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Additive Manufacturing Opportunities in the Aerospace Industry:

A TEN-YEAR FORECAST

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Chapter One Introduction

In the earliest days of the additive manufacturing industry and long before AM was actually capable of addressing advanced applications, aerospace was identified as one of the primary opportunities for AM. Aerospace is an industry with a wealth of low-volume, complex components operating in an environment where weight is key seemed ideal to maximize the value of these new technologies.

Over the last 30 years, the AM industry has grown and changed many times over, yet this optimism for AM in aerospace has stayed the same. AM equipment manufacturers have had their eyes steadily fixed on the prize of large profits awaiting them in the aerospace sector.

What has changed is AM technology itself. Rapid advancement in both metal and plastic AM is allowing AM to penetrate into aerospace markets. Machines are finally able produce large enough quantities of parts with the right properties to find use in aerospace. Consequently, AM is pushing into aerospace on a number of fronts that represent significant opportunities for AM OEMs and aerospace suppliers alike. Pioneers in the aerospace field are driving AM technology to solve long-standing inefficiencies long thought of as inevitable and they are reaping their rewards.

As a result, AM is getting a new look from aerospace companies that have long pigeonholed the technology as a prototyping and modeling technology only. Recent projects by Boeing and GE have shown that AM production of series production parts is not only inevitable, but also imminent.

However, anyone close to the industry knows that the adoption of AM technology by the aerospace sector will not be a fairy tale. More likely it will be a hard fought battle. With the limitations of still nascent production technologies, for every one part suitable for AM production, another ten are rejected. Indeed, selecting when and how to apply this new tool in the bag is half the battle.

For companies that understand the current state of AM technologies and where they are headed, this battle can be won and strategic advantages can be exercised; For AM equipment manufacturers, understanding the dynamics of a rapidly shifting and more competitive playing field is imperative to find their position in the market and position themselves best to capture new profits in aerospace.

This first chapter addresses the value proposition for AM in aerospace. More than just characterizing the main value drivers, the chapter gives real-life examples to try and understand the size and scope these value drivers represent, as well as the real signifiers that drive our analysis.

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Chapters 2 and 3 strategically analyze non-manufacturing and manufacturing AM processes that will play in aerospace over the next decade. **SmarTech** has laid out the nature of competition in each sector, as well as the technologies, major players, and commercial opportunities for each sector.

Chapter 4 focuses on how AM interfaces with commercial aviation, military aerospace, and space industries. The focus of this chapter rests on available funding, part qualification, and the character of these diverse industries that will shape AM adoption patterns.

Chapter 5 provides summary forecasts for AM equipment, materials, services, and software in aerospace over the next ten years.

AM technologies create value in a number of different ways. The position of the potential user in the aerospace value chain determines exactly how users will extract value from the technology and the aerospace industry can extract value from AM technologies in a number of different ways. These value drivers are non-exclusive, meaning many times justifications for AM technology overlap. Ideal applications of AM technology will extract value from AM technology in multiple ways. Understanding the size and nature of these value drivers is critical to understanding opportunities for AM in aerospace as a whole.

1.1 Design Improvement

1.1.1 Weight Reduction

Weight reduction has been a priority of commercial aviation since the gas price hikes of 2004. Today, weight reduction is surely the single biggest value driver for AM in aerospace today. According to aerospace folklore, American Airlines saved $40,000 dollars in 1987 from weight reduction resulting from removing one black olive from each first class meal. This perhaps apocryphal story stands to highlight the drastic cost of ownership savings airliners can recognize from even marginal reductions on plane weight.

Airlines have purged airplanes of excess weight to try to maximize fuel efficiency. In the short run, AM has potential to further this incremental weight saving. The earliest applications and case studies have shown 50-70% weight reduction in select parts. A focused AM strategy that identifies and implements AM in the right applications can amount to considerable weight savings over the next few years.

AM can reduce the weight of a part through design optimization. Intelligent CAD/CAM software analyzes the stresses put on a given part and generates latticed design structures. These new parts weigh drastically less while still resisting all the forces put on it. Brackets developed by Airbus and EOS for the A350 aircraft are 35-55% percent lighter than traditionally manufactured parts.

Another example that shows the weight reduction potential of AM technology is GE's 3D Printing Design Quest. GE invited anyone to submit an optimized bracket design. The contest spawned over 700 entries worldwide. The winning design reduced the brackets design by 84%, from 2033 grams to 27 grams.

In the long run, AM can be expected to reduce the weight on commercial aircraft on a much larger scale. Weight reduction resulting from AM implementation will commensurate to that of the larger weight reduction initiative's of the last two centuries, such as the substitution of composite materials in the 787's advanced composites airframe.

This next level of weight reduction will result from a number of new technologies within the AM field. Metal powder bed AM systems can over substantial weight reductions to titanium parts, which make up around 15% of a plane's total weight. AM manufactured high-grade thermoplastic can be substituted for aluminum structural components that make up, on average, 20 percent of the new Boeing 787. These new thermoplastics exhibit comparable properties to milled aluminum with only half the weight. Additionally, new Direct Energy Deposition (DED) techniques look to bring AM benefits to wing spar sections and other aerospace components.

All in all, GE estimates that AM technologies will allow them to reduce the weight of each engine alone by 45 kgs. Weight over an entire aircraft will be substantial as well. In a recent study by EADS Innovation Works and EOS, it was estimated that replacing the engine cowling hinge with an AM part could reduce the overall weight of the aircraft by 10kgs. Clearly, the potential to recognize significant weight reduction in commercial aircraft is there.

1.1.2 Performance Improvements

AM can lead to significant improvements in aerospace design. AM technologies, in the most optimal circumstances, are the ultimate manifestation of the benefits of CAD/CAM modeling. These improvements can reduce the life-cycle cost of the plane by increasing engine efficiency, reducing drag, and reducing mass.

The previous section highlighted AM's ability to reduce unnecessary structure that result from costing and milling production methods, or even replacing these solid structures with metal meshes or lattices. These weight reductions carve away excess materials, but leave the actual performance of the part unchanged. However, AM systems also have the ability to improve the design of the part, which in turn improves the performance of an entire system.

The shining example in aerospace is GE's fuel injector. In truth, the GE example could stand in as an example of nearly all the benefits that AM can bring to the aerospace sector. However, the example is particularly apt for how AM can improve the design of a component. GE's AM-manufactured fuel nozzle eliminates fuel nozzle coking (carbon build up) by building in support ligaments and cooling channels to the part. These improvements are enabled by CAD/CAM modeling of advanced parts and AM's ability to produce these intricate details in a cost-effective manner.

All in all, the design improvements increase the efficiency of the engine over the life of the engine and reduce maintenance costs. Fuel nozzle coking reduces the fuel efficiency of the engine. So by eliminating this build-up, the engine is made more efficient. This also extends the life of GE's new nozzle by five times. That is five times less maintenance and five times smaller replacement component costs.

Recognizing these benefits take more time and effort than simply replacing existing parts because they require manufacturers to incur the costs of design and testing. However, savings recognized in operation costs are much more significant and can justify these expenditures, as proven in Roskam's *Airplane Design Part VIII*.

1.1.3 Simplification

Simplification is the third pillar of design improvements that can be recognized by technologies. AM technologies can reduce the complexity of airplane components and subassemblies, helping to reduce COGS and maintenance costs.

Traditional manufacturing processes require the piecing together of many individual components to create a complex part. Manual manufacturing of these subassemblies amasses large labor costs, where as automation requires heavy up front investment. Either option creates a drag weight on costs structures that inflate the costs of manufacturing an aircraft. Once in the air these complicated assemblies create larger part counts checks, which have to be documented and checked at the expense of the owner.

AM systems are particularly well suited to address this long-standing inefficiency in aerospace supply chains. The complex geometries AM systems can realize can lead to the manufacture of entire subassemblies in a single part. In the GE example above, the previous generation of fuel nozzle contained 18 separate parts. Another example of extreme part reduction is in the forward fuselage for Boeing's F/A-18 E/F, where 41% fewer parts were needed for the AM-enabled parts.

AM processes can reduce the resources- equipment, labor, materials- needed to manufacture a complex assembly. These streamlined assemblies consequently reduce the costs associated with documenting and checking individual assemblies.

They also eliminate potential sources for systems failure. For example, AM is finding ample use in pressurized systems since they can eliminate connection points between components where seal failure is most likely.

1.2 COGS Improvements

Correct application of AM technology is a design optimization play, but it is also in many ways a COGS play. While **SmarTech** would argue for a more life-cycle analysis driven cost model, cost reduction alone should be substantial enough to drive adoption of AM in aerospace.

The last section already talked about the substantial assembly cost reductions that can be recognized through consolidating subassemblies. This is furthered by the newest generation of AM machines that boast more industrial related features, such as powder recovery and processing capabilities. Highly automated AM processes allow manufacturers to reduce labor costs. Together, the ability to consolidate parts and eliminate manual assemblies allows aerospace suppliers to recognize considerable savings to the bottom line.

AM technology compliments existing supply chains by reducing tooling costs. AM technologies have been successfully applied to create investment casts and directly manufacture tools. AM can cut delivery times and development costs of large tooling by significant chunks, without sacrificing quality.

Moving beyond improving existing assembly lines, AM has the potential to directly manufacture low-volume manufacturing runs with a new level of efficiency. The entire process of developing expensive tools to produce a small number of components is costly and inefficient. AM systems can eliminate the need to tooling altogether through a combination of AM and CNC milling processes. For example, eliminating tooling costs for Kelly Manufacturing Company's M3500 bank indicator toroid housing reduced the costs per parts 5%.

The speed, associated costs, and throughput of current AM machines are best equipped to handle metal part orders of 1,000 or less. Industry insiders say that AM is the right answer 70% for applications with these part counts. Plastic AM printers can address larger part counts because of more developed technology. **SmarTech** estimates that plastic AM manufacturing is a viable production option for parts counts below 10,000. As AM technology is improved over the years, the volume of parts that can be economically produced will increase, and with it the addressable market for AM in aerospace.

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1.3 Lead Time Reduction

The elimination of tooling design and implementation in the select aerospace supply chains significantly reduces the lead-time to deliver aerospace parts. In the same example for Kelly Manufacturing Company above, Stratasys Fortus systems allows lead time for the 500 toroid housings to be cut from three to four weeks to three days. AM equipment required little or no alterations to switch from one application to another. Early adopters of AM technology, because of the flexibility of AM systems to address many applications, have continually reported that they are able to quickly get larger systems running at full capacity.

This drastic reduction in lead times makes AM technology exceedingly valuable in a pinch. AM is quickly becoming the go-to technology when timing is a critical factor. For example, BAE Systems quickly went to SLS manufacturing when seeking a quick replacement for window breather pipes for the BAE 146 regional jet. In total, the lead time for this outdated part was cut from two months to one. In total, the project saved 60% of the costs associated with delivering 300 window breather pipes.

1.4 Reduced Environmental Impact

In recent years, environmental considerations have taken on more importance in new production innovation. New criteria for the FAA and EADS Technological Readiness Level (TRL) qualification require new manufacturing processes to improve on environmental affects, such as CO_2 emissions. As reducing environmental effects take on even more importance over the next decade, AM will be a critical technology for helping the aerospace manufacturing meeting their green goals.

Because only necessary structures are built up layer by layer in AM processes, buy-to-fly ratios for AM aerospace parts are much higher than for milling or casting. Additionally, unused metal and plastic powders in the AM printing process have high recycling rates. Many times, only support structures for the build need to be filtered out before powder can be reused for additional jobs. Metal powders are nearly 100% recyclable; plastic materials are 75-80% recyclable. It is estimated that AM manufacturing of some parts in an airplane could reduce material consumption by 75%.

Along with optimal CAD/CAM-enabled designs that require less materials and higher buy-to-fly ratios, AM technology allows suppliers to lessen the environmental effects of their production significantly over their product life cycle. In a study published in early February 2014 by EADS Innovation Works and EOS, the environmental benefits of AM were tracked through a cradle-to-cradle analysis of nacelle hinge. The streamlined life cycle assessment looked at the energy consumption though the life of the part. The study was comprehensive and looked at such factors as energy used to transport raw materials, argon consumption, waste, etc.

The study showed that significant energy savings were recognized through the life cycle of the hinge, even though the actual manufacturing process was much more energy intensive than traditional production methods. In total, carbon emissions were reduced over 40% over the life of the part, and raw material inputs were reduced by 25%.

The results of EOS's study are critical justification for the immediate implementation of AM processes in aerospace manufacturing. Going forward, AM will be a key tool for environmental reduction initiatives over the next ten years.

The following are generalizations of the opportunities within major sub-sectors of the aerospace industry. They should serve to give the reader a general feel of where opportunities are to be had in each sector and what issues the AM discussion revolves around. Chapter 5 elaborates on the topics mentioned below from a strategic perspective.

1.5 Opportunities For Commercial Aviation

Commercial aviation represents the largest opportunity for AM technology, both in terms of short-term and long-term opportunities. The prospects of a large and upward trending market for new aircraft create ample opportunity for AM technology to improve designs and lower costs. The size of the global commercial fleet, along with the ability to recognize substantial savings over the life of commercial planes will drive innovation in AM aerospace applications over the next decade.

AM prototyping solutions have already established a foothold in commercial aviation design processes. A natural extension of CAD/CAM modeling systems adopted by top suppliers, AM prototyping has been a part of the aerospace story since the inception of the technology in 80's and 90's. Aerospace suppliers recognize time and cost savings over alternative modeling techniques, while also building new core competencies into their corporate identity. AM prototyping will continue to gain steam in the aerospace sector, as new epoxy acrylate resins enable more functional prototyping and digital design becomes ubiquitous throughout the industry.

The other significant application outside of direct manufacturing of parts over the next decade will be direct and indirect tooling for existing assembly lines. As another tool in the toolbox, AM and dual AM and CNC milling techniques frequently offer the most cost efficient way to produce casts. AM equipment affords assembly lines the flexibility to more nimbly adapt to new production and meet gaps in demand.

AM offers two distinct advantages to tool production. Firstly, AM processes can more easily incorporate cooling channels into die casts that improve accuracy and throughput. Secondly, more efficient design of die casts outside of the immediate molding area creates considerable material savings without decreasing performance.

But for all the ways AM can benefit commercial aviation by indirectly enhancing production, AM equipment manufacturers and aerospace suppliers alike are focused on how AM can impact direct manufacturing of aerospace parts. These opportunities represent the largest opportunities to recognize savings and generate profits.

While stereolithography (SL) resins and fused deposition modeling (FDM) materials ultimately miss the mark for end user aerospace applications (as opposed to prototyping and tooling), both selective laser sintering (SLS) and direct metal laser sintering (DMLS) can produce air-worthy parts. Metal powder bed systems can further the implementation of titanium and nickel materials in commercial aircraft, while high-grade thermoplastics can replace aluminum 6061 with a 50% weight reduction.

The aerospace industry is already seeing the first implementations of AM produced parts in aircraft, including the famed GE fuel injectors, brackets, elbows, hinges, air ducts, and fuselages. While engineers will grapple with part counts, post-processing, and build size to identify ideal applications for AM in the short-run, steady technological innovation over the next ten years will open up more and more opportunities to print plane parts. Potential markets could skyrocket if new AM technologies such as direct energy deposition (DED) that aren't limited by build envelopes develop faster than expected.

The savings recognized through AM processes will only increase as digital design processes infiltrate the lower supplier groups and new application can be identified. In the end, relatively steady AM technology development and steady implementation by aerospace suppliers will shave hundreds of kgs off of the weight of each commercial plane and millions of dollars will be saved in production and operation of the aircraft.

1.6 Opportunities in Military And Defense

Military and defense sectors have seen tough times since the scaling down of the Iraq war and global defense spending cuts. More frequently, military and defense companies are being asked to do more with less. AM systems can be an answer to further R&D efforts, while increasing design efficiency and recognizing cost savings.

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The lower part orders make military and defense applications fit the addressable market for current AM technologies. Limited space, weight, and part complexity requirements also further the argument for adoption of AM processes.

AM stakeholders have particularly targeted missile systems and satellites as the best immediate implementation of AM technologies in the military and defense sectors. Unmanned systems perhaps eliminate some of the strict requirements for AM parts. Furthermore, one-time use applications are much more imminent than applications where long-term use is needed from the AM part. Announced development of AM PEKK thermoplastic materials with electrostatic properties by Northrup Grumman and Oxford Performance Materials, as well NASA's work with neat PEKK materials stands as proof that wide application of AM technology is imminent.

Down the road, AM plastic and metal systems will prove to be ideal technologies for supplying replacement parts for aging military aircraft fleets. But more importantly, CAD/CAM systems, of which AM is an integral part, have the potential change industry paradigms by streamlining jet fighter production cycles. CAD/CAM solutions will eliminate technology creep caused by lengthy production stages and changing requirements by 1) accelerating communication and collaboration with subcontractors, and 2) allowing adaptive designs that don't have to be scrapped when requirements change. In the end, a more adaptive AM enabled approach will support a constantly evolving fleet of fighter with smaller, more frequent orders.

1.7 Opportunities In Space

The AM industry has identified space applications as a large potential market for AM technologies over the next decade. Many of the value drivers for space applications are the same for military and defense application. Applications in outer space also demand the lightweight, space constrained, complex parts that AM is well suited to supply. At the same time, modern production systems and extremely finite part counts fit the addressable markets for current AM technology better than any other aerospace subsector.

These finite part counts, however, may also be a limiting factor for AM adoption by space applications. The opportunities in space don't scale up enough to drive innovation in AM technology. Instead, space applications will rely on R&D driven by applications in commercial aviation. As new AM technologies become available, however, the space sector will benefit greatly from having new tools in the bag. Along with the regular applications of pressurized channels, ducts, shielding boxes, and the like, new opportunities will quickly reveal themselves once space manufacturers integrate Am technology into their arsenal.

This is not to overshadow the value that AM prototyping has provided and will continue to provide to space manufacturers. More functional testing fits well into the new streamlined space sector and will improve the efficiency of design processes.

As far as end-use parts, lack of material allowance charts and extremely conservative requirements may hinder short-term commercial opportunities. However, AM manufactured parts have already found their way onto the KySat 2 satellite, as well as a handful of other satellite applications. As materials information becomes more available over the next 3-4 years, **SmarTech** expects space manufacturers to move quickly, in order to recognize the benefits of AM.

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