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Advanced Materials and Processes Survey for AAM and UAS Aircraft

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16. Abstract

This research project aims to identify the current and future use of advanced materials systems and processes to support the production of AAM and UAS aircraft. The research consisted of a literature review and an industry survey. The study showed that the AAM primarily adopts aerospace-grade thermoset materials for primary and secondary structural applications. The results also showed that with a change in production requirements, the industry is expected to change its selection of advanced materials to snap cure thermosets and thermoplastic material systems. The small UAS industry uses material systems such as carbon/glass fiber composites, metal alloys, and polymeric foams. The small UAS industry is not limited to aerospace-grade materials and adopts industry-grade materials and processes that enable high-production rates. For the non-small UAS industry, the material systems of interest are rapid cure thermosets and thermoplastics and fabrication processes of interest are additive manufacturing and resin infusion processes.

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

TABLE OF ACRONYMS

AAM	Advanced Air Mobility
AM	Additive Manufacturing
AFP	Automated Fiber Placement
ATL	Automated Tape Lay-Up
CMC	Ceramic Matrix Composite
CMH	Composite Materials Handbook
ETW	Elevated Temperature Wet
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
MMPDS	Metallic Materials Properties Development and Standardization
MSG	Market Satisfaction Gap
NAS	National Airspace System
NCAMP	National Center for Advanced Materials Performance
OEM	Original Equipment Manufacturer
OOA	Out of Autoclave
RTM	Resin Transfer Molding
SME	Subject Matter Expert
SQRTM	Same Qualified Resin Transfer Molding
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
VARTM	Vacuum Assisted Resin Transfer Molding

EXECUTIVE SUMMARY

Advanced Air Mobility (AAM) and Unmanned Aircraft Systems (UAS) are aviation transportation systems intended to safely and efficiently move passengers and/or cargo and perform other missions within urban, suburban, and remote environments. The success of the AAM and UAS industries requires innovative, cost-effective, and sustainable air vehicle designs. This is driven by technological advancements, the need for rapid innovation and growth, and based on best practices currently followed in the traditional aircraft industry. Novel advanced material systems and processes are at the core of the AAM and UAS aircraft design and construction due to the rapid pace of innovation, high production volume requirements, and weight and cost restrictions. This established the need to identify and document the gaps, challenges, and issues pertaining to the current and planned use of novel advanced material systems and manufacturing processes in the AAM and UAS platforms to support developing certification guidelines, best practices, and future standards. The Congressional Record for the fiscal year 2021 is directed towards supporting the "expanded role of the UAS Center of Excellence (COE) in areas of UAS research, including cyber security, agricultural applications, beyond visual line of sight technology, studies of advanced composites and other non-metallic engineering materials not common to manned aircraft but utilized in UAS, the STEM program, and to continue efforts with the UAS safety research facility at the Center to study appropriate safety standards for UAS and to develop and validate certification standards for such systems" (Congressional Record, 2022).

The objective of the research study is to review, summarize, and compile the use of advanced material systems, their applications, and the manufacturing processes used to build AAM and UAS aircraft. The research teams identified three key areas of interest and addressed them by conducting a market research survey and literature review. The market research survey consisted of interviews with various divisions along the chain of the AAM and the UAS industries, such as raw material suppliers, AAM and UAS Original Equipment Manufacturers (OEMs), tier-one suppliers, and Subject Matter Experts (SMEs) from industry and academia. This resulted in a wide range of diverse opinions and aided in comprehending these two industries' current standing and expected future growth. Additionally, the market survey analyzed the AAM and UAS market's key areas and their corresponding satisfaction data.

The findings from the research study showed that the AAM market primarily opts for legacy advanced materials and processes currently being used in the traditional aviation industry, such as continuous fiber thermoset composite materials for primary and secondary structural applications. Some of the primary reasons stated during the industry survey were that selecting legacy aerospace materials could result in an easier certification process and allows the AAM OEMs to release certified flying vehicles early into the rapidly growing market. However, there have been several technological developments in novel materials and processes by leading raw material suppliers, tier-one suppliers, and research organizations that may be suitable for AAM and UAS applications. These developments include but are not limited to rapid cure thermosets, increased use of thermoplastics, Additive Manufacturing (AM) materials and processes, and multifunctional material systems and processes. The industry survey and the literature review presented that as the industry matures and transitions into the projected high-production rate environment, the AAM manufacturers are expected to integrate these novel technologies into the construction of the aircraft.

The industry survey presented that the small UAS industry primarily uses advanced and hybrid materials systems like carbon/glass fiber reinforced composites, magnesium-based alloys, polymeric foams, and fabrication processes such as injection molding, over molding, and additive manufacturing. The industry survey with the non-small UAS OEMs presented that they are considering quick-cure thermosets, thermoplastic material systems, and fabrication processes such as additive manufacturing and resin infusion processes.

1 INTRODUCTION AND BACKGROUND

The Advanced Air Mobility (AAM) market is a revolutionary transportation solution to the ever-increasing demands rising from urbanization and the associated ground transport. The vision of AAM is to create a safer, faster, and more efficient aviation transportation system through highly automated aircraft (NASA, 2020) (FAA, 2022). The primary operation of AAM systems is to transport passengers and/or cargo within urban and suburban areas. Unmanned Aircraft Systems (UAS), commonly known as drones, are autonomous aircraft intended for a wide range of applications such as aerial observation, surveillance, cargo delivery, rescue operations, and various other commercial industries (NASA, 2020). Small Unmanned Aircraft Systems (sUAS) are defined as “a small unmanned aircraft that weighs less than 55 pounds on takeoff including its associated elements (including communication links and the components that control the small unmanned aircraft) that are required for the safe and efficient operation in the national airspace system.” (14 CFR Part 107, 2022).

UAS and AAM are outlined in the ANSI Unmanned Aircraft Systems Standardization Collaborative (UASSC) Roadmap Version 2.0. Section 8.4 calls out different use cases of UAS and AAM within the current regulatory framework of Title 14, Code of Federal Regulation (14 CFR) parts (i.e., the current design rules of parts 23, 25, 27, and 29). The ANSI UASSC’s mission is to coordinate and accelerate the development of the standards and conformity assessment programs needed to facilitate the safe integration of UAS – commonly known as drones – into the National Airspace System (NAS) of the United States (ANSI UASSC, 2022). The subsections of Section 8.4 Commercial Services (of the ANSI UAS Roadmap Version 2.0) are shown in the table below.

Subsections of Section 8.4 Commercial Services (ref. ANSI UAS Roadmap V2, published June 2020)	Use Cases mapped with 14 CFR parts (23, 25, 27, 29)
8.4.1. Commercial Package Delivery via UAS	
8.4.2. Commercial Cargo Transport via UAS	Part 25 UAS
8.4.3. Commercial Passenger Air Taxi Transport via UAS (short-haul flights carrying few passengers)	Part 23/27/29 UAS for UAM*/AAM*/IAM*/RAM* Ops
8.4.4. Commercial Passenger Transport via UAS (long-haul flights carrying many passengers)	Part 25 UAS
8.4.5. Commercial Sensing Services	Part 23/27/29/25 UAS

Note*:
UAM - Urban Air Mobility
AAM - Advanced Air Mobility
IAM - Integrated Air Mobility
RAM - Regional Air Mobility

14 CFR parts
Part 23 - Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
Part 25 - Airworthiness Standards: Transport Category Airplanes
Part 27 - Airworthiness Standards: Normal Category Rotorcraft
Part 29 - Airworthiness Standards: Transport Category Rotorcraft
Part 107 - Small Unmanned Aircraft Systems

The AAM and UAS platforms are rapidly growing markets with several promising advancements that could potentially change the landscape of air transportation in the future. This innovative and dynamic growth in the aviation industry also introduces the need for regulation to maintain the safety and security of the NAS. The Federal Aviation Administration (FAA) has organized its regulatory efforts around five areas of activity – aircraft, airspace, operations, infrastructure, and community (FAA, 2022). The focus of this research project pertains to the aircraft belonging to the AAM, small UAS, and non-small UAS platforms, specifically to the aspects of materials and processes. AAM aircraft could be categorized as "vectored thrust," describing an aircraft that uses any of its thrusters for lift and cruise, "lift + cruise," describing an aircraft that has independent thrusters for lifting and cruising, "wingless multicopter," describing an aircraft that is only equipped with lifting thrusters, "electric rotorcraft," describing an aircraft that utilizes a single lifting rotor, and "CTOL," aircraft that are conventional take-off and landing vehicles. UAS platforms include small UAS unmanned aircraft that weigh less than 55 lbs on take-off, and non-small UAS, unmanned aircraft that weigh greater than 55 lbs. on take-off.

The rapid growth of the AAM and the UAS industries could be supported by the use of advanced materials and processes. The selection of appropriate materials and processes is one of the several key factors involved in the design and production of safe and efficient UAS and AAM. This research project aims to identify the composite materials, additively manufactured parts, and other advanced materials used in AAM and UAS designs. The importance of fully understanding the varying types of composites and other advanced materials being used in UAS and AAM designs is necessary for developing appropriate standards and regulations around the design, production, and maintenance of these materials. In addition, types of these advanced materials may not be currently used in traditional aircraft, so identifying these materials and associated unique characterization requirements, properties, or vulnerabilities is also necessary. Therefore, this research will include identifying these advanced materials and the associated qualities to aid in developing standards for safe use in safety-critical aviation applications. This study also presents a market survey analysis on the AAM and UAS industries' importance vs. satisfaction data over the use of advanced materials and processes and identifies the current market satisfaction gaps.

1.1 Scope

The FAA has published comprehensive policy and guidance for certifying composite aircraft structures. However, this guidance is typically intended for traditional continuous fiber reinforced thermoset composite materials generally used for rotorcraft and aircraft applications, and therefore it may not be appropriate for AAM and UAS materials or their applications. In addition, different guidelines may be required for new materials, such as discontinuous fiber, thermoplastic composites, rapid cure resin systems, multifunctional composites, or additively manufactured parts for their use on AAM and UAS. Therefore, the main objective of this research is to identify any novel advanced material systems planned and/or in use on AAM and UAS, to identify if existing aerospace industry-related composite material systems are being used for different applications in AAM and UAS aircraft, and to document any material characteristics that are uniquely critical for AAM and UAS aircraft. The report presents the research efforts carried out to address the previous statements through an industry survey and literature review. Additionally, the industry survey was used to identify the AAM and UAS industries' current challenges, potential concerns, importance vs. satisfaction data, and the market satisfaction gaps.

1.2 Projected Benefit of Research

This research project aims to achieve the following key aspects of the AAM and UAS industries:

- Identify the novel advanced material systems and processes in use and being considered for advanced air mobility and unmanned aircraft systems designs.
- Understand the major differences between the future advanced materials and currently available traditional materials for which the FAA has already published policy and guidance for certification purposes. Identify potential limitations of current policy and guidance and propose future activities to support UAS and AAM certification.
- Identify potential limitations of current policy and guidance and propose future activities to support UAS and AAM certification.

2 RESEARCH QUESTIONS AND APPROACH

As per the scope of this research investigation, primary areas of interest were identified with a focus on the advanced material systems and processes adopted by the AAM and UAS industries. These research areas are further sub-divided into three primary research questions as described below.

2.1 Novel Advanced Material Systems and Processes

This research question focused on identifying any new or unique composite or other advanced material systems and processes currently in use or planned for future use on AAM and UAS aircraft but are currently not in use on traditional aircraft or rotorcraft. This question aims to identify all the composite materials, additively manufactured, and components manufactured through other advanced manufacturing applications currently in use or for future use in AAM and UAS aircraft. The research task would not be limited to structural components but expanded to all the applications, for example, propulsion components, brackets, systems components, etc. Additionally, the fabrication, joining, and other related processes would be documented.

2.2 Applications of Existing Advanced Material Systems

This research question focused on identifying any new or unique applications of existing composite materials. The objective is to compare and analyze the usage of advanced material systems between traditional aircraft applications to AAM and UAS. To further expand on this, the research focuses on whether the materials considered non-structural or secondary structures in traditional aircraft serve a different purpose in UAS and AAM, such as being used as primary structures. Additional areas to focus on are:

- If thermoplastics are in use, and if so, state their applications; are these thermoplastic materials the same as in the traditional aircraft, or do they differ in application, and if so, report the reasons.

- Are ceramic matrix composites used in AAM and UAS aircraft?
- Are there any new and advanced manufacturing processes, such as 3D printing of continuous fiber composites?
- Identify the maintenance, repair, and inspection criteria followed by the AAM and UAS industries. If the criteria are similar to traditional aircraft or if different repair and inspection criteria are followed.
- Identify the joint assembly methods adopted by the AAM and UAS industries. For example, if components are fastened, adhesively bonded, welded, or any other joining process is considered.
- Document the extent to which hybrid materials such as aluminum-composite structures are used in AAM and UAS.

2.3 Public Material Databases - Critical Material Characteristics for AAM and UAS

This research question focused on identifying material characteristics uniquely critical to the AAM and UAS that are not included in the material databases developed for traditional aviation applications, such as Composite Materials Handbook-17 (CMH-17) (CMH-17, 2022), National Center for Advanced Materials Performance (NCAMP) (NCAMP, 2022), or Metallic Materials Properties Development and Standardization (MMPDS) (MMPDS, 2021). The research efforts would consider if the AAM and UAS require unique characterization for static, dynamic, chemical, environmental, thermal, or other properties that are not typically included in the published material databases.

The aforementioned three research questions are addressed through an industry-based survey and literature review and are detailed in the subsequent sections.

3 INDUSTRY SURVEY AND LITERATURE REVIEW

An industry-wide survey and literature review were conducted to address the research questions described in Section 2. The results from the industry survey are presented in Sections 3.1.1, 3.2.1, 3.3, and 4. The findings from the literature review are presented in Sections 3.1.2 and 3.2.2. The industry survey was conducted using New Product Blueprinting, a commercially available market survey software developed by the AIM Institute (The AIM Institute, 2022). This tool is designed for direct market engagement, thus defining the industry's direction and the foreseeable problems.

The industry survey is divided into the following two phases:

1. Discovery Phase: This phase aims to collect the desired data through industry engagement with various raw material suppliers, AAM and UAS OEMs, tier-one suppliers, and SMEs from industry and academia. The objective was to conduct a broad set of interviews to obtain diverse and wide-ranging data from various divisions of the AAM and UAS industries.

Figure 1 presents the breakdown of the interviews conducted during the discovery phase. A total of 33 interviews were conducted, 11 interviews were conducted with raw material suppliers, 10 interviews with AAM/UAS OEMs (8 interviews with AAM OEMs and 2 interviews with non-small UAS OEMs), 5 with tier one suppliers, and 7 with SMEs from the aerospace industry and academia. In this phase, the interviewees were presented with the research questions, and their detailed responses were recorded. This data was used to address the program's three primary research questions, and the results are presented in Section 3.

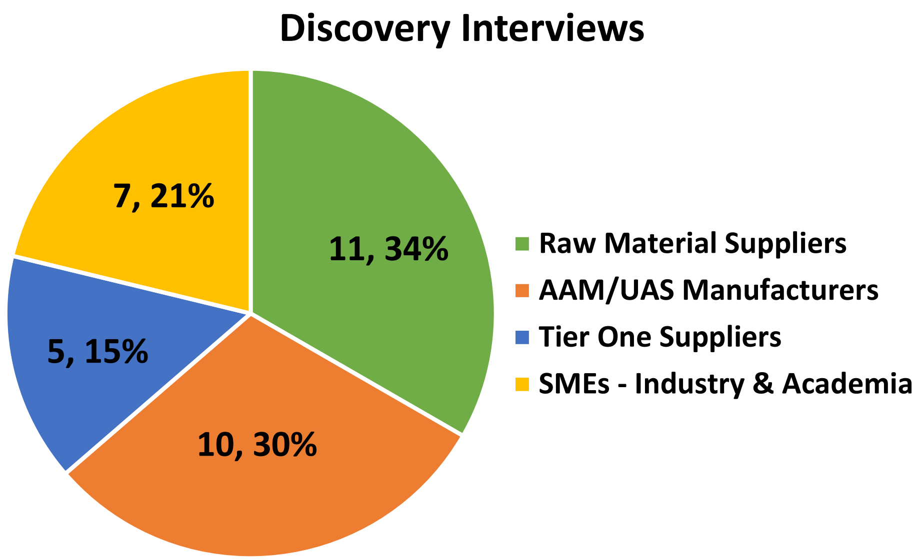

Figure 1. Discovery Phase: Interview Breakdown

Additionally, the data collected from these interviews was analyzed to evaluate the potential challenges and concerns of advanced materials and processes in the AAM and UAS industries. From each interview, problem statements pertaining to these industries were recorded, with a typical interview consisting of five to ten different problem statements. The most important three to five problem statements were chosen from this list and were identified as top picks. This process was followed for every interview, and as more interviews were conducted, the top picks identified in each interview began to get duplicated.

Upon completion of the discovery interviews, the top picks from all the interviews were categorized based on different areas of interest. In the current discovery interview process, a total of 20 unique categories consisting of 161 top picks were identified. The categories with the highest or most repeated top picks were chosen as the top 10 problem statements.

2. Preference Phase: The second set of interviews was conducted in the preference phase. These interviews were repeated with the raw material suppliers, AAM, UAS manufacturers, tier one suppliers, and SMEs from the discovery phase. Figure 2 presents the breakdown of the interviews conducted in the preference phase. A total of 11 preference interviews were conducted, which consisted of 5 interviews with raw material suppliers, 4 interviews with AAM/UAS OEMs (3 interviews with AAM OEMs and 1 interview with small UAS OEM), and 1 interview each with tier one supplier and SME.

The top 10 problem statements were presented in each interview, and the interviewee's importance and satisfaction data with each problem statement were recorded. This was followed by obtaining additional information on methods to satisfy each problem statement. Detailed information on the 10 problem statements, importance, and satisfaction data are presented in Section 4.

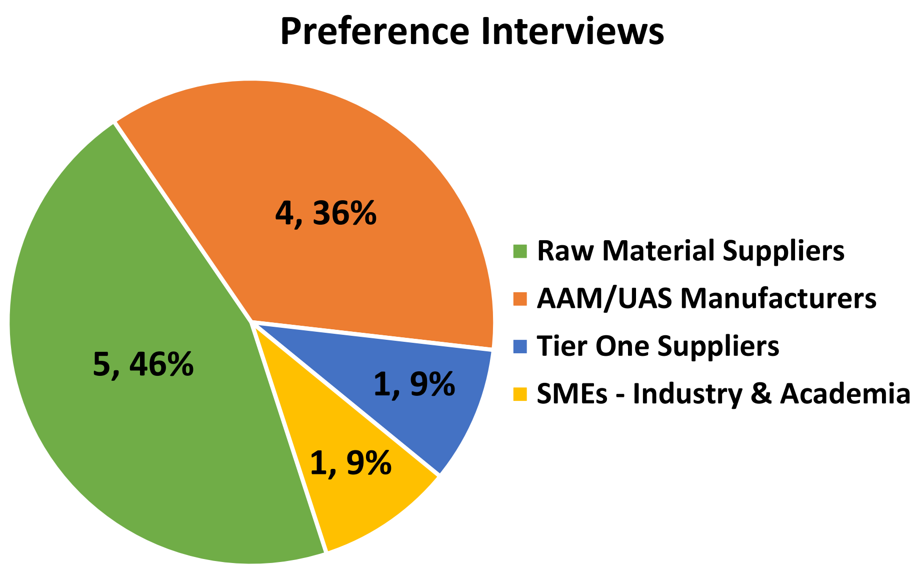

Figure 2. Preference Phase: Interview Breakdown

3.1 Novel Advanced Material Systems and Processes

With the rapid development in the AAM and UAS industries, the use of advanced material systems and processes plays a crucial role in the construction and efficient use of these vehicles. While traditional composite material systems and manufacturing processes are being considered, several other advanced material systems and processes are being explored. These advanced materials are expected to meet the requirements and tackle the challenges faced by the AAM and the UAS industries. Since several of these material systems are novel and relatively new to the market compared to the legacy materials with established datasets and public databases, there is a need to ensure that these materials will meet requirements and standards for certification purposes.

The industry survey and literature review presented that most AAM OEMs are adopting traditional aerospace-grade continuous fiber reinforced thermoset material systems. Except for two OEMs considering snap cure thermoset resin systems, one OEM adopting thermoplastic material systems, and another OEM adopting conventional metallic materials. The fabrication processes considered by the OEMs include hand layup, autoclave, cure, Automated Fiber Placement (AFP), Automated Tape Layup (ATL), Resin Transfer Molding (RTM), and compression molding. Detailed information on the materials and processes employed by the AAM and the UAS industries is presented in the following sections.

3.1.1 Industry Survey

An industry-based survey was conducted to address the research questions using a commercially available market survey software, New Product Blueprinting. A total of 33 discovery interviews were conducted with raw material suppliers, AAM and UAS OEMs, tier-one suppliers, and SMEs from industry and academia. This section presents the results from the discovery interviews pertaining to the research topic described in Section 2.1.

3.1.1.1 Material Suppliers

3.1.1.1.1 Advanced Air Mobility

One of the key points of consensus from the material supplier interviews was that the AAM market is primarily opting for traditional aerospace material systems and manufacturing processes for primary structural applications. This is due to the availability of datasets in public databases and their previous demonstration in traditional aircraft applications. As this is a fast-growing competitive market, choosing well-established legacy material systems for primary structures also aids in easier design and certification processes. However, this reliance on the traditional material and processes databases may not fully support the rapid growth of the AAM industry due to the limited availability of high-rate applicable materials and processes.

The AAM market is projected to outpace the traditional aerospace production rates, which have traditionally varied between 1000 to 2000 units a year and evolve into total production of 15,000 to 200,000 units by 2035 (Toray, From 200 to 200,000 : Challenges in Advanced Air Mobility Market Scaling, 2022). Material and processes selection for aircraft concept, design, development, certification, and manufacturing strongly affects the production rate of the aircraft. Thus, the choice of materials and processes plays a crucial role in sustaining these expected production volumes. Several AAM OEMs have opted for traditional composite material systems such as thermosets for primary structural applications. However, they are still in the prototyping and certification stages and not yet in the full-rate production stage. While the traditional materials and processes would be able to perform well in prototyping and certification phases and sustain the typical aerospace production rates, it is expected to get challenging when the AAM market transitions to greater production rates. The traditional manufacturing processes such as hand lay-up, autoclave, and oven curing perform well for traditional aircraft production but can be too labor-intensive and time-consuming at high volume production rates. The rapid cure materials and processes currently in use in the automotive industry do not meet the standards required for critical structural aerospace applications. This created an overlap between the automotive and aerospace industries with the need for aerospace-grade quality materials to be fabricated at production rates closer to the automotive industry.

This led the raw material suppliers to foresee the issue and thus offer a wide portfolio of materials for the AAM market with both conventional aerospace material systems and novel material systems suitable for high-volume production environments. It includes conventional material systems adapted for novel rapid manufacturing processes, new rapid cure materials, and processes applicable to meet aerospace standards. While these materials could support the high-volume production rates, they are novel to the aerospace industry and are either not available in public material databases such as NCAMP and CMH-17 or are currently in the material qualification process to be available in these databases. Hence, most OEMs are opting for traditional material systems currently available in public material databases to begin with, and as the technology matures, they plan on shifting to materials and processes suitable for high production rates.

Rapid cure thermosets and thermoplastic material systems are some of the advanced materials discussed by the material suppliers to tackle the estimated production volume challenge. Rapid or snap cure resin systems offer extremely short cure cycles, capable of cure times ranging between as low as five to twenty minutes, making them ideal for high-volume applications. Lower cure temperature materials that maintain mechanical performance are critical in meeting the rate requirements. So, novel materials with similar performance as legacy thermoset material systems but with a different process window are under development by many raw material suppliers. Thermoplastic material systems are also being recommended by the material suppliers for primary and secondary structural applications to meet the requirements and challenges faced by the AAM market. Thermoplastics are suitable for high-rate applicable processes such as continuous compression molding, over-molding, press/stamp forming and offer other advantages such as welding, recyclability, long shelf life, and no cold storage limitations over traditional thermoset material systems. Depending on the application, thermoplastics could play an important role in designing and constructing AAM aircraft. However, one of the major drawbacks mentioned in the interviews was the limited availability of thermoplastic material systems in public material qualification databases such as the NCAMP and CMH-17. A detailed discussion of thermoplastic materials, their applications in advanced air mobility aircraft, advantages and drawbacks will be presented in Section 3.2.1.

Traditional aerospace manufacturing processes include hand lay-up, automated tape placement, autoclave, and oven curing. Autoclave equipment can be expensive and have long cure times. Out-Of-Autoclave (OOA) processes play a significant role in the AAM industry for mid to high-rate production volumes with relatively fast cure times and minimal tooling and equipment costs. Material suppliers stated that processes such as RTM, VARTM, over-molding, continuous compression molding, and stamp forming for thermoplastic material systems, thermoset press technologies, and injection molding processes are some of the fabrication processes that AAM manufacturers are considering for the design and construction of their aircraft.

Additive manufacturing was stated as another material solution for the AAM market. AM enables the consolidation of multiple components into a single component, thus reducing part assembly time and costs. Currently, internal non-structural components such as clips, brackets, and enclosures are being considered to be additively manufactured. The process capabilities are limited to non-structural small-size components, and research is underway to expand the 3D printing technologies to mid-size secondary structures. Other AM technologies discussed in the interviews are direct-write electronics, multi-material AM, and additive composite manufacturing which includes combining traditional composite fabrication processes with AM. The need for more AM materials in public material databases was frequently mentioned in the interviews.

Some of the novel material systems, forms, and characteristics mentioned are higher modulus fibers than standard modulus fibers for weight limitations and higher performance, toughened epoxy systems, braided materials for small and complex geometries, and continuous fiber thermoplastics and powdered thermoset epoxies and metallic AM processes. The manufacturing processes mentioned by the material suppliers that the AAM industry is currently adopting and considering for future are autoclave cure, automated tape laying, resin infusion processes, resin transfer molding, vacuum-assisted resin transfer molding, snap cure, press consolidation, injection molding, compression molding, over-molding, stamp forming, thermoset press cure, and multi-material manufacturing processes to fabricate metallic-composite hybrid materials, which consists of introducing metallic details into injection molded components.

3.1.1.1.2 Unmanned Aircraft Systems

This section presents the data obtained from the interviews with the material suppliers regarding the material systems and the fabrication processes chosen by the small UAS OEMs. They have mentioned that the approach followed by the small UAS OEMs in terms of advanced materials and processes varies from the AAM industry. Small UAS (as defined in 14 CFR part 107) is a low-cost platform without the burden of certification. Hence, the small UAS are not restricted to aerospace-grade materials. Material suppliers have mentioned that the small UAS industry's primary focus is on innovation in manufacturing methods and maintaining the manufacturing consistency of the existing systems. Any new material suitable for the application that can increase throughput at a low cost and meet the target production rate is considered desirable. In the interviews, injection molding, AM, compression molding, and hand lay-up are some of the manufacturing processes mentioned for the construction of small UAS.

3.1.1.2 Original Equipment Manufacturers (OEMs)

3.1.1.2.1 Advanced Air Mobility

This section presents the results from the discovery interviews with eight AAM OEMs. The responses from the interviews with different OEMs were diverse and varied based on the technology capabilities, cost, certification concerns, and the OEM's time of entry in the market. As discussed in the previous section, several of the AAM OEMs prefer traditional aerospace advanced materials to fabricate primary structures. Lower risk to certification with material selection is one of the major objectives for many OEMs. However, based on the OEM's choice of advanced materials and processes, they could be broadly classified into two categories: OEMs preferring conventional materials and processes to simplify the certification process and OEMs selecting unconventional materials and processes while considering any potential challenges with certification. Table 1 presents the summary of the materials and fabrication processes described by the AAM OEMs in the discovery interviews.

Table 1. Summary of Materials & Processes Mentioned by AAM OEMs

OEM	Current Materials	Current Fabrication Processes	Current Use of Thermoplastics	Future Materials & Processes
OEM A	UD thermosets available in public material databases such as NCAMP, CMH-17.	Hand layup, autoclave cure. No OOA & AM.	Limited to brackets.	Snap cure & thermoplastics; Press cure, Resin infusion.
OEM B	Thermosets available in public material databases; snap cure is of interest.	OOA, oven curing, VARTM. No autoclave. AM - for internal non-structural use.	None.	-
OEM C	Snap cure resins. AM - critical components using titanium.	High pressure RTMs, SQRTM. AM.	Research ongoing. Processes of interest: Over-molding, stamp forming, CCM.	Evaluating discontinuous fiber for secondary structures.
OEM D	Thermosets available in public material databases.	AFP.	Limited use for now.	Would be heavily reliant on thermoplastics.

OEM	Current Materials	Current Fabrication Processes	Current Use of Thermoplastics	Future Materials & Processes
OEM E	Thermosets & thermoplastics available in public material databases.	Hand layup, AFP, ATL. No AM.	Brackets.	Snap cure & thermoplastics (PEEK & Ultem 9085 being evaluated).
OEM F	Materials available in public databases. AM - propellers, structural components (have not decided the AM processes).	Injection molding is of interest. Open to different processes.	Evaluating thermoplastics for any potential applications.	In prototyping phase and deciding on the current M&P.
OEM G	Thermoplastics.	No autoclave.	Primary and secondary structures.	-
OEM H	Primary: Al & other conventional metals. Secondary: Composite materials available in public databases.	-	-	-

Five out of eight AAM OEMs have selected aerospace-grade, epoxy-based continuous carbon fiber composites available in public material databases such as NCAMP and CMH-17 for their primary structural applications. They have primarily relied on thermoset resin systems. Out of these five OEMs, one OEM has chosen hand layup, autoclave cure without any OOA or AM processes, One OEM has chosen oven curing and VARTM. One OEM has opted for hand layup, AFP; one OEM has opted for AFP and one OEM is considering injection molding and is also evaluating other fabrication processes. These OEMs are heavily using carbon fiber epoxy-based material systems throughout the aircraft structure for primary and secondary structural applications such as fuselage, wings, flaps, rotor blades, seats, spars, ribs, propulsion components, and other interior structures. The OEMs recognize that while the traditional materials and processes are effective for the certification and initial production phases, they would quickly become inefficient at high-volume production rates. As the industry matures and meets the full-rate production environment, OEMs expect a shift from traditional materials and processes to high-rate applicable materials and processes. Table 1 also presents the OEMs choice of future materials and processes.

Four out of eight OEMs have selected OOA materials and processes. They have chosen not to incorporate autoclave-related processes due to the long cure times and the associated costs that cannot be justified for the AAM market. Instead, they opt between oven consolidation and resin infusion processes (RTM and VARTM). They also aim to avoid the high-cost tooling processes due to the limitations with the temperature, material type, and the entire design consideration as the manufacturing methods would likely evolve in the future. One OEM is incorporating thermoplastic materials for primary and secondary structural applications and is relying on OOA processes.

One AAM OEM has chosen aluminum and other conventional metallic materials for its primary aircraft structures. This differs from the approach followed by most of the AAM industry, which primarily relies on advanced material systems. This OEM stated that conventional metallic materials such as aluminum have already been proven in the aviation industry over several decades for their performance. This makes the certification process easier for the metallic materials over composite systems, which can be difficult to qualify under dynamic or shock loading conditions. Due to the nature of the AAM, with most frequent shorter flight duration and greater take-off and landing cycles than conventional aircraft/rotorcraft, the OEM was concerned about long-term performance and in-service aging of composite materials as primary structures. The OEM also mentioned that while composite materials as primary structures would perform well for short life cycles, metallic materials would better sustain longer life cycles They, however, use carbon and glass fiber composite material systems available in public material databases for secondary and tertiary structural applications such as rotor blades, fairings, door structures, flaps, rudders, and access panels.

One of the primary areas of interest for OEMs has been reducing cure cycle times through lower cure temperature material systems and snap cure resin systems. The emphasis has been on novel composite materials with similar performance as legacy materials but with a different process window. This creates a potential overlap between automotive snap cure resin materials and the AAM market needs. However, these materials would have to maintain the performance required for traditional aviation standards. Recently, a few snap cure material systems were released for high-rate applications, such as the AAM market. However, OEMs are wary of selecting these materials for primary structures due to potential issues with certification as these are novel material systems. To address this concern, leading material suppliers have developed snap cure versions of well-established, legacy thermoset material systems. These materials were formulated for lower cure temperature profiles, to be process flexible but designed to offer the same performance as their legacy versions for easy replacement and adoption by the OEMs. While some OEMs are interested in these new materials, they await material qualification by public databases. The OEMs' material selection process could be made easier through the availability of adequate process flexible, rapid cure thermoset material systems in public databases that satisfy the market's production rate and cost requirements.

The key approaches often discussed to address the challenges associated with the projected high-rate production rates are rapid cure thermosets and thermoplastic material systems. While material suppliers offer a wide range of thermoplastic materials to be applied for primary and secondary structures, most AAM OEMs are skeptical about using thermoplastics for these applications. While OEMs recognize that thermoplastic material systems would be greatly useful for high-rate applications, there are several concerns at the moment. Some of them are high raw material cost, high processing temperatures, technology maturity, lack of adequate materials in public material databases such as NCAMP and CMH-17, and concerns related to the certification process. In addition, the OEMs are concerned that there are high risks associated with the certification of primary structures built from relatively novel materials such as thermoplastics. As the technology matures, these OEMs intend to integrate thermoplastic materials into their aircraft designs. However, in the meantime, thermoplastics are limited to non-structural applications such as clips, brackets, etc.

AM is another advanced fabrication process considered by the AAM industry. Few OEMs use AM processes to fabricate propellers, avionics, electric motors, safety-critical metallic components, and other structural components. But most OEMs are limiting AM processes to non-structural components such as clips, brackets, and other internal applications. These OEMs are concerned about the performance and longevity of additively manufactured parts, especially under load-bearing applications. Since these are novel material systems, the OEMs are also concerned about any risks associated with the certification process.

For most AAM OEMs, publicly available material databases such as NCAMP and CMH-17 play a crucial role in the material selection process. They prefer to select material systems from these public databases for their primary and secondary structures for an easier certification process. In addition, the OEMs find adequate, relevant material systems available in public databases with the experimental datasets to be useful in the design process. On the other hand, larger established OEMs in partnerships with major tier one suppliers are open to novel materials and processes due to the in-house certification capabilities.

3.1.1.2.2 Unmanned Aircraft Systems

In the interview with a small UAS OEM with in-service drones, the OEM stated that they choose materials that are not necessarily aerospace-grade but provide good mechanical performance. Some of the material systems mentioned in use in small UAS were carbon and glass fiber composites, metal alloys like aluminum and magnesium, and expanded polypropylene foam. The OEM mentioned that multi-injection molding is a key fabrication process followed in building their drone. This OEM uses carbon fiber composites to fabricate the central body and wings of the drone. Aluminum-composite hybrid materials are used to build motor support structures. The OEM is also researching integrating thermoplastic materials available in public material databases to construct their drones. They are currently working on balancing mechanical performance and raw material cost.

The limited information from the interviews with two non-small UAS OEMs presented that they are interested in adopting the techniques followed by the automobile industry and bringing down the costs associated with the traditional aerospace applications. The material systems of interest are rapid cure thermosets and thermoplastics. The industry is not restricted to traditional manufacturing processes and is keen on using VARTM, SQRTM, and AM.

3.1.1.3 Tier One Suppliers

Many aspects discussed in the previous two sections with the interview results from material suppliers and AAM OEMs were repeated by the tier-one suppliers. In the five interviews, some of the key points mentioned regarding the novel materials and processes applicable to the AAM industry were thermoplastic material systems and snap cure resin systems. In terms of manufacturing processes, reducing material cure cycle times, minimizing tooling, and incorporating rapid cure processes were often discussed. The tier one suppliers mentioned that they are researching the technological advancement of novel materials and processes through internal research projects and collaborations with research organizations. One tier one supplier mentioned that they possess the resources to demonstrate and internally certify novel materials and processes with certification authorities without relying on public material databases.

3.1.1.4 SMEs - Industry and Academia

This section presents the discovery interview results from the SMEs from academic and aviation industry. The seven interviews with the SMEs contained some of the key points discussed in the previous sections, such as high-production rate-related issues and the need for more thermoplastic materials in public material databases. One key point from the interviews was that the materials and processes might not be very unique or different from the traditional aerospace industry, but industrialization might be the primary difference. The legacy manufacturing processes in the traditional aircraft industry have historically been labor-dependent. The AAM market could adapt minimal to no-touch labor manufacturing processes and incorporate in-situ automated inspection procedures into the different stages of manufacturing processes for robust process control. While incorporating automation would result in minimal labor-dependent processes, it would also aid with the expected high-volume aircraft production. Other key aspects discussed in the interviews align with the responses from the material suppliers, AAM OEMs, and tier-one suppliers, as detailed in the previous sections.

3.1.2 Literature Review

This section discusses the literature review findings on the advanced materials and processes in use or planned for use by the AAM and UAS industries. It also presents some ongoing research activities to tackle the challenges faced by the industry and discusses the novel materials and processes developed specifically for the high-rate needs of the advanced air mobility industry.

3.1.2.1 Advanced Air Mobility

The AAM industry predominantly uses composite material systems and related processes for aircraft construction. Most OEMs opt for legacy aerospace-grade composite material systems and are expected to switch to high-volume suitable materials and processes when in full-rate production. The advanced materials and processes used by various AAM companies based on open literature are summarized below.

- **Joby Aviation:** Joby Aviation’s Electric Vertical Take-Off and Landing (eVTOL) aircraft is a piloted 4 passenger aircraft with 6 electric motors and a maximum range of 150 miles (Joby Aviation, 2022). According to the publicly available literature, Joby Aviation is using carbon fiber-thermoset resin material systems in their aircraft. The fabrication process adopted is AFP technology. Carbon fiber material systems are used throughout the aircraft structure, propulsion systems, and interior components (Toray Advanced Composites, 2020) (Sloan, Composite aerostructures in the emerging urban air mobility market, 2020). For its composite manufacturing operations, the company would like to have materials without expiration and out-time restrictions, minimal waste, no dependence on human variables, no manual inspection, and no repairs after full build. The OEM also stated that they are open to integrating thermoplastics into their aircraft in the future (Sloan, Composite aerostructures in the emerging urban air mobility market, 2020). Metallic AM processes are used to manufacture safety-critical structural titanium components (Head, 2020).
- **Lilium:** Lilium’s eVTOL aircraft, Lilium Jet is a piloted 6 passenger aircraft with 36 ducted fans and a maximum range of 155 miles (Lilium, 2022)**.** Lilium intends to use high-performance carbon fiber composite materials in its aircraft, Lilium Jet. Carbon fiber composites are used in all the primary structures, including the fuselage, wings, and flaps

(Sloan, Composite aerostructures in the emerging urban air mobility market, 2020) (Yemsi, 2020). Lilium would use conventional, hand-laid, autoclave-cured carbon fiber prepregs to fabricate pre-production prototypes and low-rate aircraft production. However, as the aircraft enters full-rate production in the future, the conventional hand lay-up processes would not be able to sustain the high-volume requirements. The company then expects to transition to automated processes such as AFP and potentially use OOA materials, including thermoplastics. They also expect AM to be another key production solution for mass production. While the company chose well-established legacy material systems to meet the certification standards, depending on the qualification requirements, other materials and processes could be considered to meet the high manufacturing rates (Sloan, Lilium selects Aciturri for eVTOL fabrication, 2021).

- **Volocopter:** Volocopter's eVTOL aircraft, Volocity is a piloted 2 passenger aircraft powered by 18 rotors and a maximum range of 20 miles (Volocopter, 2022). Volocopter uses already proven fiber and resin composite material systems in the entire airframe, rotor blades, and seats. For prototype and demonstrator aircraft fabrication, they use carbon fiber and glass fiber materials systems through a wet lay-up process. However, when the aircraft enters full-rate production, they expect to shift to an OOA prepreg system (Sloan, Composite aerostructures in the emerging urban air mobility market, 2020).
- **Beta Technologies:** Beta Technologies' eVTOL aircraft, Alia is a piloted 5 passenger aircraft powered by 4 rotors for vertical lift and 1 rear-facing propeller for forward flight with a maximum range of 250 miles (Beta Technologies, 2022) (Transport Up, 2020). The material selection process by Beta Technologies would be based on the certification requirements. They intend to use legacy composite material systems in their aircraft, Alia. As the aircraft enters production, the company plans to use materials and processes that would apply to high-rate production and meet certification standards. Automated technologies would be employed for lay-up, inspection, and assembly procedures (Sloan, Composite aerostructures in the emerging urban air mobility market, 2020).
- **Vertical Aerospace:** VX-4, eVTOL aircraft from Vertical Aerospace is a piloted 4 passenger aircraft with 8 rotors and a maximum range of 100 miles (Aerospace, 2022). Vertical Aerospace uses Solvay MTM45-1 toughened epoxy prepreg (Solvay, MTM45-1, 2022) to design and construct their aircraft, VA-1X. This material system was chosen as it is a well-established material with flexibility for in or out of the autoclave processes. As the aircraft goes into full-rate production, the company's selection of materials and processes is expected to transition into more OOA alternatives such as thermoplastics and automated procedures such as AFP (Sloan, Solvay, Vertical Aerospace expand on UAM agreement, 2021).
- **Wisk:** Wisk's autonomous eVTOL aircraft is a 2 seater aircraft with 12 propellers and a range of 25 miles (Wisk, 2022). All the primary structures on Wisk's aircraft are manufactured using established aerospace-grade composite material systems. The fabrication processes are laser-guided hand lay-up with OOA consolidation under a vacuum bag. When under high-rate production, the company intends to incorporate automated technologies (Sloan, Composite aerostructures in the emerging urban air mobility market, 2020).

- **Novotech:** Novotech's Seagull is a piloted two-seater hybrid-electric aircraft with a single propeller (Sigler, 2022). Novotech chose Solvay MTM45-1 (Solvay, MTM45-1, 2022) and CYCOM 5320-1 (Solvay, Cycom 5320-1, 2022) resin systems in their aircraft design. These material systems were chosen as they have previously been demonstrated in aerospace applications, have publicly available datasets, and are process flexible. The fabrication process adopted is AFP (Nehls, Solvay supplies composites, adhesives, technical support to Novotech Seagull aircraft development, 2021). Novotech's other advanced composite manufacturing capabilities are OOA processes such as resin fiber infusion and thermoplastic composites manufacturing with in-situ consolidation using AFP technology (Novotech, 2022).
- **Pipistrel:** Pipistrel's Nuuva V300 is an autonomous hybrid cargo aircraft with 8 propellers and a maximum range of 1500 miles with a payload of 110 pounds (Pipistrel, 2022). Nuuva V300 consists of epoxy-based prepregs fabricated through hand lay-up, room temperature cure, and occasional autoclave cure for smaller parts. When the aircraft goes into production, the company intends to use OOA prepregs with automated procedures (Sloan, Composite aerostructures in the emerging urban air mobility market, 2020).
- **XPeng HT Aero:** Xpeng HT's X2 is an autonomous eVTOL two-seater aircraft (XPeng Motors, 2022). The aircraft comprises carbon fiber materials used in the cockpit, seats, mechanical arm, and other structural, interior, and exterior parts. A carbon fiber sheet molding compound was used to fabricate the seat frame and control panel. Complex structural components like AB pillar were fabricated through a combination of compression molding and autoclave cure (Nehls, HRC manufactures CFRP parts for XPeng HT Aero's X2 eVTOL aircraft, 2022).
- **ElectraFly:** ElectraFly's eVTOL is a 1 person hybrid eVTOL with 4 rotors and a range of 20 miles (ElectraFly, 2022). ElectraFly has adopted AM processes to print composite components using the Impossible Objects Carbon-Based Additive Manufacturing 3D printer (eVTOL, 2020). They intend to replace the aircraft's metal gears with composite fabricated parts and plan to fabricate other additional parts over time. For larger carbon fiber components that could not be fabricated using the 3D printer, the company plans to use an infusion process (Nehls, ElectraFly, AnalySwift win U.S. Air Force STTR grants, 2020).
- **Jaunt Air Mobility:** Jaunt Air Mobility's eVTOL is piloted 4 passenger aircraft with 4 propellers and a range of 80 miles (Jaunt Air Mobility, 2022). Thermoplastics are used to build the entire airframe, primary structural components, outer body, tail boom, rudder, and stabilizer (Colucci, 2021). The primary and secondary structural components are fabricated using hot press forming and are assembled using induction welding. The airframe substructure is fabricated using chopped fiber composites through a compression molding process. Wing skins, spars, and tail booms are manufactured using AFP (Colucci, 2021). The company intends to use induction welding processes to eliminate the need for fasteners resulting in weight reduction. This would also aid with the high production rate requirements. Jaunt Air Mobility's production plan also consists of robotic joining of frames, spars, and stiffeners and integrating automated systems for inspection. Due to technological maturity, aircraft's rotor blades are made from conventional carbon fiber thermosets (Colucci, 2021).

- **Renault:** Renault's AIR4 is a piloted one-passenger eVTOL aircraft with four propellers (Renault AIR4, 2022). The body of Renault's aircraft, AIR4, is made of carbon fiber composite material systems. In addition, the aircraft chassis which includes its central structure, the four arms, and the main battery pack is fabricated using aluminum alloy and carbon fiber (Branch, 2021).
- **Alaka'i:** Alakai's Skai is a piloted four-passenger eVTOL aircraft with six rotors (Alakai, 2022). The aircraft consists of carbon fiber composite airframe and landing skids (Mason, 2019).
- **Lift:** Lift's Hexa is a 1 person eVTOL aircraft with 18 propellers (Lift, 2022). The aircraft consists of a carbon fiber airframe and propellers. The pylon is additively manufactured using titanium (LIFT Aircraft HEXA, 2022) (FutureFlight, 2022).

This summarizes the advanced material systems and processes employed by some of the AAM companies based on publicly available information. Several other companies use composites in the design of the aircraft, but there is limited information available in open literature regarding the material system types and the fabrication processes followed. With the rapidly developing market, companies frequently develop and update materials and processes related information in the public domain.

In the summary of the advanced material systems and processes used by the AAM companies, it is often mentioned that most companies would like to integrate high-rate applicable materials and processes when they enter full-rate production. Material suppliers and research organizations have developed novel materials and processes to meet these requirements. Some of these research developments and technologies are presented below.

- **CYCOM EP2750:** EP2750 is an epoxy prepreg system designed especially for compression molding of primary and secondary structural components (Solvay, Cycom EP2750, 2022). This drapable prepreg system is suitable for producing complex monolithic parts. It is a process flexible material system formulated for press and autoclave cures. EP2750 has been designed to fabricate components at high-volume production rates while maintaining aerospace-grade quality. The material system is targeted toward aerospace platforms, air mobility, and drone markets. For air mobility and drone applications, the material system can be used in fuselage sections, ribs, bulkheads, brackets, and clips (Sloan, Solvay launches epoxy prepreg for aerostructures compression molding, 2020).
- **Toray 2700:** T2700 is a prepreg system developed for emerging aerospace programs. It is a drapable prepreg that can be press cured under short cure cycles, making it suitable for a rapid production environment (Nehls, Toray Composite Materials America launches flexible, adaptive 2700 prepreg system, 2021). It is a process flexible material that can be used in conventional processes such as hand layup, autoclave, OOA, and vacuum bag only but also can be adapted to automated and high-rate applicable processes such as AFP, ATL, and compression molding (Toray, 2700 Prepreg System Data Sheet, 2022). In addition, the material system can be used for high-volume production of smaller parts such as aircraft clips, molded brackets, and wing ribs or larger parts could be fabricated using out-of-autoclave and vacuum bag only processes (Nehls, Toray Composite Materials America launches flexible, adaptive 2700 prepreg system, 2021).

- **NT-350 Modified Epoxy:** Mitsubishi's NEXX Technologies developed the NT-350 prepreg resin system as part of their Enduredge Max product line (Mitsubishi, 2022). This novel system is designed to build large structures using OOA processes but could also accommodate autoclave curing. It allows for the fabrication of thick laminates without debulking processes or elaborate cure cycles (Mitsubishi, 2022). In addition, the material system does not require cold storage and is designed for over twelve months out-time at ambient storage conditions. The ideal applications of this system are urban air mobility, unmanned aircraft, secondary aerospace structures, space, satellite, and high-performance automotive applications (Mitsubishi, 2022).

The advanced materials and processes mentioned below are summarized from the Advanced Air Mobility Composites Technology conference proceedings organized by the American Composites Manufacturers Association (AAM Composite Technology Days, 2022) . The focus areas of the conference were on infrastructure, design, certification, materials, and manufacturing and repair of AAM vehicles.

- **Faster Curing Prepregs:** As previously mentioned in the discovery interviews, several AAM companies are interested in rapid-cure thermoset material systems. The raw material supplier, Hexcel, has adopted two strategies to develop fast curing prepreg systems that are applicable for high-rate production (Yancey, 2022) (AAM Composite Technology Days, 2022). The first methodology is to reduce the cure time of existing, well-understood aerospace thermoset prepregs intended for primary structural applications. For example, they have been exploring reducing the cure cycle time of the well-established 8552 system while maintaining similar mechanical performance. The second approach is to improve the performance of automotive, industrial-grade fast curing prepregs to satisfy aerospace-grade quality and requirements (Yancey, 2022).
- **Laminated Sandwich Core Materials:** The structural foam core and balsa core materials developed by 3A composites Core Materials enable processes such as thermoforming, snap cure compression molding for thermoset and thermoplastics, and resin transfer molding for thermoset systems (Elkin, 2022) (AAM Composite Technology Days, 2022). They offer advantages over traditional honeycomb in terms of weight and cost savings, superior damage tolerance, can be used in resin infusion and resin transfer molding processes, provide improved thermal and acoustic performance and have short cure cycle processing times (Elkin, 2022). In the AAM aircraft, sandwich designs could be adopted for the primary structure, fuselage, wings, and bulkheads in addition to the conventional applications such as interior components, seating, and radomes (Elkin, 2022).
- **Hybrid Prepreg–Molding Compound:** Norplex developed a hybrid prepreg-molding compound material system called EnableX to bridge the gap between mechanical performance-mass production among continuous and discontinuous fiber materials (Houchin & Dustin, 2022) (Norplex Micarta, 2022). It is co-molding, co-curing of continuous fiber-reinforced prepreg and molding compound in a single-step compression molding process. Continuous fiber prepreg material offers strength and predictability, while the molding compound offers geometric flexibility (Norplex Micarta, 2022). They are available in phenolic, snap cure phenolic, and vinyl ester resin systems on numerous reinforcement types. In addition, the material form is designed for compression molding

that applies to mid- to high-volume applications and can accommodate short cure cycle times (Houchin & Dustin, 2022) (AAM Composite Technology Days, 2022).

- **Automated Processes:** Automation would be a key driver in the AAM industry to achieve the projected production rates. Automated procedures could be adopted at various stages along the manufacturing chain with in-situ quality inspection during hand layup, AFP robotic layup, and real-time quality inspection of fabricated components through digital assembly tools (John Tyson, 2022) (AAM Composite Technology Days, 2022).

3.1.2.1.1 Ongoing Research Programs

Various organizations have conducted several research programs to understand and develop novel technologies in terms of materials, processes, sustainability, and overall design and development of AAM aircraft. For example, Smart Rotors is a research program funded by the European Fund for Regional Development to advance the development of ultra-efficient propeller and rotor blades, especially for hybrid and electric aircraft, urban air mobility, and drones (Gardiner, Development of dry fiber preforms and other technologies for Smart Rotors, 2021). The project aims to design and develop rotors for sustainable aviation with fewer emissions and less noise pollution. Furthermore, the program also explores smarter production methods for faster and large-scale production of propeller and rotor blades to be equipped onto future aircraft and drones. With the adoption of electric propulsion and other energy sources in the future, aircraft and drones will be equipped with a greater number of rotor blades than traditional aircraft. This would require a higher volume of rotor blade production than the current production processes might be able to accommodate. The research project aims to tackle this challenge by developing a new production line concept and investigating the novel technologies required to achieve this goal. One of such new technologies being developed is automated preforming of dry fibers (Gardiner, Development of dry fiber preforms and other technologies for Smart Rotors, 2021).

The next research program, Digital Propulsion, is led by Dowty Propellers and aims to explore the design, manufacture, and test of composite propeller systems (Gardiner, DigiProp positions Dowty Propellers and its customers for sustainable, next-generation platforms, 2021). One of the program's outcomes includes implementing triaxial braiding for complex structural geometries at an industrial scale. Following a case study with smaller prototypes, the researchers identified the material system and fabrication technology that is low-cost, high-performance, automatic, and environmentally friendly manufacturing process. The novel manufacturing process combines bladder molding with triaxial braids of thermoplastic and carbon fiber reinforcements. The manufacturing process of the blade involves a mandrel for braiding that is removable from the mold but is equipped with an inflatable silicone bladder after preforming. In addition, thermoplastics reduced the cure cycle time to approximately five minutes compared to thermoset epoxy resins with a four-hour cure cycle. The research program also developed a trimming methodology of stacked material through a robotic ultrasonic cutting process (Gardiner, DigiProp positions Dowty Propellers and its customers for sustainable, next-generation platforms, 2021).

3.1.2.2 Small Unmanned Aircraft Systems

In the summary below, advanced materials and processes used by small UAS companies are presented.

- **DJI:** DJI’s Mavic Air is a small UAS with unfolded dimensions of 6.6x7.2x2.5 inches, weighs 0.95 lbs., maximum range of 6.2 miles and a maximum takeoff altitude of 16404 ft

(DJI, 2022). The primary structure of the DJI's drone Mavic Air is fabricated from magnesium alloy using an injection molding process. The alloy is AZ91D, consisting of 90% magnesium, 9% aluminum, and 1% zinc, and the injection molding process allows for high-volume production applications (How it's Made - DJI Mavic Air, 2018). This material system is also used to fabricate brackets for the drone. The enclosures for the electronic components of the drone and the propellers are fabricated using the injection molding process. The foldable arms of the drone are injection molded using nylon reinforced with 30% glass fiber (Polyamide66 + 30GlassFiber), added to increase the tensile strength. The propellers of another drone from DJI, Phantom 4, are made using glass fiber reinforced composite with a nylon base (How it's Made - DJI Mavic Air, 2018).

- **Quantum Systems:** Quantum Systems's Trinity F90+ is a fixed-wing small UAS mapping drone with a wingspan of 7.85 ft, maximum take-off weight of 11 lbs, maximum range of 62 miles and maximum flight altitude of 14763.8 ft (Trinity F90Plus, 2022). The airframe is built using Elapor foam and is molded around a rigid carbon fiber structure. The mounts on the drone are additively manufactured using a laser sintering process (Shapeways, 2022) (Quantum Systems, 2022).
- **Parrot:** Parrot's Bebop 2 drone is a small UAS of 12.9x12.9x3.5 inches, with a weight of 1.1 lbs and a range of 1.2 miles (B&H, 2022). The central body and the arms of the Bebop 2 drone from Parrot are additively manufactured using WindForm® GT material. WindForm® GT is a polyamide-based glass fiber reinforced composite material system. The fabrication method used is Selective Laser Sintering, a powder bed fusion technology (Windform, 2022).
- **Applied Aeronautics:** Albatross is a small UAS of dimensions 23x7.8x5.9 inches with a maximum takeoff weight of 22 lbs and a maximum range of 155 miles intended for remote sensing, asset management, and surveillance applications (Albatross, 2022). The airframe is built entirely from honeycomb, carbon, and glass fiber composites. The wing spars, interior shelving, and rear landing gears are fabricated using carbon fiber (Applied Aeronautics, 2022).
- **Horyzn:** Horyzn's Silencio is a small UAS of dimensions 76x141x26 inches with a maximum takeoff weight of 26 lbs, range of 31 miles, at a maximum altitude of 15091 ft. intended for medical delivery applications (Silencio, 2022). Horyzn's Silencio primarily consists of carbon and glass fiber reinforced polymers. The two hover boom mounts are additively manufactured (Horyzn, 2022).
- **Cobra and HG Robotics:** Cobra International and HG Robotics developed Vetal, a small UAS intended for large scale agricultural surveys as well as general surveillance monitoring. The central body of the drone consists of a polyvinyl chloride foam sandwich shell with a low-density expanded polystyrene foam rib. The core of the tail structure is fully built from foam. The propulsion system is fabricated through moldings incorporated with glass fiber reinforcements, mounting points, and other ancillary equipment (Cobra, 2022).
- **MI-DRONE Project:** Eire Composites, Manna, and the National University of Ireland Galway are designing and developing a small UAS for commercial cargo delivery applications. The drone is built from an aerospace-grade carbon-fiber-reinforced material system. For high-volume drone production, advanced automated manufacturing processes

such as pre-programmed kitting of plies, automated tape placement, and induction welding would be used (Gardiner, ÉireComposites, Manna and NUIG to develop carbon fiber composite drone airframe, 2021).

- **Skydio:** Skydio's X2 is a small UAS with dimensions of 26.1x22.4x8.3 inches, weighs 2.9 lbs, has a range of 2.2 miles and a maximum altitude of 15,000 ft (MFE, 2022) (Skydio X2, 2022). The entire airframe of the X2 drone from Skydio is built from composite materials using Arris Composites Additive Molding™ technology (Skydio, 2020). This includes fabricating the airframe as a single structure through a region-specific material property optimization process. The X2's airframe includes a newly developed core structural element (Skydio, 2020). The forward region of the drone is made using carbon fiber composite and transitions to the top region built from glass fiber. The frame is reinforced with glass fiber in the areas that require high strength performance while having thinner sections for regions with less structural demands (Skydio, 2020).

Novel material systems such as magnesium-based alloys are increasingly being used to construct UAS (Hoche, et al., 2021). These are cost-effective, lightweight materials that are easy to machine, cast, and shape into desired profiles. The following list presents some of the commonly used material systems to build UAS and the potential use of magnesium-based alloys in these applications (Hoche, et al., 2021):

- The fuselage of an UAS is commonly built using carbon, glass fiber composites, GLARE (Glass Reinforced Laminate), or standard AA2024. These materials could be replaced with magnesium alloys such as AZ31 or aluminum-free ZE10 to build the outer skin of the fuselage (Hoche, et al., 2021). The latter material system provides improved forming properties. AM60 could be used to fabricate frames and cross members through high-pressure die-casting (Hoche, et al., 2021).
- Currently, the wings, spars, ribs, and stiffeners are commonly built using carbon fiber composite materials (Hoche, et al., 2021). These applications require materials that are lightweight but also offer necessary stiffness and limit vibrations. In this case, extruded profiles of wrought magnesium alloys could be used to build the load-bearing structures, and AZ91 or AM60 alloys could be used to build cast components necessary for the wing and spar construction (Hoche, et al., 2021).
- UAS's horizontal and vertical tails are often made of carbon or glass fiber composites with foam cores (Hoche, et al., 2021).
- The rotor blades are often built from composite materials. For example, the outer ring housing the rotor blade could be built from magnesium or magnesium-based alloys to withstand collisions better and reduce noise (Hoche, et al., 2021).

3.1.3 Summary and Major Findings

This section presents the summary and the key findings on advanced material systems currently in use and planned for future use in the AAM and small UAS. With few exceptions, advanced material systems are at the core of both the AAM and small UAS. However, the approach taken in selecting advanced materials and processes by these two aircraft could be considered different. For example, the AAM market predominantly has chosen legacy aerospace-grade materials and processes with limited and cautious use of materials and processes such as thermoplastics and AM.

On the other hand, the small UAS industry has chosen industry-grade materials and processes that would enable high-production rates with frequent use of AM-related processes.

3.1.3.1 Advanced Air Mobility Industry

The literature review and the industry survey results presented that the AAM industry primarily opts for traditional continuous fiber thermoset material systems. This includes selecting well-established legacy material systems developed for traditional aircraft primary and secondary structures. Industry survey revealed that two OEMs are interested in adopting snap cure thermoset resin systems; one OEM has chosen thermoplastics for primary and secondary structures. The fabrication processes chosen by AAM OEMs include hand layup, autoclave cure, AFP, ATL, RTM, VARTM, and injection molding. The OEMs with traditional materials and processes realize the need to transition to new materials and processes if they enter the high-rate production.

The OEMs with novel materials and processes such as snap cure thermosets, thermoplastics, and additively manufactured parts for primary and secondary structural applications are expected to better support the projected high-production rates. Most of these companies opting for new materials and processes have either research collaborations with tier one suppliers or material suppliers or are associated with existing aerospace and automotive companies. Hence, they have the capabilities and confidence in the performance of these novel materials as primary and secondary structures.

Despite the choice of traditional or novel advanced materials and processes, it was evident from the industry survey and the literature review that the criteria for certification plays a significant role in the material selection process. OEMs are willing to adopt novel advanced materials and processes such as rapid cure thermosets, thermoplastics, and AM when they are available in public material databases and the technology maturity is achieved.

3.1.3.2 Unmanned Aircraft Systems Industry

The requirements of the small UAS industry vary from the AAM industry. Due to the nature of the aircraft, the small UAS industry is not limited to aerospace-grade materials and delves into industry-grade materials and processes. Most small UAS systems are primarily made from composite material systems through fabrication processes such as injection molding, over-molding, direct infusion processes, and AM processes such as fused deposition modeling or selective laser sintering. These processes enable the high-volume, low-cost production under short cycles necessary for the small UAS industry.

The interviews with the two non-small UAS OEMs presented that they are considering rapid cure thermosets and thermoplastic material systems. The fabrication processes of interest are VARTM, SQRTM, and AM.

3.2 Applications of Existing Advanced Material Systems

3.2.1 Industry Survey

This research question focused on identifying any new or unique applications of existing composite materials. The objective is to compare and analyze the usage of advanced material systems between traditional aircraft applications to AAM and UAS. To further expand on this, the research focuses on whether the materials considered non-structural or secondary structures in traditional aircraft serve a different purpose in UAS and AAM, such as being used as primary structures.

3.2.1.1 Material Suppliers

Novel Thermoset Material Systems

The few advanced materials coming from material suppliers are toughened epoxies or prepreg systems. EP2190 from Solvay and Toray 2700 is the new toughened epoxy and epoxy prepreg system coming down the line, respectively. Toray 2700 is a replacement material for the Toray 2510 with much higher Elevated Temperature Wet (ETW) properties and shorter cure times than the 2510 material. At the ETW condition, the strength and stiffness of a polymer matrix, compression strength, and shear modulus are all reduced; therefore, a material matrix with higher ETW has greater strength, stiffness, compression strength, and shear modulus. When choosing the material system for their aircraft, most companies are also going with traditional higher modulus fibers that are already proven (IM7 or higher). The materials considered by most companies for rotors are continuous carbon fibers, while chopped fibers traditionally used in aerospace will be resigned to interior use with new formats that are not used on traditional aircraft. Chopped fiber materials also have mechanical properties that benefit the UAS drone space. Due to companies currently being in the prototyping phase, performance and certification are the main aspects for choosing an aerospace material system, but there is still room to grow in cost and rate. Most companies have mentioned continuous compression molding, a sort of press consolidation, or IR heating with lower curing temperatures while maintaining the performance of the materials to meet the rate.

Thermoplastics in AAM

PEEK is the main thermoplastic being considered, but it is too expensive to be implemented in the market. There is currently no use of thermoplastics or additively manufactured parts for primary structures. Press technologies are being investigated for thermoplastics, with the main issue being press limitation around the press size. Metal tooling will have to be used due to the extreme temperatures needed for thermoplastics. Thermoplastics require no cold storage, no shelf-life issues, the ability to meet high production rates, and are readily recyclable. They also possess the required performance for primary structures, but the major challenges are scalability and processing thermoplastics for large structures. The benefits of over-molding and welding thermoplastics could bring a unique value to this technology, with structural and secondary bonding also playing a key role.

Recyclability, Ceramic Matrix Composites (CMCs), and Hybrid Materials

Materials recycling still has a long way to go for both the UAS and AAM markets. Thermoplastics with recyclable materials that are easy to reclaim will be crucial moving forward. Material Suppliers are unsure how resin-infused products answer the recyclability question. Most companies are keen to have more recyclable materials on the aircraft and implement a complete life cycle analysis of the materials they are currently using. Materials suppliers have told us that they have not heard of implementing ceramic matrix composites or hybrid structures.

Automation

The next step in the UAS and AAM market is to make the current manufacturing processes completely autonomous due to the expectation of volume increases. Companies that traditionally provide thermoset prepregs have a snap cure system available that is in use for automotive applications and may be a basis for the UAS and AAM market to meet the massive volume expectations.

3.2.1.2 Original Equipment Manufacturers (OEMs) – Advanced Air Mobility (AAM) and Unmanned Aircraft Systems (UAS)

Novel Material Systems

UAS and AAM OEMs are looking to go with more proven processes and materials, with the main process discussed being oven curing with a vacuum bag. The process of snap cure and stamping piece parts and assembling them, then controlling over thickness variations are both being looked at by OEMs to reduce the cycle time and increase the rate. With the rate of production being a huge issue in this industry, OEMs are keen to implement more automation within their existing processes. Regarding the materials, they are looking to use whatever can bring the cost down, whether it be quick cure thermosets or lower weight prepregs. However, some OEMs think that the cost is too high to go with thermoset prepregs. Lower performance materials may be suitable for small UAS with snap cure, infusion, and OOA prepregs with additive tools for thermosets could all be material systems that could be implemented. For the AAM market, there is a higher likelihood of using high modulus type fiber aerospace materials, with weight being the critical factor. Continuous fiber thermoplastics will work for this market due to increased toughness. Crystalline polymers have greater fluid and creep resistance, and amorphous polymers would be acceptable for certain applications.

Additive Manufacturing (AM) for AAM and UAS

AM is being considered to make clips, brackets, and smaller UAS aircraft. Thermoplastics and continuous fiber ribs will be over-molded with concerns circulating single-sided tool structures. AAM OEMs are considering using various carbon fiber reinforced thermoplastics to increase the rate.

Joining Methods, CMCs, and Hybrid Materials for AAM

Contrary to the Material Suppliers, OEMs are investigating the use of Ceramic matrix composites. Ceramic matrix composites will be looked at based on firewalls related to batteries, but the flammability requirements are still unsure. Multi-materials (hybrid) are being considered for a few applications by OEMs. The material is wrapped with a structural skin to increase load bearing and safety. Multi-materials are being implemented with a combination of secondary structures and primary structures. They are also looking at creating lightning strike protection out of composites instead of metal meshes, and they want to use ablative composites for fire barriers. Investigating the implementation of new materials to create lighter battery casings to improve weight with multi-materials potentially being a solution to this. Secondary bonding is the only joint assembly method mentioned by the OEMs for thermosets. Adhesive for secondary bonding is still being evaluated, with woven material being considered.

Repair and Inspection Criteria for UAS and AAM

Small UAS is less limited by materials due to a lower certification burden and less stringent repair and inspection criteria. It can be significantly cheaper due to simpler designs, and repairability is not as important for the aircraft. The criteria for AAM have not yet been defined, but it would likely be like the practices followed in the commercial aircraft industry. Aircraft will be using very high voltages (800-1200 V) due to low current requirements for EV, which will bring safety requirements for the material systems. Aircraft need just 1 megawatt just to fly for a few minutes. This could result in an increase of accidents, more insulation, and possible overheating of the aircraft.

3.2.1.3 Tier 1 Suppliers

Novel Material Systems for AAM

Tier 1 suppliers are heading towards focusing mainly on structural composites centered mainly around carbon fiber components. Most of their efforts are in trying to enhance the structural strength of the components. This has led most Tier 1 suppliers to go with higher modulus fibers with highly toughened resins since they prioritize weight over rate. Because the rate is still a critical factor, the future of this industry will have to include snap curing or faster curing resin systems to sustain these rate demands. Intermediate modulus carbon fiber might have to be implemented in some areas to bring the overall cost down because the price is still too high to manufacture parts. The major skin of the aircraft will be fabricated out of continuous fiber thermosets; however, there are some advantages to using discontinuous carbon fiber thermosets. The material is more deformable, and the fibers move around easier. The market may prefer to use some combined processes by mixing continuous materials with short fiber over-molding.

Additive Manufacturing (AM)

Tier 1 Suppliers have reiterated that the problem with additive manufacturing is the scalability of the parts. AM is easy to implement for smaller components that do not have high strength requirements. AM does not have the strength for structural parts but can be used for electronic components. Electronic components that can go on layer-by-layer could be produced from AM.

Thermoplastics

Theoretically, rapid cure or thermoplastics should work for the rate issue in this market. However, compared to traditional aircraft, the UAS and AAM market will demand different geometries, with the best example being propellers. Making propellers with a variable thickness and out of continuous thermoplastic will be a major challenge. Shaping the thermoplastic is also an issue because they experience a large displacement of one part of a crystal (slip) relative to one another.

Joining Methods, CMCs, and Hybrid Materials

Bonding is very important to both the UAS and AAM markets. The ability to eliminate fasteners is critical to this market. Secondary bonding for thermosets seems efficient for now, even though work is to be done. Ultrasonic welding, resistance welding, induction welding, and conduction welding are the different types of thermoplastic welding. These are robust processes with minimal effects of surface contamination. While welding for thermoplastics is a reliable process for thin structures, it does not work as well for thicker structures. According to the Tier 1 suppliers, there is no work thus far with CMCs or hybrid structures.

3.2.1.4 SMEs – Industry and Academia

Novel Material Systems

The researchers have been told by SMEs from industry and academia about where the industry might be headed. The SMEs said that there is nothing too unique or different yet. Discontinuous and chopped carbon fibers might get some looks down the road, but most companies are going with continuous carbon fibers. There is a big push to get hand-touch manual labor out of these processes and make them more autonomous. The researchers were told that some propulsion devices have been unique that are made from Solvay's MTM-45. Stratasys's Antero® 840CN03, a high-performance PEKK thermoplastic material, is also being researched. Powdered thermoset materials with the same grade as PEEK is being implemented, but they only have epoxy thermoset powders. There is preliminary work to embed a thermocouple between the plies of composites while also trying to implement more sensors for health monitoring for the parts. There need to be built-in in-process checks to allow manufacturing quality along the way, and these embedded sensors would help solve that problem. Regarding bonding and joining methods, the researchers have been told that improvements to secondary bonding are a priority.

Additive Manufacturing (AM)

Due to the rate demands, SMEs do not think that additive manufacturing will work in the UAS and AAM markets. Milling can outperform the current state of AM, but AM could be combined with over-molding to help optimize the part. AM would work very well for brackets and clips but not for primary structures, with the L-PBF (laser powder bed fusion) Alloy 625-powder being the best material to make the brackets and clips. This powder bed system was studied by the SAE-AMS AM committee on Additive Manufacturing. The companies that are doing metal AM for traditional aircraft are all doing point design certification. Metal printing could be done, but 90% of the time and cost are used on certification. Topology optimization is needed to create a high-performing, lightweight structure, but this is used more for the UAS market. Thermoplastics are used currently but not widely, with one problem being the need for more public traceability from public material databases. If thermoplastics are implemented, they need to include sensors for structural health monitoring as well as thermosets. These will help lower the time of repair and inspection by monitoring the health of the parts over their lifecycle.

Hybrid Materials

Some hybrid metal and composite materials are currently in use in the AAM market, with the potential for implementation of critical titanium components. Some companies are looking to use aluminum for primary structures and stay with composites for secondary and tertiary structures. There is developmental work in taking a low melting point metal and making a metal matrix part.

Ceramic Matrix Composites

According to SMEs in the industry, ceramic matrix composites are not widely used in the AAM or UAS market. This is because high-temperature materials are not a key driver except for battery enclosures for AAM aircraft and in engines for traditional aircraft. However, there is reportedly multiple CMC materials going through NCAMP qualification to identify minimum database requirements and standardize methods for material and process control.

3.2.2 Literature Review of Bonding Applications

This section presents the literature review findings on bonding methodologies developed for AAM and UAS platforms. In traditional aircraft applications, it is common practice to integrate fasteners into adhesively bonded composite structures for structural redundancy (J. Kupuski & Freitas, 2021). However, this process can increase the assembly time, can be cost extensive, and result in increased weight of the structure (Sara Black, 2016). Some of the bonding methodologies presented below are formulated to reduce or eliminate the need for fasteners in bonded structures for time, cost, and weight savings while maintaining the performance requirements.

- **FusePly™:** FusePly™ is designed for rapid UAM manufacturing. This is a combination of co-cure and secondary bonding methodologies. FusePly™ is an epoxy-based film designed to co-cure with composite prepreg followed by secondary bonding with the help of an adhesive (MacAdams & Grobe, 2021). The co-cure process results in a chemically active surface at the interface of the FusePly™, formulated with epoxy functional groups to create a chemical bond with the adhesive. This results in a reliable bonded structure that has been bonded chemically. The FusePly™ bonding technology is compatible with most amine-cured epoxy prepregs (Solvay, FusePly, 2022).
- **AeroPaste®:** AeroPaste® is a new family of structural paste adhesives developed to satisfy some of the key requirements of the advanced air mobility industry (MacAdams & Grobe, 2021). They are suitable for high-volume production rates, rapid assembly applications, and automated processes related to metal and composite structures (Solvay, AeroPaste, 2022). These adhesives are formulated to offer a similar mechanical performance as film adhesives. In addition, the curing process is flexible with a wide range of processing temperatures varying from room temperature 75º F to 350º F (MacAdams & Grobe, 2021) (Solvay, AeroPaste, 2022).
- **Multi-Material Joining Technology:** This joining technology was developed by KTM E-Technologies and Airbus' Composite Technology Center as part of smart and efficient lightweight solutions for urban air mobility systems (Gardiner, CTC GmbH and KTM E-Technologies develop innovative joining technologies for urban air mobility, 2021). This is a robotic ultrasonic welding process developed to join composite laminates. A thermoplastic layer called the Conexus layer is applied to the desired joining areas for the welding of thermoset material systems. The thermoplastic layer acts as a catalyst and activates the joining surfaces when press cured under heat and pressure. The composite laminates can then be joined together or injection molded brackets, stiffening elements can be integrated through welding or can be over-molded directly onto the part. This process can create both spot and continuous welds with short process times and eliminates the use of rivets (Gardiner, CTC GmbH and KTM E-Technologies develop innovative joining technologies for urban air mobility, 2021).
- **Thermoplastic Welding:** One of the major advantages of thermoplastic material systems is the ability to join components through welding. This results in reduced assembly time with no part drill, machining, trimming, and other processes necessary for conventional mechanical fastening procedures (Toren, 2022). There are different types of thermoplastic welding processes, such as induction welding, ultrasonic welding, resistance welding, conduction welding, and laser welding (Gardiner, Welding thermoplastic composites, 2018). While some of these processes are still being advanced and developed for use in aircraft primary structures, some AAM companies are currently opting for induction and resistance welding procedures. In addition, these processes could be adapted to automated, robotic procedures and thus enable rapid assembly and production rates (Colucci, 2021).

3.2.3 Summary and Major Findings

This section presents the summary of facts and major findings on existing composite materials' new or unique applications. It also summarizes the use of thermoplastics and their applications, CMC, repair and inspection criteria, joint assembly methods, and hybrid structures in the UAS and AAM applications. Across both markets, new and unique applications rarely present themselves, with a few exceptions. These two markets are vastly different in terms of thermoplastic application, CMCs, repair and inspection criteria, joint assembly, and hybrid structures. AAM has started some preliminary work in the thermoplastic space but has not made any concrete steps toward full thermoplastic implementation. Due to their non-stringent certification process and low safety requirements, small UAS can implement any material they want, with cost being the driving factor.

3.2.3.1.1 Advanced Air Mobility Industry

There have been a few advanced materials that are being looked at for AAM. Due to weight requirements, intermediate to high modulus type aerospace materials will be used for AAM. A few toughened prepreg systems have been brought up (Solvay EP2400 and Toray 2700) to help with some of this market's rate and strength requirements. In addition, there has been some preliminary research on a unique propulsion device made from Solvay MTM-45. The main thermoplastic mentioned is PEEK, but it is too expensive to implement now in this market. Another thermoplastic, Stratasys's Antero® 840CN03, a high-performance PEKK-based electrostatic discharge thermoplastic for space applications, is also being researched to bring into this market for AM.

Right now, AM will not work because it cannot meet the rate requirements of the market for primary structures, lack of structural capacity, certification costs, and many other reasons. AM could work with the L-PBF (laser powder bed fusion) Alloy 625-powder bed system for brackets and clips as the best material to use. Recyclability of materials in this market is important but is not a driving factor for material selection. Regarding ceramic matrix composites, not many companies are using them, but they are being looked at for firewalls related to batteries. The main components in this market are weight, rate, and cost. To lower the aircraft's weight, companies are looking to integrate some primary components to eliminate fasteners. Secondary bonding is the most important method in thermosets' AAM market. Ultrasonic, resistance, induction, and conduction welding are all considered thermoplastics. Hybrid and multi-materials are being implemented for this market to increase load bearing and safety. This would likely be a metal with a composite wrapped structural skin around it. The maintenance, repair, and inspection for AAM would likely follow the practices used in commercial aircraft.

3.2.3.1.2 Unmanned Aircraft Systems Industry

There were far less novel thermoset materials in the UAS industry than in the AAM industry. Small UAS is less limited to material selection due to the lower certification burden. Lower modulus, weaker performance materials would be more suitable for the small UAS market with snap cure, infusion, and OOA prepregs with additive tools possibly being the material systems used. Chopped fiber materials also have mechanical properties that would benefit the UAS drone space. Metal printing could be implemented for the small UAS market, but most of the time and costs will be spent on the certification side. There needs to be a major emphasis on topology optimization for the small UAS market to create lightweight, high-performing structures. Paper products could also be easily implemented into the small UAS and drone space. No stringent maintenance, repair, and inspection criteria are set in place for small UAS due to no passengers being on board. The market also wants a more integrated structure just for ease of manufacturing to remove fasteners. Ceramic matrix composites and hybrid structures have not been mentioned in the UAS market.

3.3 Public Material Databases - Critical Material Characteristics for AAM and UAS

Throughout most of the industry surveys, multiple materials, processes, properties, and testing and joining methods were mentioned that industry would like to see added to the public material databases. In addition, a few companies are looking toward materials and processes for the UAS and AAM market that are in public material databases. Public material databases can be helpful during the prototyping phase but are not critical for the AAM market. For example, companies have stated that half of the materials used to build an airplane are not currently in the public materials databases. These materials, processes, properties, testing, and joining methods provided to us by the market are listed below in Table 2. The most common public material database reference is NCAMP.

Table 2. Public Material Database Requests.

Materials	Carbon Epoxy Prepregs
	Discontinuous Fiber Products
	Thermoplastic Prepreg Materials
	Continuous Fiber Thermoplastics
	Additive Materials
	Sandwich Panels
	Low Melt PEKK or PEAK
	Honeycomb
	Compression Molding Materials
	Intermediate and High Modulus Fiber Thermoplastics
	Higher Temperature Materials
	Stamp Formable Thermosets
	Low-Performance Material PPS
	Fiber Glass Reinforced Fabrics
	New Toughened Infusion Resins
	Powder Bed Systems
	Intermediate Modulus with Lower Manufacturing Temps.
	2x2 twill +/-45 braided materials
	2x2 twill 0, +/-60 triaxial braided materials
	Paste adhesives like Aeropaste
	AFP Materials

Processes	Resin Infusion
	OOA Processes
	Snap Cure
	Fiber Placement
	Same Applications with Different Materials
	Injection Molding
	Automatic Tape Laying (ATL)
	Automatic Fiber Placement (AFP)
	Stamp Forming
	Compression Molding
	Fatigue Properties
Properties	Elevated Temperatures
	Wet
	Nonlinear Material Properties
	Thickness Variation
	Interlaminar Fracture Properties
	Delamination Growth
	Configuration Geometry
	Toughness on Corners
	CTE
	Liquid Flow Field Properties
	Electrostatic Discharge
	Chemical Compatibility
	Gas and Liquid Gas Permeability
	Durability of Welded Structures
	Fire, Smoke, and Toxicity
	Dielectric Constant
	Creep
	Heat Deflection Temperature
	Insulation and Firewalls
	Electromagnetic Properties

	Dynamic Properties
	Compression After Impact
Testing	Repeated Loading
	Out of Plane Loading
	Interlaminar Tensile Test
	ASTM D6415
	Inspection for AAM Aircraft
	S-N Curves to Calculate the Damage in a Fatigue Analysis
	Bonding for Thermoplastics
Joining	Consolidation for Thermoplastics
	Welding for Thermoplastics
	Bolting Joint for Aircraft
	Design to Weld

4 MARKET SATISFACTION

4.1 Industry Survey – Identifying Key Problem Statements

Once current and future industry practices were well understood from initial surveys and literature reviews, the research team used New Product Blueprinting to identify areas that would have the highest potential to accelerate safe adoption of advanced materials and processes for AAM and UAS. The blueprinting process works by compiling a top ten list of Problem Statements determined from the Discovery Interview results. A second round of interviews, called the Preference Interviews, then probes the identified Problem Statements.

The first output from the Preference Interview stage is the Importance vs. Satisfaction plot; this plot highlights what Problem Statements should be first addressed by focusing on the most important and least satisfied Problem Statements found in the top left quadrant of the plot. This is not to suggest that all the identified Problem Statements are not investigated, but the topics in the top left quadrant should be investigated first. From this data, Market Satisfaction Gaps can be calculated using Equation 1, where Market Satisfaction Gap (MSG) > 30% is defined as significant by The AIM Institute. The maximum Market Satisfaction Gap is 90% and the minimum is 0% and the higher MSG the greater the dissatisfaction.

$$Market\ Satisfaction\ Gap\ = Importance\ (10 - Satisfaction) \qquad \text{Equation 1}$$

Table 3. Rating Matrix.

Rating	Importance	Satisfaction
1	Not important at all	Totally unsatisfied
3	Not too important	Unsatisfied
5	Moderately important	Barely Acceptable
7	Very important	Good
10	Critical	Totally satisfied

4.2 Targets and Summary

During the Preference Interview stage, both Important vs. Satisfaction plots are produced, and Ideal States are identified. An Ideal State is defined as what would make the interviewee fully satisfied for a specific Problem Statement. The 10 Problem Statements are found below with a short description for an Ideal State.

4.2.1 NCAMP Qualification

NCAMP qualification is defined as having a publicly available materials database, like NCAMP, AGATE, or CMH17. Several targets were mentioned to fully satisfy the interviewees. First, companies are looking for a robust and immediate path that new materials can take to qualification. Traditionally, the general timeline for qualification is around 12-18 months, and the market wants to reduce this to an ambitious 6 months with hot/wet conditioning taking the longest time. The ability to use more simulation for multiple processes like resin curing or fiber placement during qualification may also be a pathway for reducing the timeline. Finally, when it comes to thermoplastics, these companies want to see more thermoplastic entries in the databases, approaching the number of thermoset entries. Another way to speed the NCAMP qualification process is to currently begin populating the NCAMP database.

4.2.2 Good Link with the FAA

A good link with the FAA is centered around bringing down the time of certification for an aircraft. These companies have yet to have certified aircraft and it is unlikely they are fully aware of the challenges associated with certification. Having a more integrated approach with the FAA will aid these companies through this process. Additionally, guidelines for novel materials would be helpful.

The cost associated with certification is also a major burden to these companies. A reduction of time to two years for certification would be the goal.

4.2.3 Rate of Manufacturing

The Rate of Manufacturing is considered one of the most important driving factors when choosing materials and processes as these companies believe they need to produce thousands of aircraft annually. The Rate of Manufacturing is expected to require significant automation. Automation and new materials need to be evaluated and adopted quickly. The main component of the Rate of Manufacturing is maintaining the material property requirements. There needs to be a way to ramp up the rate and not increase the cost of production while not sacrificing material allowable.

Essentially, the market identifies that current thermoset prepreg carbon fiber composites can meet the design requirements but are unsure if thermoplastics will be able to.

4.2.4 Recyclability

The results for recyclability were mixed depending on the company. Some companies referred to recyclability as being able to easily repair damages to the aircraft, while others understood it to be the reuse of the raw materials in the aircraft structures. The first step in improving recyclability is standardizing and qualifying recyclable materials, then targeting them towards specific applications. The issue with this is finding the applications from the business case. It is currently known how to recycle these materials, but costs can be very high. Having an aircraft with 100% recyclable materials is the goal, although there needs to be more data on the performance of structures produced from recycled parts once the industry identifies how to recycle, what materials are used, and what applications they will be used.

4.2.5 Guidelines for Design & Build

The interviews showed the lack of understanding regarding the desired next-generation materials, i.e., thermoplastics. A way to improve these guidelines would be if some sort of technology rollout process were established to quickly evaluate new technology, assess its application, and provide guidelines for its use. Guidelines could be provided by CMH-17. There also needs to be reliability of the digital models for the new material systems.

4.2.6 Cost of Production

Most companies generally agree that the cost of production needs to be lower. Most of the expected cost controls stem from implementing some sort of automation. The market needs a systematic evaluation of costs and a diligent effort to minimize those costs, focusing on final structure costs to see production costs drop. The material is too expensive, there is too much hand labor, and the equipment is too costly.

4.2.7 Weight

Interviewees desired a lower weight while still achieving the desired high-rate production. There is a performance triangle: weight, cost, and rate. Two of these can be achieved, but not currently all three. For example, the lower weight can be achieved by autoclave cured thermoset composites, but they cannot be produced at the rate; the rate can be met but the weight is too high. A 25% reduction of weight in the aircraft is what is expected to make these companies satisfied. There are several factors that go into this: the designs, material, the performance of the material, and bonding or mechanically fasteners. The weight saved by thermoplastic materials is believed to reduce fasteners through welding.

4.2.8 Repair & Inspection

For the UAS market, these companies are not expecting stringent repair and inspection criteria.

Repair and inspection criteria have not yet been defined for the AAM market. To aid the adoption of new materials and processes, i.e. compression-molded prepregs or thermoplastics, repair processes need to be defined at the entrance of the material into the market. Twenty five percent improvement on inspection throughput would help.

4.2.9 Integration

When integrating structural components, material choice and cost are the key. Reducing mechanical fasteners safely would help cut waste and cost and increase integration with a minimum goal of 30-50% reduction. The promises of newer technology, such as resin infusion and thermoplastics, to reduce fasteners need to be realized to meet the desired manufacturing rate. The UAS/AAM market can use the automotive industry as an example for increasing manufacturing rates and integration.

Integration increases the rate of manufacturing but has a negative effect on the ease and cost of repair. Therefore, there will be a limit to integration as heavily used, or areas of high traffic needs to be easily interchanged with new structures.

4.2.10 Justification of Thermoplastics

There are only a few companies that the researchers spoke to that deal with thermoplastics. Thermoplastics are an easy choice if the rate is the only deciding factor, but their limitations come from having high raw material costs and high processing temperatures which lead to greater costs. Thermoplastics also have not been certified to use in primary structures. For companies to consider using thermoplastics in future UAS and AAM aircraft, the raw material costs and processing temperatures need to lower while still maintaining high structural performance. This might lead companies to choose lower-performance thermoplastics to meet their cost targets initially (Figure 1). AAM, typically, falls into the "Legacy OEMs" category with higher melt temp, costs, and performance, but they are looking to move into the lower category with lower melt temp and cost while maintaining the higher performance. UAS, however, will typically stay in the category labeled as "UAS/AAM" due to them not needing the high structural performance.

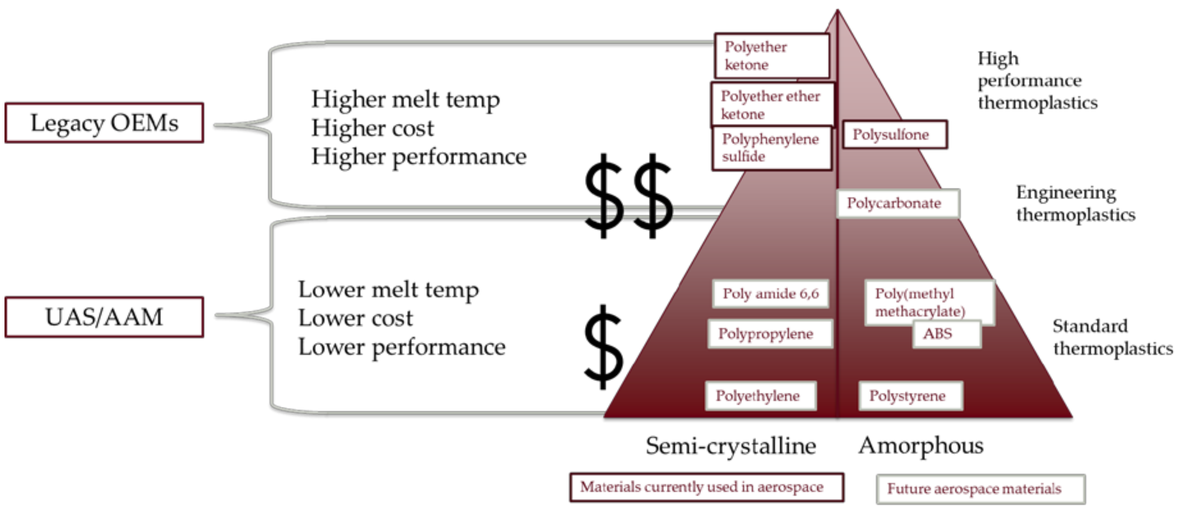

Figure 3: Thermoplastic Information.

4.2.11 Entire Market

The Importance vs. Satisfaction plot and MSG for the entire market data collected are found in. No single Problem Statement has a satisfaction score above 7, a rating of "good," suggesting the correct Problem Statements have been captured; additionally, almost all the Problem Statements were rated the importance of 7, a rating of "highly important," or higher.

The Problem Statements in the top left quadrant shown in Figure 4 are Problem Statements that are of high importance but have not yet been satisfied: NCAMP Qualification, Weight, Good Link with the FAA, Rate of Manufacturability, Guidelines for Design and Build, Cost of Production, Repair, and Inspection, and Integration are all Problem Statements that fall into the top left quadrant. This indicates accurate identification of the Problem Statements found in the Discovery Interviews.

A good link with the FAA is the least satisfied Problem Statement, also reflected in its MSG above 30% shown in Figure 5. Typically, interviewees suggested the NCAMP database is not satisfactory due to there being little to no materials or processes in the public material databases around the UAS and AAM market. This is largely because the UAS and AAM markets are relatively new, and most of these companies have not decided on which materials or processes they will use as the rate of this industry increases. This is explained further in the "Targets and Summary" section. Therefore, the need to add materials and processes in the NCAMP database was deemed critically important.

The top left quadrant of the plot highlights Problem Statements that are of high importance but are not yet satisfied in the market. The top right quadrant is the second most important problem statements, but companies are typically satisfied. The bottom left quadrant of the plot highlights problem statements that are of little importance and satisfaction. The bottom right quadrant of the plot highlights problem statements that are of little importance but are generally satisfied in the market.

Figure 4. Entire Market Importance vs. Satisfaction Plot.

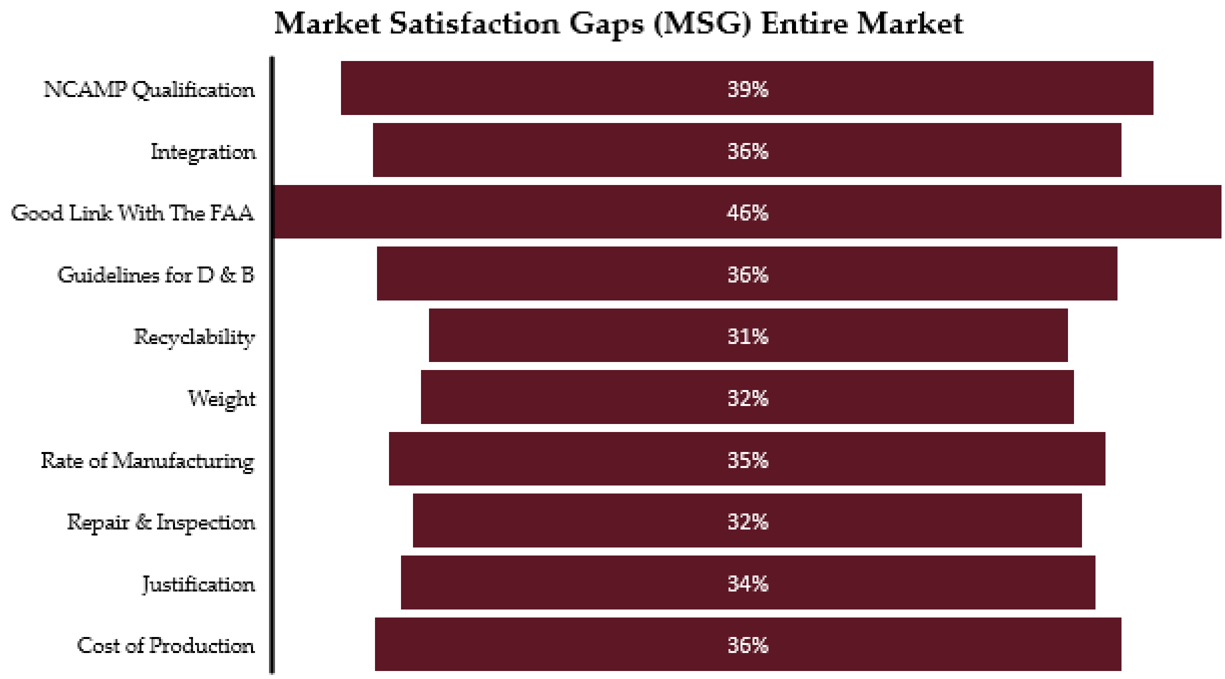

Figure 5: Entire Market MSG

4.2.12 AAM OEMs

According to the AAM OEMs interviewed, 7 of the 10 Problem Statements fall into the top left quadrant of the graph shown in Figure 6. There was not a single problem statement that had an MSG of less than 30%; this may be because the AAM OEMs interviewed were dissatisfied with the state of the market currently. The AAM OEMs were more concerned with the Rate of Manufacturing. The researchers were told that even though the desired manufacturing rate could be met with thermoplastics, it could not be done with the required weight, cost, or strength. Everything is a tradeoff whenever it comes to the AAM market. There were a few other Problem Statements, i.e., a good link with the FAA and the time it takes to certify an aircraft that the OEMs were concerned with as the time required to certify the aircraft took too long. A further explanation of these problem statements is listed in the "Targets and Summary" section.

The cost of production had the highest MSG at 52% shown in Figure 7 due to it having the highest importance and relatively low satisfaction. This highlights the need for the UAS/AAM market to meet the required rates expected, and current composite solutions will not be able to satisfy. This is the largest driver to move away from autoclave prepregs and switch to higher rate production, even as the thermoplastic raw material may be more costly.

Figure 6. AAM OEM Importance vs. Satisfaction Plot.

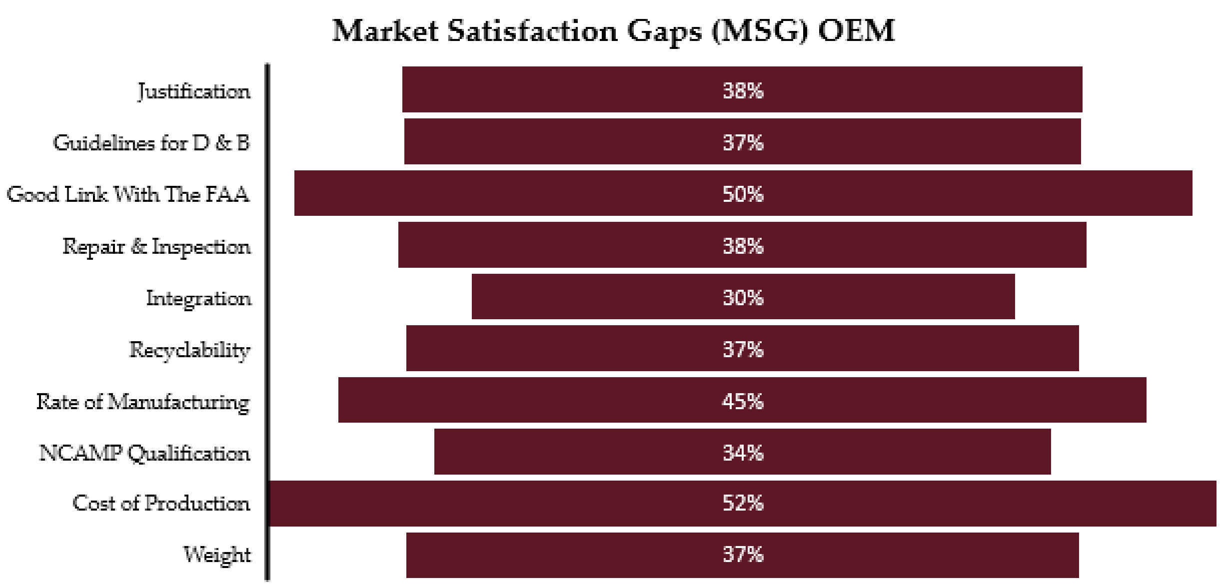

Figure 7: AAM OEM MSG

4.2.13 UAS OEMs

According to the UAS OEMs interviewed, 7 of the 10 Problem Statements are listed as critically important as shown in Figure 8: Cost of Production, Rate of Manufacturing, NCAMP Qualification, Good Link with the FAA, Justification of Thermoplastics, Guidelines for Design and Build, and Weight. Recyclability is the only problem statement with a Satisfaction Gap of “0”, due to the UAS OEMs not having an opinion on the repairability of the UAS aircraft. The UAS OEMs did, however, give recyclability a score of 5 on the importance scale. Repair and Inspection also had an MSG of less than 30% as seen in Figure 9, showing the UAS market will be doing little repair and mostly replacing the aircraft.

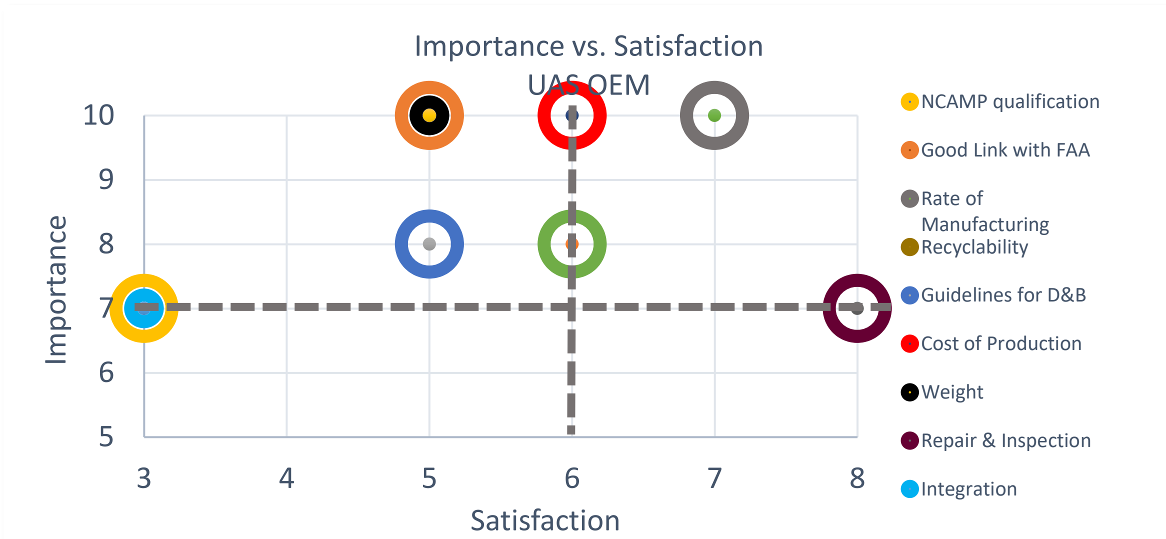

Figure 8. UAS OEM Importance vs. Satisfaction Plot.

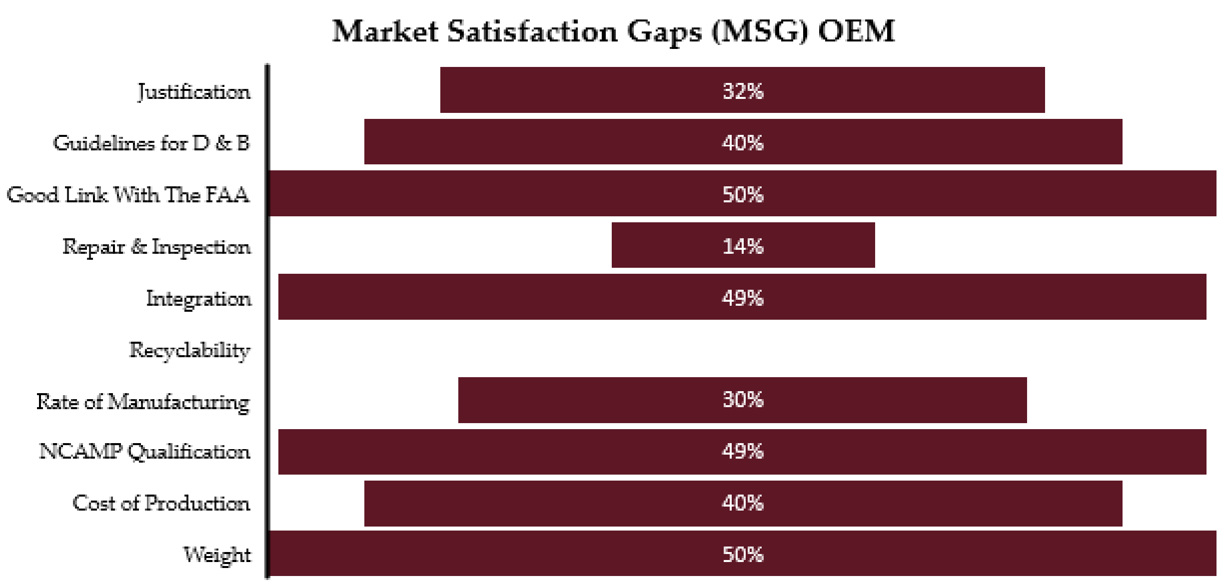

Figure 9: UAS OEM MSG

4.2.14 Raw Material Suppliers

According to the Raw Material Suppliers interviewed, 3 of the 10 Problem Statements for the raw material suppliers are in the top left quadrant of this graph as shown in Figure 10. These 3 Problem Statements are NCAMP Qualification, Integration, and Justification of Thermoplastics. This makes sense because Raw Material suppliers are directly related to the NCAMP database as well as thermoplastics. These companies did say that the application's right material and design are needed to make it easier to use additives broadly in repair-type situations. They also said that NCAMP must be involved in approving the whole process of structural components when dealing with integration. There have been a few materials and processes brought up by Raw Material suppliers that they request to be included in the NCAMP databases throughout this report, which is mentioned in section 3.3, "Critical Materials for UAS and AAM Vehicles." Most of their concerns around NCAMP Qualification have been around the time it takes to qualify a new material and process. Because the UAS and AAM market is quickly changing and growing, materials must be qualified faster than previously done.

Also, the Justification of Thermoplastics has the second-highest MSG as shown in Figure 11. This may suggest that the Raw Material Suppliers want more users to use thermoplastics, and justification of thermoplastics will aid their sales, or the Raw Material Suppliers themselves see the need for a stronger business case for thermoplastics.

Comparing the Importance vs. Satisfaction plots for the AAM OEMs and The Raw Material Suppliers, looking at Rate of Manufacturing, the data show the Raw Material Suppliers either believe their current product can meet the OEM's need for a higher rate and the OEMs do not agree (identified by the low importance) or true novel materials need to be produced. This is assuming the AAM OEMs fully understand the capabilities of current material systems.

Figure 10. Raw Material Suppliers' Importance vs. Satisfaction Plot.

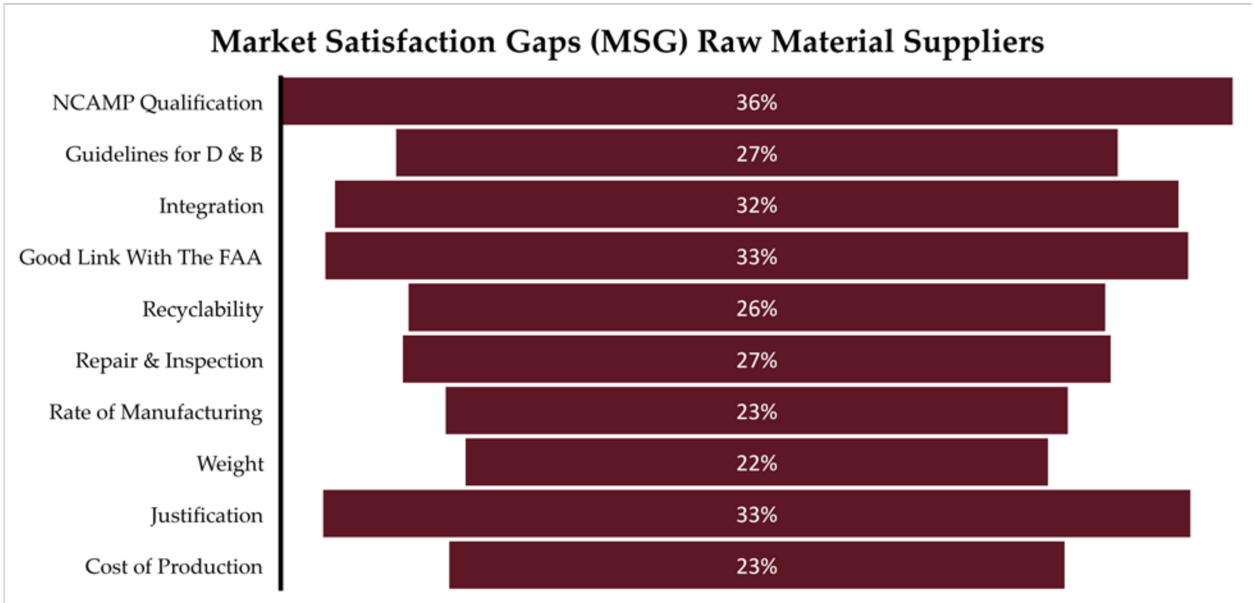

Figure 11: Raw Material Supplier MSG

4.2.15 Tier 1 Suppliers

According to the Tier 1 suppliers interviewed, 7 of the 10 Problem Statements are in the top left quadrant of the Tier 1 Suppliers shown in Figure 12. These 7 Problem Statements are NCAMP Qualification, Good Link with the FAA, Integration, Guidelines for Design & Build, Rate of Manufacturing, Repair and Inspection, and Weight.

The Tier 1 Suppliers have several extreme MSGs shown in Figure 13; all centered around manufacturing. The lowest Market Satisfaction Gaps were related to Recyclability and Justification of Thermoplastics due to the Tier 1 suppliers interviewed not using thermoplastics heavily. They agreed that raw materials need to be cheaper but are not important for the UAS and AAM market currently. They also said that while recyclability is important, it is not a key decision-maker for the UAS and AAM market. While the Justification of Thermoplastics may not be highlighted currently, the main drivers of Rate of Manufacturing, Integration, and Good Link with FAA may all be satisfied with thermoplastics in the future.

Figure 12. Tier 1 Suppliers Importance vs. Satisfaction Plot.

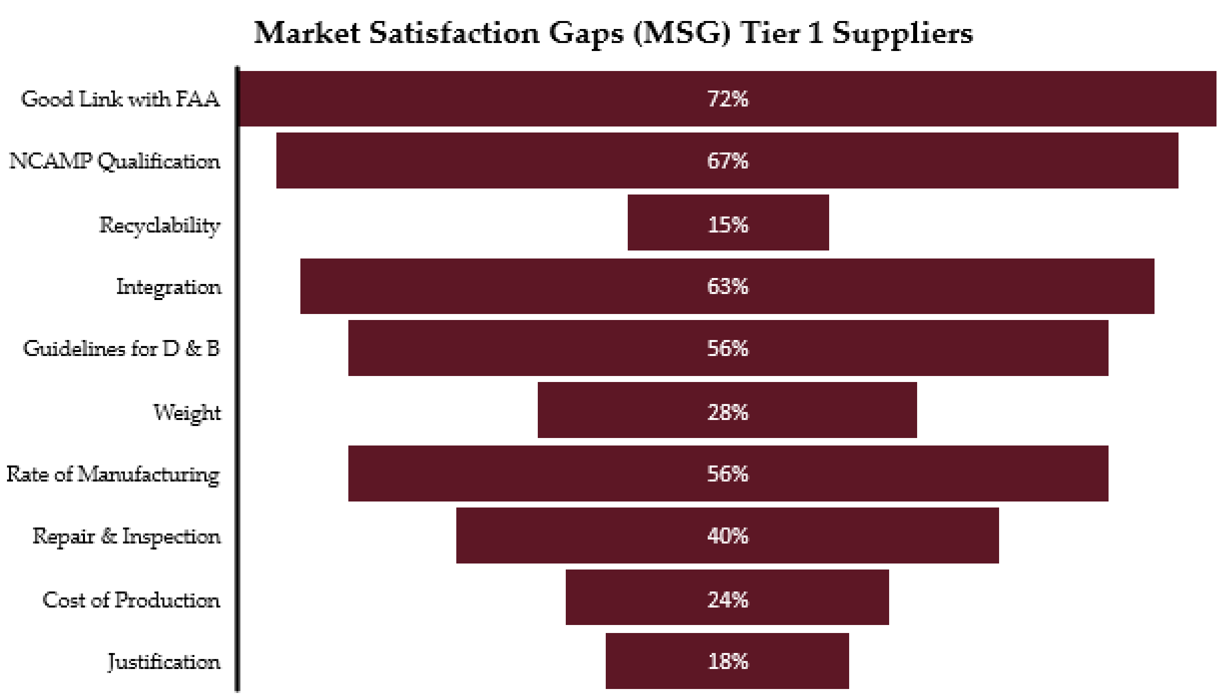

Figure 13: Tier 1 Supplier’s MSG

4.2.16 SMEs

According to the SMEs interviewed, 7 of the 10 Problem Statements fell into the top left quadrant of the graph as shown in Figure 14. These seven Problem Statements are NCAMP Qualification, Good Link with the FAA, Cost of Production, Weight, Integration, Guidelines for Design & Build, and Recyclability. The only two Problem Statements that fell below a 30% Market Satisfaction Gap are the Rate of Manufacturing and Justification of Thermoplastics as shown in Figure 15.

SMEs suggest that the price of thermoplastics and processing temperature is relatively satisfied, but there is more room for improvement. They did say, however, that the methods used on traditional aircraft (autoclave) are already well established to meet the low rate in the current market, but the bottleneck lies in the certification and qualification for novel materials needed for the high-rate environment that is expected to come.

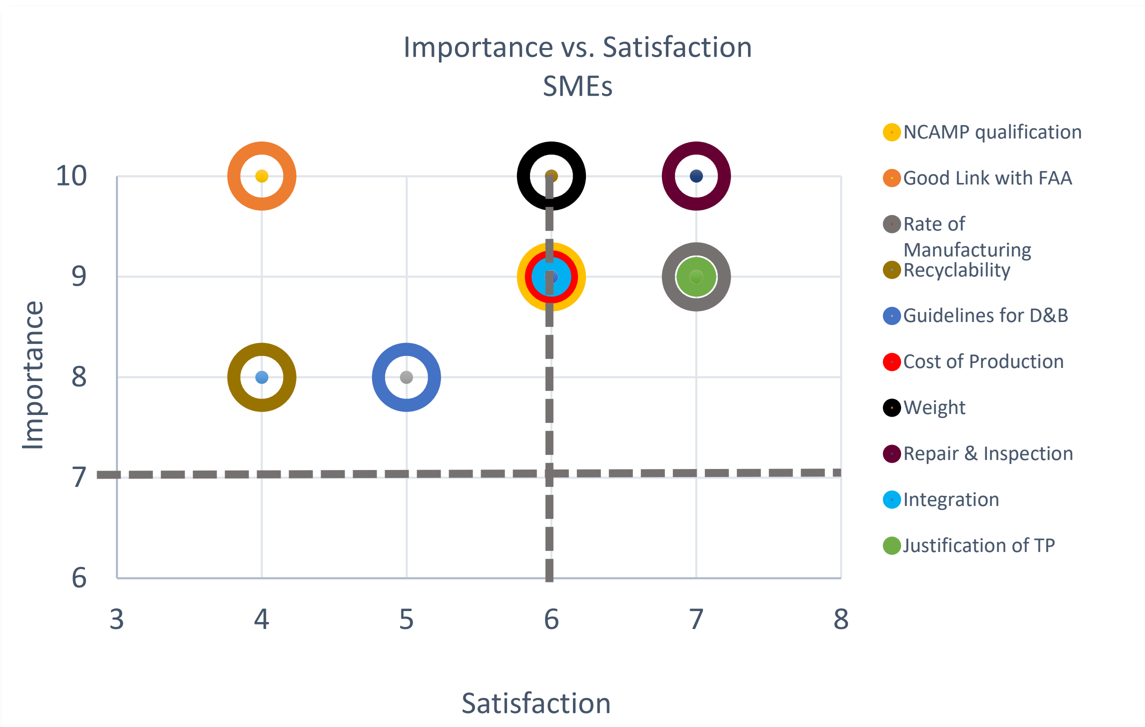

Figure 14. SMEs Importance vs. Satisfaction Plot.

Figure 15: Consultant's MSG

4.2.17 Summary

Figure 16 shows all the Market Satisfaction Gaps for each market segment and Problem Statements.

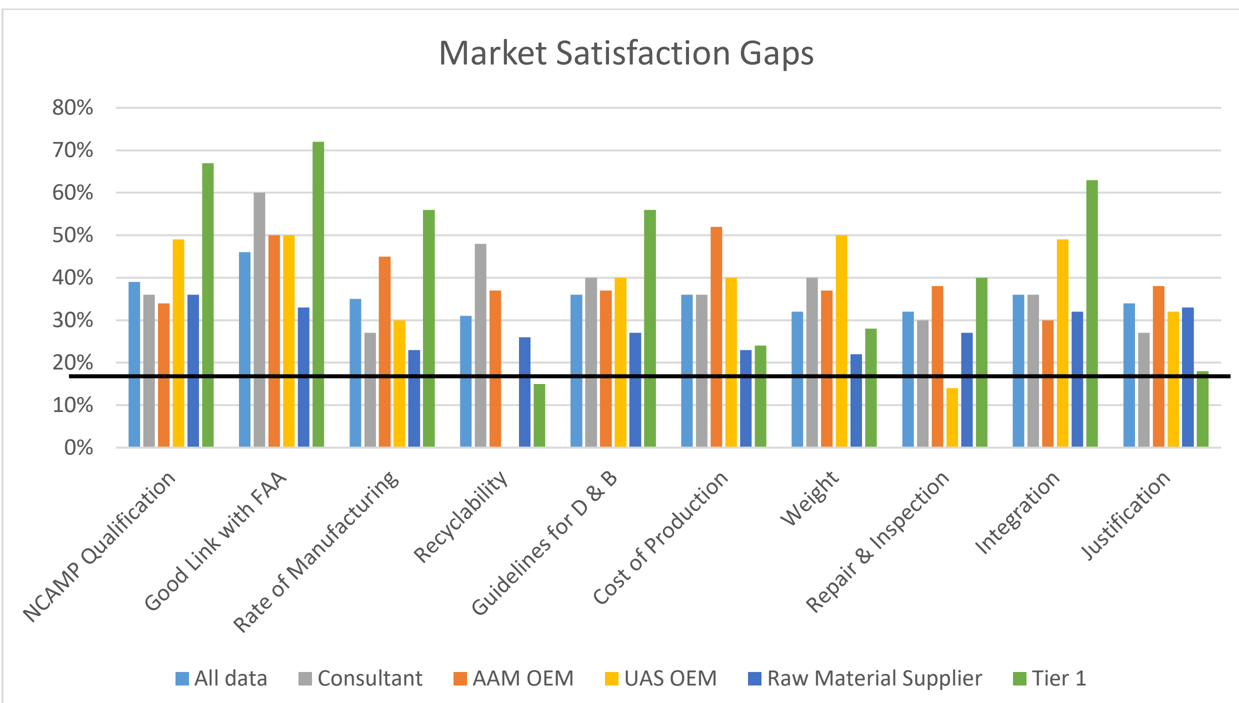

Figure 16. Summary of Market Satisfaction Gaps.

5 CONCLUSIONS AND FUTURE WORK

The current research study aimed to identify and document the different types of advanced materials and processes currently used and planned for future use in the construction of AAM and UAS. This was achieved through a literature review and market research survey with various leading raw material suppliers, AAM and UAS OEMs, tier-one suppliers, and SMEs from industry and academia. The key areas of interest were to document the use of all advanced material systems and processes in AAM and UAS aircraft, to identify if the conventional composite material systems are being used for any new applications in AAM and UAS vehicles, and to document the material characteristics that would be uniquely critical to AAM and UAS aircraft and are not currently included in material databases for traditional aviation applications. Additionally, the research study aimed to identify the use and applications of thermoplastic material systems, ceramic matrix composites, hybrid composite-metal structures, and to document the different joining assemblies and the repair and inspection criteria adopted by the AAM and the UAS industry.

Advanced Air Mobility Industry:

- Both the literature review and the market research survey, barring a few exceptions, overwhelmingly presented that the AAM industry is currently opting for well-established, legacy continuous fiber thermoset composite material systems for their primary and secondary structural applications.
- Some of the reasons for this approach are that choosing materials previously demonstrated in traditional aviation applications could result in an easier certification process, help the companies gain a competitive advantage, and release their certified vehicles early into the market. However, as the AAM industry matures, its production rate is expected to be significantly higher than the traditional aviation industry.
- To address this challenge, most AAM companies are inclined toward adopting different materials and processes in the future. Some materials and processes of interest are snap cure thermoset systems, thermoplastic materials, shift to press cure, stamp forming processes, and automated fabrication and inspection technologies.
- The industry survey presented that three OEMs, from the beginning, have chosen high-rate applicable materials such as snap cure thermosets and thermoplastics for primary and secondary structural applications.
- While there has been a general interest in thermoplastic materials and AM processes, the major concerns frequently mentioned were the limited availability of materials in public material databases such as NCAMP, and CMH-17, along with the technology maturity. Hence, these materials and processes are mostly currently limited to non-structural applications such as clips, brackets, and enclosures.
- The market survey showed that the applications of existing composite material systems commonly used in traditional aircraft applications have not differed in the AAM industry.
- In terms of joining assemblies, both the literature review and the industry survey findings showed that the AAM industry is working towards limiting the use of fasteners to meet the weight, cost, and high-production rate requirements.

- Secondary bonding was the frequently mentioned joining approach for thermoset composite structures. Induction welding was the commonly mentioned joining approach when thermoplastic materials are involved.
- While no specific repair and inspection criteria are defined for the AAM vehicles yet, these criteria are expected to be similar to the practices followed in the traditional aircraft industry. However, due to the nature of the greater takeoff and landing cycles than traditional aircraft, the key difference could lie in the frequency of the vehicle inspection.

Unmanned Aircraft Systems Industry:

- The small UAS industry relies heavily on advanced material systems and processes in the design and construction of their vehicles.
- Some advanced material systems used to build small UAS are carbon fiber, glass fiber composite materials, aluminum, magnesium-based alloys, and core materials such as honeycomb, expanded polypropylene, and polyvinyl chloride foams.
- The industry survey revealed that the small UAS OEMs are keen on choosing material systems from public material databases for the construction of their aircraft, in anticipation of future regulations in this area.
- With regards to the manufacturing processes, molding processes such as injection molding, over-molding, and AM technologies are widely used in the small UAS industry.
- The small UAS industry generally had no stringent repair and inspection criteria in place, and the industry would replace the vehicles rather than repair them. However, this is expected to change in the future, with companies focusing on designing repairable drones.
- The non-small UAS industry is interested in adopting materials and processes followed by the automotive industry and reduce the costs associated with the traditional aerospace applications. The material systems of interest are rapid cure thermosets and thermoplastics. The fabrication processes of interest are VARTM, SQRTM, and AM.

5.1 Potential Future Work

The goal of the Preference Interviews was geared towards identifying potential future work that could be studied to help improve the market. Because of the Preference Interviews, we were able to accurately gauge which problems were important depending on the market segment interviewed. It also allowed us to see which problems the different market segments were satisfied with and therefore did not need any further addressing for future work. The input given to us has led to our own list of where we think efforts need to be directed towards for solving the UAS and AAM market’s concerns and problems.

This project has identified AAM and UAS research topics that could be studied in the near future:

1) Near-term research for materials and processes that are clearly on the short-term horizon for UAS/AAM. These would include the materials in the NCAMP database that can be processed in various ways, i.e., Toray 2700, additive manufactured Ultem 9085, and PAEK/PEEK materials (both discontinuous and continuous fibers).

2) Investigate chopped fiber systems (both thermosets and thermoplastic resins) structures, processing, and controls for safe implementation and regulation.
3) Investigate continuous fiber thermoplastics with lower melting matrices, i.e., nylon, polycarbonate, etc.
4) Identifying and controlling material choices for specific aircraft (UAS and AAM) classes.
5) Comparing and contrasting various processing techniques, i.e., VARTM, RTM, press, thermoset vs. thermoplastic, etc.
6) Understanding how AM can be safely implemented.

A potential first topic is to begin populating the NCAMP database with current continuous fiber thermoset prepreg materials, i.e., Toray 2700, that are amenable for press curing but are currently cured in an autoclave. This alternative processing method, press curing, must match the high quality of an autoclave system, which should be true but must be proven. All major raw material suppliers have press cure thermoset prepregs; therefore, they would likely partner in populating the NCAMP database. Additionally, the Toray 2700 system was mentioned several times in the interview process as a likely material choice. From a business perspective, the Toray 2700 allows for a change from autoclave cure to higher-rate processing using a press but continuing with the same material. This can be easily expanded to other materials already present in the NCAMP database, whether additive manufactured Ultem 9085 or PEAK/PEEK materials.

A second potential topic, augmenting the research projects funded by other federal agencies, is to understand better the materials and processes for discontinuous/chopped/powdered fiber thermoplastics. Several large-scale projects are investigating these short fiber thermoplastic systems, including work by the University of Washington and NIAR through FAA JAMS. However, little effort is focused on understanding the technology readiness of these systems for specific applications for UAS and AAM. This A53 project was the first effort by the FAA to pinpoint better specific technologies and material systems used and potentially used in UAS/AAM. While some generalities can be found, the UAS/AAM market is heavily focused on producing their first certified aircraft with certified continuous fiber thermoset prepregs and is leaving the burden of process changes and manufacturing readiness for the impending market adoption; however, raw material providers only have a few short fiber thermoplastic product offerings in their portfolios appropriate for primary aircraft structure. This greatly narrows the choice of materials, allowing for more focused research on the current material properties, fatigue life, chemical resistance, bonding, manufacturing, etc.

A third potential topic is better producing material guidance for specific structures and aircraft classes. This research clearly showed that the UAS and AAM markets have different needs and goals for material and processing – mostly stemming from their desire for thermoplastics and integration. The above two research topics are directly pertinent to the AAM market, but research for lower-performance materials and regulation standards for them can be introduced and implemented.

A fourth potential topic is better understanding the difference in qualification requirements for structures produced via alternative methods. For example, if the AAM market changes from a conventional prepregged continuous carbon fiber system available in a public database to a novel thermoplastic system, how does one ensure the material properties and processing will provide equivalent safety? A proposed research task would be to compare the identical fiber system with various processing and matrix combinations.

A fifth potential topic is to investigate further the use of AM for the UAS/AAM market. Both metallic, thermoplastic, and thermoset AM will likely be included in future vehicles. Therefore, there is a need to build models around processing parameters effect on final part performance, chemical resistance, fatigue life, toughness, etc.

As one can see, there is a large need for research related to novel materials and processes for the UAS/AAM market. The goal of producing flying structures at rates never accomplished for aerospace will stress the status-quo and force these companies to solve their problems creatively. It must be ensured that these new materials will have the same safety record associated with current commercial flying aircraft through diligence, expanded research, and partnerships with the market.

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