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Adopting Additive Manufacturing in Aerospace Engineering Industries: A Meta Analysis of Cost, Efficiency, and Sustainable Supply Chain Operations

Aidan Zhoung

Bergen County Technical High School – Teterboro, USA

ABSTRACT

This study explores the impact of additive manufacturing (AM) on aerospace engineering. It investigates how AM influences cost efficiency, design flexibility, and sustainability within the aerospace industry. Utilizing a meta-analysis approach, the study combines quantitative data and qualitative insights from previous studies and media. Findings suggest that AM significantly reduces production costs, enhances design capabilities, and promotes sustainable practices, providing benefits to the industry that can potentially reduce disruptions within the supply chain.

Introduction

Additive Manufacturing, commonly known as 3D printing, is emerging as a transformative process in the aerospace sector by offering freedom in design and increasing material economy. Whereas traditional manufacturing is subtractive - a methodology where material is removed to make a part - AM builds parts layer by layer from a digital design, making it possible to fabricate complex geometries, lightweight structures, and custom parts [6]. Since its introduction in the 1980s, AM has evolved from a rapid prototyping tool into a capable method for directly manufacturing critical aerospace parts [16]. Many of the challenges that have confronted the traditional subtractive manufacturing method including high cost, extended lead times, and considerable material waste, are mitigated by the development of AM.

Despite these benefits, there are technical challenges for AM in aerospace regarding material properties, production speed, and post-processing requirements. The constantly changing regulatory standards of the industry have also created more challenges for broader adoption. This paper will delve into how AM is shaping the aerospace industry supply chains by discussing cost optimization, design efficiency, and lead time benefits. By means of a meta-analysis that includes quantitative and qualitative case studies, this review focuses on companies such as Boeing, General Electric (GE), and Honeywell to give an idea of the real benefits and challenges presented by AM. It is expected that this comparative examination between traditional manufacturing and AM will detail how this technology contributes to the advance in aerospace engineering and efficient manufacturing.

Evolution of Additive Manufacturing in Aerospace

Additive Manufacturing has evolved significantly since its development in the 1980s. AM begins with the invention of stereolithography (SLA) by Charles Hull in 1984, a technology that employs a laser to solidify liquid photopolymer resin layer by layer to generate objects. Primarily, AM was majorly employed in rapid prototyping [13]. In the 1990s, selective laser sintering (SLS) and fused deposition modeling (FDM) joined the list of key new processes establishing applications for AM [12]. The early emphasis for this promising new manufacturing technology was the rapid creation of prototypes and models to be used for testing and initial validation, including test fixtures and fixtures used for aerodynamics studies and structural tests.

In the 2000s, AM materials development - specifically advanced polymers, metals, and ceramics - took AM from a strictly prototyping technology into direct fabrication of parts for sale [32]. This push was the result of materials development that allowed for the manufacturing of high-precision, high-strength parts suitable for demanding industries like aerospace. These newly developed additive manufacturing techniques, like electron beam melting (EBM) and binder jetting, allowed the production of complex geometries and integrated structures with enhanced properties, further expanding AM capabilities [35].

By 2010, AM gained widespread acceptance in different work domains, especially in aerospace, automotive, healthcare, and consumer products. The aerospace industry embraced AM for the weight reduction, performance improvement, and cost reduction potential of parts [25]. Research and development efforts were concentrated on the optimization of AM processes and materials to meet the strict requirements for aerospace applications. AM development continued with digital design and manufacturing tools that aligned to increase the precision and efficiency of AM processes. The development of sophisticated AM systems for high-performance applications further solidified its role in industrial manufacturing, with firms starting to invest more in research to tailor AM techniques to specify aerospace needs.

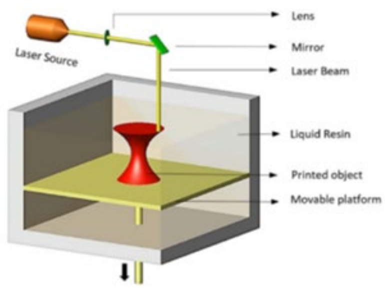

Figure 1. Stereolithography (SLA) [8]

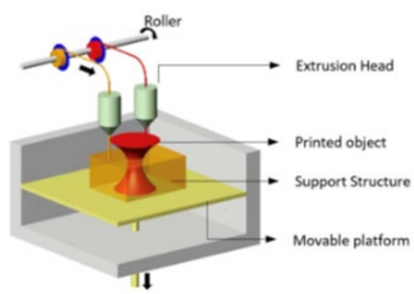

Figure 2. Fused Deposition Modeling (FDM) [8]

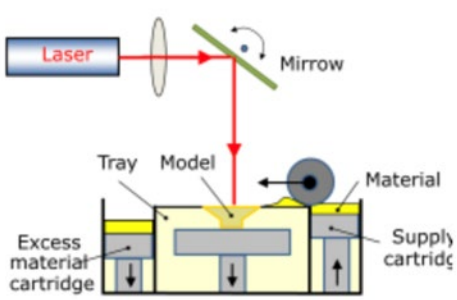

Figure 3. Selective Laser Sintering (SLS) [25]

Cost and Efficiency

Studies comparing the costs of AM with traditional manufacturing methods demonstrate substantial cost savings, even in larger volumes for aviation companies such as GE [29]. AM reduces material waste by adding material only where needed, in contrast to subtractive manufacturing methods that remove excess material. This reduction in material waste translates to significant cost savings, particularly for high-value materials used in aerospace components. For example, titanium is material commonly used in aerospace, which is costly to purchase and conventionally machine. Additive manufacturing can efficiently make use of titanium by reducing the material waste and overall cost through approaches such as Powder Metallurgy, in which a layer of metal powder is selectively fused using a laser or electron beam [14]. Other studies show that AM negates the use of expensive tooling and molds associated with conventional manufacturing. The elimination of tooling costs has specific advantages for low volumes and custom components in the manufacturing units [31]. For example, Boeing's integration of additive manufacturing is predicted to accumulate millions in savings through their 787 program [40]. Additionally, the possibility of making components on request has the potential to reduce inventory costs and minimize lead times, with benefits for overall efficiency and velocity throughout the supply chain in the aerospace sector. Companies would save on high storeroom costs and the risks of exhausting materials with additive manufacturing which facilitates just-in-time (JIT) manufacturing, where parts are made on demand [28]. AM also allows various complex component designs to be made in one manufacturing step while lessening the need for multiple other manufacturing processes and assembly operations, proving more environmentally sustainable than traditional methods [23]. This results in labor cost reductions and high production efficiency. Prototyping and iterating the design accelerates the development cycle, allowing companies to bring new products to market faster.

Supply Chain Flexibility and Resilience

AM provides new freedom in design, allowing the production of complex geometries and intricate designs impossible to achieve with conventional methods [48]. This design freedom allows for the production of optimized, lightweight structures, which are critical for improving aircraft performance and fuel efficiency. This can be realized with internal structures that have complex geometries, such as lattice structures, which improve the mechanical properties of components with less weight [9]. Other major advantages of AM are most promising in terms of flexibility, leading to the benefit of fabricating certain tools, fixtures, and specialized parts that are costly to retool. This capability is particularly beneficial in aerospace applications, where very specific solutions are often required. For example, custom brackets and fixtures produced using AM can be designed to fit specific aircraft configurations, improving the efficiency of assembly and maintenance operations. The potential for rapid iteration and optimization of designs further extends the appeal of AM in driving innovation and pioneering enabling aerospace technologies. Engineers can rapidly test and refine prototypes, incorporating feedback from testing and analysis into an optimized performance [27]. The iterative nature of AM allows continuous improvement, thus driving innovation while enabling the development of advanced aerospace systems. The ability to rapidly prototype and test new designs also reduces the risk associated with innovation, allowing companies to explore new ideas and technologies with greater confidence. Furthermore, AM enhances supply chain resilience by reducing dependency on centralized manufacturing hubs and allowing decentralized production [37]. In the event of supply chain disruptions, AM enables the rapid production of specific components at distributed locations, mitigating the impact of delays and ensuring continuous operations. The ability to produce parts on demand also reduces lead times and enhances responsiveness for changing market demands.

Figure 4. Air manifold with an (a) Normal design: (b) optimized support design [26]

Case Study

The aerospace industry has long relied on traditional manufacturing techniques such as casting, forging, and machining to produce the complex components required for aircraft. While these processes have been refined and optimized over the years to produce quality components, they nonetheless possess fundamental limitations. One of the major concerns is material waste created in these methods. For example, machining often involves cutting away material from a larger block, resulting in significant waste. In industries using materials such as titanium or high-quality aluminum, the economic impact of this waste is extremely high. Traditional methods of manufacturing are also labor intensive and often time consuming. The manufacturing of a single aerospace part often requires multiple stages of machining, heat treatment, and assembly, each adding to the overall lead time [7]. This is particularly disruptive in a field where the timing of market entry is critical, for delays mean the loss of considerable financial opportunities or falling behind the competition in the marketplace. Additionally, the complexity of aerospace parts often requires the use of custom tools, adding to high costs and extending production timelines. Another major challenge involves design limitations due to traditional manufacturing methods. Many aerospace components require complex geometries to meet performance requirements, such as optimizing airflow in engine components or reducing weight in structural parts [38]. However, traditional methods often impose design constraints that make it difficult to achieve the intended geometrical shapes without compromising performance or increasing mass.

These problems significantly determine the competitive edge of any aerospace company. Higher production costs and long lead times can erode profit margins, while design constraints can restrict the performance that companies deliver to their customers. In a highly competitive and closely monitored industry, in which safety and performance are crucial, being able to innovate rapidly and effectively has become an imperative differentiator. Where traditional methods have certain limitations, an organization might not be able to hold its competitive advantages and fulfill the changing requirements of the aerospace industry. The inefficient characteristics of traditional manufacturing processes also bear significant relevance to the environmental impact of the aerospace industry. Concerns over excess material waste and energy consumption, and the use of toxic substances in methods involving casting and machining further contribute to the environmental impact associated with the industry [47]. Presently, with increased pressure from both regulatory authorities and consumers to adopt greener methods, aerospace companies are finding ways to be more environmentally friendly without losing the high levels of quality and performance [36].

Given these challenges, the adoption of additive manufacturing (AM) presents a compelling solution. AM has been demonstrated to fabricate complex geometries with minimum waste, reduce lead times, and enhance flexibility in design, thus becoming a valid substitute for conventional manufacturing processes. However, the integration of AM into aerospace manufacturing is not without its own challenges, including the need for significant upfront investment, the development of new quality assurance processes, and the need to navigate regulatory hurdles. It is in this context that Boeing, GE, and Honeywell have developed additive manufacturing strategies that meet their operational goals and competitive positions. These strategies take advantage of the capabilities of AM to improve efficiency, reduce cost, and expand the possibilities of aerospace design.

Boeing

Boeing's AM strategy is directed at applying 3D printing in ways that contribute to aircraft weight reduction and production efficiency. Boeing started by using AM for parts that were less critical and soon scaled up to more complex and highly critical parts once reliability within the technology was proved [5]. One of Boeing's most significant achievements in AM is the production of titanium parts for the 787 Dreamliner using Rapid Plasma Deposition (RPD) technology in collaboration with Norsk Titanium [33]. The process involves layering titanium wire to create near-net-shape components, which require minimal post-processing. The result is reduced material waste and production time, while significant weight reductions also contribute to better fuel economy [45]. Apart from the titanium parts, Boeing has also expanded the use of additive manufacturing on environmental control ducting, satellite components, and experimental structures for future vehicle designs [4]. The company's investment in AM is supported by its HorizonX venture arm, which has invested in multiple startups specializing in 3D printing technologies [22]. These investments enhance Boeing's AM capabilities and position the company as a leader in the broader adoption of 3D printing across the aerospace industry.

Boeing's use of AM has resulted in substantial lead time reductions, most notably on the production of environmental control ducting and satellite components [39]. Being able to produce these parts directly from their digital designs reduced the need for extensive tooling and allowed for quicker iteration of designs. For example, production times of satellite components as well as entire satellites were reduced from around a year to a few months [15]. This allows Boeing to quickly respond to customers and market fluctuations. Other than lead time reductions, Boeing has achieved significant weight and fuel savings in its aircraft by applying AM. Rapid Plasma Deposition-manufactured titanium parts for the 787 Dreamliner have contributed to a 20% increase in fuel economy and 20% decrease in emissions resulting from the aircraft's lightweight construction [19]. This, in return, signifies an improvement in flight efficiency and reducing operating costs over the aircraft's lifetime. According to Boeing estimates, the operating savings through AM will potentially achieve as much as 3% fuel savings in the 787 Dreamliner, hence leading to economic and ecological benefits [43]. Additionally, Boeing's investment in AM has given the company significant recognition as an innovator in aerospace. The company's use of AM has opened new possibilities for aircraft design, including the possibility to develop fully 3D-printed structures in the near future. Boeing's success with AM has also reinforced its reputation as a technology leader, attracting new customers and strengthening its competitive position in the global aerospace market.

General Electric

General Electric's additive manufacturing strategy is best described by its innovative advantage in the fuel nozzles of the LEAP engine. These nozzles, which are produced using direct metal laser melting (DMLM) technology, represent a significant departure from traditional manufacturing methods. By using AM, General Electric was able to consolidate 20 components into a single unit that reduced the total assembly time and increased the strength and efficiency of the nozzle [17]. Success with the LEAP engine has validated General Electric's commitment to additive manufacturing and enabled more general deployment of the technology across the company's product line. Building on that success, the business unit GE Additive was created by GE to bring further improvements in AM to many industries. Included within this business unit is the Additive Technology Center, located in West Chester, Ohio, where engineers and scientists work together to develop new AM processes, materials, and applications [1]. In developing this advanced technology to create the next generation of aerospace components, GE also partners with top universities and research institutions [34]. The company's AM investments are not constrained to aviation only; they have their shares in healthcare, power generation, and other sectors.

GE has been using this technology for the LEAP engine fuel nozzles manufacture as one of the most critically important applications both from business and historical perspectives. The fuel nozzles are 25% lighter and five times more durable than conventionally manufactured nozzles and have become one of the key selling points of the LEAP engine [41]. Furthermore, by consolidating multiple parts into one single 3D-printed component, GE has reduced assembly time and the need for complex supply chains. The engine's success has led to airline companies posting thousands of orders, corresponding to a sum of over 32 billion US dollars [24]. The LEAP engine's reliability and favorable in-flight qualities such as better fuel consumption and reduced emissions through AM grants its success among aviation corporations. Accordingly, with increased durability due to AM, airline maintenance costs are reduced which makes the engine more customer-friendly.

Honeywell

Honeywell's AM strategy is to continue improving and enhancing the performance and efficiency of its aerospace products by using advanced 3D printing technologies. Honeywell has focused on producing high-performance parts such as turbine blades, heat exchangers, and fuel system parts with the help of AM. These components require precise control over material properties and geometry, which AM provides through techniques like selective laser sintering (SLS), electron beam melting (EBM), and hot isostatic pressing (HIP) [3]. One of Honeywell's notable achievements in the field of AM includes the certification by the Federal Aviation Administration (FAA) of the first 3D-printed critical engine component [44]. Further proof of Honeywell's commitment to AM is provided by its investments in R&D, as well as partnerships with AM technology.

With the integration of AM into its technology, Honeywell has greatly improved efficiency and performance in its aerospace products. For instance, the employment of AM in the manufacturing of mounts has enabled it to decrease as much as 50% of the weight [20]. Optimized designs made possible by AM also enhanced the thermal performance of Honeywell's heat exchangers, further enhancing overall efficiency of the engine. Besides these improvements in performance, Honeywell has been able to cut production time and cost for critical components drastically. The company reports that AM showed a 50% cost reduction while simultaneously decreasing lead times over traditionally manufactured high-temperature heat ducts [21]. These time savings can be invaluable especially in the aerospace industry as meeting strict delivery schedules can be an important factor in securing contracts and satisfying customers.

Discussion

Boeing, GE, and Honeywell demonstrate the practical potential of additive manufacturing within the aerospace industry. By utilizing these capabilities, the companies have found solutions to limitations of traditional subtractive manufacturing, achieving higher levels of efficiency, cost savings, and performance in products. The ability to design and produce lightweight, complex components with reduced lead times while reducing material waste have allowed these companies to remain proficient in a highly regulated and demanding industry. The success of AM within these companies showcases how a phased-based approach to implementing new strategies is essential for the success of businesses within an industry such as aerospace. Starting from non-critical components and gradually scaling towards more significant parts allows AM quality to be ensured and fortified at every stage. This approach has proven effective in reducing risks associated with adopting new technologies, as shown in the three aerospace companies in this study. Furthermore, the experiences of these companies suggest that AM can be used in broader circumstances and industries as it continues to evolve with use. AM has shown an increasingly central role in the production of high-performance parts in the aerospace industry due to its ability to increase efficiency and has notable benefits for the supply chain. Reduced cost in production Hallows companies to save and increase their budget for other aspects, although there are initial investments to be made when first switching to AM that include equipment and AM operating costs. However, the excess material waste that is avoided with AM proves benefits in environmental and material efficiency for businesses as this characteristic reduces strain on inventory. Rapid production times also aid in preventing disruptions within the supply chain that would result in smoother interactions within the industry and alleviate concerns for congestion within the supply chain, thereby supporting a faster innovation cycle.

Conclusion

AM is a manufacturing process gaining widespread recognition for its ability to enhance design flexibility, shorten lead times, and reduce material waste and manufacturing costs. Corporations such as Boeing, GE, and Honeywell have shown significant progress in the implementation of AM in the modern aerospace industry and demonstrated the significant practical benefits that the manufacturing process has to offer. For example, the short production time for AM parts directs this process to be used widely for rapid prototyping which functions as an enabler for constant innovation. This, in combination with the reduced price and increased flexibility of aerospace components, provides companies within the aerospace industry to experience less disruptions and more savings. For those that can afford and implement AM, this manufacturing process can provide long-term benefits and progress in creating a more efficient work environment. Consequently, its potential can be fulfilled and utilized in broader and more general industries with further implementation as AM itself evolves within workspaces.

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References

[1] Anusci, V. (2018, May 2). *GE's Additive Technology Center in Ohio uses 90 metal 3D printers to make aircraft parts*. VoxelMatters. https://www.voxelmatters.com/ges-additive-technology-center-ohio-uses-90-metal-3d-printers-make-jet-engine-parts/

[2] Ben-Ner, A., & Siemsen, E. (2017, March 24). *Decentralization and localization of production: The organizational and Economic Consequences of Additive Manufacturing (3D printing) - Avner Ben-Ner, Enno Siemsen, 2017*. Sage Journals. https://journals.sagepub.com/doi/abs/10.1177/0008125617695284

[3] Bhate, D. (2017, September 1). *Honeywell: AM Application & Supply Chain Development in Aerospace*. Metal Additive Manufacturing. https://www.metal-am.com/articles/honeywell-driving-3d-printing-application-supply-chain-development-aerospace/

[4] *Boeing Satellites*. The Boeing Company Official Website. (n.d.). https://www.boeing.com/space/boeing-satellites#overview

[5] Boeing. (2022). *Add It Up: Discover how additive manufacturing will shape aerospace - and already has.* Boeing. https://www.boeing.com/content/dam/boeing/boeingdotcom/features/innovation-quarterly/2022/09/Boeing-additive-manufacturing-IQ.pdf

[6] Bourell, D. L. (2016, July 1). *Perspectives on Additive Manufacturing*. Annual Review of Materials Research. https://www.annualreviews.org/content/journals/10.1146/annurev-matsci-070115-031606

[7] Bruml, S. (2023, January 24). *Additive Manufacturing and lead times: How they impact each other*. 3D People UK. https://www.3dpeople.uk/3dpeopleuk-blog/addtive-manufacturing-lead-times

[8] C, R., Shanmugam, R., Ramoni, M., & BK, G. (2024, February 6). *A review on additive manufacturing for aerospace application*. ResearchGate. https://www.researchgate.net/publication/377642005_A_Review_on_Additive_Manufacturing_for_Aerospace_Application

[9] Chen, L.-Y., Liang, S.-X., Liu, Y., & Zhang, L.-C. (2021, October 28). *Additive manufacturing of metallic lattice structures: Unconstrained design, accurate fabrication, fascinated performances, and challenges*. ScienceDirect. https://www.sciencedirect.com/science/article/abs/pii/S0927796X21000437

[10] CORDIS. (2019, September 6). *Electron beam melting technology takes to the air*. https://cordis.europa.eu/article/id/386869-electron-beam-melting-technology-takes-to-the-air

[11] Davies, S. (2017, April 11). *Norsk titanium to deliver 3D printed titanium parts for Boeing 787 dreamliner*. TCT Magazine. https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/norsk-titanium-deliver-3d-printed-titanium-parts-boeing/

[12] Deckner, A. (2024, June 11). *The History of 3D Printing: From the 80s to Today*. Sculpteo. https://www.sculpteo.com/en/3d-learning-hub/basics-of-3d-printing/the-history-of-3d-printing/

[13] Drupa. (n.d.). *Pioneers of Printing: Chuck Hull and the Beginning of 3D Printing*. https://www.drupa.com/en/Media_News/drupa_blog/Print_Technologies/Pioneers_of_Printing_Chuck_Hull_and_the_Beginning_of_3D_Printing

[14] Dutta, B., & Froes, F. H. (2017, January 17). *The Additive Manufacturing (AM) of Titanium Alloys*. Metal Powder Report. https://www.sciencedirect.com/science/article/abs/pii/S0026065716305045

[15] El-Hasan, M. (2017, September 6). *Boeing's new method cuts satellite production time*. Daily Breeze. https://www.dailybreeze.com/2012/01/27/boeings-new-method-cuts-satellite-production-time/

[16] Elgendy, M. (2023, November 13). *How is additive manufacturing revolutionizing the aerospace industry?*. AZoM. https://www.azom.com/article.aspx?ArticleID=23156

[17] GE Aviation News Staff. (2021, May 7). *Game Changer: Four Parts Proving Additive Manufacturing Can Compete with Casting on Cost*. GE Aerospace News. https://www.geaerospace.com/news/articles/technology/game-changer-four-parts-proving-additive-manufacturing-can-compete-casting-cost#:~:text=The%203D%2Dprinted%20fuel%20nozzle,just%2010%203D%2Dprinted%20components

[18] Ghadge, A., Karantoni, G., Chaudhuri, A., & Srinivasan, A. (2018, April 11). *Impact of additive manufacturing on Aircraft Supply Chain Performance: A system dynamics approach*. Journal of Manufacturing Technology Management. https://www.emerald.com/insight/content/doi/10.1108/JMTM-07-2017-0143/full/html

[19] Giurgiutiu, V. (2022). *Boeing 787 Dreamliner*. Boeing 787 Dreamliner - an overview | ScienceDirect Topics. https://www.sciencedirect.com/topics/engineering/boeing-787-dreamliner

[20] Godfrey, D. (n.d.). Additive Manufacturing (AM) and the Honeywell Global Initiative. https://drc.libraries.uc.edu/server/api/core/bitstreams/66343362-fa12-4f38-b689-ff1a664f3ea6/content

[21] Hassen, A. A., & Kirka, M. M. (2018, April 1). *Additive manufacturing: The rise of a technology and the need for quality control and Inspection Techniques*. Materials Evaluation. https://www.osti.gov/servlets/purl/1437906

[22] *HorizonX*. AE Industrial Partners, LP. (2022, April 19). https://www.aeroequity.com/horizon-x/

[23] *How sustainable is additive manufacturing with global supply chain disruptions?*. LuxCreo. (2022, May 26). https://luxcreo.com/how-sustainable-is-additive-manufacturing-with-global-supply-chain-disruptions-lc/#:~:text=Additive%20manufacturing%20reduces%20the%20number,parts%20into%20one%20printed%20piece

[24] Jewell, J., Soret, C., Bradley, P., & Almahmood, T. A. (2011, November 14). *Leap Engine Orders and Commitments Surpass $32 Billion*. CFM International. https://www.cfmaeroengines.com/press-articles/leap-engine-orders-and-commitments-surpass-32-billion/

[25] Jimenez, M., Romero, L., Dominguez, I. A., Espinosa , M. del M., & Dominguez, M. (2019, February 19). *Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects*. Wiley Online Library. https://onlinelibrary.wiley.com/doi/full/10.1155/2019/9656938

[26] Khorasani, M., Ghasemi, A., Rolfe, B., & Gibson, I. (2021, September 2). *Additive manufacturing a powerful tool for the aerospace industry*. Rapid Prototyping Journal. https://www.emerald.com/insight/content/doi/10.1108/RPJ-01-2021-0009/full/html

[27] Kruth, J.-P., Leu, M. C., & Nakagawa, T. (2007, July 10). *Progress in additive manufacturing and Rapid Prototyping*. CIRP Annals. https://www.sciencedirect.com/science/article/abs/pii/S0007850607632405

[28] Kyber, J. (2024, June 10). *Additive Manufacturing in aerospace and Defense*. Endeavor 3D. https://endeavor3d.com/additive-manufacturing-in-aerospace-and-defense/

[29] Laureijs, R. E., Roca, J. B., Narra, S. P., Montgomery, C., Beuth, J. L., & Fuchs, E. R. H. (2017, May 10). *Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes*. ASME Digital Collection. https://asmedigitalcollection.asme.org/manufacturingscience/article/139/8/081010/376354/Metal-Additive-Manufacturing-Cost-Competitive

[30] Lu, Y., Witherell, P., Lopez, F., & Assouroko, I. (2016, December 5). *Digital Solutions for Integrated and Collaborative Additive Manufacturing* . ASME Digital Collection. https://asmedigitalcollection.asme.org/IDETC-CIE/proceedings-abstract/IDETC-CIE2016/50084/258086

[31] Lynch, P., Hasbrouck, C. R., Wilck, J., Kay, M., & Manogharan, G. (2020, June 10). *Challenges and opportunities to integrate the oldest and newest manufacturing processes: Metal casting and Additive Manufacturing*. Rapid Prototyping Journal. https://www.emerald.com/insight/content/doi/10.1108/RPJ-10-2019-0277/full/html

[32] Munsch, M. (2023, November 15). *Metal Additive Manufacturing's journey to industrialisation: Are we there yet? And what does the destination even look like?* Metal Additive Manufacturing. https://www.metal-am.com/articles/metal-additive-manufacturing-journey-to-industrialisation-are-we-there-yet/

[33] *Norsk Titanium to deliver the world's first FAA-approved, 3D-printed, structural titanium components to Boeing*. Norsk Titanium. (n.d.-a). https://www.norsktitanium.com/media/press/norsk-titanium-to-deliver-the-worlds-first-faa-approved-3d-printed-structural-titanium-components-to-boeing

[34] *Northeastern Partners With General Electric*. Bachelor's Degree Completion. (2024, May 24). https://bachelors-completion.northeastern.edu/general-electric/

[35] Pellby, O., & Larsson, A. (2015, June 1). *Powder-bed additive manufacturing for aerospace application: Techniques, metallic and metal/ceramic composite materials and trends*. DIVA. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A815321

[36] Quinn, K. P. (2024, February 6). *Aviation's green horizon: 2024's eco-friendly push*. Clyde & Co. https://www.clydeco.com/en/insights/2024/02/political-and-regulatory-uncertainty-could-stall-m

[37] Rinaldi, M., Caterino, M., & Macchiaroli, R. (2021, November). *Additive Manufacturing and supply chain configuration: Modelling and performance evaluation*. Journal of Industrial Engineering and Management. http://jiem.org/index.php/jiem/article/view/3590/1000

[38] Saadat, M. (1970, January 1). *Challenges in the Assembly of large aerospace components*. SpringerLink. https://link.springer.com/chapter/10.1007/978-3-642-17384-4_4

[39] Samwill. (2024, August 2). *SLS 3D printing in Aerospace: The future of flight*. ZONGHENG3D. https://www.zongheng3d.com/sls-3d-printing-in-aerospace-in-the-future/

[40] Sansbury, T. (2018, November 13). *Boeing: Additive Manufacturing adding enough?*. Technology and Operations Management. https://d3.harvard.edu/platform-rctom/submission/boeing-additive-manufacturing-adding-enough/#:~:text=%5B2%5D%20Chip%20Yates%2C%20VP,of%20a%20787%20is%20estimated

[41] Shaikhnag, A., Tyrer-Jones, A., Lara, A. T., Jackson, B., & Petch, M. (2019, June 18). *CFM International closes largest ever order for 3D printing enabled Leap Engine*. 3D Printing Industry. https://3dprintingindustry.com/news/cfm-international-closes-largest-ever-order-for-3d-printing-enabled-leap-engine-157257/

[42] Sher, D. (2020, February 25). *Additive manufacturing history in the making as Boeing 777X makes maiden flight with GE9X engines*. VoxelMatters. https://www.voxelmatters.com/additive-manufacturing-history-in-the-making-as-boeing-777x-makes-maiden-flight-with-ge9x-engines/
[43] Sinnett, M. (n.d.). 787 No-Bleed Systems: Saving Fuel and Enhancing Operational Efficiencies. http://www.boeing.ch/commercial/aeromagazine/articles/qtr_4_07/AERO_Q407_article2.pdf

[44] Team Kimya. (2021, March 22). *Honeywell certifies the first 3D-printed critical engine part*. Kimya. https://www.kimya.fr/en/honeywell-certifies-the-first-3d-printed-critical-engine-part/

[45] *Technology*. Norsk Titanium. (n.d.-b). https://www.norsktitanium.com/technology

[46] Thomas, D. S., & Gilbert, S. W. (2014, December). Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion. https://edisciplinas.usp.br/pluginfile.php/5797982/mod_resource/content/1/Manufatura%20aditiva%20NIST%20.pdf

[47] *What Are the Hazards of Metal Casting?*. Galfand Berger. (2022, August 3). https://www.galfandberger.com/2021/11/03/hazards-metal-casting/#:~:text=Chemicals%20and%20solvents%3A%20Alkalis%2C%20detergents,penetrate%20deep%20into%20the%20lungs

[48] Yang, S., Tang, Y., & Zhao, Y. F. (2015, July 10). *A new part consolidation method to embrace the design freedom of additive manufacturing*. Journal of Manufacturing Processes. https://www.sciencedirect.com/science/article/abs/pii/S1526612515000699