings will be published in a forthcoming ORNL technical report.

3. AM MANUFACTURABILITY ASSESSMENT

3.1 Additive Manufacturing Assessment Process

The AM manufacturability assessment followed the standardized workflow depicted in Figure 1. Both conventional and additive manufacturing steps were developed for each part in order to evaluate the complexity and challenges associated with fabrication and to compare the two methods. It is noted that all parts evaluated in this study were originally designed for conventional manufacturing, so the CM manufacturing steps were therefore straightforward to evaluate. A professional machinist was asked to sequentially breakdown the steps required to fabricate each part beginning with material stock selection (e.g. 3” OD x 24” 4140 roundbar), followed by specification of the machine type to be used for each machining step (e.g. slat bed lathe with live y-axis tooling) and sequence of machining operations required to produce intermediate and final dimensions of the part.

AM steps were similarly broken down but required additional attention to material considerations and dimensional tolerances because AM compatible materials are not currently available for all parts evaluated, and the combination of material and dimensional requirements involved tradeoff comparison between potential AM technologies because of resolution capability and material availability. In cases where an AM feedstock is not currently available, alternative materials were recommended for manufacture. AM machine type, build orientation, special machine setting considerations (if necessary), additional support structure needs, additional CM machining required to achieve final tolerances, and post-processing of materials (e.g. heat treatment, nitriding, etc.) were specified. In some cases, hybrid machines with the flexibility to perform both additive manufacturing and subtractive machining were recommended. A brief opinion was then provided on whether or not there would be any advantage to production of the part by AM.

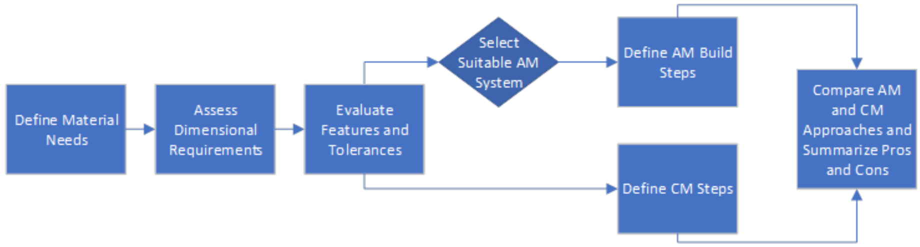


Figure 1: Manufacturability assessment process flow

3.2 Parts Selected for Evaluation

The parts selected for evaluation were intended to be representative of typical downhole tools used in the geothermal industry as well as more sophisticated hardware associated with developmental geothermal drilling technologies. This decision was made to capture a range of relevant technology features but was also because one of the participating organizations on the project, Sandia National Laboratories, was able to provide detail drawings of parts used in tools it has developed in recent years (Su et al 2017, Raymond 2018). Thermochem, a geothermal service company, was also gracious enough to provide drawings of parts from one of its proprietary tools. The part set collectively represents relevant form factors, complexity, and dimensional challenges associated with the manufacturing of downhole tools. In total, 17 parts were evaluated. These parts came from two drilling motor assemblies, a seismic monitoring tool and a logging tool. A subset of the parts is shown in Figure 2.

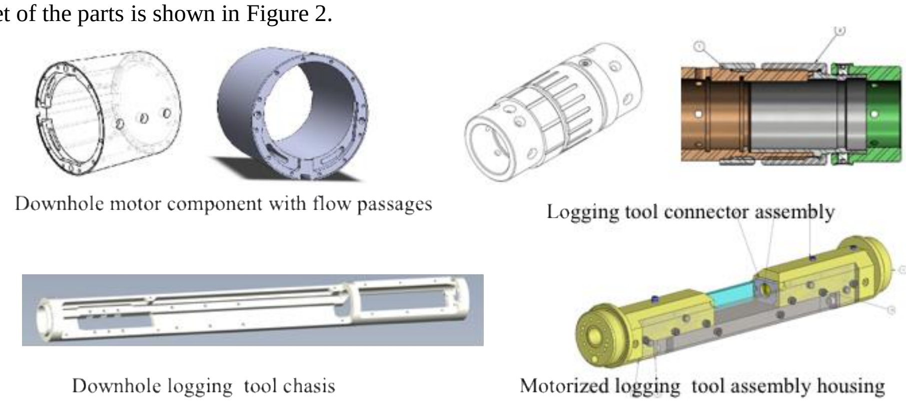


Figure 2: Example parts selected for evaluation

3.3 Materials Evaluation Summary

All parts selected for this study are composed of metals so only AM metal systems such as Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Directed Energy Deposition (DED) were considered in the manufacturability assessment. The commercial material inventory for metal AM is currently limited but several metal alloys relevant to geothermal applications, including super alloys, are commercially available (Frazier, 2014). Currently available AM feedstocks include commercial alloys such as Ti-6Al-4V, 6061 Al, H13 tool steel, 316 SS, 316L SS, 17-4 PH SS, and super alloys such as IN 625 and IN 718AM. The inventory of available powders and other feedstock forms for metal AM processes is continuously increasing with R&D and compelling business cases that justify development efforts.

Senvol analyzed the material and dimensional requirements for each part and verified whether or not a suitable AM feedstock material existed. If the material was not currently available, it outlined recommended procedures required to qualify the new powder for AM of and recommended an alternative material with comparable mechanical properties. For example, 4140 is not currently available as an AM powder but was used as the material for some of the parts. It was recommended that if 4140 powder is to be developed and used with an SLM AM system, evaluation and in-depth analysis of AM machine settings and parameters along with the optimized powder morphology must be performed for each type of OEM AM machine used to perform the SLM build. If DED AM equipment is used, the power and feed rates and particle size and shape must be optimized to achieve a true metallurgical bond along with end required mechanical properties of the material to meet the functional design requirements. In the case of 4140, 17-4 PH stainless steel was recommended as an alternative material. This material is available for a number of AM processes including SLM and DED. It is also commonly used as an alternative to 4140 in the O&G industry when improved corrosion resistance is required for the part because it has comparable strength and fatigue characteristics.

Similar evaluations were performed for all parts in the study and complete details will be available in the forthcoming ORNL technical report. Other materials in the original part set specifications include 8620, Nitronic 60, 17-4 PH, Aluminum 6061-T6, 316 SS. Only 316L and 17-4 PH are currently available in powder form for SLM, the preferred AM approach for most of the parts requiring high dimensional precision. Alternative powder materials were recommended for all other materials with the caveat that the final material properties would have to be evaluated against design requirements.

The materials included in the part set are generally aligned with the interviews conducted with geothermal and O&G OEMs prior to initiating the manufacturability assessment. All large companies interviewed had active programs associated with implementing AM and material selection and quality emerged as a significant consideration for all manufacturers. One particular material consideration that uniformly emerged is the high stress and cyclic loading typically experienced in many downhole applications. Materials with high yield stress and fatigue strength are therefore commonly used. This and other harsh environment material performance criteria such as hardness, abrasion resistance, and corrosion resistance must be evaluated following the AM part fabrication process to ensure that suitable properties are retained and design intent is met.

3.4 Features/Tolerances Evaluation Summary

The features and dimensional tolerances of a part are important for a number of reasons. In the case of CM, features and tolerances generally determine the type of machine that must be used to produce the feature, sequence of machining steps, setup requirements including holding or fixturing, potential for part warpage during fabrication, complexity of the machining operation, and skill required to produce the part. These factors are generally considered when designing the part and the design process often involves compromise between desired part functionality, the ability to fabricate desired features, and the cost associated with increased complexity.

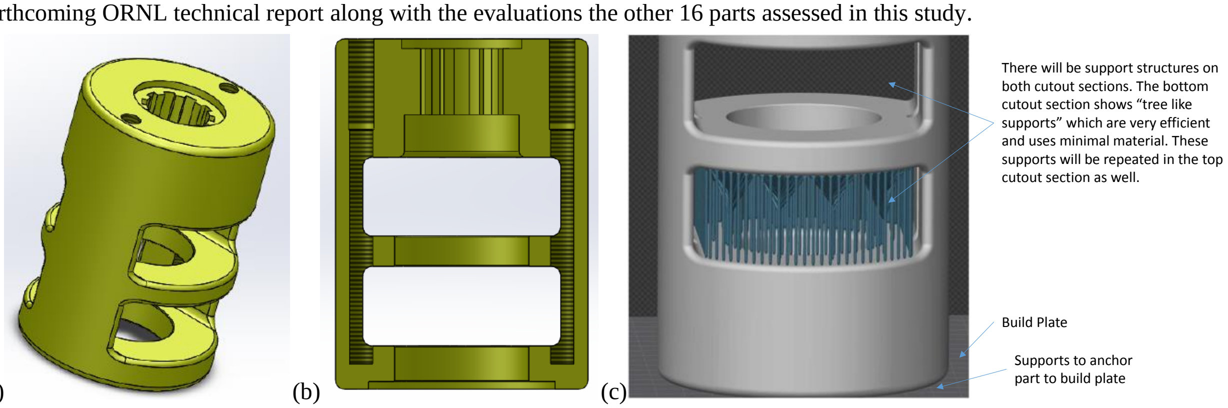
AM manufacturing possesses similar considerations, but build sequence is generally determined by: build orientation; energy deposition parameters to optimize the speed of the build; optimization of energy deposition parameters to achieve desired dimensional tolerances; optimization of energy deposition parameters to minimize warpage and residual stresses; and the need to add structure to support overhanging features or increase structural stiffness during the build. Some general observations were:

- Tolerances less than 0.005 inches generally require post-build machining because of AM resolution limits
- Fine features, such as threads, typically require post-build machining
- Surface finishes below 32 microinches typically require post-build machining

On the other hand, it was noted that the build process for AM can have the comparative advantage of improved efficiency, particularly for features that involve removal of large amounts of material such as boring, and incremental or no additional cost associated with additional complexity because the sequence of fabrication operation steps are largely contingent on the placement and intensity control of an energy source (e.g. laser or electron beam). The layer-by-layer build approach for additive processes allows for the fabrication of arbitrarily complex shapes by manipulation of the energy beam or print head provided that certain structural and process guidelines are followed, e.g. overhang constraints and minimization of warpage associated with large thermal gradients (Gaynor and Guest, 2016). Subtractive fabrication processes from monolithic feedstocks, by comparison, can require planning of complex operational sequencing, challenging setup requirements, and there are physical limits to the types of structures that can be produced because material removal, as opposed to deposition, is the method for producing geometry. As will be shown in the TEA section, the sequential nature of CM tends to proportionately increase the time and cost required to produce the part as the number of features increases. This is not the case for AM for reasons that will be explained later. With respect to complexity, features such as closed cavities or tortuous internal cavities, for example, can in some cases be easy to produce additively whereas those same features might be impossible or more difficult to produce subtractively. Creation of closed cavities using CM in particular typically involves the production of two or more pieces followed by a joining method.

3.5 Example AM Part Manufacturability Assessment

Excerpts from an assessment of the motor shaft coupling part shown in Figure 3 below are given in this section to provide an example of the nature of the manufacturability assessment. The complete evaluation for this part is 8 pages long and will be found in the forthcoming ORNL technical report along with the evaluations the other 16 parts assessed in this study.



(a) (b) (c)

Figure 3: (a) Isometric and (b) Cross-section views of motor shaft coupling as designed. (c) Support structures needed for AM of part

<u>Material Considerations:</u> The design drawing for this part calls out AISI 8620 or 4320 to be case hardened to 57-60HRc to a case depth of .040-.060 inches. This case hardening is to a substantial depth alluding to required strength, impact and wear characteristics required

for functional performance. Additional material considerations are provided related to AISI 8620 as part of the Senvol report and an alternative material, 17-4 PH, is recommended for AM of the part. Options for hardening the material to meet hardness requirements, if needed, including heat treatment, boriding and nitriding.

Geometry: This part is its finished state is nominally 5.75 inches in length and 4.150 inches at its maximum finished diameter. There are numerous Laser Powder Bed Fusion (LPBF) systems that can build this part and multiples of this part simultaneously. DED, as well as Hybrid multi-axis machines that use DED, could also AM build and concurrently machine this part during AM build.

Features/Tolerances: This part has several tight tolerance dimensions that can only be manufactured through conventional methods as outlined in the Conventional section below. The tightest tolerance is a +.0000/-.0005 inch dimension on an outside end which can be readily achieved via conventional machining. There are other features such as the sprockets that have a +.002/-.000 inch tolerance. There is a +.005/-,000 inch tolerance on an inside bore. All of these can only be accomplished via conventional machining methods. All threads must be machined into the part using conventional methods. The set-ups described in the Conventional section below are all required to achieving these tight tolerances on the part even if a near net shape part is built via AM first. The dimensioning of this part was reviewed by ORNL and, where it did not compromise design intent, dimensions were relaxed. This greatly improved the ease and potential benefits of fabricating this part using AM.

Potential AM Steps: Due to the relatively small size of the part and the selection of a common AM material, 17-4 PH, the number of laser powder bed fusion AM machines that could potentially manufacture this part is quite large. It is recommended to use a laser power bed fusion AM machine, such as a 3D Systems ProX 320 or an EOS M290 machine. Additionally, several parts could be laid out on one build bed to decrease cost per part. A quick search of the Senvol Database (www.senvol.com/database) of LPBF machines that process steel materials and that are larger than the overall dimensions of the part showed that nearly 100 AM machines would potentially be suitable for making this part.

It is recommended that the part be AM built in the Z axis of orientation on the build plate as indicated in Figure 3(c). The z-orientation of build minimizes the number of overhangs that require support structures. This helps to reduce build time and the amount of 17-4 PH powder required to perform the AM build. The Hammer Frame larger mass is recommended to be AM built closer to the build plate as shown in the below pictorial to help provide additional control of residual stress buildup as the part is AM built. To ensure concentricity and perpendicularity of the part and to machine the "sprocket" hole, additional material of .020" to .030" on either end is recommended to be added. This will be machined off later to true up the part and provide well defined surface datums for subsequent required conventional machining.

By controlling the size and shape of the support structures as indicated, they can be easily removed and deburred by hand. A hand polish of these surface via the use of a Dremel tool or Pencil Grinder (pneumatic tool with light sand paper) would be sufficient to clean up these areas and any surface artifacts from the AM build where the support structures were necessary to complete the build of the part features. In addition to the hand removal of these supports, a light glass bead blast of the outside surfaces to further clean up all outside surfaces is recommended. The support structures depicted in the pictorial would be repeated on the AM build of top end of the Hammer Frame as this top surface is an overhanging surface.

It is recommended that a 1.31" diameter center hole be AM built into the part in its top section for later conventional machining to the final "sprocket" dimensions as indicated in Detail B of drawing DW-0202. The 2.20" diameter on the opposite end of the 1.31" diameter AM built hole can be AM built and be considered a finished as-built dimension due to the dimensional relief provided.

Not shown in the above pictorial are the support structure required to anchor the part to the build plate. These support structure would be attached around the base of the part. The support structures extending from the build plate to the bottom surface of the Hammer Frame can be either saw cut off the base plate or removed from the base plate via wire EDM after stress relieving the Hammer Frame on the build plate.

After the build is complete, the entire build plate with the parts attached would be stress relieved. A standard stress relief recipe of heating at 1150°F for 3-4 hours, followed by oven cooling to room temperature is suggested.

All pink and yellow highlighted dimensions, as noted in the drawing (included in the forthcoming ORNL technical report), indicate relaxed dimensional tolerances that can be achieved in the as-built AM condition. Not having to machine and bevel the edges of the outside surface edges of the slots removes several machine set-ups and required machining saving both time and cost.

All other features (those in green, sprockets and all threaded hole) will be required to be machined into the near net shape AM built Hammer Frame. A Mazak Integrex or a Mori NTX or NT with opposing spindles would be ideal to perform the required post AM build final machining. (The specific details of post-build machining are provided in the forthcoming ORNL technical report).

3.6 Key Takeaways from AM Manufacturability Assessment

Of the 17 parts that were selected for evaluation, all parts could potentially be fabricated by additive manufacturing, although many would require the use of an alternative material and conventional machining to produce features with the desired tolerances. In many cases, Senvol indicated that there was not an obvious advantage to producing the part using AM vs CM. This is not surprising given that all parts evaluated in the assessment were designed for conventional manufacturing. Many attempt to utilize additive manufacturing as a replacement for conventional manufacturing without re-designing the part: this is, almost always, a mistake as none of the benefits offered by AM are exploited. A production part that was designed for multi-axis CNC machining will generally be more expensive to manufacture using AM and is likely to still require CNC machining to give it the required surface quality and achieve tight tolerance dimensional accuracy that cannot be obtained with AM alone. There is general agreement that for AM to offer maximum value the parts must be designed for additive manufacturing (DfAM). Additional takeaways are noted below:

- Compared to conventional manufacturing, AM materials are still very limited and the vast majority of the materials that are called out on the drawings are not readily available in AM. Even if the material is advertised as being available in metal powder for AM that does not mean that there are known or validated AM process parameters to process that material. In other words, availability of metal powder does not equate manufacturability in AM. The number of AM candidate parts would increase if there was an expansion in the number of AM materials, particularly materials that are commonly used for geothermal applications.
- In addition to having more AM materials available, an understanding of how post-processing steps such as stress relief or heat treatment would affect material properties is needed in order make more detailed recommendations on AM process steps. This is not such an issue for conventional manufacturing as material properties are already well defined and post-processing steps are well known. The number of AM candidate parts would increase if AM materials had well documented relationships between material properties/performance and AM processing steps and post-processing steps.
- There are a wide variety of AM processes but for metal, the most common are LPBF and DED. Hybrid is also a possibility, but that technology is less proven. In general, LPBF machines are best suited for making small precise parts, whereas DED machines are best suited for making large but more imprecise or near net shape parts. However, the precision that is achieved by LPBF is still not sufficient to avoid post-processing or machining. Hence, production of a near net shape in AM does not diminish in any significant way the number of machining steps that are needed to achieve tolerances. The number of AM candidate parts would increase if AM could increase its accuracy and surface finish and reduce the amount of support materials needed.
- An understanding of the functional requirements is critical in attempting to consolidate parts into a monolithic assembly that could be made via AM. Since the current parts have already been optimized for manufacturing via conventional manufacturing techniques, it is very unlikely that such a part could be more suited for AM, since AM is often at odds with conventional manufacturing techniques. Hence, in order for parts to be more appropriate for AM than for conventional, a re-design is often necessary. But without an understanding of the functional requirements a re-design is not within the scope of this document nor possible. The number of AM candidate parts would increase if functional design requirements were known and the parts could be redesigned for AM.

4. TECHNOECONOMIC ANALYSIS OF CONVENTIONAL VERSUS ADDITIVE MANUFACTURING

4.2 TEA Methodology

The first phase of the TEA reviewed the manufacturability assessment performed by Senvol in order to identify fundamental drivers that influence the construction and cost of CM and AM. These fundamental drivers include material, geometry, features & tolerances, manufacturing technology, and operation type. This evaluation was used to develop a calculator for estimating part costs for both AM and CM. Cost estimate procedures were developed for different manufacturing technologies using a parametric breakdown of the fundamental drivers described above. Interviews with CM and AM fabrication subject matter experts were also conducted to obtain more specific CM and AM data on cost-impacting parameters. The calculator was then applied to the 17 geothermal parts analyzed in the manufacturability assessment. Costs and fabrication time were calculated for both CM and AM. Cost quotes from two online machine shops (3D Hubs and Xometry), three machinists, ORNL subject matter experts and, in one case, actual fabricated part cost from a geothermal OEM were obtained to test the accuracy of the calculators. Technoeconomic analysis of the part set was then performed using the calculator to identify primary cost drivers, part characteristics driving cost and production time, and potential economy of scale benefits.

4.3 Cost and Time Calculation Overview

4.3.1 CM Calculator Calculation

Input parameters developed for the CM cost analysis include feedstock material cost, number of parts to be produced, machinist and shop hourly rate, and machining time. In the case of machining time, an approach was developed to estimate the time associated with the individual machining operations used to produce the part, based on the part features. This approach was based on defining a correlation between the mass removed during each operation, which can be determined from the CAD solid model of the part, and the time estimated to perform each operation. A set of generalized machining operations was first defined: bore, drill, face, mill, turn and other. In the case of the 17 parts analyzed, a machinist was used to estimate the time required for each machining operation performed on the part set. A precision level indicator (Precise, Normal or Quick) was then used to distinguish operations of a type requiring different feature tolerances. This precision level descriptor was assigned based on a weighted average of the mass removed and the quoted time to complete the step. Time and mass removed were normalized and equally weighted for each operation (mill, drill, bore, etc.) to create a score between zero and one as determined by equation (1) below

$$W = 0.5\left(\frac{m_r}{\bar{m}_r}\right) + 0.5\left(\frac{t}{\bar{t}}\right) \quad (1)$$

where m_r is mass removed, t is the time to complete the CM operation, and the overbar represents the maximum value observed in the data for the specified operation type. The precision labels were applied based on this score: Quick for a score less than 0.33, Precise for a score greater than 0.67, and Normal for a score in between.

This approach allows the time required to machine the part to be approximated by defining the sequence of machining operations including the operation type and precision. Accuracy of the time calculation was checked by comparing the calculator time estimate to the machinist estimate for producing the part. For the entire part data set, the calculator estimate average was within 7% of the machinist's estimate with a standard deviation of 10.4%. Screenshots of the summary and CM input tabs of the calculator developed for these calculations are shown below in Figure 3. A comparison of the calculator cost estimate to quoted costs from four other sources and a breakdown of the number of machining operations by precision and time for all 17 parts are shown in Figure 4(a) and Figure 4(b) respectively.

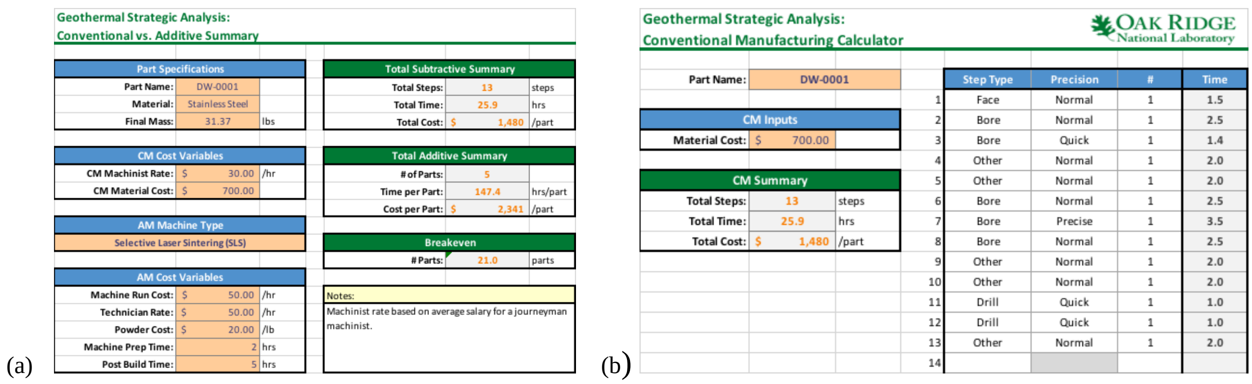


Figure 3: (a) Summary and (b) Detail tab screenshots for CM calculator

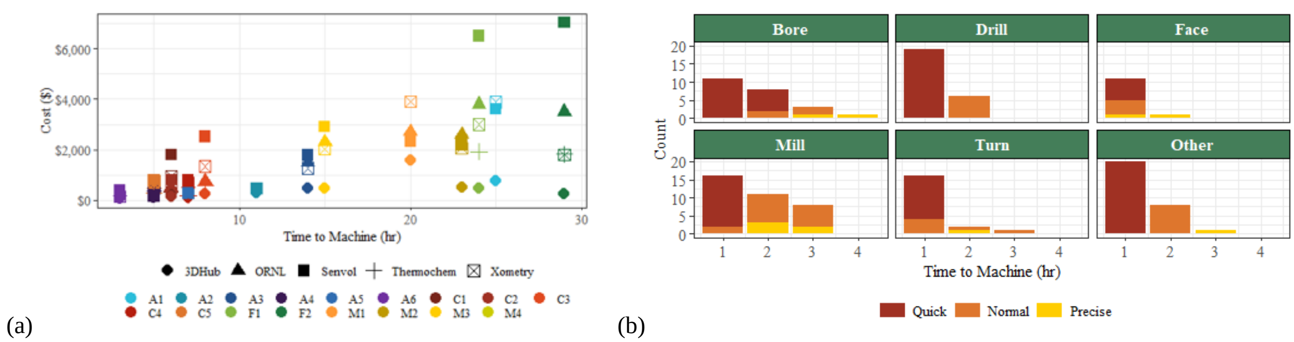


Figure 4: (a) Comparison of cost quotes to time to machine (CM) from 5 sources and (b) Breakdown of machining time by operation

4.3.2 AM Calculator

The AM cost calculations similarly have material feedstock, setup and post-processing cost components. AM material feedstocks for powder-based systems in particular are significantly more expensive than the bulk materials used for CM, largely due to the current size of the market for such materials. Setup and post-processing for AM generally involves actions such as loading material into the printer (powder or wire), uploading build files into the machine, and machine warm-up procedures. Post-processing time includes powder recovery and recycling, removal from the build plate (while this typically involves machining, this input value excludes additional machining time), and heat treatment. Many AM parts also require post-process machining to improve surface finish and achieve tight tolerances. The machining time involved in post-processing of AM parts is comparatively much lower than for CM because less removal of material is required (AM inherently produces near net-shape parts) but setup involves comparable times. Each of these factors is accounted for in the calculator.

The time and associated cost with building the AM part is highly dependent on the machine type used. For the purposes of this study, generic calculators were developed for SLM and DED systems. In the case of SLM systems, the calculator allows for the specification the number of layers in a part and average time to build each layer (including layer preparation). Additional input parameters include scan rate (e.g. linear speed of the laser over the layer), hatch distance (i.e. distance between rasters of the laser scan), and layer heat time. The DED time and cost estimations are based on specification of the mass deposition rate of the printer. Both SLM and DED cost calculators also allow specification of post-build CM operations required to meet part tolerance requirements. An example screenshot of the SLM input tab is shown in the figure below.

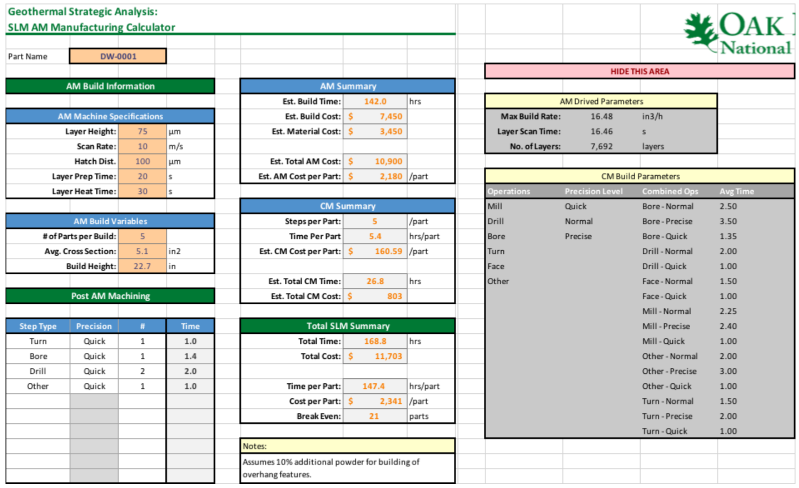


Figure 5: Example SLM cost input tab of AM calculator

4.4 TEA Results

A comprehensive summary of the TEA findings and conclusions is beyond the scope of this paper and will be found in the forthcoming ORNL technical report. The following results are meant to highlight fabrication time drivers for the parts using the different manufacturing methods, primary factors driving part cost, and economy of scale considerations. This discussion is also meant to illustrate the value of the calculators for evaluating the benefits of manufacturing the part by AM versus CM. It is again noted that all of the parts selected for evaluation were designed for CM; had they been designed for AM it is likely that cost to manufacture could have been significantly improved.

Estimates of the fabrication time for each part by manufacturing method are shown in Figure 6. A few points of clarification for this figure are needed to prevent misinterpretation of what is shown. In the case of CM, the time shown reflects the sum of setup and processing time for the discrete steps required to fabricate the part. This does not necessarily reflect the total time required to build the part. It does not take into account material procurement lead time, scheduling of the machining, daily work shifts and down time when the shop is closed, as well as other aspects of the discrete nature of CM. AM is generally a continuous process once the build file has been developed and material has been loaded into the machine, with the exception of post-build processing. It is therefore likely the case that many of the parts in this study could be manufactured significantly more quickly using AM if these other discrete CM characteristics, which are difficult to quantify and highly variable, are accounted for. Furthermore, as will be shown in the economy of scale section, SLM AM systems are capable of producing many parts during a single build provided that the parts fit within the build volume. This ability to produce multiple parts simultaneously using a single machine significantly decrease the time to manufacture parts in quantity and is not possible with CM.

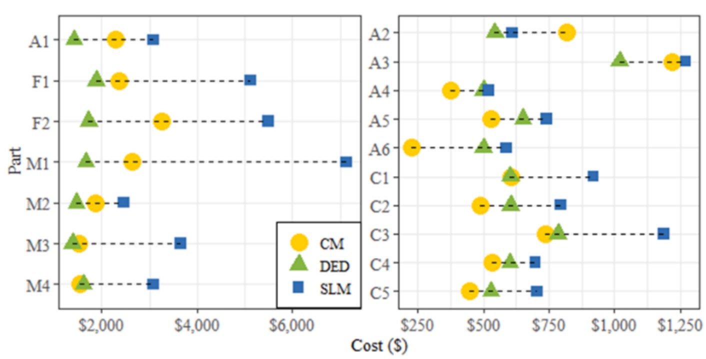


Figure 6: Comparison of calculated production times for AM and CM

A cost comparison of producing a single part by manufacturing method is shown below in Figure 7 broken down by categories of material, printing, machining and pre/post processing. CM and AM costs are dominated by the cost of machining and printing, with the exception of DED which required extensive post-process machining for the 17-part set. In the case of CM, machining costs are driven by labor or the capital cost of the equipment, depending on the level of automation. CNC machining, for example, is largely automated but has a higher capital cost investment than manual machining equipment. AM printing costs are largely driven by the capital cost of the AM system which, in the case of metal parts, can be 45% - 74% of the total part cost according to a NIST study performed in 2014 (Thomas and Gilbert 2014). This is consistent with the estimates of the SLM calculator. As AM market penetration grows and the number of AM production systems increases, it is reasonable to expect that the cost of metal AM systems will decrease. This reduction in costs is consistent with historical trends and is increasingly making AM more competitive with CM as fixed costs for AM drop (Hagel et al 2015).

Not captured in this cost analysis is the unique expertise sometimes required to fabricate parts by CM. Delicate (e.g. parts with slender features) or complex features often require machinists with high skill level or vision to fabricate. The frame parts denoted as F1 and F2 in the part set (see "Downhole tool logging chassis" in Figure 2), for example, require special fixturing to fabricate because of their high slender features and susceptibility to warpage during fabrication. Such specialized manufacturing requirements are not typically captured in the design package for the part and must be developed on an as needed basis by the machine shop. This can add significant cost and fabrication time. Because AM fabrication typically requires the specification of energy deposition parameters and warpage considerations, optimal manufacturing parameters for a part can be developed based on the AM system and incorporated into the CAD package for the part allowing it to be more easily fabricated by a larger field of potential shops provided that the build capabilities of the AM system are suitable. This is of great potential utility for the geothermal industry where the fabrication of tools is often on an as needed basis and there is a risk of losing an in-depth understanding of how to fabricate specialized hardware within the manufacturing ecosystem. Similar concerns were voiced during the interviews with O&G service companies. Many service companies use a select group of machine shops with specialized tooling for making specific products. The unique knowledge and tooling required to make these tools limits the ability to drive down the costs of producing these parts, which tend to be low production volume as is characteristic for the industry.

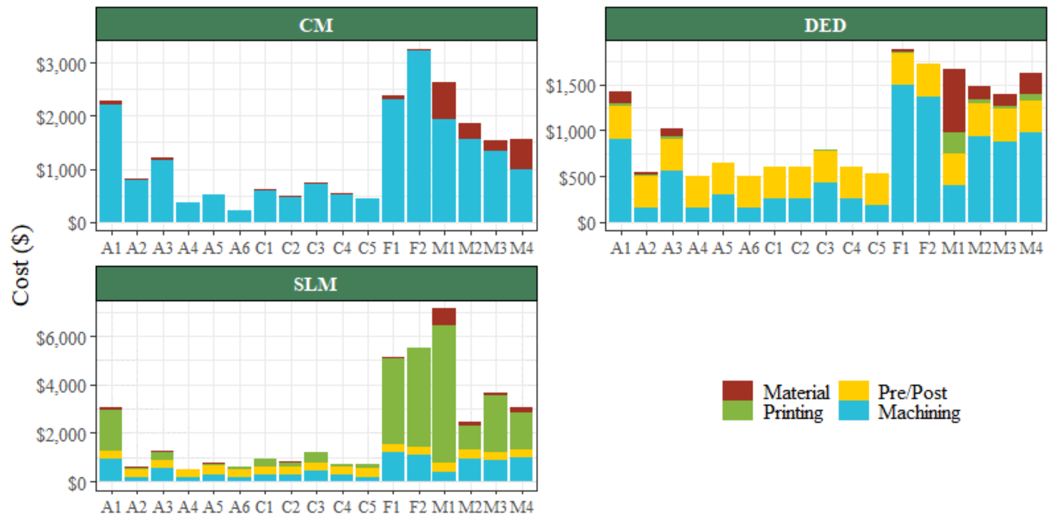


Figure 7: Cost breakdown by material, printing, pre- and post- printing activities and machining for all 17 parts

From a purely economic perspective, the cost and production time benefits of AM are often not favorable to CM if only a single part is made. However, the fabrication of a single part is generally not as favorable as mass production, regardless of the manufacturing method. The TEA calculator was therefore used to explore economy of scale considerations by estimating the individual part costs if up to ten parts were produced. This low production volume is consistent with the numbers typical of geothermal and O&G subsurface applications involving well construction and logging. A bulk discount rate of 20%, 40%, and 60% for the production of 2, 5 and 10 parts, respectively, was defined for machining based on interviews with machine shops. These discounts come primarily from efficiency improvements related to machine setup for each fabrication step. It is recognized that this discount is not a universal rule. The cost benefits of increased production volume for AM have a similar basis for DED, for which cost is largely determined by material deposition rate when the system utilizes a single print head, though a discount is still applied to the post-printing machining.

Cost benefits of increased production for powder bed systems, such as SLM, arise because multiple parts can be produced within the build volume and because the time to build each layer of the part is dominated by the raking of the layer and pre-heating. The rapid raster scan speed of the laser results in energy deposition being a comparatively smaller time component of the build process, making the inclusion of multiple parts a trivial addition to the total print time. Part M1, for example, was estimated to have a layer scan time of 3.3 seconds and 50 seconds for layer preparation and heating. If 10 parts can be spatially arranged to fit on the build plate then the layer print time becomes 83 seconds, less than twice the time required to build a layer for a single part. The potential for SLM to provide volume discounts is therefore quite large because part cost is dominated by print time, which is less dependent on the number of parts per layer, and many parts can be included in a single build, provided that they fit on the machine's build plate. The TEA calculator has an expedient algorithm for estimating how many parts can fit on a build plate based on the build plate dimensions and a simplified representation of the cross-sectional dimensions of the part.

Figure 8: Economy of scale comparison for three different manufacturing methods compares the economy of scale benefits for the three manufacturing methods for parts A1 through A6 and Table 1 summarizes the least expensive method based on production number, but also including mass removed and build height of the part. It is evident from this data set that CM and AM

using DED are the most cost-effective fabrication methods when only a single part is made. However, as production volume increased to 10, SLM became more economical for 13 of the 17 parts.

Figure 8: Economy of scale comparison for three different manufacturing methods

Table 1: Least expensive technology for each part based on production numbers

Part	CM Mass Removed (lb)	Build height (in)	Least expensive technology based on production			
			1	2	5	10
A6	0.02	0.375	CM	CM	CM	CM
A4	0.04	0.08	CM	SLM	SLM	SLM
A5	0.15	0.38	CM	CM	SLM	SLM
C4	0.16	0.406	CM	SLM	SLM	SLM
C5	0.28	0.75	CM	CM	SLM	SLM
C2	0.30	0.813	CM	CM	SLM	SLM
C1	0.33	1.348	DED	CM	SLM	SLM
C3	0.63	1.713	CM	CM	SLM	SLM
F2	2.53	17.25	DED	DED	DED	SLM
A2	3.27	0.25	DED	SLM	SLM	SLM
A3	6.84	0.969	DED	SLM	SLM	SLM
F1	11.39	15	DED	DED	DED	SLM
A1	18.72	6.906	DED	DED	DED	SLM
M3	19.46	9.58	DED	DED	CM	CM
M2	25.00	4.06	DED	DED	SLM	SLM
M4	26.54	5.75	CM	CM	CM	CM
M1	64.49	22.71	DED	DED	DED	CM
CM Least Expensive			8	7	3	4
DED Least Expensive			9	6	4	0
SLM Least Expensive			0	4	10	13

This economy scale for SLM also applies to complete utilization of the build volume, regardless of whether or not the parts are identical. This has potential benefits if many of the components of a geothermal tool can be fabricated using SLM. A complete tool was not analyzed in this study, but a comparable analysis exercise can be performed by placing all of the analyzed geothermal AM parts into a single build box, including duplicates (i.e., Assembly 1, 2, 4, and 5) that are required to completely populate the build volume. Figure 9 shows the footprint of each part placed in a 19.75” by 11” by 33.5” build box, with the left of the figure showing the print configuration from the top perspective view of the build plate and the right showing the side perspective view. Machine time alone for all these parts using CM (not including factors such as material lead time, shop operating shifts, etc.) would take over 290 hours and cost approximately $24,500 (including the economy of scale discount for the duplicate parts). However, printing them with SLM would take less than 260 hours and cost less than $18,200. This example demonstrates how properly planning a build to most effectively utilize the build box could make SLM a more attractive option for geothermal tool manufacturing.

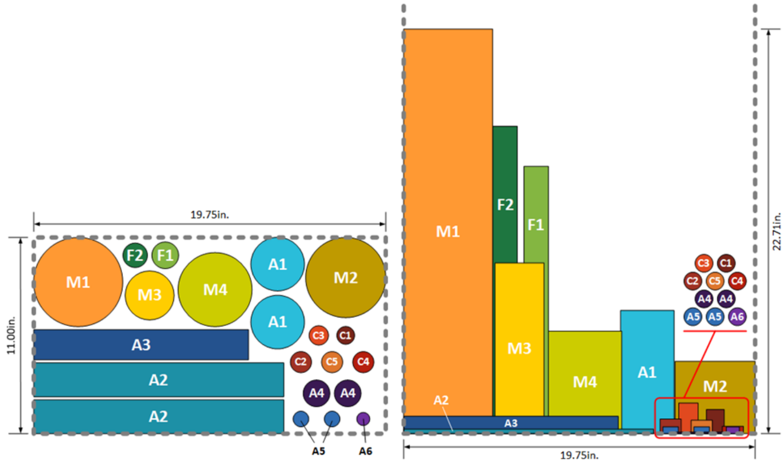


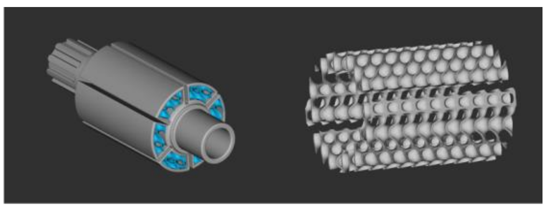
Figure 9: Possible configuration to print all 17 analyzed parts in a single SLM print as viewed from above (left) and the side (right)

5. ADDITIONAL DESIGN CONSIDERATIONS

This section provides a brief example of another potential benefit of AM that was not explored in the TEA. It was remarked in section 3 that the parts evaluated as part of this study were designed and optimized for CM and therefore did not utilize the characteristics of AM that can improve manufacturing economics. Another potential benefit of AM not explored in the TEA is the fabrication of parts with improved performance characteristics or reduced assembly requirements that cannot be fabricated conventionally.

To illustrate an example of the potential benefit of performance improvement enabled by AM, one part was selected for enhanced performance evaluation following the in-depth face-to-face design analyses of geothermal tools developed by Sandia National Laboratory (SNL) researchers. Figure 10 shows an original version of a rotor that is part of a vane motor in a drilling tool and a version of the part redesigned for AM. The objective of this design exercise was to improve the power transmission characteristics of the rotor by significantly reducing its polar moment of inertia. The part redesign utilized topological optimization to develop a rotor configuration with a polar moment of inertia that is roughly half of the original. With this redesign, the rotational speed of the rotor increases by 27% and the maximum speed of the motor assembly increases by 5% without significant compromise of rotor rotational stiffness. The topologically optimized rotor shown in Figure 11(b) could not be practically manufactured conventionally. Optimization of the other components in the drive train could lead to additional performance improvements but are beyond the scope of this simple exercise. The improvement of component functionality and performance enabled by novel manufacturing capabilities such a AM has tremendous potential for impact that is likely to grow as old design constraints imposed by manufacturing limitations are eliminated and new design methodologies such as topological optimization and generative design become more widely used by the design community.

(a) Original Part



(b) Topologically Optimized Part

Figure 10: (a) Original and (b) Redesigned rotor part

6. CONCLUSIONS

An overview of an in-depth manufacturability and techno-economic assessment (TEA) of the potential benefits of additive manufacturing for advancing geothermal tool development was provided in this paper. The manufacturability assessment found that many of the materials used in the evaluated part set are not currently available for AM systems that utilize powder as a feedstock material. This is primarily a consequence of the relative immaturity of the metal AM industry and is likely to change as the industry grows and builds its material inventory. It was also initially found that in many cases there was not an obvious advantage to fabricating the part using AM because the part had been designed for CM and did not utilize the advantages of AM. Design for Additive Manufacturing (DfAM) was recommended as a practice to more fairly compare CM and AM approaches. In some cases, dimensional tolerances of parts were relaxed without compromising design intent and AM was found to be potentially favorable from a cost and production time perspective.

The TEA portion of this study developed a set of calculators that broke down the manufacturing processes and estimated cost and production times for CM and two AM processes (selective laser melting and directed energy deposition). These calculators were used to quantitatively compared the three manufacturing methods. It found that CM and DED AM were each more cost-effective for roughly half of the analyzed part set. When economy of scale was considered for up to 10 parts it was found the SLM AM was more cost-effective for 13 of 17 of the parts. While a complete geothermal tool was not evaluated in the study, the potential benefits of simultaneously fabricating multiple parts in a single SLM build was explored (by building all of the parts evaluated in the study on a single build plate) and a 25% percent reduction in the cost and a 10% reduction in the machining/printing time was found compared to fabricating all the parts using CM.

The results of the manufacturability assessment and TEA confirm that while there are improvements needed to make metal AM in particular more viable for fabrication of geothermal tools, there is great potential for improving the economics and production time of geothermal tool production using this emerging advanced manufacturing method.

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