Sustainability Transitions of Additive Manufacturing in an Aerospace Context

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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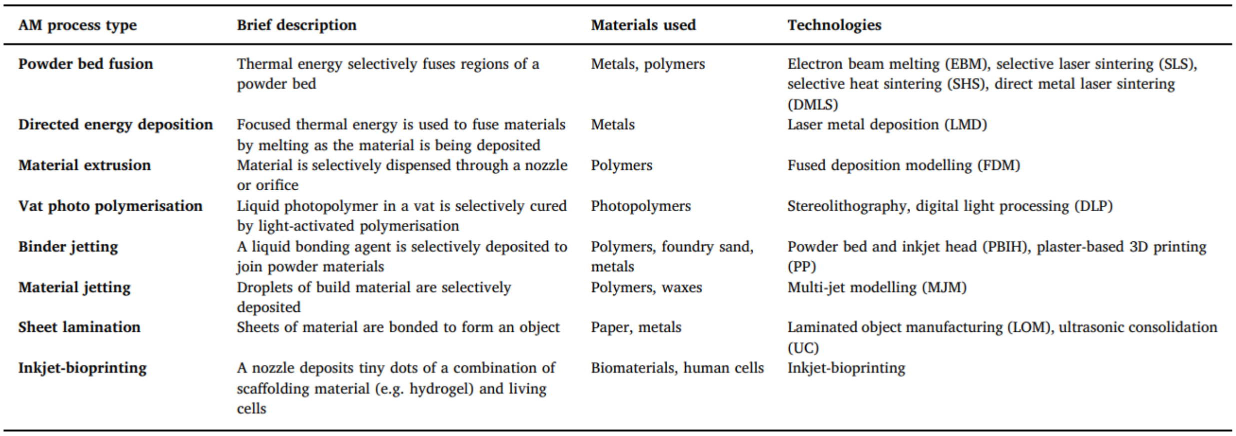
1. Introduction

Additive manufacturing (AM) is disrupting the manufacturing landscape through the introduction of unprecedented opportunities for technological and commercial advancement and restructuring (Godina et al, 2020; Blakey-Milner et al, 2021). Additive manufacturing, also known as 3D printing, is a layer-by-layer approach in which objects are fabricated layer by layer using feedstock materials such as polymer wires and metal powders. The feedstock material is typically melted or fused together by a heat source and solidifies to create an object based on a computer aided design (CAD) model. The primary additive manufacturing methods developed thus far are described in Table I. The counterpart to additive manufacturing is traditional manufacturing (TM) which is typically characterized as a subtractive synthesis process in which material is wasted during fabrication via cutting, forming, or machining stock material into a desired shape.

From AM's introduction in the late 1980's to the 2000's, patent restrictions have limited growth and commercial opportunity (Wohlers, 2014; Sai Kaylan et al, 2021). After the expiry of patents, AM has rapidly developed the past two decades, interrupting various facets in the manufacturing landscape particularly supply chain management, business operations, policies, academia, and industry (Sai Kaylan et al, 2021; Godina et al, 2021). In a broader lens, AM is part of the socio-technical landscape of manufacturing with various actors that challenge and limit a rapid shift to AM. Being one of the early adopters and largest users of AM, the aerospace industry is one of the primary driving forces that shape the transition from TM to AM (Deloitte, n.d.). AM offers sustainability benefits through improved resource efficiency, extended product life, increased energy savings, and simplified supply chains which in turn contributes to a more sustainable industrial market and society (Ford et al, 2016; Verhoef, 2017). This study explores the sustainability transition from traditional manufacturing to additive manufacturing within the aerospace industry through analysis of the incumbent regime and niches. This inquiry will be approached by presenting case studies of several early adopter aerospace corporations and case studies of niche level, current AM adopting aerospace companies within the context of a changing landscape of manufacturing. The aim of this research is to provide insight to the progressions and challenges of additive manufacturing in the aerospace ecosystem.

Table 1



AM process type	Brief description	Materials used	Technologies
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed	Metals, polymers	Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), direct metal laser sintering (DMLS)
Directed energy deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Metals	Laser metal deposition (LMD)
Material extrusion	Material is selectively dispensed through a nozzle or orifice	Polymers	Fused deposition modelling (FDM)
Vat photo polymerisation	Liquid photopolymer in a vat is selectively cured by light-activated polymerisation	Photopolymers	Stereolithography, digital light processing (DLP)
Binder jetting	A liquid bonding agent is selectively deposited to join powder materials	Polymers, foundry sand, metals	Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)
Material jetting	Droplets of build material are selectively deposited	Polymers, waxes	Multi-jet modelling (MJM)
Sheet lamination	Sheets of material are bonded to form an object	Paper, metals	Laminated object manufacturing (LOM), ultrasonic consolidation (UC)
Inkjet-bioprinting	A nozzle deposits tiny dots of a combination of scaffolding material (e.g. hydrogel) and living cells	Biomaterials, human cells	Inkjet-bioprinting

Overview of additive manufacturing process types, the materials used, and the relevant technologies (Verhoef, 2017).

2. Framework

2.1. Sustainability Transitions

Since the transition from TM to AM contributes to global sustainability goals in reducing energy and material consumption, utilizing the multi-level perspective (MLP) framework in a sustainability transitions (ST) lens will offer proper guidance when exploring this line of study. The MLP framework is commonly employed in socio-technical transitions (STT) research as a mode to understand the interactions between actors, innovations, and environments (Steward, 2012). The study of STs also widely uses the MLP framework but is distinct from STTs in that the relatively slow pace of STTs will lead to detrimental environmental effects in the case of STs (Hess, 2013). MLP poses that these transitions primarily operate within three hierarchical levels: niches, regimes, and the socio-technical landscape (Bilali, 2019). The niches level is where radical innovations emerge through pioneering efforts of entrepreneurs, researchers, and coalitions (ISC, 2019). The regimes level refers to the already existing infrastructure and institutions at which the niche acts upon to bring forth change and evolution. In particular, the incumbent regimes are organized agents that mobilize against these radical innovations that are perceived to threaten their short-term profitability and long-term existence (Hess, 2013). The landscape refers to the wider context in which the regime responds to and where changes occur.

The ST framework proposed by Hess (2013) utilizes MLP at a fundamental level but considers the political and power dimensions of STs which resonates with other criticisms of MLP that posit that it may benefit from greater emphasis on politics (Kern, 2011; Meadowcroft, 2011). Hess (2013) recognized that the inclusion of the politics of STs offers a broader picture and draws out wider implications for the study of STs. Hess (2013) also emphasizes the consideration of countervailing industrial powers in the study of STs. Hess' research in clean energy transitions benefited from the inclusion of countervailing industrial powers as it provided new perspectives to ST research, particularly the study of conflicts among coalitions within STs. Hess posits that the study of conflicts among coalitions will become a core framework to the general study of STs. However, this framework is only beneficial when there is apparent conflict and antagonism within and between the regime and niche levels. Sustainability transitions to AM does not have as vocal anti-AM mobilization as in clean energy transitions, suggesting that Hess' proposed framework may not be very beneficial to this study and proposes that this framework should not be blindly applied in the general study of STs. Although Hess' framework will not be used as the central core of this research, the study of conflicts within coalitions and the inclusion of countervailing industrial powers will not be disregarded as it may offer unforeseen yet critical perspectives to this study. Non-technical papers and news articles studying additive manufacturing in a larger context, particularly the aerospace industry, that employ aspects of actor-network theory and socio-technical transitions are used to explore the research inquiry. Although the papers selected do not perfectly align with the line of inquiry, they do have overlap and can provide a more cohesive image if stitched together.

2.2. Multi-level perspective

The incumbent regime for the transition from TM to AM is composed of physical and non-physical actors such as industry leaders, supply chains, political leaders, and certifications and policies. Besides the early adopting companies of AM, other industry leaders express discomfort to transitions to AM (Deloitte, n.d.). Industry leaders have difficulty in staying up to date with the latest AM innovations in research due to its high complexity and the high level of knowledge ownership and secrecy within the public domain of the aerospace industry (Deloitte, n.d.). They have also grown comfortable with traditional manufacturing processes and are hesitant to explore AM (Deloitte, n.d.). Additionally, the recent introduction of and rapid advancements of AM have outpaced the certifications, design guidelines, and regulations used by these corporations which were originally created for TM based processes and design (Khorasani, 2021; Sai Kaylan, 2021). This lack of proper certifications and regulations also fuels these industry leaders' hesitance to utilizing AM technologies.

The political agents in the national government also influence the transitions to AM via budget changes to national agencies and institutions, such as the Department of Energy (DoE), Department of Defense (DoD), Defense Advanced Research Projects Agency (DARPA), and NASA, that fund AM related research in both academia and industry (Matisons, 2019). The political orientation of national government regimes dictates the views on profitability and benefits of funding AM related research and business (Matisons, 2019). Although the political regimes have historically prioritized funding towards the defense industry, the funding towards public-private aviation and space is more volatile which can limit or halt AM innovation. Despite this volatility, in large part, there is minimal opposition to AM in comparison to other sustainability transitions in renewable energy and agriculture (Hess, 2013; Bilali, 2019). This is apparent with the early adoption of AM in the aerospace industry and the AM-supporting industry leaders and government agencies that provide public-private sponsorship of AM research and political support. Early adopters of AM, such as General Electric, Boeing Pratt & Whitney, and Airbus, and national agencies, such as the DoD and NASA, provide funding to researchers in academia to advance AM. These groups also help to shape AM related policy proposals in government through lobbying and funding. Other actors consist of consulting agencies and standards development organization (SDOs) that work to resolve challenges in the incumbent regime and to quicken the transition from TM to AM. SDOs, such as the American Society of Testing and Materials (ASTM) and International Organization for Standardization (ISO), are developing standardized tests and guidelines so that AM can be successfully validated and adopted into aerospace technologies (Sai Kaylan, 2021). Consulting agencies, such as Deloitte, are working with businesses to develop successful adoption plans towards AM and sustainability (Deloitte, n.d.; Godina, 2021).

AM offers a very streamlined and simplified supply chain in comparison to TM, which has implications on businesses' supply chain management strategies and TM suppliers' business models that pose as challenges to AM's successful transition from TM (Khorasani, 2021; Sai Kaylan, 2021). The local level fabrication capabilities of AM for aerospace grade components and technologies allow for in-house manufacturing and fosters shifts to domestic supply chains which influences both the national market and international trade policies (Mohanavel, 2021; Matisons, 2019). The simplified supply chain of AM aligns with the ideals of profit driven corporations as it drives down both production costs and lead time of new and existing technologies.

The niches in support of AM are composed of researchers who produce AM innovations and entrepreneurial ventures that explore such innovations within the AM ecosystem. Coalitions provide support for pro-AM mobilization through the sharing of ideas and education. Researchers in national research laboratories and institutes, industry R&D sectors, and academia are constantly advancing AM manufacturing technologies at a rapid pace. The techniques, processing methods, materials are being improved, optimized, and developed to produce higher quality, more complex, and more reliable AM parts (Blakey-Milner, 2021; Sai Kaylan, 2021). Several large aerospace companies, such as General Electric, Boeing, Pratt & Whitney, and Air Bus, have extensive research programs solely dedicated to AM development and have recently begun to implement such technologies into the production of aerospace grade AM parts and assemblies (Sai Kaylan, 2021). Several key startups have also contributed to AM innovations such as Boom Supersonic, Relativity Space, and Launcher that have all utilized AM to fabricate additively manufactured components for aerospace vehicles. Grassroots coalitions, such the Additive Manufacturing Coalition and nonprofit associations like SME, work with professional engineering communities to disseminate knowledge on successful AM adoption techniques and to educate others on recent AM innovations in the public domain.

2.3 Methodology

Relevant case studies and non-technical papers will be investigated to provide more concrete context onto how the inter-actor dynamics influence decision-making processes and to provide insight into the advances and challenges at play within the AM landscape. Looking the early adopters of AM and their relevant AM technologies may provide key insight as to why the aerospace industry adopted AM at an early phase and why there is minimal apparent opposition to current transitions to AM within the aerospace industry. Comparing this case study about the early adopter corporations to case studies about AM adoption within the past several years may help to clarify any changes that might have occurred that either accelerated or hindered the transition to AM.

3. Case Studies

3.1. Overview

The historical context of the developments of additive manufacturing in both the general realm and within the aerospace industry provide a crucial foundation for acquiring a holistic understanding of the progressions and challenges at play. In particular, the general timeline of key techno-economic developments of AM within various industries will be explored with congruent consideration of its impact on the AM adoption within the aerospace industry. The developments of AM within recent years will also be explored to provide key insight into the changes that occurred between the past and the present. Comparing the two timeframes will position this study to clearly demonstrate the presence of or lack thereof successful adoption of AM within the aerospace industry.

3.2. Historical Context and Early Adopters

3.2.1. Historical Context

AM first emerged in the 1987 with the commercialization of stereolithography (SL) technology from 3D Systems Corporation and consequently by Electro Optical Systems (EOS) in 1990 (Wohlers, 2014). SL is a process that solidifies thin layers of ultraviolet light-sensitive liquid polymer using a laser source to iteratively build a desired shape (Wohlers, 2014). Since 1987, key AM technologies, such as powder bed fusion (PBF), direct energy deposition (DED), and material extrusion (ME), quickly began to emerge on the market. These AM processes are described in Table I. AM entrepreneurial companies promoted their technologies to be used for rapid prototyping, tooling manufacturing, and parts repair for various industries. AM was quickly adopted by aerospace companies like GE Aviation and Pratt & Whitney, both aircraft engine manufacturers, for use in rapid prototyping as it significantly reduced manufacturing costs and manufacturing lead time for prototype testing. AM was also used by these companies for parts repair as it reduced maintenance costs for any damaged parts in their aircraft engines. AM allowed materials to be deposited and fused to the damaged part for quick repair instead of manufacturing a whole, separate replacement part using traditional manufacturing processes. AM was not used as a main mode of direct manufacturing – manufacturing parts to be used in service – as the technology was very new and not very well understood.

Beginning in the 1990's, government bodies began to fund research institutions and create collaborative programs with industry partners and entrepreneurial groups. In particular, the DoD played a critical role in the funding, education, outreach, and management of the development of AM technologies (Kobryn, 2006; Wohlers, 2013). DARPA, the U.S. Office of Naval Research (ONR), and the Materials & Manufacturing Directorate of the Air Force Research Laboratory (AFRL/ML) were actively involved in research and development with the additive manufacturing of aerospace alloys. In 1991, the DoD formed the Metals Affordability Initiative (MAI) to provide funding for AFRL/ML R&D AM projects and facilitated the formation of industry collaborative teams to help the development process. Participants included Boeing, Lockheed Martin, Pratt & Whitney, and AeroMet. AeroMet was an entrepreneurial subsidiary of MTS Corporation that developed a fusion-based metal AM process, called Laser Additive Manufacturing (LAM^{SM}), by a team of researchers from Johns Hopkins University and Pennsylvania State University under funding from ONR and DARPA. As a result of the MAI project and AFRL/ML's leadership, a select few non-safety-of-flight-critical airframe components in Boeing aircraft were manufactured using the LAM^{SM} process with titanium alloys. AeroMet had production orders for titanium parts for both the Boeing F-15 and C-17 aircraft (Grimm, 2005). This research project demonstrated the techno-economic gain of AM processes for the aerospace industry. Since the aerospace industry requires low volume, high complexity parts, the design freedoms of AM offer direct manufacturing of lightweight, high strength parts with greatly reduced lead time and costs. However, despite the promising benefits of AM, AFRL/ML outlined that due to the lack of maturity and understanding of AM in terms of design methodologies, the absence of standards and certifications, and lack of research outlining the process-property relationships of AM processes and related feedstock materials are the largest barriers to implementing AM as a main mode of manufacture in the aerospace industry.

Beginning in the late 2000's to early 2010's, AM began to pique interest in several industries, such as the dental industry, hearing aid industry, and the hobbyist 3D printing industry (Wohlers, 2013). In 2009, ASTM Committee F42 on Additive Manufacturing Technologies was formed to produce the first standards on testing, processes, materials, design, and terminology for AM technologies. In 2011, ISO created its own committee ISO 261 for AM standards development (Seifi, 2020). In 2013, ASTM International and ISO announced a collaborative agreement between the ASTM International Committee F42 and ISO Technical Committee 261 on Additive Manufacturing to develop standards as a joint venture. Metal AM garnered significant interest and growth within the aerospace industry after the first few releases of standards and certifications by ASTM/ISO.

3.2.2. Case Study: General Electric (GE)

The most notable AM end-use part application in aerospace is the GE LEAP engine fuel nozzle, a crucial part within an aircraft engine that undergoes high pressure and intense temperatures. LEAP engine is one of commercial aviation's best-selling engines, a product of CFM International which is a joint venture between GE and French engine manufacturer Safran. The fuel nozzle was patented in 2013 and began production in 2015, with over 30,000 nozzles produced by 2018. The integration of the AM fuel nozzle brought savings of three million USD per aircraft in service. Traditional fuel nozzles are complex assemblies consisting of the joining of more than thirty components which are generally expensive to fabricate and repair. The new fuel nozzle, designed using the metal AM PBF process with a Cobalt-Chrome alloy, is 25% lighter and five times stronger than its predecessor. The new design also consolidated 20 separate parts of the previous design into a single component reducing manufacturing costs, improving ease of assembly, providing improved thermal protection, and reducing potential leakage (McMasters, 2013). The fuel nozzle can be manufactured in about a week as opposed to the previous design normally taking three to five months to fully produce and assemble (Rao, 2016).

The adoption of AM direct manufacturing and the mass production of AM fuel nozzles did not occur on the whim for GE. GE has been utilizing DED processes for over a decade to repair worn-out, high value industrial parts such as compressor blades and gears (Rao, 2016). GE Aviation has been collaborating with entrepreneurial ventures Morris Technologies and its sister company Rapid Quality Manufacturing for over a decade prior to the development of the fuel nozzle. Morris Technologies, a Cincinnati-based rapid prototyping company, had been experimenting with PBF of aerospace alloys and optimizing this manufacturing process for several years. In 2011, Morris Technologies brought a plan to redesign the fuel nozzle which led to GE's acquisition of Morris Technologies and Rapid Quality Manufacturing in 2012 to expedite the R&D process. The successful implementation of AM technologies to the LEAP engine fuel nozzle acted as a catalyst for GE to significantly increase investments and funding to AM R&D and manufacturing with the AM adoption within other GE subsidiaries, the $50 million USD expansion of the GE Auburn facility for AM work in 2014, the inauguration of a $200 million USD "multi-modal" manufacturing facility in Chakan, the creation of the subsidiary GE Additive in Europe in 2016, and the establishment of GE Additive Technology Center (ATC) in 2018, which is the world's largest and most advanced AM and development facility (Rao, 2016; GE, n.d.; Anusci, 2018; GE, 2018). After the success of the AM fuel nozzle, GE continued to develop a myriad of additive parts for the new GE9X engines which were first put in service in 2018 and GE ATC has been working on both the redesign and novel design of aerospace components to be used in next generation GE products. As an established company, GE saw the opportunity to invest in emerging technologies, particularly additive manufacturing, during the budding stages of AM technologies in the 1990's. Particular to the aerospace industry, GE saw sundry environmental, economic, and technological benefits to using AM as a potential main mode of direct manufacture and therefore invested time and capital to R&D ventures like Morris Technologies which expedited the adoption of AM within GE Aviation.

3.2.3. Case Study: Boeing

Although it did not make as large of a public appearance as GE's LEAP fuel nozzle, Boeing, Pratt & Whitney, and Airbus have also been pioneers in utilizing AM technologies for manufacturing aerospace parts. Boeing and Pratt & Whitney had collaborations with the DoD in the early 2000's to develop AM technologies through the MAI project. Beyond the production of non-critical, titanium airframe components for Boeing aircraft using the LAM^{SM} process by

AeroMet in 2005, Boeing also utilized AM to fabricate non-safety-of-flight-critical air-cooling ducts for the F-18E jet in 2001 (Singamneni, 2019; Frost, 2015; Boeing, 2001). The additive air-cooling ducts reduced production time by 67%, reduced part count, improved cost savings, and simplified the supply chain. Boeing collaborated with Advanced Laser Materials to develop aerospace grade, flame retardant polyamide material to first fabricate environmental control system (ECS) ducts for the F-13 jets and then to the Boeing 787 line using PBF processes (Frost, 2015). The ECS ducts were previously made out of aluminum which were hard to manufacture due to the notorious difficulty in welding aluminum parts together (Zelinski, 2012). This was the first time AM parts were produced for in-service aircraft and consequently used in commercial aircraft. With the first approval of an additive titanium part for commercial aviation by regulatory agency Federal Aviation Administration (FAA) in 2017, Boeing began to manufacture AM titanium parts for the Boeing 787 in collaboration with Norsk, a Norwegian AM supplier (Power, 2017).

3.2.4. Case Study: Pratt & Whitney

Similar to Boeing's feat, Pratt & Whitney was the first company to feature AM parts in an aircraft jet engine in 2013 (Peach, 2015). The Pratt & Whitney PurePower PW1500G jet engine was designed for Bombardier's CSeries passenger aircraft. Pratt & Whitney fabricated compressor stators and synch ring brackets using PBF AM processes for the jet engine. Prior to this achievement, the company has been utilized AM for rapid prototyping and has been in collaboration with AM entrepreneurial ventures, such as EOS and Stratasys, for the past decades, similar to GE. The new AM parts offered up to 15 months lead-time saving and up to 50% weight reduction. To promote AM R&D opportunities, Pratt & Whitney invested more than $4.5 million USD to create the Pratt & Whitney Additive Manufacturing Center at the University of

Connecticut, one of the most advanced AM laboratories in the country (UConn, 2013). The center was created to push the boundaries of AM and to train and educate the next generation of researchers and engineers interested in this emerging technology. Pratt & Whitney has also made research collaborations with Penn State's Applied Research Laboratory, North Carolina State University, and the University of Texas at El Paso to improve AM by furthering the obscure underlying materials science of this relatively novel field (Brown, 2014).

3.2.5. Case Study: Airbus

Successful adoption of AM requires a robust understanding and development of both AM hardware and software. AM hardware refers to the design and operation of printing machinery to produce high quality AM parts. AM software refers to the design tools, such as CAD and simulation software, used to create digital models and analyze the structural integrity of AM parts prior to printing. Allowing for highly complex and biomimetic structures, AM requires a design approach fundamentally different from a traditional manufacturing design approach. A large portion of the presented AM advancements by GE, Boeing, and Pratt & Whitney stemmed from the development of AM hardware using a conventional design approach. Airbus has taken a different approach to cultivating AM by improving AM software and design methodologies in collaboration with key corporate leaders of the software realm.

Airbus pushed AM R&D and demonstrated the benefits of AM adoption through collaborative studies of the redesign of Airbus critical airframe components using AM processes and an advanced design method called topology optimization (TO). TO is a mathematical design methodology that utilizes simulations to iteratively optimize a shape geometry based on the given load constraints (Blakey-Milner, 2021). TO has rapidly advanced to include machine learning methods and neural networks to create highly complex, biomimetic geometries which can only be feasibly fabricated using AM processes that would not have been feasible through TM processes. Through EADS Innovation Works, a corporate research center of the European Aeronautic Defense and Space (EADS), Airbus explored the application of AM and TO for the redesign of a hinge bracket for the Airbus A320 aircraft in 2011 (Tomlin, 2011). Airbus conducted a variety of collaborative studies with leading CAD and simulation package developers Altair Technologies and Autodesk. These studies demonstrated that the redesign of airframe components using AM offers significant weight reduction and consequent drastic carbon emission reductions and fuel savings (Singamneni, 2019). Congruent to these systematic studies, Airbus also began to produce AM parts to be used in the Airbus A320, A330, A340, and A350 fleets in recent years after achieving certification for such parts (Sertoglu, 2021). After Boeing began manufacturing AM titanium parts in 2017, Airbus began production and installation of a titanium AM critical support bracket for the Airbus A350 XWB to remain competitive in the airframe manufacturing market (Blakey-Milner, 2021; Power, 2017).

3.3. AM Adoption in the Current Landscape

3.3.1. Overview

Since additive manufacturing is still a new technology with early adoption within the aerospace industry only occurring in the 1990s with significant developments made in the early to mid 2010’s, the actual time frame difference between the case study of early adopter actors and the case study of current adopters overlaps to some degree. The established companies, notably GE, Boeing, Pratt & Whitney, and Airbus, were all early adopters to AM and have continued to exponentially develop AM aerospace parts in recent years. The developments of AM within the past couple years will be explored, with primary focus to entrepreneurial aerospace ventures, in particular Boom Supersonic, Relativity Space, and Launcher.

3.3.2. Case Study: Boom Supersonic

Boom Supersonic is an aircraft manufacturing startup from 2014 that is attempting to redesign a supersonic commercial airliner after the Concorde, the first supersonic commercial airliner, failed to successfully scale up in the late 1900's due to a series of technological and economic issues. As a startup, Boom has positioned itself as the first aircraft manufacturer to incorporate "sustainability from day one" by taking a sustainable approach to aircraft design, manufacture, testing, and recycling (Boom Supersonic, n.d.). Boom has adopted a plethora of advanced technologies such as advanced carbon fiber composite manufacture, supersonic propulsion system, and high efficiency computer optimized aerodynamic control systems to create a more fuel and aerodynamically efficient aircraft. In addition to these technologies, Boom created a partnership with a lead AM supplier Velo3D in 2019 to manufacture complex aerospace hardware for their first airliner, XB-1, in alignment with its sustainability initiatives. Velo3D produced 21 AM parts for Boom by 2020 (Metal AM, 2020). By using AM, Boom was able to create a localized supply chain and significantly reduce material waste and energy consumption during manufacture. As a niche level actor and a budding aircraft manufacturer, Boom was able to offer the aircraft industry to rethink the possibilities and implications of using AM for ground-up aircraft design.

3.3.3. Case Study: Relativity Space

Relativity Space is a space startup from 2015 that is developing launch vehicles and rocket engines for commercial launch services and spaceflight (Gohd, 2022). The startup is using additive manufacturing to fabricate its first rocket, Terran 1. Terran 1 is a fully 3D printed, two-stage, fully reusable launch vehicle spanning 110 feet tall and 7.5 feet wide using AM techniques from a proprietary alloy (Gohd, 2022; Blakey-Milner, 2021). Relativity Space benefits from AM as it greatly reduces the supply chain for their launch vehicle and significantly reduces the manufacturing and assembly complexity by consolidating hundreds of separate parts into large, single components. Their launch vehicle can be fully fabricated in 60 days as opposed to rockets typically taking two years to fully build. The company also created a partnership with microwave plasma technology developer 6K to develop space rocket components using recycled materials (Aerospace Technology, 2020). Through this partnership, Relativity Space was able to create a closed-loop supply chain in which certified scrap materials produced from Relativity Space would be turned into metal powder by 6K which in turn would be reprinted into components by Relativity Space. By incorporating AM processes with recyclability and demonstrating the utility of AM technologies, Relativity Space was able to market itself as a forward-thinking brand, pioneering new avenues for the aerospace industry regime with a novel manufacturing business model.

3.3.4. Case Study: Launcher

Launcher is a space startup from 2017 that is developing high performance rockets to put small satellites in orbit (Youssef, 2021). Launcher is utilizing additive manufacturing to deliver these satellites using cost effective rockets. Launcher is working with Velo3D to print its fuel pump, flight turbine housing parts, and orbiter pressure vessels for its proprietary liquid oxygen (LOX) turbopump to be used in its rockets. The startup is taking advantage of AM to rapidly prototype and rigorously test many design iterations with quick lead times and cost-effective business models. With the demand for satellite launch systems to grow from $8 billion today to $38 billion in 2030, Launcher is using AM to meet the growing demand by drastically increasing their satellite launch capabilities with faster production times of their launch vehicle products (Launcher, n.d.). Similar to Relativity Space and Boom Supersonic, Launcher is utilizing AM to give their products a competitive edge in the aerospace industry.

4. Discussion

The early adopters of AM within the aerospace industry were all established firms that all held competitive positions in the market. With the emergence of AM, these companies established collaboration with entrepreneurial ventures, such as AM suppliers and manufacturers, to explore the emerging technology as a potential asset to give the firm a competitive edge in the aerospace ecosystem. These companies observed the experimentation of new products and services conducted by the niche level actors using a low-risk approach. When such actors demonstrated apparent growth potential or established a lucrative strategic position, the established firms began to heavily invest. This is apparent with GE and Pratt & Whitney with the development of AM parts for their aircraft engines after close collaboration with additive manufacturing ventures. As competing airframe manufacturers, both Boeing and Airbus have supported AM R&D initiatives and have consequently utilized AM to advance their respective airframes. All of the early adopters posited themselves as innovators within the manufacturing landscape by pushing the boundaries of AM with the release of unprecedented AM products to the market. By acting as innovators, they remained competitive leaders in the market by exploiting emerging technologies to offer more cost-effective products and more efficient business models.

The startups that have started to adopt AM within recent years have the unique position of niche exploration, taking risks and using emerging resources to develop products and services in response to potential economic opportunities. The startups have the opportunity the explore a range of opportunities that may bring drastic change to the ecosystem. Boom Supersonic, Relativity Space, and Launcher have all worked towards evolving the manufacturing landscape by establishing new precedents for the aerospace industry and utilizing AM as part of their core business frameworks. Established firms do not have such position as they have preexisting revenue streams that need to be maintained and have to take low-risk approaches to integrating emerging technologies into their current business models.

Since the commercialization of AM in 1987, AM technologies have greatly advanced through increased investments from actors in the incumbent regime to niche level actors. The production of more standards and certifications from ASTM and ISO have enabled industry leaders to begin to use AM for direct manufacturing. The Department of Defense and military related agencies provided funding to research institutions and created joint projects with research institutions, corporate leaders, and entrepreneurial ventures to advance AM as a socio-technical system. These government bodies acted as mediums for established firms to be exposed to this emerging technology and helped to expedite the transition from TM to AM. Similarly, established corporations like GE, Boeing, Pratt & Whitney, and Airbus have invested into AM by funding and collaborating with researchers from both research centers and startups. These investments have enabled these companies to be early adopters of AM and to be pioneers in the aerospace ecosystem. As the barriers to mass adoption of AM begin to fade as technology improves, more and more aerospace companies will be seen adopting additive manufacturing in the future.

5. Conclusion

This paper explored the sustainability transition from TM to AM within the aerospace industry using ST and MLP frameworks. The aim of the study was to provide insight to the progression and challenges of AM in the aerospace realm. Case studies regarding the early adopter aerospace corporations and newer adopter aerospace startups were presented as an opportunity to better understand why the aerospace industry was an early adopter and what are the barriers to successful integration of AM within the field. The study was by no means comprehensive but rather highlighted key developments and insights in relation to the line of inquiry. Beyond the mentioned MLP actors in this study, Honeywell Aerospace, Lockheed Martin, Aerojet Rocketdyne, SpaceX, Blue Origin, NASA, grassroots coalitions, and others have made significant contributions to the AM ecosystem.

The transition to AM within aerospace offers the key benefits of cost and lead time reduction. Weight reduction and part consolidation are also significant factors with the use of topology optimization technologies and advanced simulation and design packages. AM has exponentially developed since its commercialization in 1987 with improved fundamental understanding of the technology and with the proliferation of many AM processes, as shown in Table I, yet many challenges still exist that hinder its adoption. AM faces challenges of part design standards and certifications, processing challenges, lack of understanding of long-term process-property relationships, high cost of machines and expertise required to fabricate high quality parts. These barriers hinder AM from scaling up to large volume production and to the widespread integration into aerospace systems. Despite these obstacles, the sustainability transition to AM from TM is highly promising and has demonstrated successful adoption within the aerospace industry with benefits to creating a more energy efficient and sustainable society, which will further catalyze unprecedented development in the ever-expanding manufacturing landscape.

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