Design Proposal for Responsive Aerial Firefighting Aircraft
(Technical Topic)

Sustainability Transitions of Additive Manufacturing in an Aerospace Context
(STS Topic)

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By

Christopher Kwon

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Technical Team Members:

Andreas Damm
Del Irving
Jason Le
LeeYung Chang
Andrew Wheatley
Aaron Huynh
Matteo Harris

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.

ADVISORS

Dr. Sean Ferguson, Department of Engineering and Society

Dr. Jesse Quinlan, Department of Mechanical and Aerospace Engineering

Introduction

As part of the aerospace engineering capstone offerings at the University of Virginia, students in the Aircraft Design course series are challenged with the conceptual design of next generation aerial firefighting aircraft through their participation in the Aerospace Institute of Aeronautics and Astronautics (AIAA) 2021-2022 Aircraft Design Competition. This design challenge was developed in response to the lack of development in specialized aerial firefighting aircraft and the increased frequency of wildfires in correlation to the worsening effects of climate change. While meeting the technical design mission requirements and objectives outlined in the AIAA Design Competition rules, students also consider the use of state-of-the-art technologies and methodologies for the development of an affordable, sustainable, and high-performance aircraft. Some of the technologies and methodologies explored are autonomous aircraft systems, propulsion systems such as hybrid and electric vehicles, and advanced manufacturing methods such as additive manufacturing.

In relation to sustainability and state-of-the-art technologies, the STS research study explores the sustainable transition from traditional manufacturing to additive manufacturing within the aerospace industry. The objective is to grasp a holistic understanding on current socio-technical landscape of manufacturing in the aerospace industry through analysis of the incumbent regime and niches. This research will provide insight into the progressions and challenges of additive manufacturing and feasibility of its incorporation into next generation, sustainable aerospace vehicles such as aerial firefighting aircraft.

Technical Topic

The design proposal for responsive aerial firefighting aircraft is the focus for the undergraduate capstone Aircraft Design course series at the University of Virginia. This design challenge defines the Request for Proposal (RFP) for the AIAA 2021-2022 Design Competition (AIAA, 2021). Students in the Aircraft Design course are divided into three teams of eight to nine members that will participate in and submit a design proposal report to the AIAA 2021-2022 Design Competition.

The RFP was motivated by the growing effects of climate change and the subsequent increased occurrences in wildfires (AIAA, 2021). Although wildfires are not a recent phenomenon and have occurred as commonplace and pivotal in the shaping of many natural landscapes and forest ecologies, the likeness of wildfires occurring has substantially increased from the past (UCSUSA, 2020). Wildfires strain public health and local ecosystems with the endangerment of wildlife and human wellbeing and the destruction of infrastructure and habitat. With the increasing number of wildfires, its evermore important to suppress wildfires through the development of novel technologies, particularly the production of specialized aircraft for firefighting purposes.

There is a lack of development and research for large aircraft that are specifically designed for aerial firefighting. Most aircraft currently used in aerial firefighting are repurposed, modified military or commercial aircraft (CALFIRE, n.d.). These aircraft are modified to integrate aerial firefighting equipment, such as a fire suppressant tank module and fire suppressant payload drop mechanism, into the airframe. Since these aircrafts' original design mission were not designed for aerial firefighting, the incorporation of foreign equipment introduces inefficiencies and compromises to the performance and structural integrity of the aircraft. The creation of specialized aircraft designs mitigates such issues and supports the global mission of fire suppression.

The student teams are responsible for the developing an aerial firefighting aircraft concept that meets the technical requirements and objectives outlined in the RFP, such as fire suppressant payload capacity, payload drop speed and altitude, and other aircraft performance parameters. The design objectives are to minimize operations and support cost by integrating modularity into the structure, to minimize production cost by selecting affordable and reliable materials and manufacturing methods, and to make the aircraft reliability, operational availability, and maintenance better than or equal to that of comparable aircraft (AIAA, 2021). Tied to climate change and the design objectives, an external consideration is the development of an aircraft that aims to meet sustainability goals such as net-zero carbon emissions, fuel efficiency, and extended product life. The team is structured with a team lead who acts as the liaison between the faculty advisor Dr. Jesse Quinlan and the team members. Each team member, team lead included, is assigned to a secondary team that focuses on a state-of-the-art (SOA) topic that is relevant to the design challenge. The SOA topics are as follows: Aerial fire fighting business/operating model/requirements, aerodynamic design and modeling, structural design and modeling, propulsion system design and modeling, anti-icing aircraft systems design and modeling, autonomous aircraft technologies, Federal Aviation Administration (FAA) regulations and guidelines, and cost modeling (Quinlan, 2021b). The secondary teams are composed of a team member from each of the three primary teams. This allows for cross-team data acquisition and collaboration on the SOA topics while each of the primary teams work separately to design three different aircraft concepts. I am part of the structural design and modeling SOA topic team. Within the secondary team, I focus on the research and trade studies on state-of-the-art structures, materials, and manufacturing methods of the main aircraft components such as the fuselage (aircraft body), wing, landing gear, empennage (tail), and propulsion. Within the primary team, I lead the structural design and modeling of the conceptual aircraft and act as the liaison between the SOA topic team and the primary team.

The pedagogical objectives for both the AIAA Design Competition and the Aircraft Design course series is for students to develop a fundamental understanding of the methods, techniques, and processes required to design an aircraft (AIAA, 2021; Quinlan, 2021a). The Aircraft Design course series is divided into fall term and spring term courses, each with different objectives. The fall term course is driven by frequent lectures and homework assignments to prepare students with the knowledge required for the spring term. The primary deliverable for the fall term is to submit an SOA topic research paper and presentation. The spring term course is more application-based in which students will perform independent, team-based work to submit a design proposal report to the AIAA Design Competition in response to the RFP.

STS Topic

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 is a layer-by-layer approach in which objects are fabricated layer but layer using materials such as polymers, metals, and composites (Deloitte, n.d.). The counterpart to additive manufacturing is traditional manufacturing (TM) which encapsulates a varied set of methods such as extrusion molding, subtractive manufacturing, and casting. 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 (Ford et al, 2016; Verhoef, 2017). Regarding global sustainability goals and initiatives set forth by sustainability entrepreneurs and institutions in response to climate change, the transition to AM will greatly contribute to achieving such ambitions in creating a more sustainable society. This study explores the sustainability transition from traditional manufacturing to additive manufacturing within the aerospace industry through analysis of the incumbent regime and niches. The aim of this research is to provide insight the progressions and challenges of additive manufacturing in the aerospace ecosystem.

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. Scientific papers 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 provide a preliminary dive into 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.

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, such as the DOE, DOD, 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 Boeing and General Electric, 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 Federal Aviation Administration (FAA), 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 (Khorasani, 2021; Sai Kaylan, 2021). These implications on supply chain management and business models pose as challenges to AM's successful transition from TM. The on-site customization 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 Air Bus, Boeing, and General Electric, 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 Relativity Space and SpaceX which both utilize AM to fabricate additively manufactured rocket engines and launch 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.

Next Steps

Several of the actors in relation to sustainable transitions from traditional manufacturing to additive manufacturing were briefly introduced as starting positions for further inquiry moving into the spring term. A range of sources will be analyzed to describe the roles and relationships of the niche and the incumbent regime more thoroughly and how they relate to the transition from TM to AM and to the consequent challenges and advantages in the socio-technical landscape. The types of sources to be referenced are sociotechnical papers regarding AM, government and industry documents, and interviews with academic researchers and industry professionals who are invested in the AM ecosystem. Another potential context to be explored is the Fourth Industrial Revolution and how it interplays within the sustainability transitions of AM by considering other actors such as the Internet of Things and artificial intelligence. Relevant case studies 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. Looking the early adopters of AM, such as General Electric and Boeing, 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 early adopter corporations to case studies revolving “slower to adopt” corporations may help to clarify the nuances and discrepancies within transitions to AM. These goals will ultimately culminate to the draft and submission of the STS research thesis in the spring term.

For the technical topic, the immediate objectives are to become familiarized with my SOA topic through research and trade studies which will lead up to an SOA technical report and presentation to be submitted in the middle of the fall term and to develop the technical knowledge required to conduct team-based independent work in the spring term. This team-based work on the conceptual design of aerial firefighting aircraft will be solidified into a technical report to be submitted to the AIAA 2021-2022 Design Competition at the end of next semester.

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