Directed Energy Deposition Additive Manufacturing Supplier Sourcing for Aerospace

by

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Submitted to the MIT Sloan School of Management
MIT Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of
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Master of Science in Mechanical Engineering
in conjunction with the Leaders for Global Operations program
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Abstract

Pratt & Whitney (P&W) is a major aerospace Original Equipment Manufacturer (OEM) of gas turbine engines for both commercial and military sectors. Historically aerospace part designs require more iterations compared to other industries due to the high level of complexity and the need to minimize weight on the aircraft. P&W has been utilizing Additive Manufacturing (AM) for rapid prototyping and Research & Development (R&D) cost reduction for three decades. However, most of the past metal additive manufacturing applications have utilized Powder Bed Fusion technology, which has limited size and unique capabilities. P&W wants to explore the potential of Directed Energy Deposition (DED), an AM technology that could be used for bigger parts and adding features to existing parts.

The project objective is to bring on DED suppliers to enable the acquisition of development metal hardware for P&W's advanced programs. We do this first by learning about the technology and gathering information on prominent suppliers via virtual interviews and site visits. We then come up with a list of criteria based on P&W's advance program outsourcing needs and evaluate the suppliers based on the criteria. The final product of this project is a report to P&W documenting all the findings on suppliers and final scores for each of the suppliers based on the criteria we developed for evaluation.

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Acronyms

ACT Joining Tech - American Cladding Technologies. 7, 28, 29, 39
AHP Analytic Hierarchy Process. 7, 41, 42, 44, 49, 53, 55
AM Additive Manufacturing. 2, 3, 13–15, 17, 20, 23, 24, 29, 30, 32–34, 37, 42, 43, 45, 46, 49, 51, 53–56
ASTM American Society for Testing and Materials. 34

CAD Computer-aided Design. 14, 17
CAGR Compound Annual Growth Rate. 13
Company A . 34, 35, 39
Company B . 35, 36, 39, 46
Company C . 37–39

DED Directed Energy Deposition. 2, 5, 7, 13–15, 17–20, 22–25, 27, 28, 30, 32–37, 39, 44, 48, 54–56

EBAM Electron Beam Additive Manufacturing. 19

FAA Federal Aviation Administration. 24

LE Lincoln Electric. 29–31, 39
LGO MIT Leaders for Global Operations Program. 3, 13

NDA Non-disclosure Agreement. 15, 28, 38

OEM Original Equipment Manufacturer. 2, 24, 32, 33, 39

P&W Pratt & Whitney. 2, 3, 13–15, 27, 28, 41, 45, 49, 54–56

PBF Powder Bed Fusion. 14, 20, 22, 23, 32

PPM Parts Per Million. 28

R&D Research & Development. 2, 27, 30, 32, 39, 47, 50, 53

RPD™ Rapid Plasma Deposition™. 23

TRL Technology Readiness Level. 56

TRUMPF The TRUMPF Group. 28, 32, 33, 39

WAAM Wire Arc Additive Manufacturing. 30

Chapter 1

Introduction

Pratt & Whitney, a division of Raytheon Technologies Corporation, is a world leader in the design, manufacture, and service of aircraft engines and auxiliary power units[1]. P&W was founded in 1925 and headquartered in East Hartford, Connecticut. In 2020, P&W reported 36,000 employees globally and net sales of $17.2 billion. The global aircraft engine market is valued at $60.8 billion in 2021 and expected to reach $92.9 billion by the end of 2026, at a Compound Annual Growth Rate (CAGR) of 8.9% from 2021 to 2026[2]. As a major player in the global aircraft engine market, P&W is actively pursuing state-of-the-art technology to improve product quality and shorten the developmental cycle for new products. Additive Manufacturing (AM) is one of the technologies that P&W has been invested in since the 1980s. This chapter is an introduction to the AM DED project and an overview of the rest of the thesis.

1.1 Problem Motivation and Problem Statement

The concepts that laid the foundation for Additive Manufacturing (AM) can be traced to the mid 1950s. Jeff Epperson (LGO'21), wrote a concise summary of eight different types of AM technologies as well as their applications in the chapter four of his thesis[7]. The focus of this thesis is metal AM - Directed Energy Deposition (DED). DED is an AM process that uses high-intensity energy sources such as laser, electron beam, or plasma arc to selectively deposit metal powder or wire, layer-by-layer, to shape three dimensional components, directly from the Computer-aided Design (CAD) model[17].

Due to the lack of technology maturity in the past, DED was primarily used for part repair and metal cladding. P&W has explored DED in the past, however the available data and proven application at the time were not promising enough to warrant more investment into the technology. As the technology matures, more desirable applications such as printing large metal parts with competitive quality against casting parts and adding high resolution features onto existing parts became available. Other established metal AM technologies such as Powder Bed Fusion (PBF) are usually limited by the size of the part, or not able to build on existing structures. P&W is interested in tapping into those DED applications which could enable faster design iterations and part optimizations for developmental hardware in Advanced Programs and to complement other AM technologies.

1.2 Project Approach

To further understand the current capabilities of the existing DED resources in the market, P&W can either procure machines and build parts in-house, or send out purchase orders to the qualified suppliers who provide DED services. Procuring DED machines requires a large amount of up-front capital investment while bringing on suppliers for part production services is a more economical choice, given the current knowledge of the state-of-the-art DED capabilities and the desire to establish relationships with DED suppliers. Thus, the decision was made to onboard DED suppliers to enable the acquisition of development hardware for various Advanced Programs.

The approach of this project is to explore the DED AM supplier landscape via a series of steps (not necessarily in the exact sequence as listed):

1. Conduct open-source web searches on DED suppliers, research the companies and contact them via websites.

2. Conduct initial virtual interviews once contact is established.

3. Down-select companies based on established criteria.
4. Establish Non-disclosure Agreement (NDA)s.
5. Conduct supplier site visits.
6. Refine selection criteria.
7. Request for quotes using relevant parts.
8. Document the findings and construct a report / matrix to aid P&W's AM outsourcing needs.

1.3 Thesis Organization

This thesis starts with an introduction to layout the motivation and problem statement of this project. Chapter two discusses the technical details of DED, the pros and cons of DED compared to other AM methods, and some existing use cases of DED applications in Aerospace. Chapter three documents detailed information on the DED suppliers after on-site visits. Permissions to share supplier information were obtained prior to drafting of this thesis. Some of the supplier company names are codified for proprietary reasons. Chapter four details the framework of the supplier selection criteria and results (modified for proprietary reason). Chapter five provides a summary of the thesis and recommendations for future research opportunities.

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Chapter 2

Literature Review

The purpose of this chapter is to showcase what DED is, the advantage and disadvantage of DED compared to other metal AM methods available on the market, and selected use cases of DED applications in aerospace. This chapter should outline the foundation of knowledge needed to understand DED and its state-of-the-art applications.

2.1 Directed Energy Deposition (DED) Overview

DED is a technology that can be applied to build parts from scratch, add features to existing parts, or repair damaged or worn ones. As with any 3D printing/AM technique, the design of a part begins with the creation of the 3D model using CAD. The part is then cut into a multitude of layers by slicing software, representing the various layers of material needed to form the piece. The resulting file is typically a .stl or .stp file that can be loaded into a 3D printing machine and get translated into tool path for additive manufacturing of the part.

Once the tool path is loaded into the machine, the DED technique works by depositing material onto a base or component that is being repaired through a nozzle mounted on a multi (usually 4 or 5) axis arm. The metal material that is fed to the nozzle is either provided in wire or powder form. As it is being deposited, a heat source melts the material simultaneously, usually using an electron beam, laser or plasma arc

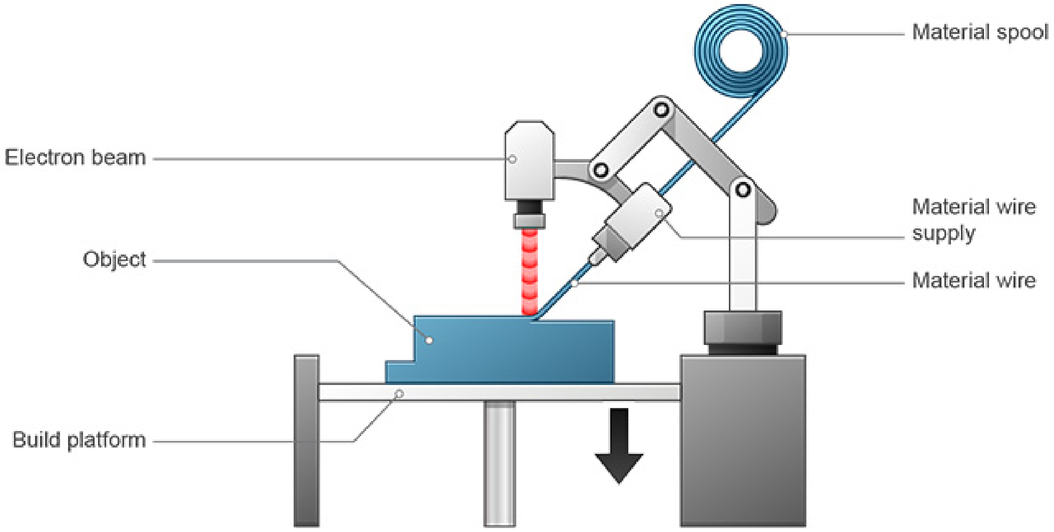

Figure 2-1: The DED additive manufacturing process using an electron beam[16]

(see Figure 2-1 for an graphic illustration of the electron beam DED process). This procedure is done repeatedly, until the layers have solidified and created or repaired an object.

In the case of an electron beam powered DED system, the process must be performed in a vacuum to prevent the electrons interacting with or being deflected by air molecules. For laser/plasma powered systems, a fully inert chamber is usually required if working with reactive metals such as titanium, which requires a significant amount of gas and time to achieve the desired oxygen levels[6]. Alternatively, it is possible to use a shroud of shielding gas as illustrated in Figure 2-2, which is sufficient to protect the metal being deposited from contamination. In the case of laser-based systems, special care has to be taken when dealing with highly reflective materials such as aluminum and copper where light from the laser could be reflected back onto the delivery fibers and cause damage.

It is possible to use DED with polymers and ceramics, however the focus here is with metal applications only. For metals, almost any metal that is weldable can be 3D printed with DED. The list includes (but not limited to) alloys of titanium, inconel,

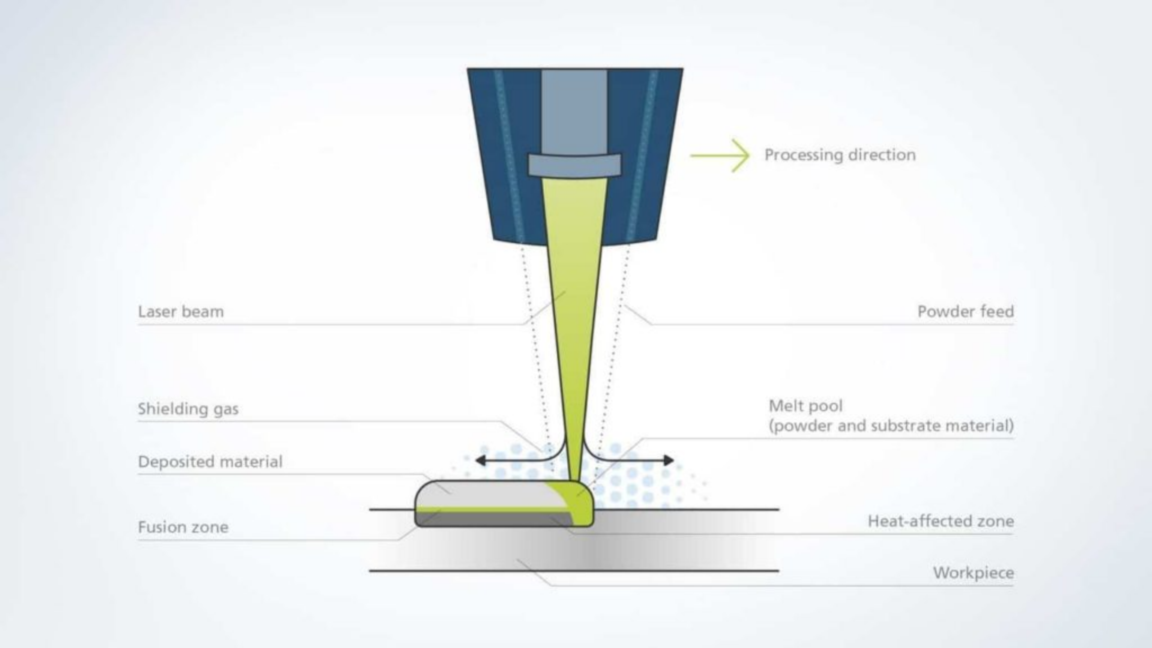

Figure 2-2: The DED additive manufacturing process using laser beam (Credit: Trumpf)

tantalum, tungsten, niobium, stainless steel, aluminium, etc. The wire used typically ranges from 1-3 mm in diameter and powder particle sizes are similar to those used in powder metallurgy processes, between 50 and 150 microns.

DED has the ability to produce relatively large parts (build volume > 1000 mm^3) while requiring minimal tooling for heat treatment and post processing. In addition, DED processes can be used to produce components with composition gradients, or hybrid structures consisting of multiple materials having different compositions and structures[8]. Today, the market counts quite a few manufacturers of DED 3D printers and/or DED service providers. Laser DED machine/service suppliers include (but not limited to) RPM Innovations, Trumpf, Optomec, FormAlloy, Addere, DMG Mori, InssTek, Relativity, etc. In terms of electron-beam DED systems, Electron Beam Additive Manufacturing (EBAM) is a technology commercialized by Sciaky Inc. along with another manufacturer Evobeam. Finally, plasma arc DED 3D printer manufacturers/service providers include Lincoln Electric, Norsk Titanium, WAAM3D, GEFERTEC, and Prodways. Some of the listed suppliers are documented in detail in chapter 3 based on the business interactions conducted for this project.

2.2 Advantage of DED Compared to Other AM Methods

When comparing to the other AM techniques applied to metallic builds, DED has the following advantages. This is not a comprehensive list since different techniques can be improved using additional adaptations:

1. High build rates – wire-fed DED machines are capable of higher deposition rate at relatively low resolution compared to other AM techniques.
2. Reduced porosity – wire-fed DED creates higher density parts hence their mechanical properties are typically as good as cast or wrought material.
3. Large parts - without the constraint of powder bed size, DED machines can be creative in building larger-sized parts (up to a few meters tall).
4. Repairing and/or add-on features – the technique is suited for application requiring metal addition to existing parts.
5. Reduced material waste – DED only deposits the material it needs during the process, meaning less waste compared to processes like Powder Bed Fusion (PBF) where the full build platform has to be filled with metal powder.
6. Flexible build environment - less stringent environmental control requirement, allowing hybrid system to combine DED with subtractive post processing.
7. Multi-material range – latest DED machines have the capability to have several different powders or wire containers which could build parts with customized alloys (See Figure 2-3)[10].
8. Easier material change - since the material is fed during the process on demand from separate powder/wire containers, it's easy to refill or change the material during build.

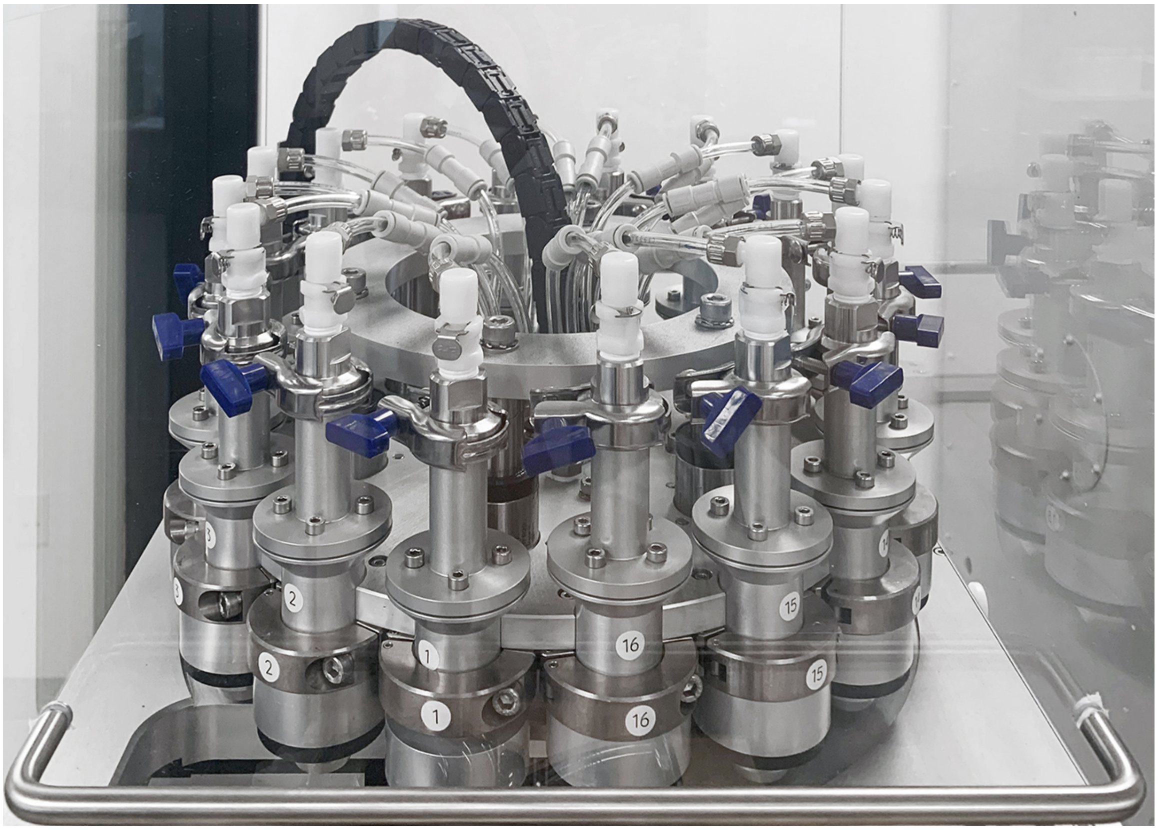

Figure 2-3: Alloy Development Feeder, designed for materials development and research (Credit: FormAlloy)

2.3 Disadvantage of DED Compared to Other AM Methods

There are a number of disadvantages of DED compared to other techniques such as PBF. It is important to note that wire-fed DED and powder-fed DED are very different, some of the disadvantages are associated with wire-fed only, since powder-fed can achieve similar qualities to PBF:

1. Low resolution - wire-fed DED systems typically use 1-3 mm diameter wire. The melt pool (deposition width) is usually 5-10 times wider than the wire, yielding a print bead about the size of a finger (10-20 mm). The printed parts will look like sand or investment castings and would require secondary processing such as machining or aqua blasting, hence adding more time and cost.

2. No large support structures - due to its nature of how the DED technology builds parts, large support structures cannot be used during the build process. However, the lack of ability for overhang geometry can be compensated by designing a tilting mechanism into the printing process.

3. High capital cost – laser and electron beam DED systems are comparably more expensive to the other types of metal additive manufacturing systems due to the power required for this technique. Plasma arc systems, however, are generally cheaper since the energy systems are the same as the ones used for welding and has been proven for decades.

4. Residual stresses - as each layer been deposited over previous layers, some portion of the existing layers are re-melted again. Significant residual stresses build up during printing, requiring additional process or advanced software and simulation expertise.

2.4 DED Applications in Aerospace

The DED technology has been applied in the aerospace industry for repairing the high value components, adding on to existing surfaces, speeding up new alloy development iterations, building rocket nozzle components with internal cooling ducts, building airfoils with embedded cooling channels, and building fuel tanks for rockets, etc. In this section, some of the high-profile use cases are illustrated to help build more intuition around the applications of the technology. The cases described here are full build examples instead of add-on and repairs because the full builds are the focus of this project.

Two use cases are selected to present here, the Boeing - Norsk Titanium part and Relativity Space 3D printing rockets. The Boeing part was a great showcase for how DED improves buy-to-fly ratio (the ratio of the mass of the starting billet of material to the mass of the final finished part) for reducing cost. The high-speed wire-fed DED printing method made the business case better compared to PBF method. The Relativity 3D printed rocket components showcase the size and versatility of the DED method.

2.4.1 Boeing - Norsk Titanium Structural Components

Boeing and Norsk Titanium were selected as one of the winners of Aviation Week & Space Technology's 61st Annual Laureate Awards, in the category of Commercial Supplier Innovation, in recognition of the companies' qualification of the first structural titanium parts for a commercial aircraft made using Additive Manufacturing[5]. Boeing designed the components and collaborated closely with Norsk Titanium throughout the development process. To certify these initial structural components on the Dreamliner, Boeing and Norsk Titanium undertook a rigorous testing program with FAA certification deliverables completed in February 2017.

The part is a structural titanium component manufactured using Norsk's proprietary Rapid Plasma Deposition™ (RPD™) process powered DED technology (see Figure 2-4), the delivery of these first parts represents significant progress for AM.

Figure 2-4: Norsk Titanium and Boeing qualified the first AM structural titanium parts for 787 Dreamliner in 2017[5]

Structural/load-bearing aerospace application of DED parts are rare even now due to the stringent requirement of in-flight safety - a large amount of data is required to qualify the parts for manned-flight applications; however it takes in-flight tests and/or plenty of ground test simulations to gather enough data. The qualification with the OEM, certification with the Federal Aviation Administration (FAA), and the ability to transition to production and meet customer cost, quality and delivery expectations were all monumental achievements for the technology.

2.4.2 3D Printing Rockets

DED technology is attractive to rocket manufacturing because of the freedom in building large size, low resolution parts in shorter time period. Due to low production volume and high complexity nature of rocket parts, NASA, SpaceX, and Blue Origin have heavily invested in AM technologies to reduce development cost and cycle time. The lack of tooling needs for large parts and the flexibility of creating new alloys made DED a valuable option for building combustion nozzles and fuel tanks. Traditional rocket manufacturing for fuel tanks and exhaust nozzles uses metal casting, which could take up to six months for tool construction alone. It is not uncommon to have a 48-month long design iteration for new model of rockets because every design update would require a newly constructed casting mold. With properly configured wire-feed DED machines, no new casting mold is needed for modified design, and design iteration for fuel tanks and nozzles could be shortened to months even weeks. The forward leap of design efficiency is unheard of. Even if the cost of DED process might not be significantly lower than the traditional method, it is reasonable for the rocket industry to be the first ones heavily investing into DED.

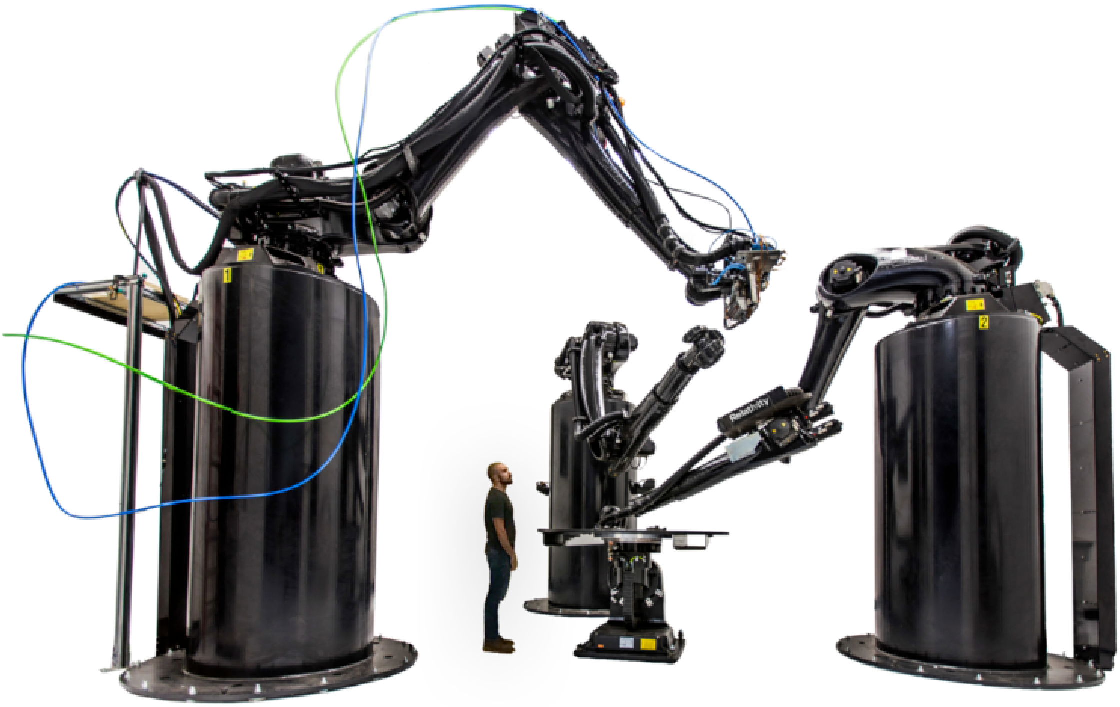

Figure 2-5: The Stargate 3D Printer by Relativity Space[14]

Relativity Space is a start-up aimed to 3D print an entire rocket. What makes Relativity stand out is that it has the means to 3D print entire rockets with almost no intervention from humans (at least 90% completed by 3D printing so far). The company's massive Stargate 3D printer (Figure 2-5) is a wire based DED machine that utilizes 18-foot-tall robotic arms equipped with lasers. Directed by custom software, the robotic arms are capable of producing the entire body of the rocket in one piece.

Using a giant 3D printer allows Relativity Space to reduce the part count of a typical rocket from 100,000 to 1,000[13]. This greatly saves on time, labor and money, which in turn saves customers millions of dollars per launch. Figure 2-6 shows a 11-foot-tall aluminum fuel tank 3D printed by Stargate. The 3D printer worked for three weeks to complete the tank, which would usually take much longer time if metal casting was involved. With a rocket fully 3D printed, the amount of complexity reduction in supply chain and savings from shortened build time and design iteration cycle are incredible. According to Relativity, their build time is shortened to two months compared to the traditional 24 months period, and design iteration is shortened to six months compared to the traditional 48 months period[13].

Figure 2-6: Fuel Tank Built by Stargate[14]

Chapter 3

DED Suppliers

As described in the approach section 1.2, the initial phase of this project focused on researching about DED suppliers that provide part manufacturing services. The initial list of companies were compiled from internal interviews with P&W Engineers and open source web searches. During initial interviews, the following questions were used as guideline for downselect:

- Does the supplier take production orders or R&D orders?

  If yes to production orders, what's the general build process?

- Any post processing capabilities or supplier partnered?
- What are the machine details (power source, feed stock type, size, resolution capability, etc)?
- Any material restrictions and supply chain limitation?
- What's the quality system in place for additive manufacturing processes?
- Other customers in the aerospace industry? Past use case?
- Experience working with the defense industry /government contract?
- Allow on-site visit (due to COVID restrictions, some companies were not fully open to site visits)?

Based on the criteria, six companies were selected for subsequent site visits. Prior to site visits, NDAs were established with the companies per P&W legal policy. According to NDA with each of the companies, not all details from the visits are documented here. Some companies also requested to be anonymous for proprietary reasons, hence code names such as Company A are used in this section. The companies are listed alphabetically in the subsequent sections.

3.1 Joining Tech - American Cladding Technologies

Founded in 1992 and based in East Granby, CT, Joining Tech - American Cladding Technologies (ACT) develops high quality, cost-effective and sensible solutions for hard-facing overlays, corrosion-resistant overlays, original material restoration and other in-demand results. ACT primarily serves the waste-to-energy power industry, the aerospace, national defense and valve industries, locomotives, and industrial gas turbines.

ACT uses laser cladding – also known as laser metal deposition or Directed Energy Deposition (DED) – to protect, restore, and strengthen the surfaces of metal components (see Figure 3-1). The company's Chief Engineer, Scott Poeppel, turned the company's DED expertise from cladding into 3D printing free-formed parts. ACT builds most of the hardware and machines on their own, with the exception of lasers which are purchased from TRUMPF. ACT currently has three 5-axis Cartesian DED platforms, one 6-axis Cartesian DED platform, one 10-axis robotic DED platform, and one metallurgical lab on site. All machines use metal powder as feed stock, the biggest machine is capable of building parts up to 40 ft long. Print resolution can be as detailed as 0.2 mm depending on the machine deposition rate. All machines utilize an open system, their special designed nozzles are able to achieve a much higher powder efficiency than most of the open powder blown systems (usually around 50%). ACT is capable of printing titanium parts by keeping the oxygen Parts Per Million (PPM) low during the build process. Their proprietary technology also enables printing with reflective materials such as aluminum.

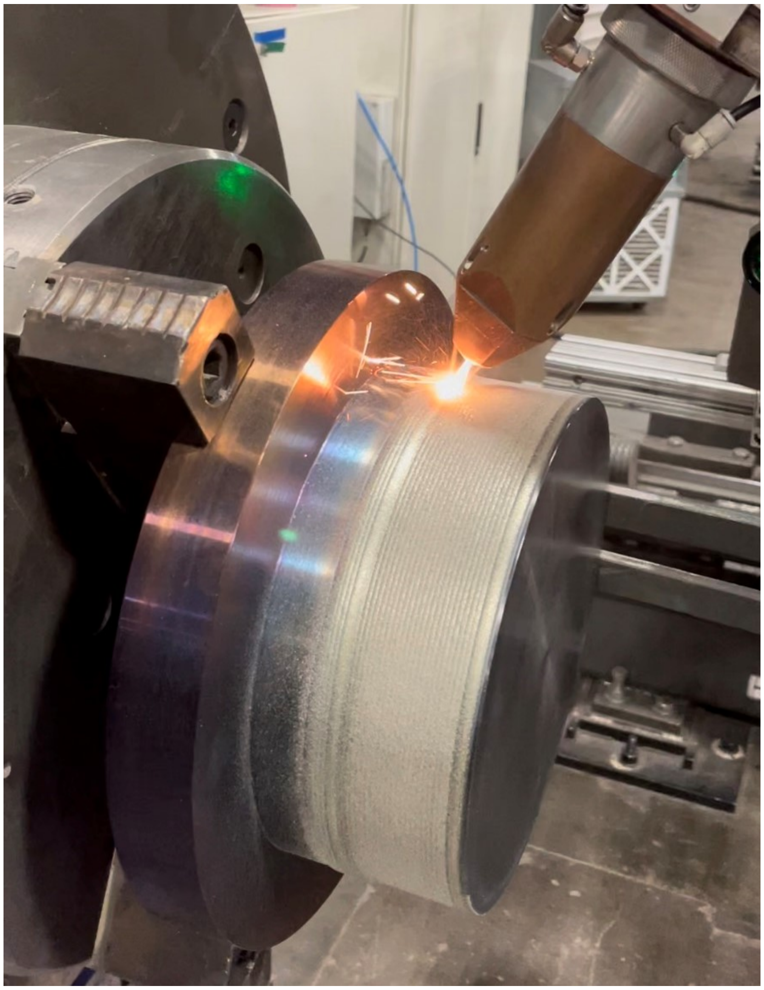

Figure 3-1: Photo Taken at ACT During the East Granby Site Visit - Surface Cladding in Progress

With an in-house machine shop, ACT can do surface treatment and heat treatment in-house depending on geometry and size. The company is also in the business of selling their AM systems on a make-to-order basis.

3.2 Lincoln Electric

Founded in 1895 and Headquartered in Cleveland, Ohio, Lincoln Electric (LE) is an American multinational and a global manufacturer of welding products, arc welding equipment, welding consumables, plasma and oxy-fuel cutting equipment and robotic welding systems. LE has an international reputation as a pioneer in arc welding.

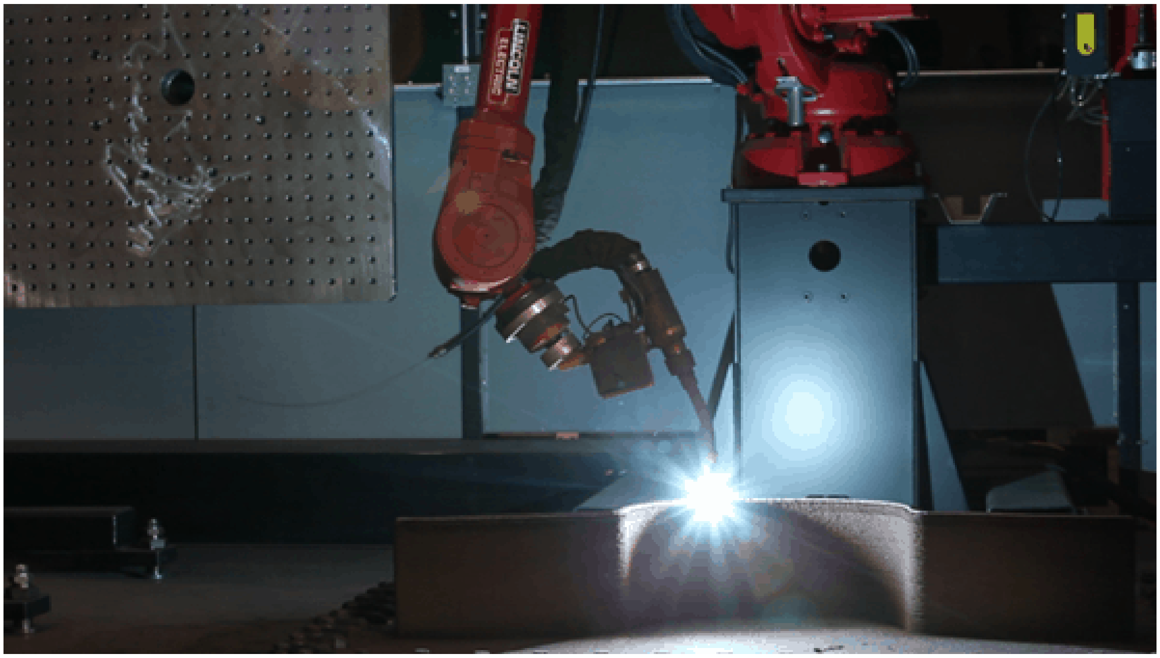

Figure 3-2: Lincoln Electric - Wire Arc Additive Manufacturing Machine[4]

LE started to fully invest in AM in 2018, leveraging their welding expertise in metal deposition, materials, automation, software, and machining into Wire Arc Additive Manufacturing (WAAM) machines shown in Figure 3-2. In their 75,000 sq. ft. dedicated AM facility, there are 19 current working cells (18 gas arc wire machines and one laser hot wire machine) and 60 more planned to be installed in the next three years. LE's current AM business primarily comes from tooling applications (see Figure 3-3), with strong progress in the R&D and part production applications. There are four operators per shift, three shifts/day with a dedicated Engineering team supporting daily operations.

The machines use ABB robotic arms because ABB allows customization of the robotic features and software while most of the other automation suppliers don't allow much freedom for modification. LE has its own software program for their AM operations - Sculpprint, which allows great flexibility and creativity in 3D printing path planning and real time quality verification. The current maximum build size is 4' x 6' x 6.5' with feature resolution of 2-10 mm (as explained in section 2.3, wire-fed DED usually has lower resolution compared to powder-fed systems) but the high

Figure 3-3: Lincoln Electric - Tooling Demo during Cleveland Site Visit

printing speed allows LE to provide customers with 2-3 weeks of turn-around time for low complexity jobs.

All of their machines operate in open atmosphere, the gas arc wire machines currently do not have the capability to print titanium parts. Most of the current customer orders utilize materials such as nickel-based alloys, steel, invar, and stainless steel. LE has been partnering with Oak Ridge National Laboratory to come up with ways to use titanium on their gas arc wire machines, meanwhile titanium parts could be built using the one laser hot wire machine in the shop.

LE owns Baker Industries, which handles most of the post printing machining and surface treatment. If a part requires heat treatment, it is out-sourced to suppliers in the Detroit area with two-day turn-around time. LE also owns the majority of its wire supplies. Most of the current customer orders come from oil and gas for rapid prototyping and aerospace projects are on the rise with leading customers such as Boeing and Blue Origin.

3.3 TRUMPF

The TRUMPF Group (TRUMPF) is a German industrial machine manufacturing company. It is a family-owned company with its head office in Ditzingen near Stuttgart. TRUMPF is one of the world's biggest providers of machine tools. The company has two major divisions: Machine Tools and Laser Technology. The product range in laser technology comprises laser systems for the cutting, welding, and surface treatment of three-dimensional components. 3D printing machines for metal components were added to the portfolio in 2015 as a natural application for their various laser systems.

Figure 3-4: Trumpf - Beam Source, Powder Feeder, Optics, and Nozzle

TRUMPF is one of the major OEMs for AM. The company provides a variety of AM systems including PBF and DED systems and components such as laser, powder feeders, and nozzles (see Figure 3-4). The DED systems are close atmosphere, laser-powered powder-fed systems, their biggest machine TruLaser Cell 7040 (see Figure 3-5) can change flexibly between cutting, welding, and laser metal deposition. Although TRUMPF is primarily an OEM provider, the company also takes on R&D projects to test out the capabilities of their machines as well as providing their customers (usually

AM suppliers who take production orders or major aerospace/automobile OEMs) with proof of concept for parts.

Figure 3-5: Trumpf - TruLaser Cell 7040

The site visit was arranged at TRUMPF's Plymouth, MI. facility, where three different types of DED machines were demonstrated. The maximum build size is flexible but confined to the geometry of the largest machine - TruLaser Cell 7040. The machines require special set-up for materials such as titanium. Feature resolution can be as detailed as 0.5 mm depending on deposition rate and material. Using co-axial nozzles can achieve a powder efficiency of up to 90%, however the efficiency is highly depended on tool path since the powder blown stays on to maintain steady flow condition. TRUMPF has no post processing capabilities in-house since it is not in the business of part production.

3.4 Company A

Company A is a leading engineering and technology organization in North America dedicated to developing, testing, and implementing advanced manufacturing technologies for industry. Since 1984, Company A has offered applied research, manufacturing support, and strategic services to companies in the aerospace, automotive, consumer electronic, medical, energy, government and defense, and heavy manufacturing sectors.

Company A is an independent engineering consultancy with comprehensive labs and advanced manufacturing technology resources dedicated specifically to production process development and improvement. The company supports broad adoption and optimization of advanced metal 3D printing and large-scale AM technologies throughout all industrial sectors. With capabilities in all seven AM process categories identified by the American Society for Testing and Materials (ASTM) (Powder Bed Fusion, DED, Binder Jetting, Sheet Lamination, Material Extrusion, Material Jetting, and Vat Photopolymerization), Company A can assist at any stage – or through all stages – of the AM process. As a result, Company A offers extensive services in AM innovation such as:

- Material and process development
- Additive manufacturing tooling and equipment development
- In-process sensing and monitoring
- Post-process inspection
- Material database development
- Heat treatment development
- Metallurgy
- Machine design and build
- Design for Additive Manufacturing Processes and Materials

- Qualification, Certification, and Design Allowable Generation

In addition to the services and products available to customers on a per-project basis, Company A offers membership with direct access to the company's technical staff, facilities, and library research services. Membership benefits include:

- Technical Inquiry Service with unlimited technical inquiries and design review needs
- Library Service to access technical documents and information by performing literature searches and article retrievals
- Design Reviews
- Access to the company's member central web site and view detailed reports, obtain Cooperative Research Program results and more

With the understanding of Company A's business model, the company visit was not focused on DED systems, but more of an educational tour of all the state-of-the-art additive manufacturing systems as well as new technologies in development.

3.5 Company B

Company B became involved in the application and advancement of Laser Deposition Technology in 2001. Since then Company B remains focused on progressing the DED technology through innovative laser systems and continual growth of DED services. The company specializes in "blown powder" DED which comprises Free-form, Repair, and Cladding capabilities. Company B provides application development, manufacturing services, and repair solutions for its customers.

The company manufactures a complete line of DED Systems that includes three major models of 5-axis systems, which they maintain at least six machines in-house to run manufacturing services 24/7. All six machines are usually in operation with 2-3 operators each shift, and with closed atmosphere, the machines are capable of building parts using most of the commonly used commercial alloys (including but not limited to titanium alloys, steel alloys, nickel alloys, cobalt alloys, tunsten carbide, copper alloys, and aluminum). Company B has designed and developed the Tool Path Generation Software used in all their machines internally to meet industry needs over the last 15 years. The accumulated expertise in 3D printing software allows the company to offer a full suite of software for slicing code, viewing code, and machine control.

The design of the powder delivery system also allows multiple powder feeder systems on each laser system. With the multi-powder feeding system, Company B can create multi-material deposits by selectively mixing or transitioning alloys within a single build. The images in Figure 3-6 reveal a single blade that comprises Inconel 625, Alloy 230, and Inconel 718 all in one freeform build.

Figure 3-6: From the Company Website - Single Blade Built with Material Gradients

The use cases and DED knowledge demonstrated by Company B during site visit showcased strong and robust DED capabilities of the company. A laser deposited part demonstrated on the company website can be viewed in Figure 3-7. In addition to the technological strength, Company B maintains a quality management system that is certified to both the AS9100 and ISO 9001 quality standards. The current lead-time for the machines is around six months, where lead time for manufacturing services can vary depending on service job backlog and the complexity of the job. For customers who purchase the machines, 1-week training service is provided in Company B facility

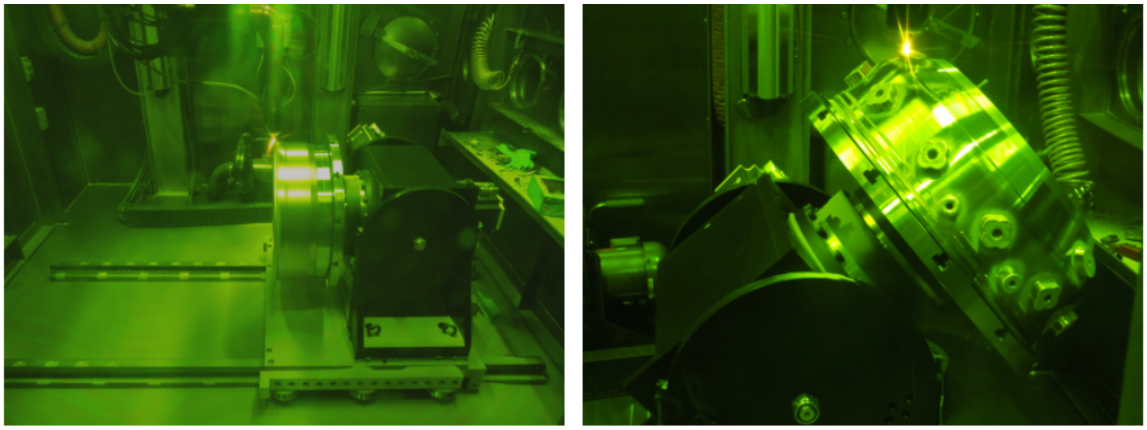

Figure 3-7: From the Company Website - Company Demonstration of a DED Part

and follow up training is available as needed.

3.6 Company C

Company C's DED venture started in 2017. Company C's parent organization has a long history of welding and automation business. The accumulated expertise in both welding and automation merged to make AM possible.

Since launch, the company has developed three distinctive laser powered wire-fed DED systems, the smaller systems consist of a high accuracy 6-axis industrial robot combined with a 2 axis coordinated motion work piece positioner. The laser wire additive systems are capable of building components from a number of common or specialty metal-based materials like stainless steel or Inconel 718. An optional Argon environment extends to capabilities of the systems to build parts out of titanium. Although without a positioner, the largest system (see Figure 3-8) allows for additive build sizes up to 1575" wide, 310" long, and 75" tall, it also has the capability to weld on both sides of a substrate to allow for higher additive manufacturing flexibility. All three systems use software packages developed by Company C.

The additive DED is a small but growing portion of the parent company's business. Currently the company only provides manufacturing services. The parent company has in-house machine shops that can take care of most post processing needs for less complicated parts. Figure 3-9 was taken during the site visit to demonstrate a quick

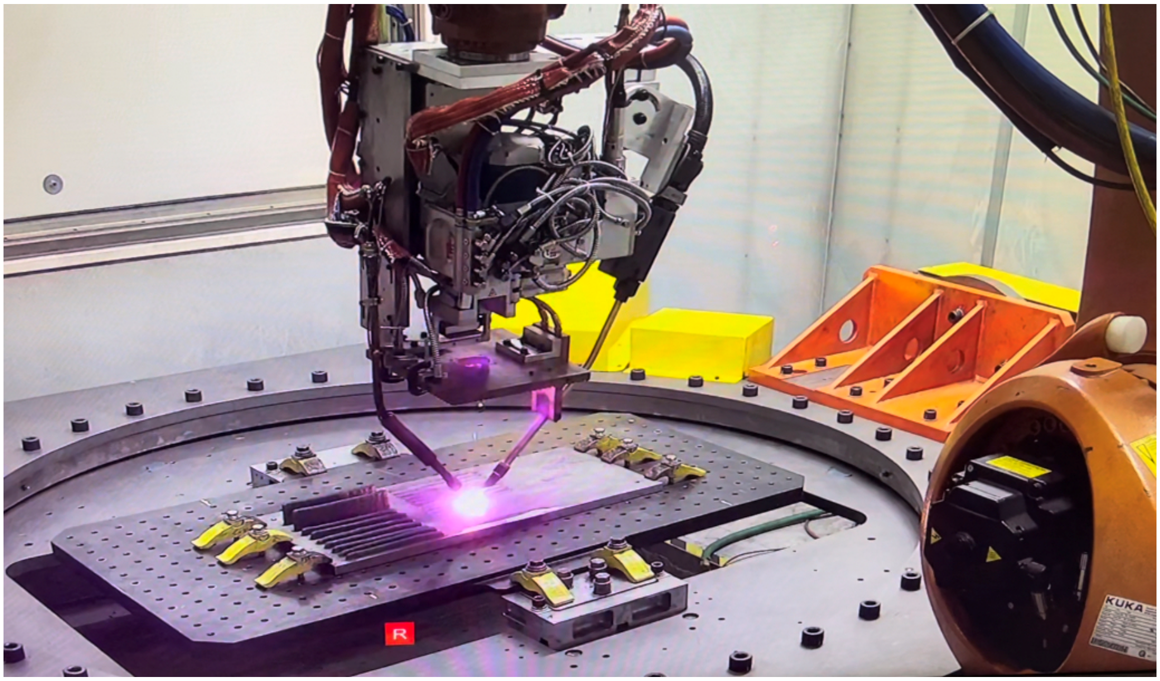

Figure 3-8: Photo During Site Visit - Largest System Operating in Argon Purged Chamber

view of the completed jobs. Only a small portion of the demonstrated parts were shown here to respect the NDA agreement with Company C.

The company supports industries such as aerospace, defense, marine, and oil & gas. For wire materials like Inconel 718, titanium and other exotic materials that require the Argon purged chamber, there is a minimum order requirement due to the cost of operating the chamber. The current wire supply has diameter of 1.6mm, which allows the minimum feature resolution of approximately 6mm. However, the lower resolution always has the upside of high build speed - the largest system can deposit steel up to 30 lb/hour. Typically turn-around time for first prototypes are 3-6 weeks depending on job material and complexity.

Figure 3-9: Company Demonstration of Finished Parts

3.7 Summary from Company Visits

Table 4.2 summarizes the service type, machine power supply, material feedstock type, and OEM status of DED suppliers visited during this project. Based on the information learned through those visits, supplier selection criteria were refined and will be discussed in the next chapter. Only the suppliers that provide manufacturing production service would move onto the step 7 - Request for quotes.

	Service Type	Power Source	Wire/Powder	Machine OEM
ACT	Production&R&D	Laser	Powder	Yes
LE	Production&R&D	Gas Arc&Laser	Wire	Yes
TRUMPF	R&D	Laser	Powder	Yes
Company A	R&D	All	Both	No
Company B	Production&R&D	Laser	Powder	Yes
Company C	Production&R&D	Laser	Wire	No

Table 3.1: Supplier Summary

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Chapter 4

Analytic Hierarchy Process (AHP) Methodology for Supplier Selection Criteria

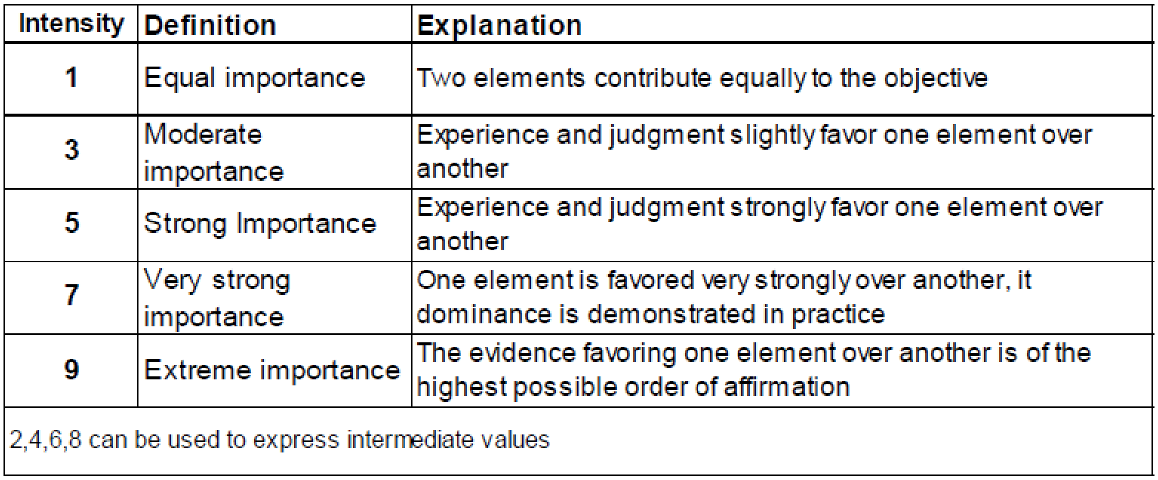
Relevant information collected during the company visits were coupled with P&W's objective for this project to create two sets of selection criteria - Capability Criteria and Supplier Criteria. The Capability Criteria assess the manufacturing capabilities demonstrated by the company during the visit, whereas the Supplier Criteria assess additional aspects such as cost, lead time, and quote quality. The Capability Criteria also get incorporated into the Supplier Criteria as "quote confidence" criterion, the idea is the higher the capability demonstrated, the more confident we would be with the quote received. This chapter will dive into both sets of criteria as well as the Analytic Hierarchy Process (AHP) methodology used to assign weight to the criteria system.

Although the selection criteria lists will be accurate, the weights and company scores will be made up, and the company names will be simplified as Company 1, Company 2, Company 3, and Company 4 in the results documented in this chapter.

4.1 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Thomas L. Saaty in the 1970s. Saaty partnered with Ernest Forman to develop Expert Choice software in 1983, and the AHP has been extensively studied and refined since then[9]. The AHP represents an accurate approach to quantifying the weights for decision criteria. Individual experts' experiences are utilized to estimate the relative magnitudes of factors through pair-wise comparisons. Each of the respondents compares the relative importance for each pair of items using a specially designed questionnaire. Ultimately, the AHP provides an analytical and numerical framework for making decisions in complex systems. The AHP does not produce absolute scores for alternatives, rather it provides a relative score based on defined criteria[3].

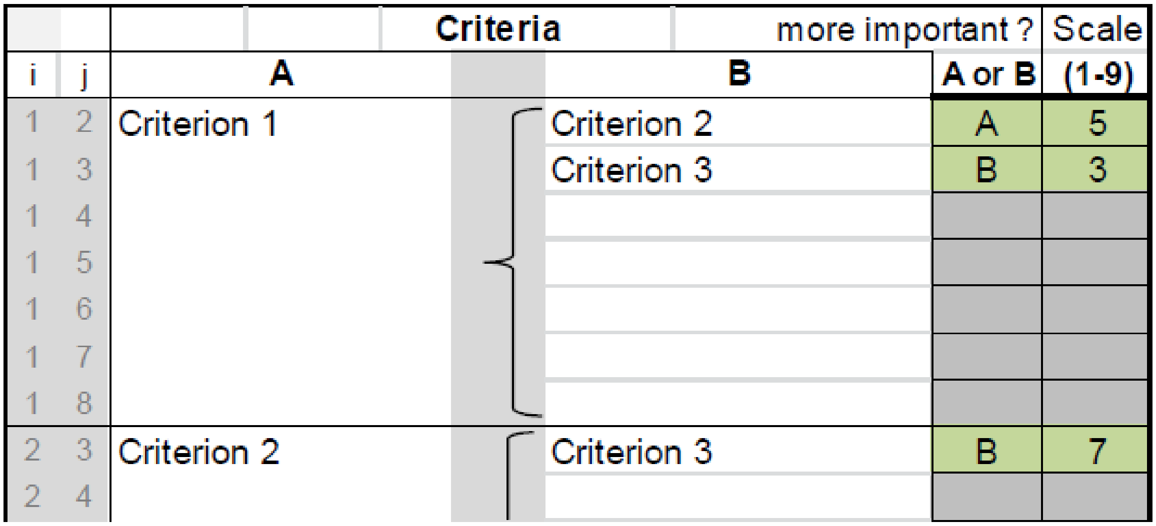
Each of the selection criteria set has 6-7 criteria, to apply AHP, we would begin with an expert in AM expressing how two criteria compare to each other using the scale shown in Figure 4-1. Psychologists suggest that the 1-9 rating scale gives the appropriate level of detail without giving the decision maker difficulties expression opinion[3].



Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

Figure 4-1: AHP Comparison Scale Guide[11]

Figure 4-2 shows a simple example of three criteria pair-wise comparison case. the first comparison is criterion 1 versus criterion 2. In the second last column the



		Criteria		more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	Criterion 1	Criterion 2	A	5
1	3		Criterion 3	B	3
1	4				
1	5				
1	6				
1	7				
1	8				
2	3	Criterion 2	Criterion 3	B	7
2	4				

Figure 4-2: Input Table for Pair-wise Comparison[11]

participant has to select either A (criterion 1 more important than 2), or B (criterion 2 more important than 1). In the last column of the table the participant specifies the intensity - how much more important is 1 compared to 2 using the scale in Figure 4-1. The participating AM expert would complete an input table like this for all the criteria in each set.

Once the AM expert completes their input for a set of criteria, it is compiled into a pairwise comparison matrix. The matrix would need to be checked for consistency because conflicts could arise due to human involvement. For example, if the expert rates criterion A as 5 in comparison to criterion B and rates B as a 4 in comparison to criterion C, they would be expected to rate A as more important than C. However, the expert could instead rate criterion C as more important than criterion A, thus creating an inconsistent condition. Inconsistency happens very often with large number of criteria. If the expert's overall consistency falls below a set threshold, their ratings could be invalidated.

Following the consistency check, a priority vector is computed to determine relative weights for each criterion. The eigenvector method was proposed by Saaty to calculate the priority vector[15]. According to the eigenvector method, a priority vector, or the Perrono-Frobenius eigenvector, is the principal eigenvector the pairwise comparison matrix (X). Each element in the X matrix is a ratio between weights and there are

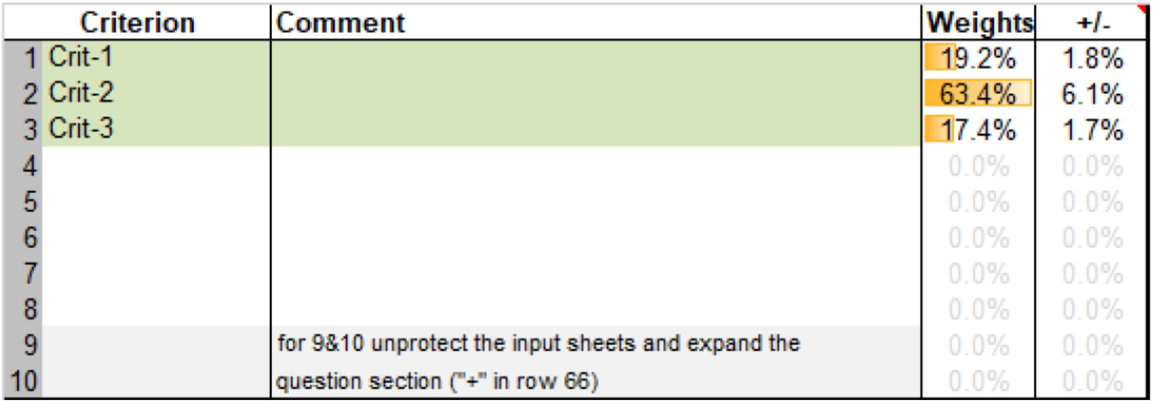
n weights, thus X is a size $n \times n$ matrix. The method then multiples X by ω and creates a formulation as shown in Figure 4-3[3]. This formulation implies that n is an eigenvalue and ω is an eigenvector of X. The eigenvector ω can be calculated by solving the equation system.

$$Xw = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \cdots & \cdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ nw_2 \\ \vdots \\ nw_n \end{bmatrix} = nw$$

Figure 4-3: Matrix X of size $n \times n$ multiplied by the principal eigenvector ω[3]

The AHP tool used for this project was developed by Goepel, Klaus D., which also utilized the eigenvector method. For this project the emphasis is not the AHP method mechanism but the assessment of DED suppliers we visited, all technical explanations of the AHP tool could be found in Goepel's paper published back in 2013[11], we will not go into detail in this thesis. Multiple participants could provide their input for the comparison matrix regarding the same list of criteria, which would then be compiled to produce final weights for each of the criterion (see Figure 4-4 for a result table showing all calculated weights and errors based on one participant's input).

Essentially, the AHP method applies structure to the decision-making process with the support of automation, which can greatly reduce the difficulty in deciding the



	Criterion	Comment	Weights	+/-
1	Crit-1		19.2%	1.8%
2	Crit-2		63.4%	6.1%
3	Crit-3		17.4%	1.7%
4			0.0%	0.0%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the question section ("+" in row 66)	0.0%	0.0%
10			0.0%	0.0%

Figure 4-4: Example Result Table[11]

final weights for the criteria based on multiple participants' input. In the case of this project, two AM experts' inputs were compiled to produce the final weights for the two sets of criteria.

4.2 Capability Criteria

In this section we dive into the supplier manufacturing capabilities that are considered important when evaluating whether the supplier can perform the AM jobs P&W intended to contract out. The six criteria are modified based on existing AM supplier criteria to fit the project needs.

To simplify the scoring system, each criterion can be scored as 1, 3 or 5 (5 being the highest score). Each criterion also has a different set of guiding principles for scoring and the guiding principles could be modified to fit different projects.

4.2.1 Material Availability

Material availability does not refer to how much materials are available for production at a given time, it refers to the type of materials available for build. For example, steel offers strong mechanical properties and a good surface finish, it's the most popular metal used in 3D printing, thus most of the suppliers we visited are capable of building parts out of steel. As a baseline material available, if the supplier is only capable of building parts out of steel and/or stainless steel, they will be scored "1" for this criterion. Nickel-based superalloys exhibit excellent creep strength, oxidation resistance, corrosion resistance and fracture toughness, thus are next in-line on our list of desired materials. If the supplier is capable of printing parts out of nickel based alloys, they will be scored "3". Further on the desired material list is titanium. Titanium metal is a very durable metal for engineering applications because it is not only corrosion-resistant, but also very strong and very light. It is 40% lighter than steel but as strong as high-strength steel. The weight saving aspect made titanium a highly desirable material on aerospace applications. If the supplier is capable of printing parts out of titanium and/or its alloys, they will be scored "5", the highest score for Material Availability criterion.

4.2.2 Feature Resolution

In AM, the 3D printing feature resolution corresponds to the accuracy of the 3D printers along the manufacturing axes (xyz). 3D printers build objects layer after layer, a distinction must be made between the resolution along the manufacturing axis (layer thickness) and the work plane (a single layer). The printing resolution is limited by the bead size (wire-fed) or particle size (powder-fed) as well as the energy input. For example, a low power laser would melt powder in a smaller area, thus printing the part slower but with higher resolution.

In aerospace engine applications, the cooling channels typically are formed by very thin walls, thus the minimum wall thickness is a very important aspect when considering the feature resolution capability of the suppliers. Since the minimum wall thickness is depended on the minimum single layer height during the printing process, we decided to use the minimum single layer height to set the scoring system for feature resolutions. If the supplier can only build parts with layer height higher than 1 mm, the supplier would be scored "1" in this criterion. If the supplier is capable of layer height between 0.2 mm - 1 mm, the supplier would be scored "3". The capability of printing layer height of 0.2 mm or thinner would grant the supplier of a "5" in this criterion.

4.2.3 Multi-Feeder

The multi-feeder capability refers to the machine's build-in capability of printing different materials during the same job without pausing to switch materials. This feature is important when printing developmental alloys, or printing parts that required certain material gradient across the build such as Company B demonstrated in section 3.5, Figure 3-6. If the supplier can only build parts with a single material in one build without pausing and switching material feedstock, the supplier would be scored "1" in this criterion. If the supplier can achieve up to two different materials during the same printing session, the supplier would be scored "3". If the supplier can print four or more different materials during the same build without pausing and switching, the supplier would be scored "5" in this criterion.

4.2.4 Material Efficiency

Material Efficiency refers to the raw material capture rate / material yield during build. If the machine uses wires as feedstock, the capture rate would be close to 100% since all melted wires continue to form into the part and the material is deposited where needed. If the machine uses powder-based materials, it is likely that the capture rate / material yield is around 50% - 80% depending on the path planning and powder blown technology of the machine. To maintain a consistent flow rate, powder material feed normally won't be shut off during path transition even when no material is needed at some part of the path, which results in higher material waste compared to the wire-fed systems.

This criterion is important when the production quantity is large, but not as important in R&D projects or one-off parts. There are only two scores for this criterion: "3" if the supplier's machines can only achieve up to 95% of material capture rate, or "5" for machines that can achieve 95% or higher capture rate. Typically a wire-fed system would be scored a "5" in this criterion and powder-fed system would be scored "3".

4.2.5 Hybrid Capability

Hybrid Capability refers to machines that are capable of hybrid machining. Hybrid machining combines additive and subtractive manufacturing methods in one single solution. The concept has been around since 1990's but it was not commercially popular until recently. Today, more and more manufacturers are developing hybrid 3D printers as the demand for such machines keeps growing. Some manufacturers are offering even more functions than 3D printing and CNC – laser engraving and cutting and paste extrusion are often added to offer a versatile solution for the customer.

Therefore, such hybrid printers are also known as “All-in-one printer” or “3-in-1 printer”.

Hybrid machining has a lot of potentials, especially if the concealed areas require some kind of surface finishing but are not stringent on tolerances (parts that require heat treatment post printing are subject to shape shifting, thus the surface finish might not remain the same after the subtractive work being performed). Applying surface finish post print of an enclosed looping pipe could be very difficult if not nearly impossible. With hybrid machining however, surface finish could be done before the area is closed off. This criterion only has two scores: "1" if the supplier does not have hybrid machining capability, "5" if the supplier does.

4.2.6 Overhang Angle

Overhangs are geometric shapes in a 3D model that extend outwards and beyond the previous layer. Overhang angle is the angle of inclination of the print wall from the vertical axis as illustrated in Figure 4-5. There is a general rule when it comes to 3D printing overhangs - the angle of the overhang should not exceed 45°. Overhangs have no direct support so it is difficult to be printed. Having the overhang angle not exceed 45° is to make sure that each successive layer has enough support on it. This also means that at 45°, the 3D model is printed well because every layer is in about 50% contact with the layer below it.

Despite the general rule, the complex designs in jet engines often requires an overhang angle greater than 45°. With special maneuver of the rotating axis, modern DED machines are capable of coming up with creative solutions for printing overhangs with angles greater than 45°. Being able to achieve higher overhang angle means better design freedom, mostly for hidden areas. If the supplier can only build parts with overhang angle up to 45°, a score of "1" will be assigned. If the supplier can achieve overhang angle of greater than 45° but less than 80°, a score of "3" will be assigned. Any capability of achieving overhang angle of greater than 80° would obtain a score of "5" for this criterion.

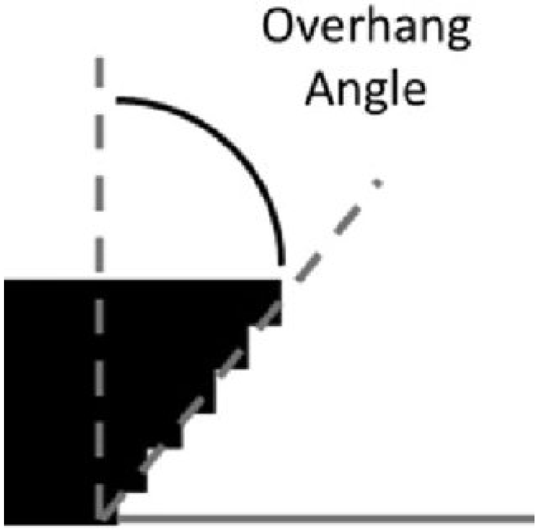


Figure 4-5: Overhang Angle Measurement[12]

4.3 Supplier Criteria

In this section we dive into the list of important attributes when evaluating suppliers for their AM fit of P&W's developmental projects. The list of criteria is compiled based on the project motivation and goal using experts' input and information gathered during this internship. Similar to the scoring of the Capability Criteria, each criterion can be scored as 1, 3 or 5 (5 being the highest score), except Quote Confidence, which is the final weighted score based on the Capability Criteria scores. Each criterion also has a different set of guiding principle for scoring and the guiding principles could be modified to fit different projects.

A quote exercise was conducted with the four suppliers that take on production orders as mentioned under Service Type in table 4.2. The return quotes are used to score the majority of the Supplier Criteria. In an effort to limit the number of criteria assessed in this list to seven to avoid comparison fatigue while going through the AHP pair-wise comparison exercise, some of the criteria were combined into one criterion.

4.3.1 Cost

Cost is a straight-forward criterion - how much does the supplier quote the specific job? Since the request for quote for the same jobs went out to multiple suppliers, the cost rating would be based on the relative price comparison against each other. If the supplier quotes the lowest price out of the comparison pool, the supplier would be scored "5" in the cost criterion. If the price quoted is in the middle of the pool, the supplier would be scored "3". If the price quoted is the highest among the supplier pool, the score would be "1".

It is worth noting that the lowest cost is not always the best if the lead time, quote quality, and quote confidence are lacking against other higher cost suppliers.

4.3.2 Lead Time

Lead Time refers to the period of time between order placement and part delivery. It is also relative among the suppliers when quoting the same part orders. If the supplier quotes the shortest lead time out of the comparison pool, the supplier would be scored "5" in the cost criterion. If the lead time quoted is in the middle of the pool, the supplier would be scored "3". If the lead time quoted is the longest among the supplier pool, the score would be "1".

Sometimes a supplier would quote longer lead time but the finished print requires much less post processing compared to the other suppliers due to the quality and resolution of the build. In that case the quote quality score will make up the lower score in the lead time criterion.

4.3.3 Service Type

Service Type refers to what kind of orders could the supplier fulfill. Some would only accept R&D orders, some would only accept production orders, and some would be able to accept both R&D and production orders. If the supplier is only able to accept R&D orders, a score of "1" would be assigned. If the supplier is only able to accept production orders, a score of "3" would be assigned. If the supplier is able to take on both R&D and production orders, a score of "5" would be assigned.

4.3.4 Production Capacity

Production Capacity refers to the level of highest achievable productivity for each of the suppliers. In this project we use the number of production ready machines, the size of the operation team (number of operators per shift and number of shifts), and the size of engineering support team as the guiding principle. Not every supplier has a stand-alone operations team, in some cases the engineers also run the machines. If the supplier has less than three machines and less than three total engineers/operators, a score of "1" would be assigned. If the supplier has three or more machines, but less than five total engineers/operators, a score of "3" would be assigned. If the supplier has more than five machines, stand-alone team of operators by shift, and a team of more than five engineers supporting operations, a score of "5" would be assigned.

4.3.5 Production System Maturity

Production System Maturity refers to the maturity level of the machine software and the production quality system. Machine software maturity is usually built upon years of printing experience, being able to make in-house software is an important aspect of constant improvement of a supplier's AM capability and quality.

Our project's focus is the developmental parts, knowing that the supplier has a working quality system in-place (AS9100, ISO9001, etc) and an adaptive software system is important in painting a realistic picture of the supplier's capability. If the supplier has no qualified quality system in-place and the software maturity is less than a year, a score of "1" would be assigned. If the supplier has a pending qualification for quality system such as ISO9001 and the software maturity of more than one year, a score of "3" would be assigned. If the supplier has qualified quality such as AS9100 or ISO9001 and the software maturity of more than three years, a score of "5" would be assigned.

4.3.6 Quote Quality

Quote Quality refers to the detail level of the build plan and cost items, as well as the intended completion level of the finished print. The higher the level of completion per drawing, the less post processing such as surface finish required, thus reducing the overall cost & lead time of the part prior to mission ready. If the supplier provides a vague description for build plan and cost items, and the intended finished part requires a lot of post processing work, a score of "1" would be assigned. If the supplier provides a more thorough description for build plan and cost items, but the intended finished part still requires a lot of post processing work, a score of "3" would be assigned. If the supplier provides a thorough description for build plan and cost items, and the intended finished part is very close to mission ready, a score of "5" would be assigned.

4.3.7 Quote Confidence

As mentioned earlier in this subsection, Quote Confidence is the final weighted score based on the supplier's Capability Criteria. The idea is that we are generally more confident with the quote if the supplier has demonstrated a high level of production capability.

4.4 Results

The two criteria scoring systems' guiding principle are summarized via the following two tables Table 4.1 and Table 4.2.

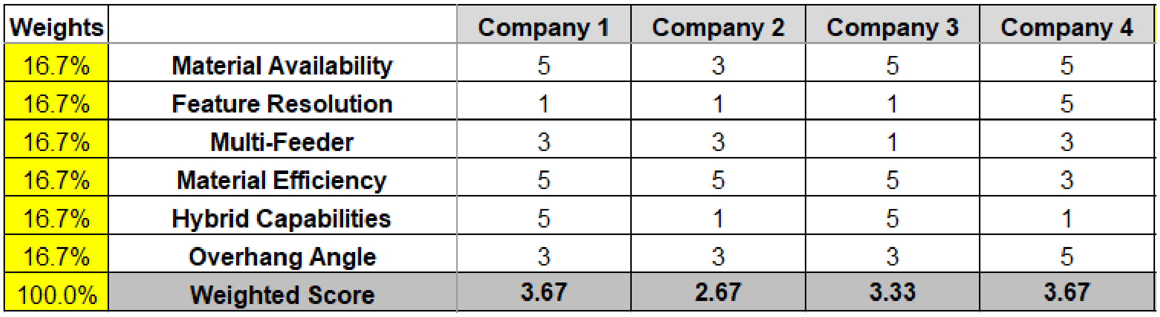
	5 Points	3 Points	1 Point
Material Availability	Ti64	Nickel Based	SS and Others
Feature Resolution (Layer Height)	.03 - 0.2 mm	0.2 - 1 mm	$\geq$ 1 mm
Multi-feeder	4	2	No
Material Efficiency	$\geq$95%	<95%	N/A
Hybrid Capability	Yes	N/A	No
Overhang Angle	>80°	45° - 80°	$\leq$45°

Table 4.1: Capability Criteria Summary

	5 Points	3 Points	1 Point
Cost	Low	Median	High
Lead Time	Short	Median	Long
Service Type	Both	Production only	R&D only
Production Capacity	≥5 machines, teams of engineers & operators	≥3 machines, <5 engineers & operators	<3 machines, <3 engineers & operators
Production System Maturity	Quality system in-place, ≥3 years of software maturity	Quality system in-work, ≥1 year of software maturity	No quality system, ≤1 year of software maturity
Quote Quality	Thorough and less post processing required	Thorough but required more post processing	Vague on build plan and finished product description
Quote Confidence	Supplier's Capability Criteria final score		

Table 4.2: Supplier Criteria Summary

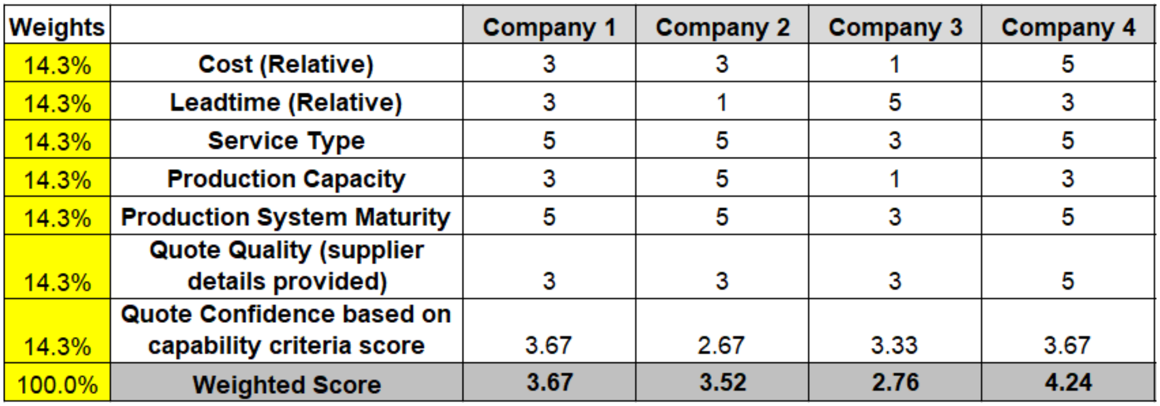
The weights for each criterion are compiled using the AHP tool[11] with two AM experts' inputs. The weights are assigned equally across all criteria in their respective systems in the example final results presented in Figure 4-6 and Figure 4-7. The scores for each of the suppliers are arbitrarily assigned in this thesis for use case demonstration.



Weights		Company 1	Company 2	Company 3	Company 4
16.7%	Material Availability	5	3	5	5
16.7%	Feature Resolution	1	1	1	5
16.7%	Multi-Feeder	3	3	1	3
16.7%	Material Efficiency	5	5	5	3
16.7%	Hybrid Capabilities	5	1	5	1
16.7%	Overhang Angle	3	3	3	5
100.0%	Weighted Score	3.67	2.67	3.33	3.67

Figure 4-6: Example - Capability Criteria Company Scores (scores are assigned arbitrarily for proprietary reason)

When evaluating the suppliers, the Supplier Criteria set is the final judging criteria since the final weighted scores in the Capability Criteria set are translated into one criterion in the Supplier Criteria set. According to the example capability criteria scores, Company 1 and Company 4 both have the highest capability scores (3.67) out



Weights		Company 1	Company 2	Company 3	Company 4
14.3%	Cost (Relative)	3	3	1	5
14.3%	Leadtime (Relative)	3	1	5	3
14.3%	Service Type	5	5	3	5
14.3%	Production Capacity	3	5	1	3
14.3%	Production System Maturity	5	5	3	5
14.3%	Quote Quality (supplier details provided)	3	3	3	5
14.3%	Quote Confidence based on capability criteria score	3.67	2.67	3.33	3.67
100.0%	Weighted Score	3.67	3.52	2.76	4.24

Figure 4-7: Example - Supplier Criteria Company Scores (scores are assigned arbitrarily for proprietary reason)

of the four companies. However, Company 4 has better cost and quote quality, which makes the final score of Company 4 (4.24) much higher than Company 1 (3.67).

The final weighted scores in the Figure 4-7 - Example Supplier Criteria Company Scores indicate which company should P&W move forward with job contracting after the quoting exercise. In this example scenario, Company 4 would be the go-to supplier for the specific parts quoted to all the suppliers. However, if there are multiple parts / jobs quoted and different suppliers appear to be stronger in different jobs, a score sheet could be assigned per job to break down the best job matches. The intent of the tool and process illustrated in this thesis is to help streamline the DED supplier vetting process. The tool and process are fairly fluid and could be adapted to fit other AM projects as well.

Chapter 5

Conclusion

5.1 Summary

This project fulfilled the objective of bringing on DED suppliers to enable the acquisition of development metal hardware for P&W's advanced programs. The DED technology and its pros & cons were explained in chapter 2 and the prominent supplier site visits were conducted and documented in chapter 3. Based on the information gathered during the visits and constant collaboration with P&W AM experts, two sets of criteria were established as a ranking system to assess suppliers according to P&W's advance program outsourcing needs. The two sets of criteria and an example of supplier evaluation were explained in chapter 4.

Two AHP tool excel documents, one DED Weighted Final Scores excel document, and supplier information gathered throughout this internship were submitted to P&W as the deliverable of this project.

5.2 Future Research Opportunities

During my internship, we weren't able to make as much progress as we planned because the secrecy surrounding AM data and aerospace industry in general. Technical data and expertise in specific printing applications were only available if a purchase order was initiated. Even then, the only data available would be the information generated from our specific job request, which is also proprietary and not allowed to be published. There is a significant amount of repeated research amongst different companies and suppliers. As a result, the AM application in aerospace for non-tooling purposes is progressing very slowly and painfully.

Another big show-stopper was the general reluctance in accepting AM designs in the structural engineering community related to material properties and associated stress. The lack of data due to secrecy and the reluctance in believing the design until more robust data is available creates a dilemma that hinders the progress of DED applications in aerospace. This dilemma is unlikely to be resolved quickly, it will likely require multiple successful use cases with open-source data sharing to make the broader aerospace engineering community more confident in AM technology and trust its designs.

Future research in this area could seek to expand the pool of DED suppliers. It takes time to get to know the suppliers and build relationships with them. Due to the time and resource constraints of this internship, we were only able to establish connection with a handful of DED suppliers. There are many other capable DED suppliers that we were not able to connect either due to their physical distance or COVID restrictions. Internally, P&W could also spend resource to reassess the Technology Readiness Level (TRL) for DED. Once the TRL is assessed to be on a higher level than previously deemed, more resources could be deployed to further develop the DED technology internally, increasing engineering and supply chain teams' familiarization with the DED technology, and to bring on more capable DED suppliers.

Bibliography

[1] *About Pratt and Whitney*. en. `https://prattwhitney.com/company/about-pratt-and-whitney`. [Online; accessed 15-November-2021]. 2021. (Visited on 11/15/2021).

[2] *Aircraft Engine Market share Forecast to 2026 | MarketsandMarkets™*. `https://www.marketsandmarkets.com/Market-Reports/aircraft-engine-market-14300744.html`. [Online; accessed 15-November-2021]. (Visited on 11/15/2021).

[3] Nickles Alex. "Identifying and Assessing Aerospace Parts for Production in Additive Manufacturing". English. Graduate. MIT, May 2021.

[4] *Article – Large Format Metal Additive Manufacturing Parts | Additive Solutions*. `https://additive.lincolnelectric.com/resource_type/article/`. [Online; accessed 03-January-2022]. (Visited on 01/03/2022).

[5] *Boeing and Norsk Titanium recognised for metal AM structural components*. Metal Additive Manufacturing. `https://www.metal-am.com/boeing-norsk-titanium-recognised-metal-additively-manufactured-structural-components/`. [Online; accessed 18-November-2021]. Jan. 25, 2018. (Visited on 11/18/2021).

[6] Milan Brandt. *Laser Additive Manufacturing*. English. Woodhead Publishing Series in Electronic and Optical Materials 88. Matthew Deans, 2017. ISBN: 978-0-08-100434-0.

[7] Jeff Epperson. "Creating Optimized Value Creation Conditions: An Additive Manufacturing Model". English. Graduate. MIT, May 2021.

[8] F42 Committee. *Standard Guide for Directed Energy Deposition of Metals*. en. Tech. rep. [Online; accessed 17-November-2021]. ASTM International, 2021. DOI: `10.1520/F3187-16`. (Visited on 11/17/2021).

[9] Ernest H.; Saul I. Gass Forman. ""The analytical hierarchy process—an exposition"". In: *Operations Research* (July 2001), 49 (4): 469–487.

[10] *From aerospace engineering to AM: Melanie Lang on FormAlloy and the future of Directed Energy Deposition (DED)*. en-GB. `https://www.metal-am.com/articles/from-aerospace-engineering-to-am-melanie-lang-on-formalloy-and-the-future-of-directed-energy-deposition-ded/`. [Online; accessed 17-November-2021]. Oct. 2020. (Visited on 11/17/2021).

[11] Klaus D. Goepel. “Implementing the Analytic Hierarchy Process as a Standard Method for Multi-Criteria Decision Making In Corporate Enterprises – A New AHP Excel Template with Multiple Inputs”. In: *Proceedings of the International Symposium on the Analytic Hierarchy Process 2013* (2013), pp. 1–10.

[12] Owen Hildreth et al. “Dissolvable Metal Supports for 3D Direct Metal Printing”. In: *3D Printing and Additive Manufacturing* 3 (June 2016), pp. 90–97. DOI: `10.1089/3dp.2016.0013`.

[13] *Relativity Space - Stargate.* en-US. `https://www.relativityspace.com/stargate`. [Online; accessed 12-December-2021]. (Visited on 12/15/2021).

[14] *Relativity Space 3D Prints 11-Foot-Tall Fuel Tank with Stargate 3D Printer*. 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing. en. `https://3dprint.com/231703/relativity-space-3d-prints-fuel-tank/`. [Online; accessed 12-December-2021]. Dec. 12, 2018. (Visited on 12/15/2021).

[15] Thomas L Saaty. “A Scaling Method for Priorities in Hierarchical Structures”. In: *Journal of Mathematical Psychology* (June 1977), 15 (3): 234-281–487.

[16] *The Complete Guide to Directed Energy Deposition (DED) in 3D Printing*. en-US. `https://www.3dnatives.com/en/directed-energy-deposition-ded-3d-printing-guide-100920194/`. [Online; accessed 16-November-2021]. Sept. 2019. (Visited on 11/16/2021).

[17] T. Wang et al. “Grain morphology evolution behavior of titanium alloy components during laser melting deposition additive manufacturing”. In: *Journal of Alloys and Compounds* 632 (2015), pp. 505–513. ISSN: 0925-8388. DOI: `https://doi.org/10.1016/j.jallcom.2015.01.256`. URL: `https://www.sciencedirect.com/science/article/pii/S0925838815003540`.