A Review of Aviation Manufacturing and Supply Chain Processes

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Abstract— **This paper provides an overview of modern aviation manufacturing and supply chain practices, including machining processes, 3D printing processes, and automation processes. Continuous improvement efforts in both manufacturing and supply chain practices are necessary for the industry to meet the increase in production demand of 35,000 aircraft over the next two decades.**

***Keywords*—** *aviation manufacturing, machining, automation, 3D printing processes, aviation supply chain*

1. Introduction

Airplanes have always been complex machines that require many components. Improvements in airplane design have increased airplane complexity and the required number of parts. In, the 1930's an improvement in technology birthed the modern turbine jet engine and in the 1970's the development of the high-bypass turbofan jet engine. Higher altitude flights required pressurized cabins as well as heating and cooling. Today's aircraft are a product of thousands of refinements [1].

Each of these improvements places more demand on the plane manufacturer. Construction takes longer and requires more specialized fabrication machines. Fabrication of airplane parts requires great attention to detail due to the demands of flying. Flying is dangerous and places great stress on supporting components which are also required to be lightweight. Given these requirements of being light and strong, components must be manufactured with high tolerances. Manufacturing components with such tight tolerances requires that all parts be machined as a final process. This takes a significant amount of time. When components require tight tolerances a high level of quality control is required to ensure that the components meet the requirements. The combination of specialized machining requirements and quality control effort results in an extended time duration just for component manufacture.

Assembly requires the same level of precision and attention to detail. Automation of these complex assembly processes requires intense simulation and programming. Some processes can be automated such as painting, riveting, and welding. These processes benefit from the precision that automation can provide. Paint can be applied to an exact thickness; rivets can be placed to within a thousandth of an inch, and welding beads can be perfect every time. Robots can be as precise as necessary and never miss a detail. However, they cannot be utilized for major operations such as joining the wing to the fuselage. This process is not automated due to the scale of the operation. The number of sensors and programming required would be immense.

Some processes require more computing power than is currently available. Automation is not now a viable solution for such instances. Plane production will require ever-increasing component production rates. Components must be manufactured and assembled faster without compromising quality. Future innovations in automation and computer technology will aid heavily in reaching this goal.

The demand for air travel drives the need for increased aircraft production. With a predicted production requirement of 35,000 commercial airplanes between 2014 and 2032 it is imperative that manufacturers update their processes to accommodate the predicted demand [2]. Progress of aviation technology will contribute to space craft progress as well. Although processes may not directly transfer to space craft they will still influence design due to the similarities between

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airplanes and space craft. Advances in manufacturing technology can offer an improvement in overall efficiency by increasing the number of materials available to designers.

2. Literature Review

2.1 Machining Processes

The process of machining airplane components requires many different milling machine steps due the intricacy of the components' shape. Components are also often made of materials that are hard to machine, such as titanium. When milling titanium, more time is required because the milling machine cannot remove material from the work piece as fast as it can on other metals. This is due to titanium's low heat conductivity and low modulus of elasticity. Heat conductivity is critical in cutting parts. If the heat is not transferred from the work surface to the environment, waste chips can end up welded back onto the work piece. A low modulus of elasticity makes thin parts hard to machine because the piece will bend if too much force is applied, so less material must be cut off in one pass. To combat this, new cutting tools have been developed that employ special coatings and micro-grain carbide substrates [3]. These new cutting tools work in tandem with more traditional approaches such as coolant application to the cutter tool and removal of chips from the machining path. A byproduct of better cutting tools is a longer tool life which results in less downtime for machine maintenance. A machine can cut parts faster and complete more cycles before having to be serviced. The end result is a higher production rate of components, helping to produce more airplanes.

Traditional three axis milling machines clamp a work piece in one spot and the cutter head fixed in one place as well. The milling machine table moves in two axes with a third axis being provided by the cutter head spindle. This limits the how much milling can be done in one configuration because of the limited cutting paths and accessible work surfaces. More advanced five axis milling machines are already available and are becoming more frequently used. The five axis machine can tilt and rotate the milling table offering two more axes to operate on. This setup is called a "three plus two". The name is derived from the fact that it can be used on normal three axes milling machines as an upgrade adding two axes. Continuous five axes milling machines have cutter heads which can articulate to make up three of the axes while the table still provides two axes. There are variations on how the two extra axes are obtained, but the end result is always five total axes. A cutting program allows the machinist to see where the machine will cut during its cycle and is useful when first setting a machine up. The cutting program also converts three dimensional model files to cutting path files. Five axis machines provide benefits such as reduced fixture setup and use of a shorter cutting tool due to increased work piece accessibility [4]. These improvements significantly shorten the time required to make each part, and allow more parts per work shift to be manufactured.

Quality control ensures that parts are within specifications and is an important part of component manufacturing. A part can be checked while still on the milling machine using a process called "on-machine verification". A probe creates a three dimension map of the part to determine if it matches with the specifications. If not, the part can be fixed while still on the milling machine. This is a powerful tool because it allows parts to be fixed immediately before advancing in the manufacturing process. On-machine verification also adds an additional quality control check point, allowing for defect trends to be found and eliminated. Smaller operations that require only machining processes for a component to be completed may find that there is no further quality check needed after using the on-machine verification. No matter what setup is used, on-machine verification speeds the component manufacturing process up by either eliminating or improving the quality control process.

It is estimated that 1,800 new milling machines will be needed to meet the demand predicted [2]. The need for the new machines comes from the size of the components. Currently there are machines in use that can handle the size of the components but there simply are not enough of them to handle the new demand. Another 2,400 continuous five axis machines will be required for the increased production of turbine and fan blades [2]. Retrofitting old machines will not solve this problem as it would be too costly and inefficient. A company's initial capital outlay for new equipment can be justified by the increased capacity for production. New improvements and acquisitions of milling machines will lead the effort in ramping up production capabilities for airplane components.

2.2 3D Printing Processes

Computer technology has allowed completely new approaches to manufacturing. Three dimensional ("3D") printing allows a computer model to be printed three dimensionally in plastic or metal. There is a big difference regarding the details of each process since liquefying plastic is much easier than liquefying steel.

One of the newest plastic releases from Oxford Performance Materials Incorporated is a PEKK based polymer. PEKK is a polymer approved for use in certain aerospace applications. A variant, OXFAB-ESD, has characteristics consistent of that demanded for structural applications. This variant is the normal PEKK but it has a carbon core. The PEKK strength to weight ratio is better than that of cast aluminum [5]. Therefore, the 3D printed PEKK parts offer significant improvements in fuel efficiency. This is a benefit that will continue to pay for itself as time goes on by saving fuel. With the ability to make parts in any shape and at a lighter weight, it is no surprise that this is a perfect match for the aviation industry. Additionally, the cost of polymer printing is much cheaper than metal printing, making it a more viable option.

The metal printer allows damaged parts to be fixed. Specifically, if a part has had too much material removed the material can be replaced by simply printing more material back on to it. This new advancement is a big one, allowing a damaged part to be salvaged rather than scrapped. Less scrapped parts means more parts produced for service.

Recently it has also been found that controlling the melting and solidification process during the 3D printing of metal allows for the control of materials' properties in different areas of the part [6]. This enables a component to have unique properties in various locations without additional specialized manufacturing processes. Increasing the number of steps completed at one workstation reduces the intermediate time in between machines. Overall this advancement not only facilitates increased production, but allows designers to make components better suited for their application.

A future benefit will be utilizing 3D printing parts at maintenance facilities. Having a capability such as this would be a tremendous benefit. It would allow maintenance personnel to simply print the parts needed for each specific repair. This would also eliminate the need for ordering parts and the delay in time associated with shipping. In order to be able to print parts at a satellite facility there would have to be quality control checks to ensure the printed parts met specifications. Developing a procedure for satellite printing would take a substantial investment, but the benefits for high priority repairs would outweigh the cost.

3D printing also allows for even the most intricate components to be created and in some situations printing the component is faster than machining it from a billet piece of metal. General Electric is currently creating fuel nozzles made of multiple materials [7]. Normally this fuel nozzle would require the different materials to machined separately and then fused together. Replacing this process with a 3D printer allows the entire process to be completed with one machine. It should be noted that finishing processes such as machining take place after the part is printed. This is just one example of 3D printing in the aviation field. Other examples include brackets for satellites and various turbine components. There is potential for major use of 3D printing but the cost is still too high to justify creating high volume parts with it. As with any technology the price will eventually come down and at that point high volume manufacturing with 3D printing will be possible. Overall, the benefits afforded to the aviation industry from 3D printing are a time reduction in manufacturing highly unique parts. However, the future for 3D printing is limitless in terms of application. Its contribution to the future of airplanes and space craft is the ability to create complex parts at a fast pace and light weight. Furthering the production rate of airplanes and lowering their weight.

2.3 Automation Processes

Many assembly processes are now being automated due to the improvement in sensors and computer programing. Processes such as drilling rivet holes on, and painting, the fuselage are now automated. These processes require great accuracy, a perfect application for robotics. Robotics never fatigue, are cost effective, and can complete any task to the exact detail, consistently. There are two types of accuracy when it comes to robotics: path accuracy and position accuracy [8]. Position accuracy is important for drilling holes or affixing fasteners. Path accuracy is important for processes that require accuracy while the robot is moving, such as painting. There are robots which combine both accuracies, often completing multiple processes at once. Dual encoders are used to achieve these levels of accuracy [8]. Dual encoding uses two levels of programmed spatial awareness. The first level is the generation of the most efficient process sequence and work path. The second level monitors this path with optic sensors. If the robot deviates from its set course it can correct itself.

It is imperative that larger robots have multiple sensors for spatial awareness because the margin for error increases with size of the machine. The ability to apply robotics to larger processes is extraordinarily beneficial. More operations can be completed with robotics. An increase in process automation increases production and consistency. Production increase will support the anticipated future demand. Robotics developed for airplane assembly will also be applicable to spacecraft. Spacecraft assembly processes may be different but the technology will still be applicable.

For example, both air planes and spacecraft use composites. Airplane manufacturers have already automated the fiber and resin process used for making composite components. Sierra Nevada Corporation's new Dream Chaser space craft employs a composite structure, making it possible to apply composite automation processes from the airplane industry [9]. Molds are often used for making composite components out of carbon fiber. Once the molds are completed, the process can become automated. Each particular carbon fiber laying robot will be different to a certain degree, but the basic operating principles will remain the same.

Another shared requirement between airplanes and spacecraft is the necessity for safety. In any flight related industry quality is of high concern for this reason. Quality control and maintenance demand that each part be exactly the same as the one before it. This allows replacement parts to require no modification. Consistency of parts' quality level lets the customer and manufacturer know what to expect. With greater accuracy comes greater cost, so defining accuracy metrics is important in each unique application. Although the upfront cost of new machinery is often steep, the return is much greater in value. The improvement of these systems is important to the aviation industry because automation increases production and quality. Pioneering new automation now for airplanes will lay the ground work for automation on space craft.

New technology and manufacturing processes require proficient operators who have been trained on the new operating procedures. As production increases through new manufacturing processes so will the demand for employees. Although automation will cut back on the number of man hours put into any single component, the demand for more aircraft will increase the need for skilled operators. Increased airplane fleet sizes will also mean an increase in size of the ground crews required to maintain them.

Industries with growing production numbers benefit not only the company but the surrounding economy. A strengthened economy is good for everybody and allows for further advancement of all industries. Innovation is what drives society and makes a country strong. For space travel to become viable it will require an innovative work force. When space travel becomes possible, the infrastructure will be available to support it with bolstered manufacturing technologies and ground facilities in place. Skilled employees are still essential to increased production and will be required for years to come.

2.4 Supply Chain Processes

Many manufacturing assembly processes have to deal with effective material handling within their supply chains. Researchers have pursued efforts to optimize these flows in the manufacture of large units, including incorporating optimal decisions regarding line locations, storage locations, dock locations, and material handling considerations in conjunction with the manufacturing process [10-11]. Additionally, applying Lean and Six Sigma principles within supply chains has eliminated waste and streamlined the quality of the process; including using Bayesian Network Analysis to make optimal decisions and measure impact [12-13]. Research has also been conducted on transportation systems, such as biomass transportation, to optimize the supply chain of such complex systems [14]. Furthermore, the application and analysis of performance measures of global manufacturing industries, such as the steel industry, and its massive supply chains have been examined using data envelop analysis [15].

3. Methodology

Research for this report was conducted solely through literature. As a starting point research was conducted to identify technologies that were essential to the airplane manufacturing industry. Then research efforts were focused onto those specific areas. Equipment such as the milling machine is not a new piece of equipment but has evolved and is now much more sophisticated. It was important to highlight advancements to the milling machine that offer higher production rates. For newer equipment such as the 3D printer it was important to highlight its capabilities and applications. Finally automation was included since it is such a broad category. It has nearly limitless applications and will continue to be implemented in manufacturing into the future. There is new technology emerging everyday but there is not always published information about it. The topics covered here are both relatively new and have enough published literature to gather information from.

Research into milling machines identified multiple areas of interest. As a starting point five axes machines were shown to be the most capable at manufacturing airplane parts. From this fact more research revealed that new machines and up fitting old equipment were both viable options. These options were then explained in detail. New tooling and attachments for the milling machine were also covered because advancements in these categories make the milling machine more productive. Tooling for titanium was chosen due to the fact that this material is used extensively in the aerospace industry as a whole, also because titanium has properties which make it difficult to machine. On machine verification was chosen because it offered a quality control process which is a major part of manufacturing. The equipment, tooling, and attachments examined here offer options which will maximize production for airplane manufacturers.

Three dimensional printing is a technology that is still being adopted and implemented. It has not reached its full manufacturing capacity yet. This topic was covered because it is a relatively new process that is still evolving. Research into how it works, the newest advances, and its applications were important to defining why it is useful to the airplane manufacturing industry. As it evolves more literature will be available covering new processes. The research presented here highlights the beginning of 3D printing in the airplane manufacturing industry.

Automation is a broad category covering the application of technology to manual processes. Research into this category was done to show current and future processes within the aerospace industry utilizing automation. Another goal was to highlight how airplane manufacturing techniques could carry over to aerospace manufacturing. Aerospace manufacturing is a growing industry that promises to be the future of flight.

All research conducted was done so in a manner as to show what is currently possible and what will be possible in the future. The goal of this research was to be a starting point for further research and development into new technologies for the airplane manufacturing industry.

4. Discussion

How do all of the presented technologies work in tandem? The most efficient approach to utilizing equipment is to assign tasks to each piece that is reasonable. For example turbine blades are much too large to be 3D printed, it would be more efficient for it to be machined on a five axes milling machine. Although there will be applications where a part is 3D printed and then machined. Looking at the process of manufacturing an airplane from a larger perspective, 3D printing and milling machines will be used to make parts while the automated assembly processes will be used to assemble the airplane. For the system to work as a whole both the manufacture and assembly of parts will have to progress at equal pace. Parts should be assembled as fast as they are being made. Processes that cannot be automated should have well trained personnel who are efficient at their job. The procedure the personnel use to assemble parts should also be reviewed periodically to ensure it is efficient. Manufacturing requires multiple pieces of equipment to work at the same pace to accomplish a goal in the shortest amount of time.

After design, manufacturing the individual parts that make up an airplane is the first step to producing one. Creating the parts is the job of the 3D printers and milling machines. This is why updating how parts are produced is a major area of interest. If more parts are produced in less time more aircraft can be assembled in the same amount of time. The processes for making parts presented in this paper offer competitive solutions. Five axes milling machines and 3D printers are the future of part production. Each system has broad application and the flexibility to adapt to future demands.

Having the parts necessary to create an airplane now means that they need to be assembled. The faster the airplane is assembled the quicker it can be utilized for service. Automation offers an efficient solution to assembly. In order for automation to be utilized it will require new automation processes to be created for individual applications. An analysis of the assembly process examining which stages take the most time would reveal where the most time savings would be seen. The stages taking the most time would then have an automation solution created for them. As an example the process of riveting presented in this paper shows how a simple process can take an enormous amount of time due to the volume required during assembly. It was identified and a unique solution was developed to automate that process. Time savings can now be seen by the increased production of planes.

At the core of new technology for production is the cost associated with it. There is a predicted demand for a large amount of airplanes but will this demand create enough revenue to cover the costs associated with a streamlined production line. Simply put planes can be produced as fast as needed it is just a matter of how far a manufacturer is willing to go to achieve these results. For some manufacturers new technology will not be the answer to their problems, rather an increase in the number of machines currently used for production will solve their production short comings. This solution is one that has been used in the past, there is no challenge associated with it. New solutions created to solve a problem in an innovative way are challenging but advance society through new technology. Thinking smarter not working harder is the future of airplane manufacturing. This is why automation and new equipment is the way forward.

5. Conclusion

Production rate improvement requires all of the above-mentioned processes and technologies. Not all of the methods will be implemented at the same rate. Some, such as the 3D printing, will require more time to become viable from an investment standpoint. Updating equipment and improving manufacturing methods will, however, be mandatory for higher production rates. This upfront investment should be seen as an investment in the future. By using and refining these techniques today it will position companies to be better equipped for the future of air travel. The focus of this paper was to provide an overview of the aviation manufacturing industry, with specificity on machining processes, 3D printing processes, and automation processes.

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