Cost Estimating Challenges in Additive Manufacturing

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Abstract— Additive manufacturing (AM) is quickly becoming a popular topic among Aerospace and Defense (A&D) companies as well as government agencies. Additive manufacturing differs from traditional manufacturing processes in that raw material is added or combined together to form the end product. Most existing processes remove raw material from a "slug," leaving behind the end product. These existing processes are sometimes called subtractive manufacturing or traditional manufacturing. Additive manufacturing is not new, by any means. In fact, 3D printing (one form of additive manufacturing) has been around since the early 1980s. The past few years have shown us that the possibilities are virtually endless: from rapid prototyping, to printing food, to recreating human tissue and bones. This presentation will highlight the challenges of additive manufacturing and offer some guidance for the cost estimator.

Additive manufacturing uses in Aerospace and Defense (A&D) have been previously restricted to rapid prototyping. Rapid prototyping allows engineers to determine design feasibility quickly, saving time and money. Shortened development cycles may result in getting the product to the user more quickly and for less money. Additive manufacturing could also mitigate some diminishing manufacturing source (DMS) issues. As sources shrink for obsolete weapon system components, end users could simply print a replacement component rather than rely on manufacturers to build small lots of spares or one-off components at prohibitively high cost.

Of course, there are some limitations such as material choices, though these are expanding. However, most AM technologies are focused on plastic media. Speed is also a factor. Speed of printing will likely prevent AM from replacing traditional production methodologies for large quantities for the foreseeable future. Finally, there is a high cost of initial startup. The non-recurring cost for industrial grade AM devices is declining, but still remains out of reach for many smaller manufacturers. AM will blur the lines between traditional hardware and software estimating. Printed components rely on extensive software modeling to build the "blueprints" used by the machine.

How does a cost estimator take this into account for a long-term weapon system acquisition? Parametric modeling will help us overcome some of these unique cost considerations. Comprehensive, automated cost estimating tools already help estimators calculate the non-recurring, recurring, and sustainment cost of software and hardware. Modeling AM impacts to a program may be as simple as acknowledging the differences from traditional manufacturing and properly calibrating the key activities used during the AM process.

What does the future hold for additive manufacturing? Based on advances made in the last thirty years, this method of manufacturing continues to grow in popularity and capability. The estimator will find it challenging to stay abreast of the impacts to cost and schedule. Through robust data collection, analysis, and parametric modeling, we can turn this cost estimating challenge into a program cost opportunity.

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1. EXECUTIVE SUMMARY

Additive manufacturing is currently gaining traction in aerospace and defense. AM could lead to cheaper and better structural components faster than traditional subtractive processes. Parametric modeling is well suited for estimating AM components due to the limited amount of available data. Early research suggests AM processes could lead to first piece costs which are 40%-50% lower than traditional manufacturing methods. White and Lynskey provide in Figure 1 a quantitative economic model comparing traditional high pressure die casting (HPDC) versus Selective Laser Sintering (SLS) of an aerospace component.[1] The cost reduction is seen across all activities for development and production. Several recommendations are provided to guide the estimator through parametric modeling adjustments to account for unique AM processes.

2. CHALLENGE

Parametric, or statistical, cost estimating methods use regression analysis from a database of at least two or more similar systems to allow meaningful cost estimating relationship (CER) development which estimate cost based on one or more system performance or design characteristics (e.g., weight, power, speed, range, thrust, etc.)[2].

Parametric models utilize large databases with the flexibility to model many manufacturing techniques. Many models contain a significant number of input parameters to support modeling of cost and schedule for systems, system of systems, sub subsystems and components over the complete lifecycle. When estimating components, a

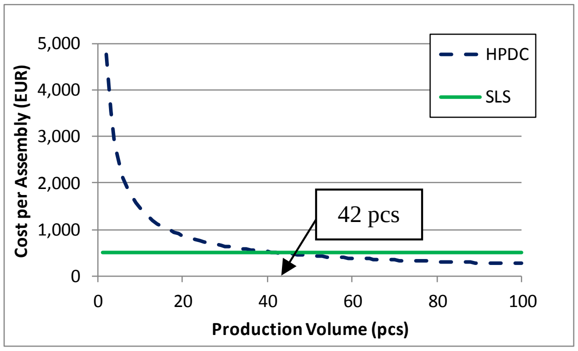

Figure 1 – Economic Model Contrasting Traditional vs AM Showing an Aerospace Sample Breakeven

lifecycle approach should be considered to capture all of the development, recurring and provisioning costs[3].

Providing high confidence estimates for hardware implementing AM is difficult. Many databases currently do not contain enough historical data to allow for accurate estimates. However, Watson and Kwak[4] support the use of parametric models when estimating in a technology driven environment. While they state "*There are assertions that it may be difficult or that the results may lack the precision of a detailed estimate, however, parametric estimating technique does play a very significant role in the early stage of project lifecycle.*" This paper addresses that issue and demonstrates parametric estimating techniques used to estimate the cost of AM manufactured hardware. We investigate how to modify an existing parametric model, which has been used to estimate traditionally manufactured hardware, and show how modifications to the input parameters can provide credible results for AM components.

3. AM IN AEROSPACE AND DEFENSE

History

Additive Manufacturing (AM) has roots dating back almost 150 years. The early technologies are categorized as a manual "cut and stack" approach to building free formed objects layer-by-layer. One of the first successful AM processes was a powder deposition method with an energy beam proposed by Ciraud in 1972[5].

Many techniques for additive manufacturing used today were invented, developed and patented in the 1980s. Bourell, et al, provide a "brief history" of AM and outline a roadmap focused on early AM patents and those of recent times[6]. National Science Foundation (NSF) is performing basic research and development to mature the technology[7].

A key enabler to the state-of-the-art is advanced computer aided design (CAD) and solid modeling tools combined with machine language translators to interpret the models so that they can be constructed in a 3D fashion. Table 1 summarizes some of the enabling technologies when combined with traditional manufacturing and inspection methods support the AM business model.

Drawing from the NSF study we present some of these technologies, the inventor and their concept of operation[8].

Stereolithography *invented by Charles Hull, the founder of 3D Systems, Inc. (patent 4575330 filed in 1984, awarded in 1986). This process, sometimes called vat photopolymerization, begins with a vat filled with a special resin; resins are thick liquids that can permanently harden into solids. Some resins cure rapidly when exposed to a certain light spectrum. Dentists use similar light-activated materials as adhesives, because they can be set quickly with the help of a laser.*

	Technology	Enabler
1	Stereolithography	3D vison
2	CAD and Solid Modeling	Mathematical Models
3	Machine Language Interpretation	Digital translation to 3D Layering
4	Selective laser sintering	Advanced materials
5	Sheet lamination	Complex laminates
6	Material extrusion	Layer Fusing
7	3-D printing	Broad array of applications
8	Traditional Post Processing	Surface finishing/Quality Inspections

Table 1 Enabling Elements of AM

Next, following a digital design, a laser targets an area just above a platform within the vat, causing the liquid resin there to selectively harden. Then, the platform moves down slightly, and the laser activates the next layer of liquid resin, linking the molecules together in a process called polymerization to form a solid object.

Selective laser sintering *was invented by a University of Texas at Austin graduate student, Carl Deckard, and his advisor, Joseph Beaman (patent 4863538 filed in 1986, awarded in 1989). Also known as powder bed fusion, the technique uses a computer-controlled laser to selectively "sinter," or fuse, cross-sections of powder into a solid. The powder can be ceramic, metal, plastic or polymer, depending on what properties the object must have.*

The energy from the laser heats the powder just enough to join the pieces together, similar to how the gentle warmth of hands can form powdery snow into a solid snowball. After one layer is sintered, the next layer of powder is applied and sintered according to the design.

Sheet lamination*, also known as laminated object manufacturing, was invented by Michael Feygin, the founder of Helisys, Inc., formerly Hydronetics, Inc. (patent 4752352 filed in 1987, awarded in 1988). In this process, a laser cuts a thin sheet of paper, plastic or metal into the desired shape, and then another layer is bonded on top and also cut. By repeating these steps, objects with intricate, complicated shapes can be quickly formed at low cost.*

Material extrusion *was invented by S. Scott Crump, founder of Stratasys Ltd. (patent 5121329 filed in 1989, awarded in 1992). The process, sometimes called fused deposition modeling, pushes liquid plastic or metal out through a nozzle, right along the path on the digital map. A similar technique is used by a pastry chef while piping a layer of melted chocolate through the pointy tip of a pastry bag.*

The molten material quickly cools and hardens, and a new layer can then be added on top. Just as chefs may use different concoctions and piping tips to create unique shapes with exactly the flavor, stiffness or other properties needed, material extrusion allows engineers--and enthusiasts--to quickly make new designs into objects meeting their specifications.

3-D printing *was developed by a Massachusetts Institute of Technology team led by Emanuel Sachs (patent 5204055 filed in 1989, awarded in 1993). Also known as binder jetting, the technique involves laying down a layer of a powder and then squirting a liquid binder on the areas to be solidified. While similar to conventional ink jet printers, 3-D printers are able to build additional layers on top of previous ones to construct 3-D objects, even sophisticated objects that could serve one day as medical implants.*

Other additive manufacturing techniques include various material jetting processes and directed energy deposition.

The AM field continues to advance; larger machinery, more efficiency and expanded use is likely in the near future.

Current Uses in Aerospace and Defense

The A&D industries have adopted AM use and continue to develop processes and techniques to enhance the usability of this promising method. While uses today are limited due to a number of factors, the barriers are broken down daily to support long term growth in the industry[9].

One example is the F-18 Hornet, which has been in service for over 20 years. There are nearly 100 parts on the F-18 that are additively manufactured. As manufacturing and spares procurement sources diminish, non-load bearing or other components not critical to flight safety may be easily recreated with a 3D printer as needed. This eliminates the need for suppliers to build, stock, and maintain components with low failure rates, particularly for older weapons systems[10]. The result is lower operations and sustainment (O&S) foot prints.

Similarly, The Joint Strike Fighter contains nearly 1,000 additively manufactured parts. Here, the focus is not on diminishing manufacturing sources. Rather, engineers see AM as a way to build complex assemblies lighter, with fewer parts. This should help achieve target reliability rates and total ownership costs[11].

4. COST MODELING IMPLICATIONS OF AM

Additive manufacturing processes in general have some similarities and differences with traditional manufacturing (TM). Both still require some development and tooling / machine setup. Also, both AM and TM typically require some amount of finishing processes such as surface finishing, grinding, polishing, etc. Post-processing is often overlooked as a requirement for AM. The state of the industry is not advanced enough to typically create a fully finished end product. However, this is changing as tools, processes, controls, and materials continue to advance. As noted in Figure 2 below, the goal of the AM process is to produce the same (or better) component faster while utilizing a tenth of the material.

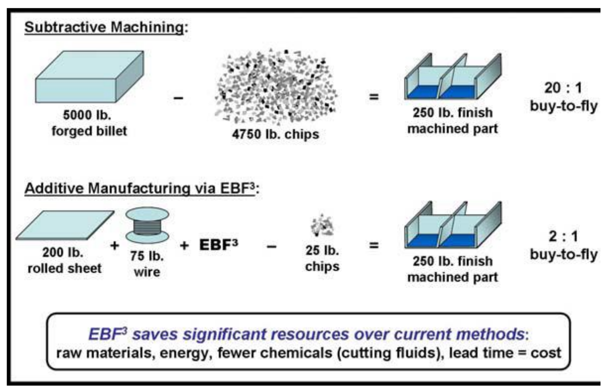

Figure 2 - Comparison of traditional machining versus additive manufacturing.

Before covering cost implications of AM, consider a typical work process flow for an additively manufactured component using electron beam melting (EBM) illustrated in Figure 3. It is worth noting, not all AM processes are the same. In fact, processes (and cost implications) can vary widely between technology and techniques, and even between machines and raw materials using similar processes.

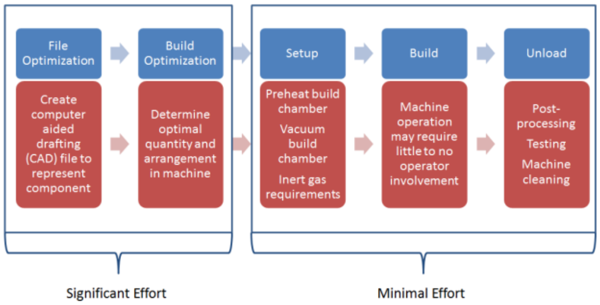

Figure 3 - Typical additive manufacturing process flow

Efficiency and Part Count Reduction

A key AM benefit is that complex components can be manufactured together as one part. Assemblies with complex internal geometries, connections, or integrated tubing can now be created as a single item. Reduction in the number of parts has the obvious, immediate benefit of reducing the effort required to assemble an item. It also reduces the logistical burden on a program. For each part eliminated from the supply chain, support costs decrease.

Reducing part count can also improve reliability and maintainability, thereby reducing support costs further. Figure 4 below shows an example how a hand tool that normally requires some assembly of moving parts can be printed as one component, retaining the wrench adjustment capability.

Figure 4 - Additively manufactured hand tool
Courtesy of www.3ders.org

Figure 5 shows how additively manufactured components with very complex internal structures can be manufactured as one component, another example of eliminating assembly and integration effort.

Tooling and test costs during development and production may be greatly reduced or possibly eliminated. AM does not require expensive tooling usually seen in a forging, casting, or machining process. In fact, some tools for the traditional manufacturing processes can be made through AM. However, capital investment for an AM machine can be high. Organizations should consider how these investment dollars can be amortized across a number of programs instead of attributing the cost to a single program.

Figure 5 - Additively manufactured wing assembly
Courtesy of www.growit3d.com

Rapid prototyping through AM can eliminate or drastically reduce the need for engineering change orders (ECOs), as well as reducing overall development time. Form, fit and function can be quickly and inexpensively validated during development through the creation of rapid prototypes. The cost impact would be seen by a comparable reduction in Production Engineering effort.

Reduction in weight is often another goal for transitioning from traditional manufacturing to additive manufacturing. Internal voids and supports are easier to create with AM, resulting in less overall weight while maintaining the same structural integrity. Typical manufacturing processes do not readily allow intricate designs. We often find some of the product design is not for the intended end use, but a limitation of a forging or casting process.

In general, AM processes may have a lower overall manufacturing complexity than traditional processes. Less material is needed, fewer parts are required, and there are fewer steps to be completed during the manufacturing process. All of these point towards a simpler or less complex manufacturing process[12].

While we have focused on those attributes of AM which may lower cost, it is important to acknowledge a few attributes that may increase cost. Even though we may use much less raw material in AM, the raw material cost per pound can be ten times as expensive[13]. Powders used in AM machines are often proprietary blends made by the machine manufacturers and designed for use in a specific model. Raw material prices are falling, however, as third party vendors enter the market. The cost estimator will need to compare and contrast weight based CERs since historical cost per pound techniques may not provide realistic results for AM processes without calibrating the model.

Additive manufacturing is not a "silver bullet." One should not expect a fully functional end product to come out of a machine. In particular, with titanium powders and other metals, some post-processing is required to render the component usable or meet the specifications. This post-processing could be further machining, surface finishing, polishing, or some other step.

Finally, one major concern for AM components is the cost of certification by aviation administrations throughout the world. Some administrations have been slow to adopt a set of standards before certifying some parts, materials, or manufacturing processes. Obviously, components that bear dynamic forces or are load bearing will need to meet higher standards than an internal air duct, as was discussed in the F-18 case study. Standardization of certification procedures will likely cause the most uncertainty in AM use in the aerospace and defense industry[14].

Titanium Aerospace Bracket Case Study

To fully demonstrate early modeling strategies of AM components, the authors focused on a simple titanium aerospace bracket used in military aircraft[15]. The existing component is manufactured using subtractive processes. It is constructed of Ti-64 (Titanium 6Al-4V). The finished component weighs 40 grams and is approximately 2.5 in x 2.1 in x 1 in.

The bracket was first modeled "as is", based on available historical weight and calibrated complexity values of analogous components. Four factors and inputs in a commercially available parametric estimating framework were modified to represent the unique attributes of AM:

> Manufacturing Complexity: empirical factor representing technology, producibility and yield. The complexity for the AM component was lowered based on more simple process and less material removal during manufacturing.
>
> Resource Multiplier for Material: accounts for eight-fold increase in raw material for AM machines.
>
> Manufacturing Process Index: accounts for degree of automation and familiarization with process. The index value for the AM component was increased due to unfamiliar process of additive manufacturing.
>
> Labor Learning Curve: Higher learning curve used to represent a more automated process. Labor learning curve works in conjunction with the Manufacturing Process Index to calculate first piece cost and recurring unit production costs.

Based on early parametric modeling of this simple titanium aerospace bracket, adoption of AM processes appears to lower development and production costs across most activities and resources. Note that in Figure 6, the first piece cost (T1) of an additive process is nearly half of a traditional process.

The analysis takes into account the eight-fold increase in material costs and clearly demonstrates the impact of a lower manufacturing complexity on first piece cost. Again, manufacturing complexity encompasses material type, effort of process, number of parts, operating environment of the component, surface finishing, and several other factors. The more apparent upward trend of the AM cost curve is due to the adjusted material costs.

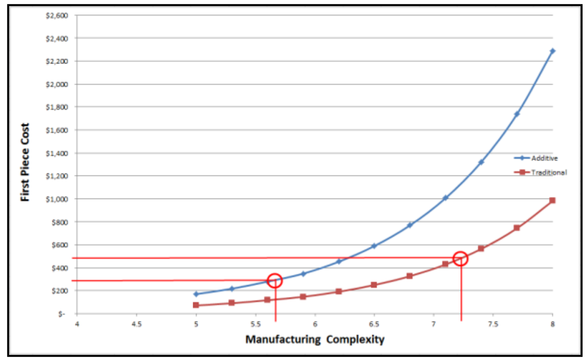

Figure 6 - Manufacturing Complexity and First Piece Cost

Viewing costs in each activity for development and production, we see similar opportunities for cost savings. Note the relative cost per category when comparing AM processes to TM processes in Figure 7.

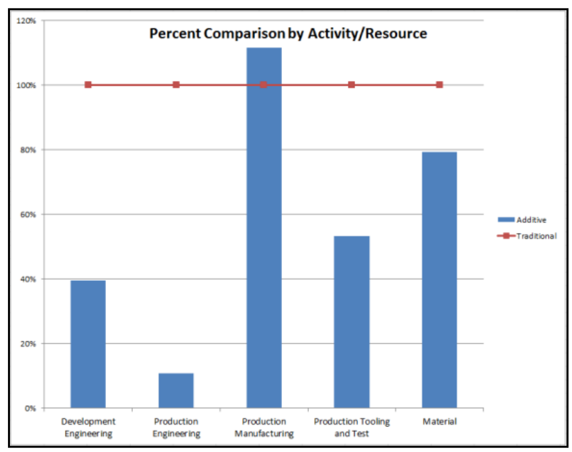

Figure 7 - Magnitude of Potential Cost Savings in AM

One area of interest is the higher production manufacturing cost for AM when producing a large quantity. The learning curve for AM processes is relatively flat compared to TM processes. While the first piece cost was lower for AM, it is nearly constant. Higher quantity production runs may result in a total production cost that is less with TM. However, there are tradeoffs between cost and schedule that must be considered. Figure 8 demonstrates the trade space between cost and schedule. For low quantities (highlighted in green), AM is cheaper and faster. For mid-level quantities (highlighted in yellow), TM is cheaper but AM is faster. In this yellow zone, schedule benefits may outweigh higher cost. For larger quantities (highlighted in red), it may not be economical or feasible to utilize AM processes.

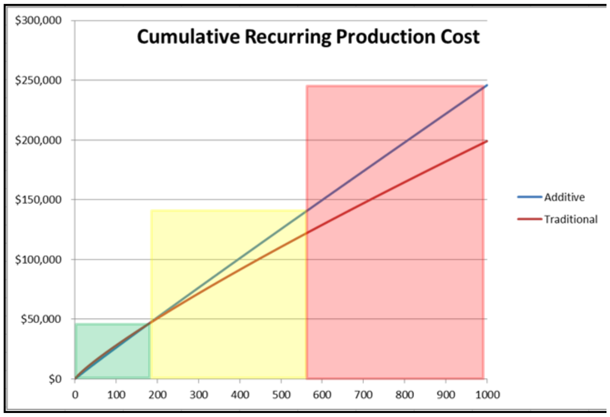

Figure 8 - Magnitude of Potential Cost Savings in AM

Refer to Appendix A for a full list of potential impacts to activity-based, parametric estimating models. These impacts may be easily incorporated into an estimate by modifying activity multipliers, inputs or other adjusters to obtain reasonable model results. For optimal results, any modification to current models should be based on calibrations between unadjusted estimate results and accurate, relevant, historical data.

5. CONCLUSIONS AND FUTURE STUDY

The AM industry continues to grow. New data are being collected and analyzed to support better cost estimating databases, enabling estimators to do a better job of identifying costs and cost drivers in AM.

Early modeling efforts show that AM has the advantage for short production runs of non-load bearing or non-flight critical components. Less material requirements, lower unit production cost, and shorter schedules were observed when modeling a switch from a TM environment to an AM environment. Results are consistent with widely available studies and literature on effects of additive manufacturing.

Estimators used a combination of research, historical data, empirical analysis, and subject matter expert opinion to select and modify four key components in an existing parametric model to reflect the unique nature of AM. This list includes material cost, component complexity, manufacturing process, and labor learning curve.

Efforts are underway to capture historical AM costs from several aerospace and defense manufacturers. Specific recommendations for parametric modeling adjustments will then be analyzed, validated and published.

Future studies should focus on cost and labor requirements for combinations of specific materials and AM processes, to include analysis of results across different vendor machines. Airworthiness certification processes for load bearing components will require more understanding as standards are developed and refined in the U.S. and abroad. Special attention should be paid to schedule impacts. It is likely there is a trade space between cost and schedule for some production quantity ranges.

AM techniques, equipment, and materials are evolving at a rapid pace. The “cutting edge” of aerospace manufacturing is happening now. As a result, manufacturers are reluctant to share information with other companies to avoid disclosure of proprietary data. Lack of sharing will hamper the efforts of the cost estimator for the foreseeable future until processes, materials, and other factors become standardized across the industry.

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BIOGRAPHIES

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APPENDIX A

Parametric Cost Estimating Implications of Additive Manufacturing

Phase	Activity	Resource	Cost Impact	Rationale
Development	Development Engineering	Labor	↘	Rapid prototyping of designs allows for faster development engineering effort
	Development Manufacturing	Labor/Material	↘	Less raw material needed, potentially offset by higher cost of material and need for post-processing
	Development Tooling and Test	Material	⇔	Potenially higher capital investment offset by lower number of machines
	Assembly, Integration and Test	Labor/Material	↘	Reduced part count eliminates steps and material in assembly process
	Certification	Labor/Material	↗	Increased time and steps required for flightworthiness; Increased number of articles required for destructive testing
Production	Production Engineering	Labor	↘	Significant reduction in engineering change orders due to more thorough valdiation during development
	Production Manufacturing	Labor/Material	↘	Less raw material needed, potentially offset by higher cost of material and need for post-processing
	Production Tooling and Test	Material	⇔	Potenially higher capital investment offset by lower number of machines
	Assembly, Integration and Test	Labor/Material	↘	Reduced part count eliminates steps and material in assembly process
	Initial Spares Procurement	Material	↘	Reduced part count may lead to higher reliability and lower number of items required for spares
Sustainment	Replenishment Spares Procurement	Material	↘	Reduced part count may lead to higher reliability and lower number of items required for spares
	Shipping	Other	↘	Fewer parts and assemblies require less logistics, vendor management, supply management
	Initial Supply Administration	Labor	↘	Fewer parts and assemblies require less logistics, vendor management, supply management
	Support Supply Administration	Labor	↘	Fewer parts and assemblies require less logistics, vendor management, supply management