NPS-AM-26-279

ACQUISITION RESEARCH PROGRAM SPONSORED REPORT SERIES

Scaling Drone Manufacturing Through the Gigafactory Model

December 2025

Capt Zechariah M. Lund, USMC
LT Peter Obeng, USN

Thesis Advisors: Dr. Nicholas Dew, Professor
Lt Col Jamie Porchia, Assistant Professor

Department of Acquisition, Finance and Manpower

Naval Postgraduate School

The research presented in this report was supported by the Acquisition Research Program of the Department of Acquisition, Finance and Manpower Naval Postgraduate School.

To request defense acquisition research, to become a research sponsor, or to print additional copies of reports, please contact the Acquisition Research Program (ARP) via email, arp@nps.edu or at 831-656-3793.

ABSTRACT

Modern warfare has demonstrated an increasing demand for unmanned aerial systems (UAS) that provide critical battlefield advantages. For example, the war in Ukraine has highlighted drones' role in defense operations, demonstrating their ability to enhance situational awareness, conduct reconnaissance, and deliver kinetic effects efficiently. While drones have historically been overlooked by military planners due to perceived operational limitations, their recent success in modern conflicts has solidified their importance.

However, the U.S. faces significant challenges in rapidly scaling drone production. Many UAS components rely on foreign supply chains, and the domestic manufacturing infrastructure remains fragmented. To address these issues, companies such as Anduril have pioneered the Gigafactory model—centralized, high-volume production facilities that integrate supply chains to achieve economies of scale and enhance supply chain security.

The focus on the Gigafactory model stems from its demonstrated success in industries like electric vehicles and semiconductors, where rapid scaling, cost efficiency, and supply chain control are critical. Applying this model to the defense sector presents a promising pathway to overcome current production and sourcing limitations.

This thesis explores the viability of Gigafactories as a model for increasing the domestic production of UAS to meet DoD requirements.

THIS PAGE INTENTIONALLY LEFT BLANK

NPS-AM-26-279

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Scaling Drone Manufacturing Through the Gigafactory Model

December 2025

Capt Zechariah M. Lund, USMC
LT Peter Obeng, USN

Thesis Advisors: Dr. Nicholas Dew, Professor
Lt Col Jamie Porchia, Assistant Professor

Department of Acquisition, Finance and Manpower

Naval Postgraduate School

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION....1
- A. CHALLENGES.... 2
- B. PROBLEM STATEMENT.... 6
- C. RESEARCH QUESTIONS.... 7
- D. THESIS STATEMENT.... 7

II. UAV PRODUCTION MODELS AND TECHNOLOGICAL ENABLERS....9
- A. OVERVIEW OF UAV PRODUCTION PROCESS.... 9
- B. SUPPLY CHAIN CHALLENGES AND RESILIENCE STRATEGIES.... 12
- C. DUAL SOURCING AND IN-HOUSE FABRICATION.... 12
- D. SECURITY AND EMBEDDED TRUST.... 12
- E. RESILIENCE.... 13
- F. AGILE PARTNERSHIPS AND FEEDBACK LOOPS.... 13
- G. DECENTRALIZED “CROWD PRODUCTION” AS A RESILIENCE MODEL.... 14
- H. EMERGING TECHNOLOGIES IN UAV MANUFACTURING.... 14
- I. ADDITIVE MANUFACTURING AND MODULE TOOLING.... 15
- J. INTERNET OF THINGS AND DIGITAL TWINS.... 15
- K. ANDURIL’S GIGAFACTORY: A NEW PARADIGM FOR DEFENSE MANUFACTURING.... 16
- L. COMPARATIVE UAS PRODUCTION MODELS.... 17
- M. SILICON VALLEY EMBEDDED TEAMS.... 17
- N. DECENTRALIZED CROWD PRODUCTION.... 18
- O. ADDITIVE SURGE MODEL.... 19
- P. PRIME-STARTUP DIGITAL CONSORTIA.... 20
- Q. FORD MODEL T FOR DRONES.... 21

III. METHODOLOGY....23
- A. INTRODUCTION TO RESEARCH METHODOLOGY.... 23
- B. OPEN-SOURCE BOM CONSTRUCTION.... 24
- C. FUNCTIONAL CLASSIFICATION AND SUBSYSTEM DECOMPOSITION.... 25
- D. RISK ASSESSMENT METHODOLOGY AND COST MODELING.... 25

IV. ESTABLISHMENT AND UTILIZATION OF THE GIGAFACTORY MODEL: A CASE STUDY....29
- A. OVERVIEW.... 29

B. ADVANTAGES 31

V. ANALYSIS OF BOM IMPLICATIONS FOR CENTRALIZED UAS PRODUCTION 33

A. SUBSYSTEM CLASSIFICATION AND FUNCTIONAL DECOMPOSITION 33

B. GIGAFACTORY IMPLICATIONS FOR SCALABLE UAS PRODUCTION 47

C. DATA SOURCING AND SUPPLIER MAPPING 53

D. DATA INTEGRITY CONSIDERATIONS 55

E. SUMMARY OF FINDINGS AND PRODUCTION IMPLICATIONS 55

VI. CONCLUSION AND RECOMMENDATIONS 57

A. U.S. INDUSTRIAL RESPONSE AND STRATEGIC INVESTMENT 57

B. SUMMARY OF KEY FINDINGS 59

C. IMPLICATIONS OF SUPPLY CHAIN CONSTRAINTS 64

D. RECOMMENDATIONS 65

E. FOR THE DEPARTMENT OF DEFENSE (DOD) 65

F. FOR INDUSTRY STAKEHOLDERS 66

G. SUMMARY 68

AI DISCLOSURE STATEMENT 69

SUPPLEMENTAL: FUNCTIONAL BOM OF GROUP 2/3 UAS WITH GIGAFACTORY CONSIDERATIONS 71

LIST OF REFERENCES 73

LIST OF FIGURES

Figure 1. UAV Design and Manufacturing Process. Source: El Adawy et al. (2023). 11

Figure 2. Anduril Gigafactory Layout – Factory Model. Source: Semenyuk et al. (2024). 30

Figure 3. Brushless Motor Design. Source: T-Drones (2025). 34

Figure 4. PCB Manufacturing Process Flow Chart. Source: Wonderful PCB (2025). 38

Figure 5. ESC Composition and Subsystem Integration. Source: Mogensen (2016). 40

Figure 6. Development and verification workflow using MathWorks based toolchain for safety critical systems. Source: Dmitriev et al. (2020). 44

Figure 7. DevSecOps Life cycle Phases (Infinity Loop). Source: Department of Defense CIO (2024). 45

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1. Gigafactory vs. External Procurement Suitability by Subsystem 50

Table 2. Comparative Assessment of Six U.S. UAS Production Models........................... 61

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AOI	Automated Optical Inspection
BoM	Bill of Materials
BVLOS	Beyond Visual Line-of-Sight
BMS	Battery Management System
CAD	Computer Aided Design
CNC	Computer Numerical Control
COTS	Commercial-off-the-Shelf
DoD	Department of Defense
DoE	Department of Energy
DIU	Defense Innovation Unit
DPA	Defense Production Act
ESC	Electronic Speed Controller
FC	Flight Controller
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
GPS	Global Positioning System
HE	High Energy
IMU	Inertial Measurement Units
MES	Manufacturing Execution System
MOSA	Modular Open Systems Approach
NPS	Naval Postgraduate School
PCB	Printed Circuit Board
PLA	Polylactic Acid
PLM	Product Life cycle Management
POM	Program Objective Memoranda
QA	Quality Assurance
QC	Quality Control
RFP	Request for Proposal
SLAM	Simultaneous Localization and Mapping
SLS	Selective Lasering Sintering

SMT	Surface Mount Technology
SWaP	Size, Weight, and Power (electrical)
UAS	Unmanned Aircraft Systems

EXECUTIVE SUMMARY

Modern warfare has revealed a growing operational reliance on unmanned aerial systems (UAS) to provide reconnaissance, surveillance, and strike capabilities at low cost and high responsiveness. The conflict in Ukraine has demonstrated that small, attritable drones can affect battlefield operations drastically, altering the pacing and scale with minimal adverse effects. Despite this emerging importance, the United States lacks the industrial capacity to scale drone production rapidly to meet Department of Defense (DoD) requirements. The domestic manufacturing base remains fragmented, and U.S. supply chains for key subsystems continue to depend on foreign suppliers.

To address these limitations, this thesis examines how the Gigafactory model could serve as a scalable, resilient production framework capable of enabling manufacture of UAS in scale. Drawing inspiration from industrial models in the electric vehicle and semiconductor sectors, the Gigafactory integrates advanced automation, subsystems standardization, and digital engineering to consolidate production and reduce supplier fragmentation. The research analyzes whether this centralized approach can strengthen industrial base resilience, reduce cost and lead time, and support DoD objectives for rapid drone fielding in future conflicts.

The study applies a grounded, data-driven methodology anchored by a comprehensive Bill of Materials (BOM) analysis of multiple UAS platforms. This approach decomposes each drone into its major subsystems (Powertrain, Electronics, Structure, etc.) to identify common manufacturing dependencies and assess which are best suited for centralized production. By integrating open-source technical data, supplier classifications, and component sourcing trends, the research evaluates both the feasibility and risk of applying a Gigafactory model to large-scale defense production.

Findings demonstrate that subsystem standardization offers the most direct pathway to achieving economies of scale in UAS manufacturing. The Gigafactory model enhances throughput and labor efficiency by reducing customization and aligning subsystem design to modular, repeatable production processes. Components such as airframes, propellers, and motor assemblies are particularly compatible with centralized manufacturing due to their physical uniformity and commercial availability. However, the study identifies several critical constraints: domestic production of lithium-ion battery cells, rare-earth magnets, and specialized electronics remains limited, with many key inputs sourced from China or other non-allied nations. These supply chain dependencies expose the Gigafactory model to risk of disruption and emphasize the need for redundant sourcing strategies and strategic mineral reserves.

Economic and policy considerations also shape the model's long-term viability. The current "Buy American" environment and onshoring incentives create tension between cost efficiency and strategic autonomy. While centralized manufacturing can reduce per-unit costs and improve quality control, it cannot fully offset the vulnerabilities associated with single-source or foreign sourced components. The research therefore advocates for a hybrid approach, combining centralized production for standardized subsystems with decentralized or buffered manufacturing for globally constrained components. This approach balances efficiency with resilience, ensuring continuity of operations even under supply chain stress or geopolitical friction.

Ultimately, this thesis concludes that the Gigafactory model presents a compelling vision for the future of defense manufacturing. A model that shifts from bespoke, prototype-based production to scalable, commercially informed industrialization. By applying the principles of standardization, automation, and modularity, the Gigafactory approach can strengthen the U.S. defense industrial base and position the DoD to meet surge production demands in prolonged or high-intensity conflicts. Its success, however, depends on concurrent policy efforts to secure critical materials, incentivize domestic manufacturing of high-risk subsystems, and align public-private investment in dual-use production infrastructure.

I. INTRODUCTION

Modern warfare has demonstrated the increasing demand for unmanned aircraft systems (UAS) that provide critical battlefield advantages. The war in Ukraine has highlighted drones' role in defense operations, demonstrating their ability to enhance situational awareness, conduct reconnaissance, and deliver kinetic effects efficiently. While drones have historically been overlooked by military planners due to perceived operational limitations, their recent success in modern conflicts has solidified their importance.

UASs have been utilized extensively across multiple functions but have been found to be particularly useful in warfare. Such technology has found applications in persistent intelligence, surveillance, and reconnaissance, thus reducing the number of soldiers needing to be stationed in areas of interest (Martins, 2024). UAS provide close to real-time video and data generated by their sensors, while reducing the risk to human beings, who would, otherwise, need to man the aircraft (Martins, 2024). Because UAS do not require a pilot, they reduce the harm that would be incurred by such an operator if the drone is shot down over hostile territory (Rogers, 2021). UAS are also quite cost efficient with the low acquisition and operational costs that they incur when compared to manned systems of equivalence, which allows the military to reallocate some of its resources to other vital projects and functions (Martins, 2024). UAS also tend to be highly precise in terms of the objects that they are targeting, which allows operators and the military to reduce the risk of collateral damage (Martins, 2024). Such precision is particularly important when warfare takes place in areas occupied by civilian populations. Such aircraft can also be rapidly deployed and scaled, allowing for mass-deployment to quickly augment any human operated aircraft (Weldon et al., 2021). This rapid deployment capability gives military planners flexibility during short notice operations and conflict escalation. What makes these aircraft valuable is the fact that they can be easily integrated into the DoD's existing technological infrastructure and into civilian aviation hubs, enabling more integrated operations across military and civilian agencies during domestic or coalition missions (Rogers, 2021).

A. CHALLENGES

However, the U.S. faces significant challenges in rapidly scaling drone production. Many UAS components rely on foreign supply chains, and domestic manufacturing infrastructure remains fragmented (Aldemir, 2024). To address this, the Gigafactory model, which is focused on centralized production and which brings ties together the processes of fabrication, assembly, and testing under one roof has been implemented in some scenarios. This thesis will explore the viability of Gigafactories as a model for increasing the domestic production of UAS to meet DoD requirements.

UAS technology has vastly advanced over the last few decades and even over the last few years. Such technology refers not only to the actual aircraft that is being flown but rather to the broader system of systems required for the drone's safe and legal operation (Aldemir, 2024). UAS incorporates the elements of the vehicle, any payloads that it may be carrying, the ground-based control station, any links required for communication between the aircraft and its operator, any equipment needed for the vehicle's launch and potential recovery, and any infrastructure that needs to be in place for the vehicle to operate properly (Weldon et al., 2021).

While solving production issues is essential, UAS deployment also depends on a coherent global regulatory environment. In various areas of the world, there are different laws that attempt to govern the use and operations of UAS. The disparity in terms of laws in different areas of the world creates a challenge for the operation of such aircraft in various regions, and particularly by the military. For instance, in the United States, 14 CFR Part 107 governs the operations of UAS, including aircraft operations, the certification of remote pilots, flight times and altitudes, and operations of aircraft in populated areas (Rauhala et al., 2023). Additionally, the Federal Aviation Administration is responsible for any additional rule and policy making to augment portions of Part 107 to ensure safety when operating UAS (Rauhala et al., 2023). In the European Union, EASA Basic Regulation (EU) 2018/1139 and Regulations and Deregulations 2019/947 and 2019/945 help to create the regulatory structure overseeing the operations of drones in this region of the world (Marshall, 2024). In the United Kingdom, Civil Authority Civil Aviation Publication, or CAA CAP, 722 Series and Articles 94 and 95 of the Air Navigation Order

2016 fulfill this same function (Marshall, 2024). In India, operations of UAS are governed by the Directorate General of Civil Aviation, or DGCA, Drone Rules 2021, while, in China, the same aspect is controlled by Civil Aviation Administration of China, or CAAC, UAS regulations (Huang et al., 2021). Finally, in Australia, drone operations are controlled by the Civil Aviation Safety Regulations, or CASR, Part 101 (Huang et al., 2021). Internationally, various countries utilize the Procedures for Air Navigation Services and the harmonized Standards and Recommended Practices as the templates and blueprints for the creation and advancement of (Rauhala et al., 2023). Each of these regulatory frameworks reflects the approach of each government in terms of creating a proper working balance between innovation, safety, and the integration of airspace to accommodate the diverse types of aircraft that need to share the airspace.

A frequently cited potential bottleneck in UAS production is the United States' dependence on fragile and foreign-controlled supply chains for key drone components. One such challenge, described in recent literature, is the fragmented and sometimes unreliable supply base that UAS manufacturers depend on to source critical components (Vashishth et al., 2024). This thesis uses these concerns as a motivating starting point and will systematically investigate the extent to which supply-chain fragility and foreign dependence constrain U.S. UAS production capacity.

Disruptions in the availability of items like GPS systems, flight controls, and safety sensors can stall production and delay inventory buildup (Vashishth et al., 2024). Key components such as GPS systems, flight controllers, and safety sensors are essential for UAS stability and navigation, but they are frequently sourced from multiple external vendors. As a result, disruptions in the availability of even one component can halt production and delay inventory buildup (Vashishth et al., 2024). Many manufacturers rely on multiple vendors from which to source these components, and some vendors are facing their own operations and sourcing challenges. For example, in 2021, SZ DJI Technology Co. paused production of its Phantom 4 Pro units due to shortages of Inertial Measurement Units (IMUs), which play a critical role in stabilizing and navigating the drone during flight (Mohsan et al., 2023). In this instance, the company's vendor was unable to meet the company's demand for this component, which prompted a pause in production that lasted over multiple months (Mohsan et al., 2023). Another issue is that the electro-optical and infrared turrets, such as FLIR systems, are difficult to replace due to vendor incompatibility (Mohsan et al., 2023).

Another production issue facing UAS manufacturers relates to the integration of the complex technological systems that drones depend on since there are multiple hardware and software systems that need to interoperate to create seamless functionality (Michaelides-Mateou, 2023). Due to the disparate systems that are often installed into drones and many such components coming from third-party vendors, it can be difficult to seamlessly operate drones (Michaelides-Mateou, 2023). Interoperability between multiple software and hardware systems are important as small mismatches can cause significant disruptions in production, requiring engineers to redevelop code or reconfigure components (Rana & Singh, 2021). This situation is further complicated when using third-party autopilots, software used within ground-control systems, and payloads, which can lead to mismatches between these different systems (Michaelides-Mateou, 2023). As an example, the employees handling the ScanEagle program carried out by Insitu were forced to rewrite the coding for the datalink and its operations once they discovered that a new sensor installed into its UASs led to the drones sending data in a data format that was not supported by the company (Rabiu et al., 2024).

Although many manufacturers attempt to leverage off-the shelf systems, such a technique does not work well with high-volume drone production. In addition to domestic compliance, manufacturers must navigate divergent regulatory frameworks across countries. Components built into FAA airworthiness standards, for instance may not meet the EASA requirements without modification, further complicating the international production pipelines (Askerbekov et al., 2024). Such disparities can slow integration efforts, require expensive recertification, or limit cross-border vendor partnerships. Prior to introducing finished units to the market, they need to ensure that the units have been extensively tested to make sure that they perform at the expected level (Askerbekov et al., 2024). As a result, high-volume production can be hindered by the regulatory framework overseeing this industry.

Aside from regulatory limitations, high-volume production can also be hindered by shortages of skilled workers, as automation cannot yet fully replace technicians, who specialize in the structuring of advanced composites, the integration of complex electronics, and the validation of embedded software systems (Nwaogu et al., 2024).According to the Aerospace Industries Association, nearly 40% of firms reported difficulty filling advanced manufacturing roles in avionics and unmanned systems. These gaps delay production and force companies to rely more heavily on automation and outsourcing which introduce new risks in production. There is a high degree of demand for highly trained and qualified specialized workers. Unfortunately, manufacturers struggle with sourcing such talent and ensuring that workers, once hired, are trained and prepared for the job (Nwaogu et al., 2024).

In the United States, high-volume manufacturing also requires a high degree of quality control efforts and initiatives to minimize the risks of units with impaired quality and obvious issues being sold to customers (Fareed et al., 2024). This function incorporates scaled quality control measures that increase the operating costs of manufacturers (Fareed et al., 2024). This is just one aspect that contributes to this industry being very capital and resource intensive. To ensure that all such initiatives are properly supported, manufacturers must make upfront investments into 3D printers, assembly pods, riveting rigs, and robotic layup cells (Sanders & Holderness, 2023). However, these costs can be effectively spread across production volumes as they increase to high levels (Sanders & Holderness, 2023). Quality control efforts can also be further stymied by the modularization of technologies integrated into UAV units, as well as the need for rapid component replacement and upgrading (Vanderhorst et al., 2023). Finally, this process can also be impacted by the security requirements stemming from cyber and physical risks, as manufacturers may have to reinspect multiple units to ensure they fulfill these once deployed as part of a mission (Vanderhorst et al., 2023).

Drones' interoperability manufacturing issues have created significant and critical problems for the military, which relies on such aircraft operating, as intended, when such operations are required. For example, UAS being operated by the armed forces need to connect to a C2 networks to transmit data, receive potential updates to mission parameters, and coordinate with other battlefield assets (Ramesh & Muruga, 2021). Mismatch between drone software, third-party autopilots, or datalinks can disrupt this connectivity, leading to operational degradation or even mission failure (Rabiu et al., 2024). The 2024 ScanEagle case, where engineers had to rewrite the datalink interface due to incompatible sensor outputs, illustrates the operational risk introduced by inconsistent hardware-software integration (Rabiu et al., 2024). This highlights the need for updated manufacturing models, such as the Gigafactory Anduril is opening, that prioritize vertically integrated production and early adaptation of systems engineering throughout the design phase to ensure interoperability with the standard military C2 structure. By intertwining these requirements throughout the production process, UAS manufacturers can effectively mitigate risk of integration failures and improve the operational readiness of UAS fleets.

One company that has been working on scalability with the goal of maximizing the scope and speed of its UAV production is Anduril. The company, which was founded in 2017, is structured as an industry disruptor, and, within this context, can be compared to tech giants like Apple, Tesla, and SpaceX, mainly due to its focus on scope expansion and maximization (Caldwell, 2024). In comparison to more traditional organizations operating within this industry, such as Boeing, Lockheed Martin, and Raytheon, Anduril's operations are rooted in the creation of prototypes before engaging in large scale manufacturing of drones (Caldwell, 2024). Within its own industry, Anduril can be effectively compared to Epirus, Scale AI, and Palantir (Caldwell, 2024). Over the last few years, the company has gained quite a bit of prominence as a result of drones being widely used in the Ukrainian war effort against its Russian counterpart (Shah & Kirchhoff, 2025).

B. PROBLEM STATEMENT

Despite the growing strategic importance of UAS, the United States lacks the manufacturing capacity to scale drone production to meet current and future Department of Defense (DoD) demand (Caldwell, 2024). Existing production is fragmented, heavily dependent on foreign sourced components and constrained by a limited domestic supplier base. These limitations jeopardize the speed, cost-efficiency, and security of UAS deployment in response to evolving threats. A scalable, resilient, and secure production model is urgently needed to ensure that the U.S. can field drone capabilities at the volume and pace required for modern warfare.

C. RESEARCH QUESTIONS

To assess the feasibility of scaling UAS production through centralized mass manufacturing, this study identifies four guiding questions. The analysis focuses on material requirements, supply chain risks, financial tradeoffs, and the structure of production at scale.

1. Which UAS components/subsystems are most critical and at risk and therefore should be a priority to enable, secure U.S. production?
2. Across existing production models versus a centralized "Gigafactory" model, what are the comparative advantages, constraints and prerequisites for scaling U.S. UAS production?
3. What are the cost implications of moving from today's distributed/ outsourced approach to a more centralized, U.S.-based production approach?

D. THESIS STATEMENT

The United States defense industrial base faces significant challenges in meeting the growing demand for UAS. This thesis analyzes to what extent a centralized, high-volume Gigafactory approach represents a promising solution to these manufacturing constraints. Companies like Anduril have already taken the leap in investing in the Gigafactory model and infrastructure necessary to improve manufacturing efficiency and output. We analyze their strategy to understand to what extent applying the Gigafactory model to drone production could revolutionize how the defense industry approaches UAS manufacturing.

THIS PAGE INTENTIONALLY LEFT BLANK

II. UAV PRODUCTION MODELS AND TECHNOLOGICAL ENABLERS

Chapter II examines the production processes and enabling technologies that shape the viability of high-rate UAS manufacturing. The first section outlines the standard UAS design and manufacturing process via flowchart to establish a baseline understanding of the industrial workflow. This process includes manufacturing technologies such as additive manufacturing, digital twins, and blockchain effects redefine efficiency, quality assurance, and production resilience for UAS. These enablers are then considered alongside modern supply chain challenges and strategies to mitigate disruption, including cybersecurity, dual sourcing, and decentralized fabrication. Lastly, alternate production models are introduced, such as the Gigafactory concept, and compared to current terms of scalability, speed, and integration. In combination, these elements provide the technical foundation in which to evaluate whether Anduril's Gigafactory model can meet the DoD typical, and sometimes short notice demand for resilient and high-volume production for future conflicts.

A. OVERVIEW OF UAV PRODUCTION PROCESS

To understand how UAS can be produced in scale, it is first necessary to examine the conventional design and production life cycle. This section outlines the typical process of UAS development, including concept generation to manufacturing, highlighting the technical and logistical constraints in the process. An analytical model of the design and production process associated with the manufacturing of UAS can be seen in Figure 1 (El Adawy et al., 2023).

As can be seen in Figure 1, the UAS production process begins with the fleshing out of the concept generation, initial weight and sizing, and performance analysis aspects (El Adawy et al., 2023). Much of this process relies heavily on customer needs, as UAS manufacturers, due to the high degree of rapidly changing technology, need to remain as competitive as possible (Salinas et al., 2024). The process then shifts to the targeting of any constraints that are present within the process, before moving on to the analysis of key performance parameters, or KPPs, and their alignment with the specifications of the model being designed (Salinas et al., 2024).

Figure 1 outlines the overall processes that guide that of manufacturing at this early stage. These processes include that of planning, risk and trade analysis, engineering, and evaluation phase. The products of these processes comprise the UAV units that are designed and manufactured. The first aspect of planning is reliant on data obtained from market participants so that the manufacturer is able to shift production into the direction of the needs and wishes of the general public.

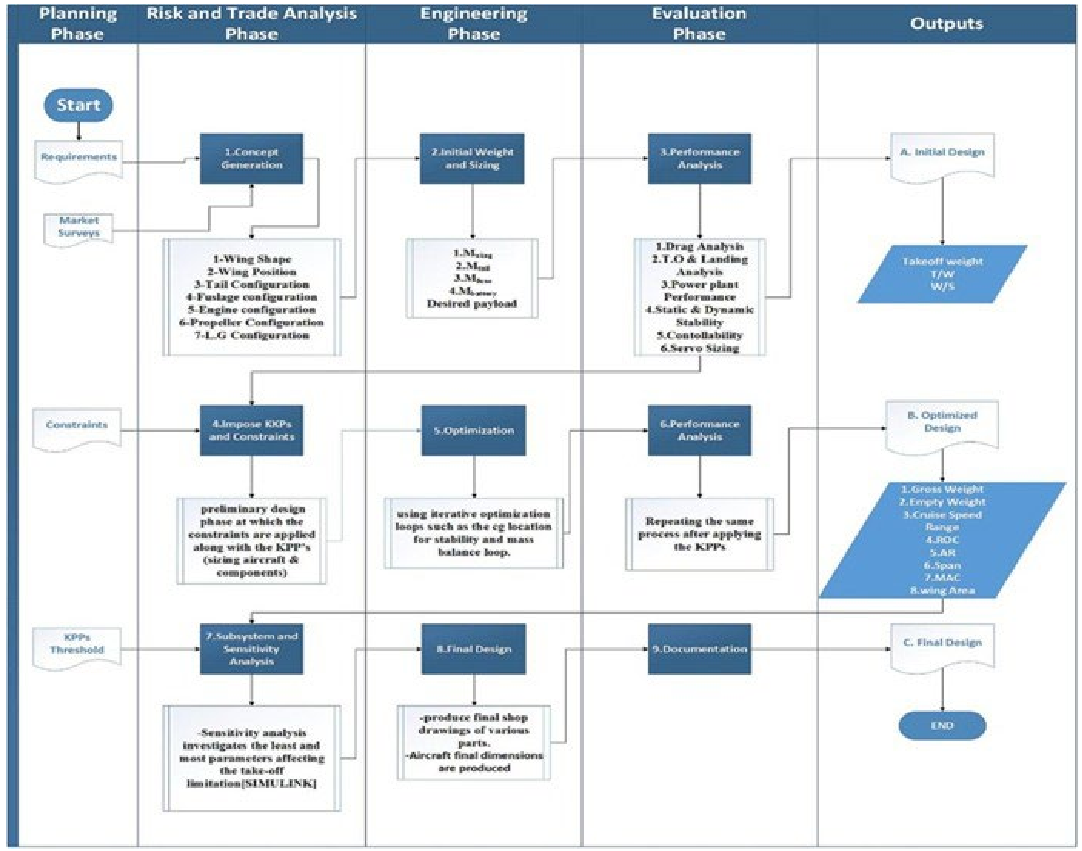

Figure 1. UAV Design and Manufacturing Process. Source: El Adawy et al. (2023).

B. SUPPLY CHAIN CHALLENGES AND RESILIENCE STRATEGIES

While emerging technologies are consistently improving production efficiency, the UAS manufacturing industry remains vulnerable to supply chain risks. This section evaluates the various challenges that corporate entities operating within this industry experience. This sheds light on the challenges that Boeing was experiencing during this time frame that may allow readers to gain insight into any factors that may have prompted Boeing leadership to be unethical. This section examines key challenges in the supply chain such as bottlenecks in electronic components. This section specifically targets supply chain challenges, resilience strategies, dual sourcing, cyber security hardware, agile defense-based partnerships, feedback loops, and decentralized crowd production. These challenges were identified within the context of UAV because they are all interrelated.

C. DUAL SOURCING AND IN-HOUSE FABRICATION

To reduce risk from single points of failure, drone manufacturers are increasingly adopting dual sourcing and localized production strategies. This approach would allow manufacturers to procure critical components such as flight controllers, inertial sensors, and power modules from a variety of independent vendors (Gereffi et al., 2021). Increased variety of vendors to acquire these critical assets reduces the risk of production stoppages if one of the suppliers experiences such delays or shortages (Gereffi et al., 2021). A complimentary strategy, in-house fabrication, would focus on small-batch, high value components, which would add an additional layer of supply security during surge demands or geopolitical disruptions (Panwar et al., 2022).

D. SECURITY AND EMBEDDED TRUST

Drone manufacturers have used modules and other tools to expose employees to UAS units that have integrated advanced functions. For example, using root-of-trust modules, these modules bolster UAS supply chains via the incorporation of so-called trust anchors into the unit's critical components, such as the flight controller (Rowland & Karch, 2022). These trust anchors function like digital "seals" to ensure that only authorized software can run on the drone, preventing tampering or unauthorized access during deployment. Additionally, secure-boot chains can also be utilized to reduce the risk of the manufacturer's firmware being tampered with (Rowland & Karch, 2022). This level of cyber hardening significantly lowers the odds of operational compromise in hostile environments, where adversaries may attempt to hijack or disable drones' mid-session. In terms of the latter, for example, experts believe that such risk can be reduced by as much as a minimum of 90%, thus showing dramatically increased security (Rowland & Karch, 2022). Within the context of UAVs, and as part of the military environment, such devices can be described as flying computers that incorporate an advanced degree of autonomy, data processing that is carried out in real-time, and secure communications (Panwar et al., 2022). Together, all these components have allowed such manufacturers to expand their operations and capabilities beyond traditional functions like GPS spoofing and the jamming of radio frequencies (Thiessen et al., 2023).

E. RESILIENCE

Resilience in relation to UAVs is critical, as the units need to be sufficiently equipped with features that can block, isolate, and recover vital functions without the need for operators on the ground to intervene as a means of addressing or fixing the issue when it does take place (Thiessen et al., 2023). The aspect of resilience is further supported by the integrity of the overall supply chain that the drone manufacturer uses and relies on when producing its units (Shah & Kirchoff, 2025). Resilience also facilitates operational continuity of UAVs, as secure hardware helps drones to more easily revert to autonomous behaviors and functions in the event that command links become compromised (Finkhauser & Larsen, 2021). As drones become more software-reliant, cybersecurity embedded at the hardware level has emerged as a critical resilience measure.

F. AGILE PARTNERSHIPS AND FEEDBACK LOOPS

Collaborative design feedback loops between manufacturers and operators can rapidly reduce integration cycles and minimize downtime. Such relationships tend to be optimally structured when they have a high degree of agility and when they create stable and responsive partnerships and collaborations (Moradlou et al., 2020). For instance, the

U.S. Defense Innovation Unit embeds small engineering teams into front-line units (Sodhi & Tang, 2021). This practice provides the military with real-time and immediate feedback of the drones' positions and actions in the battlefield (Sodhi & Tang, 2021). In turn, data obtained through this feedback has reduced the length of development cycles by almost half when software on the UAS units needs to be upgraded or updated (Sodhi & Tang, 2021).

G. DECENTRALIZED "CROWD PRODUCTION" AS A RESILIENCE MODEL

An alternative approach to centralized production involves dispersing manufacturing tasks across a network of agile micro-producers. Supply chain security can also be facilitated through the process of so-called crowd production. As part of this concept, UAS units are manufactured through the collaboration of multiple smaller workshops (Waller et al., 2023). This process effectively leverages the benefits that can be generated through 3D printing and commercial off-the-shelf, or COTS, electronics (Bazaluk et al., 2024). This last process has also been applied in the Russia-Ukraine conflict, allowing Ukraine to produce millions of drone units that could be readily deployed to the frontlines of the conflict (Waller et al., 2023).

Various startups have also been used to address these identified production gaps and challenges. For instance, Palantir and Anduril have supplied equipment to the Ukrainian government (Waller et al., 2023). These two newer organizations have joined more established aviation corporations, such as Lockheed and Boeing, in the creation of a unified digital engineering framework (Waller et al., 2023).

H. EMERGING TECHNOLOGIES IN UAV MANUFACTURING

Technological advancements are reshaping how UAS are built, evaluated, and fielded. This section explores emerging manufacturing processes, such as additive manufacturing, digital twins, and blockchain. These processes enhance the speed of production, reduce overall cost, and improve system reliability.

I. ADDITIVE MANUFACTURING AND MODULE TOOLING

For instance, ongoing research at the University of North Texas, which heads the MUREP project, has centered on the concept of the UAS supply chain ecosystem becoming increasingly more resilient to be able to withstand rapid technological changes and foster adaptability on the part of suppliers and vendors (Eslami et al., 2023). This initiative focuses on the use of modular tooling, as well as digital technology, to speed up the design and manufacturing process from the initial drone prototype to batch-level manufacturing, to reduce the length of time that the process of retooling would typically require (Eslami et al., 2023).

The UAS manufacturing process has also focused on the integration of selective laser sintering, the installation of automated rivets, and the use of robotic composite layups, all of which has been shown to drastically reduce the length of required manufacturing time by up to 60% (Sarhadi, 2021). This reduction has direct implications for military readiness, allowing units to restock or modify drone fleets far more quickly than with traditional methods. For instance, the use of wing jigs that could be 3-D printed in-house by manufacturers has reduced this period by at least 70% on smaller drone lines (Sarhadi, 2021). This integration reduced the length of time needed for the changeover of fixtures within the manufacturing process, thus streamlining the overall process (Sarhadi, 2021). Over time, this could be scaled to support larger scale of manufacturing.

J. INTERNET OF THINGS AND DIGITAL TWINS

Manufacturers have also integrated Internet of Things, or IoT, into various lines, which serves and conducts multiple functions. This innovation has allowed manufacturers to gain real-time insight into the manufacturing process, so that any issues, such as those stemming from impaired quality, can be identified and addressed as rapidly as possible (Rodrigues et al., 2022). In this instance, IoT can be utilized to create a digital twin of the drone being manufactured, allowing the company to monitor this process as it is occurring (Rodrigues et al., 2022). Aside from being able to quickly catch any manufacturing errors or aberrations, integration of digital twins and IoT platforms also serve as a tool to allow the manufacturer to keep a tighter degree of control over its inventory (Mahobiya et al., 2024). This enables the manufacturer to predict which inventory parts may be in short supply and reorder them so that shortages do not occur and production is not stalled (Mahobiya et al., 2024). Overall, these changes help to ensure that proper throughput is maintained during times of peak demand and production (Haghnegahdar et al., 2022).

K. ANDURIL’S GIGAFACTORY: A NEW PARADIGM FOR DEFENSE MANUFACTURING

While each of the above models offers advantages in flexibility or speed, they also face limitations in scaling, standardization, and integration. To address these, some firms have pioneered Gigafactories, which consolidate the entire supply chain and engineering life cycle.

Although much research has been conducted on the topic of high-volume UAV production, there still seems to be a gap around Gigafactories. The concept of a Gigafactory can be traced to Tesla (Greitemeier & Lux, 2025). The Gigafactory model is rooted in the concept of a massive manufacturing campus that is vertically integrated and has the ability to combine the key critical functions of manufacturing, comprising of fabrication of individual components, the processing of raw materials, and research and development, all integrated into a singular facility (Naor et al., 2021). The same model, when applied to the drone manufacturing industry, can generate multiple advantages. However, it could also pose some unique challenges that manufacturers would need to attempt to overcome.

One of the main benefits of the Gigafactory model is the ability to manufacture components in-house and without needing to outsource this function to external vendors or suppliers (Naor et al., 2021). For instance, housing such functions, as software testing labs, within the same manufacturing facility can reduce order lead times and positively impact the aspect of margin stacking (Han et al., 2024). Such an organizational setup also allows for the various subunits or departments of the manufacturing company to share their infrastructure, thus reducing costs and creating additional opportunities for the creation of economies of scale for the manufacturer (Naor et al., 2021). Finally, the shared singular space also allows for the creation of research and development loopbacks, as the research and development teams can gain insight from the production line to make tweaks or changes to the next prototypes (Greitemeier & Lux, 2025). This ability has the potential to reduce costs associated with tooling and retooling changes that would typically be done externally (Greitemeier & Lux, 2025).

The Gigafactory model, when adopted by the drone manufacturing industry, can also add resilience to the industry's supply chains. For instance, when alloy stocks, along with semiconductor supplies, are already on the site of the company's manufacturing premises, the company is buffered against industry shortages that may be occurring in other areas of the world and any sudden changes in export regulations (Greitemeier & Lux, 2025). Such buffering allows for the minimization of operational risk (Greitemeier & Lux, 2025). Because all these components are already on hand, the company can incorporate more stringent quality control measures at every level of the manufacturing process (Wicke et al., 2025). Additionally, due to operations being localized, companies can create more local supply chains by co-locating vendors inside the campus or nearby, which aligns with the just-in-time inventory management model and reduces the degree and incidence of delays on the part of suppliers and any associated bottlenecks (Wicke et al., 2025).

L. COMPARATIVE UAS PRODUCTION MODELS

There are multiple defense production models that can guide the design and manufacturing processes pertaining to UAS. The four models that are dominant within this context include the "Silicon Valley" embedded model, the decentralized "crowd-production" model, the additive-manufacturing surge model, and the prime-startup and digital-engineering consortia model. Each of these models takes on a different approach to meet the unique demands of UAS customers' requirements. Recent research on UAS manufacturing highlights two predominant production approaches: boutique manufacturing that customizes drones for specific client needs, and agile, scalable production models designed to grow with a company's evolving life cycle (Tahmina et al., 2022).

M. SILICON VALLEY EMBEDDED TEAMS

The "Silicon Valley" embedded model is rooted in the use of small technology teams that excel in agility (Baker & Welter, 2024). Such civilian units work together with the military to speed up the rate at which the manufacturer receives feedback and the generation of each new iteration of the UAS model (Bremner & Eisenhardt, 2021). This model combines the technological civilian side of the design aspect of UAS, while the military provides the applications of the UAS (Bremner & Eisenhardt, 2021). The tech teams can enhance and change the model that they are working on based on the information obtained from the military unit testing or using the given model (Bremner & Eisenhardt, 2021). Both teams gather UAS data in real-time and work to rapidly make updates to the model's software, hardware, or both, if needed (Baker & Welter, 2024). This practice has dramatically reduced the number of iteration cycles that are part of the UAS design and manufacturing processes.

N. DECENTRALIZED CROWD PRODUCTION

The second prominent model is that of decentralized "crowd production." As previously discussed, this model is employed when multiple workshops work together in a decentralized fashion (Bazaluk et al., 2024). In such a scenario, workshops can specialize in the use of additive tools and create a more cohesive workspace model. Additionally, this model allows such workshops to specialize in one area of the drone creation process or a specific part, for example, thus facilitating the mass production of drones. Workshops typically rely on open-source designs that can be easily and readily altered, as well as on techniques and strategies that support the rapid prototyping of UAS units and innovative designs (Bazaluk et al., 2024). These workshops have been observed within the ongoing conflict between Russia and Ukraine, as the latter has been able to leverage crowdfunding and donations from all over the world to generate a decentralized grassroots production ecosystem. This creates networks of volunteer-led workshops and fabrication labs that are capable of mass producing critical UAS units, circumventing the traditional defense industrial bottlenecks (Waller et al., 2023). Producers were able to scale this strategy to millions of units with integrated first-person view, or FPV, technology along with the loitering of munitions (Waller et al., 2023). This strategy was instrumental in offsetting the typical bottlenecks that often cripple and slow down the traditional supply-chain underlying UAS production (Panou et al., 2024).

O. ADDITIVE SURGE MODEL

The third major model is the additive-manufacturing surge model, which relies on the 3D printing of specific components. Such components are typically subsystems and airframes (Paul & Paul, 2023). This structure minimizes the inventory required for the manufacturer to keep in terms of base parts and raw materials, as subunits can be 3-D printed when they are needed (Wang et al., 2024). It also eliminates the need for the manufacturer to retool their operations (Paul & Paul, 2023). Furthermore, it also allows for the creation and use of rapid-production cell kits, which can speed up production more (Wang et al., 2024). This model has been exemplified through the U.S. Army's 3-D printing of target drones, allowing this branch of the military to construct composite airframes in under the span of a month (Paul & Paul, 2023). By engaging in this strategy, the U.S. Army was able to ready hundreds of UAS units that could be rapidly deployed in military exercises to prepare enlisted personnel for battle (Bird & Ravindra, 2021).

3-D printing is cost effective in certain scenarios and under specific circumstances. Such scenarios and circumstances occur when production volumes are low, as the printer does not need as much configuration to adjust for variances between units (Muralidharan et al., 2021). More specifically, this applies when manufacturers design and produce prototypes and the batches are kept to under 500 units with every printer setup and configuration (Muralidharan et al., 2021). Another instance that makes 3-D printing cost and time effective is when the geometry of the drone's parts is complex enough that more traditional machining or injection molding methods would prove to be far more expensive due to the complicated tooling involved or the fact that several processes would need to be integrated into the manufacturing function (Candi & Beltagui, 2019). 3-D printing is also useful and reduces aggregate costs when there are frequent changes to the overall design process that are expected on the part of the manufacturer (Candi & Beltagui, 2019). In such instances, when using 3-D printers, manufacturers can avoid the need to remake molds or have to retool machines, thus saving both time and money (Muralidharan et al., 2021). Finally, 3-D would be ideal with there is a high need to customize various parts of the unit being produced, as the printer can easily make such changes with programming and command inputs (Kamonsukyunyong et al., 2025).

3-D printing is, overall, well-aligned with the manufacturing of smaller batches, as other manufacturing methods, such as die casting and injection molding, are better suited to large batch formats (Kamonsukyunyong et al., 2025). When compared against one another in relation to larger batches, these other manufacturing techniques can drastically reduce the per-unit cost (Kamonsukyunyong et al., 2025). At the same time, the main disadvantage is that those manufacturing methods lack the flexibility of being able to easily adjust the design of the unit during the manufacturing process (Kamonsukyunyong et al., 2025). Furthermore, conventional large scale manufacturing also requires a high upfront cost pertaining to molds and dies, which becomes a clear disadvantage in situations where a military effort may be strapped for resources, which is an example of what is taking place in the Ukrainian war effort against Russia (Shah & Kirchhoff, 2025). Additionally, in this particular instance, the function of research and development, or R&D, is useful in the creation of smaller batches that can be further worked on to improve specific features to achieve a greater degree of success on the battlefield (Shah & Kirchhoff, 2025). Finally, when manufacturing is not dispersed, Russian forces can more easily target entire facilities, which increases the risk of a large hub being destroyed in the process (Shah & Kirchhoff, 2025).

P. PRIME-STARTUP DIGITAL CONSORTIA

The fourth major production model is that of prime-startup and digital-engineering consortia model. This approach combines the traditional partners that have historically played a key role in defense strategies and startups and other venture-backed firms (Vrana & Singh, 2021). This strategy allows such mutually beneficial operations to take place under the umbrella of a digital-engineering network as a means of reducing production timelines (Vrana & Singh, 2021). This strategy is rooted in the creation of digital twins that can be shared between partners, as well as the use of model-based systems engineering, or MBSE, and pipelines that operate based on secure data (Vrana & Singh, 2021). Together, all these tools allow diverse groups of stakeholders to share a single virtual platform to accomplish individual and collective objectives (Mosterman & Vangheluwe, 2024). This can be seen in the shared work of Lockheed Martin and Boeing partnering with Palantir and Anduril to increase their drone manufacturing output, as such efforts have yielded at least 1,000 UAS units equipped with AI capabilities (Mosterman & Vangheluwe, 2024). Without such collaboration, it would have taken far longer for production of these same units. Although this is a relatively small degree of output, Anduril is working on enhancing and increasing the number of units that can be manufactured in such a manner (Mosterman & Vangheluwe, 2024).

Q. FORD MODEL T FOR DRONES

The fifth such model is that of the Ford Model T in relation to UAVs. This model is rooted in Henry Ford's Model T, which made its debut in 1908 (Keagle & Cahall, 2011). The model is founded on the basis of standardization of parts, a streamlined assembly, and a focus on affordability (Keagle & Cahall, 2011). In terms of standardization, units utilize the same basic frame, but the individual components are fully interchangeable (Keagle & Cahall, 2011). In relation to the assembly, the actual assembly line is a moving one, which has, historically, reduced the time to build units from roughly 12 hours to about 90 minutes for the Ford Model T (Keagle & Cahall, 2011). Ford also focused on affordability, so that the company's vehicles could be easily purchased by what would be considered the average consumer, as opposed to restricting such goods to only those consumers with sufficient financial resources (Keagle & Cahall, 2011). When the model came out initially, Ford worked on reducing the per unit price from $850 to under $300, greatly expanding the range of who could feasibly make such a purchase (Keagle & Cahall, 2011).

As an example, Anduril has used this model in practice. For instance, the company is focusing on generating standardized drone platforms that account for payload bays that are swappable, as well as batteries and communication modules that can fit multiple drone types and models (Munoz et al., 2022). The company is also working on tuning its manufacturing processes to align them with the production volume, as well, so that any custom rework can be reduced to a minimum (Munoz et al., 2022). Furthermore, the company is also focusing on lowering and pushing down its per-unit cost to increase the affordability of its drones (Munoz et al., 2022). This would also allow the company to deploy drone units in large numbers to accomplish their intended missions (Munoz et al., 2022). Beyond this, Anduril is following that model in relation to software-defined capabilities that allow for the same base hardware to carry out various types of tasks, such as strikes and logistics simply by swapping sensors and uploading new mission-specific software systems (Munoz et al., 2022).

This particular model is well-aligned with the company's need for resilience, as the Model T drone platform has multiple advantages. For instance, it simplifies supply chains, enables rapid replacement, drives economies of scale, and supports field repairs (Munoz et al., 2022). Together, this allows Anduril to shift away from a model that focuses on a high degree of customization, which correlates with very small batches and allows it to shift to a model of mass production (Salvador, 2023).

III. METHODOLOGY

This study relies on a grounded, data-driven methodology centered on a comprehensive Bill of Materials (BOM) that was co-developed with a team researching UAS systems (see Berg, 2025; Gonzalez, 2025; Rhodes, 2025). The purpose of the BOM is to identify similarities across subsystems at the component level to lend credibility to the Gigafactory as the most advantageous model for the production of UAS at scale. A key point of this BOM is that the team studying UAS models focused on small, attritable systems that could be produced en masse, and therefore, the material costs are low. Additionally, the specific production cycles of each subsystem will help identify the processes that need to be implemented in the Gigafactory to support serving as a "one-stop shop" for the end item.

A. INTRODUCTION TO RESEARCH METHODOLOGY

Our goal was to assess whether the U.S. defense industrial base, in its current state, can support high-volume drone production by means of the Gigafactory model. We leveraged operational insights from the Russo-Ukrainian conflict to translate drone acquisition and throughput in a wartime environment against how the U.S. currently acquires UAS today. While the Ukrainians can mass-produce drones to fit their requirements, they have far less political and acquisition "red-tape" than the U.S. has. "Ukrainian drone factories import components – in particular, Chinese components – and they also depend in part on foreign financing" (Axe, 2025). As the conflict between Russia and Ukraine highlight the importance of drones, some have speculated that Ukrainians have been able to produce their drones entirely by themselves which is not the case as foreign third-parties are able to source Chinese manufactured parts to aid Ukraine. However, even through their own foreign dependence on drone production, the Ukrainians are still producing over 2.2 million drones a year and are expected to produce 4.5 million drones in 2026 (Axe, 2025). The drones that were used in the development of the BOM constitutes the goal to determine how to create the most cost-effective platform to serve as a baseline.

Specific data is relayed on components, costs, sourcing origins, and surge production capabilities, utilizing open-source information.

Our methodology combines platform decomposition, supplier sourcing analysis, and a spreadsheet data model to help decision-makers visualize individual component vulnerabilities and prioritize mitigation strategies. While this analysis is grounded in technical data, the structure of the model is designed to inform assessments at the strategic, programmatic, and industrial base level. As the DoD continues to expand its use of autonomous systems in contested environments, this analysis will supplement decision-making to guide important strategies.

The study focused on multiple drone manufacturers and platforms with varying capabilities, such as loitering munitions, ISR, quadcopters, and reusable interceptors. The use and analysis of multiple platforms allowed us to identify recurring component requirements and functional commonalities relevant to high-rate production. This allows the analysis to reflect broader trends in the defense UAS ecosystem rather than the proprietary nature of the designs. This section serves as the foundation for understanding how we used component-level data to evaluate the feasibility of production, which will shape the recommendations in Chapter Six.

B. OPEN-SOURCE BOM CONSTRUCTION

The core dataset was developed using a combination of open-source technical specifications, teardown imagery, supplier databases, and commercial-off-the-shelf (COTS) catalogs. The output is a master Excel workbook featuring:

- A unified master BOM to cross-reference parts by drone type, weight, cost, and criticality
- Categorization of parts into functional subsystems (i.e., powertrain, electronics, etc.)
- Aggregated weights, costs, and vendor classifications (U.S., allied, foreign adversary) for each component

- Use of proxy weights and estimated unit costs when exact data was unavailable which is clearly annotated.

This format enables consistent scaling of part-level costs across the various platform weights and configurations.

C. FUNCTIONAL CLASSIFICATION AND SUBSYSTEM DECOMPOSITION

Each component was mapped to a subsystem category to enable system-level insights and functional relevance. The categories include:

- Powertrain – Motors, propellers, and batteries
- Electronics – FC/autonomy processor, ESC, ECU/onboard computers
- Structure – Airframe assembly, and mounting and fastening hardware
- Software – Development and architecture, integration and testing, and sustainment and scalability
- Miscellaneous – Peripherals

This structure facilitates horizontal comparison across subsystems to highlight commonalities, cost drivers, and sourcing risks.

D. RISK ASSESSMENT METHODOLOGY AND COST MODELING

One of the primary objectives of using the Gigafactory model in our studies is due to companies like Anduril (U.S.) and Velter Drone Brigade (U.K.) adopting this model to expand their drone manufacturing capacity while accelerating production timelines (Anduril, 2025; Velter Drone Brigade, 2024). The Gigafactory model can be used to implement mitigation strategies and reduce risks associated with the materials. The variety of different strategies therefore create potential use-scenarios that can support decision-makers in guiding future investments. To clearly and concisely communicate these insights, we developed a matrix to assess risk and highlight key materials that are susceptible to supply chain constraints and limited scalability defined earlier in this chapter.

The matrix uses a scoring methodology based on open-source data available at the time of analysis. Each component was evaluated using the following criteria:

- Origin of Source Risk: – Are the components dependent on foreign suppliers or non-allied nations.
- Production Bottleneck Risk: – Do the components have long lead times or rely on limited domestic production capacity.
- Material Criticality: – Do the components rely on rare earth elements, lithium, or materials classified as critical by the DoD or U.S. Geological Survey.
- Availability Risk: Are the components highly susceptible to supply shortages.

The risk assessment uses a 1–5 risk scale (one is the least risky, five is the most) to evaluate each subsystem. The assigned numbers are based on the total number of components that make up the system, which are subject to availability outside domestic production sources. For example, "China for years has been the world's largest refiner of Lithium, with roughly 70% market share; these Lithium refineries turn the metal into a form that can be used to make cathodes for batteries" (Scheyder, 2025). This will lead to a riskier rating for batteries, especially as we currently navigate through economic and trade tensions with China.

To complement the supply-chain risk matrix, an additional scoring framework was developed to evaluate how well each subsystem aligns with a Gigafactory-style production model. While the risk matrix identifies external vulnerabilities such as foreign sourcing, material criticality, and price volatility, the Gigafactory scoring system assesses internal manufacturability and scalability factors that influence whether a component benefits from centralized, high-rate production. Each component was evaluated across the following criteria:

- Standardizability: The degree it can be produced through repeatable uniform processes.

- Automation Potential: How feasible is mechanizing its fabrication or assembly.
- Centralization Value: Cost, speed, and efficiency advantages received from producing the component in-house.
- Co-Location Feasibility: Whether production can be integrated into a consolidated facility.
- Scale-Curve Intensity: The degree of cost decline per-unit with increased production volume.
- Sourcing Fragility: Susceptibility to supply-chain bottlenecks or single-source dependence.
- Unit Production Time: Estimated labor or machine time to produce each component.

These metrics combine into an overall Gigafactory suitability index, which highlights which subsystems provide the greatest return on investment when integrated into a centralized automated production line. Together the supply-chain risk matrix and the Gigafactory suitability model provide a dual-lens assessment that captures both the vulnerabilities of the current supply base and the manufacturing opportunities available through industrial coordination.

Per-drone costs were calculated by summing the total BOM cost per system, weighted by part inclusion and factored for the drone size. These costs will provide decision-makers with a baseline for production and acquisition decisions. With an approximate base cost, it will be easier to discern end-item costs from tangible hardware, intangible hardware, and manufacturing overhead to be undertaken by the Gigafactory. This enabled modeling of cost differentials between distributed and centralized production scenarios, which will provide further detail to DoD requirements owners when conducting market research. While the Gigafactory model can leverage modularity to adapt end items to owners' specifications, the cost increases exponentially as the capabilities sought become more niche and tailored to specific scenarios (Anduril, 2025). Finally, software can make or break large-scale production due to its iterative nature, the need for consistent updates and support, and the risk of overreliance on vendors because of its proprietary nature.

IV. ESTABLISHMENT AND UTILIZATION OF THE GIGAFACTORY MODEL: A CASE STUDY

A. OVERVIEW

Anduril's (2025) Gigafactory model has been commonly known as either Arsenal-1, or, just simply, Arsenal. This moniker was selected by the company as the organization wishes to evoke the image of a traditional arsenal, or a large industrial-style site that manufactures and supplies weapons (Anduril, 2025). Beyond this, the company also selected this nickname as a means of highlighting the idea that this project is the first of its kind in terms of hyperscale and industrialized lines of defense factories (Hopkins & Tavares, 2025). This is identified by the number 1 following the name of Arsenal (Anduril, 2025). The company utilizes this name both literally, as a place where the organization manufactures weapons in the form of UAVs, as well as figuratively to show its manufacturing scaling efforts (Hopkins & Tavares, 2025).

Anduril's (2025) new Gigafactory in Ohio is designed to be about 5 million square feet in space and is located on about 500 acres of space. The objective of the company is to generate multiple thousands of UAV units every year and create approximately 4,000 jobs (Anduril, 2025). The company has been incentivized to create and expand its Gigafactory model by the state in which its factory is located in (Anduril, 2025). Such incentives have been promised to the company over a period spanning multiple years, thus providing the company with a high degree of financial security (Anduril, 2025). Overall, this particular location is intended to be Anduril's (2025) flagship Gigafactory location. Figure 2 shows the design of the facility (Jarrell, 2025).

Figure 2. Anduril Gigafactory Layout – Factory Model. Source: Semenyuk et al. (2024).

The company's Gigafactory model is its push to shift the manufacturing of defense hardware, which includes UAVs and its various components (Semenyuk et al., 2024). Such components range from low volume and highly tailored units to a mass produced high volume model (Semenyuk et al., 2024). The premise behind this model is the scaling of production to maximize the number of units produced, while keeping incurred costs to a minimum (Semenyuk et al., 2024).

The Gigafactory model used by Anduril is rooted in designing the factory to create an architectural framework as part of which the machinery, any test rigs, and the actual production lines share various interfaces, as well as tooling, amongst themselves (Tomasso, 2025). Such a strategy has the ability to drastically push down costs so that the platforms that are available to the company can be utilized to their greatest capacity (Tomasso, 2025). Additionally, this strategy also reduces the length of time that is required to set up equipment for a specific manufacturing part or process and increases the company's flexibility in terms of its manufacturing capacity (Tomasso, 2025). As part of this model, UAV components and units are manufactured through the use of modular building blocks that share common subsystems, such as power, so that units can be assembled in high numbers, as opposed in small batches (Olanipekun et al., 2023). As such, it is the aspect of standardization that serves as the foundation of the company's Gigafactory model.

The company's Gigafactory model is reliant on a strong layer of software technology that connects the functions of design, supply chain management, assembly, and testing (Olanipekun et al., 2023). This is advantageous due to the fact that such actions, as quality checks of the components and units can be automated, thus reducing the length of time between design and sales (Miske, 2023). As opposed to treating its software stack as an advantage that facilitates its ability to effectively compete with other organizations in the industry, as opposed to as part of its overhead (Miske, 2023).

B. ADVANTAGES

The Gigafactory model also allows the company to utilize robotics and automation abilities as a means of addressing tasks that are repetitive in nature (Karali et al., 2024). This positions the company to focus its human resources on roles that require a higher degree of skill (Karali et al., 2024). This framework also allows the company to simplify its existing and any new processes as a means of widening its possible pool of available and qualified workers (Semenyuk et al., 2024). This means that the future plans for further Arsenal-1 expansion incorporate thousands of new jobs in spite of the increased automation that the framework inherently entails (Semenyuk et al., 2024).

Anduril's Gigafactory model uses vertical integration, which helps to increase the resilience of its supply chain. Through vertical integration, Anduril has been able to internalize many of its manufacturing processes (Semenyuk et al., 2024). This, together with tooling that can be reused repeatedly can reduce lead wait for new orders and units (Karali et al., 2024). Additionally, this reduces the company's need to rely on defense supply chains that have traditionally been utilized within the industry (Karali et al., 2024). Furthermore, this is vitally important within the defense industry due to the fact that this strategy helps it to replenish required units during times of conflict and war (Cury, 2024).

V. ANALYSIS OF BOM IMPLICATIONS FOR CENTRALIZED UAS PRODUCTION

This chapter outlines the process used to create the Bill of Materials (BOM) and assesses the resiliency of various UAS platforms concerning production at scale. When assessing the production of UAS platforms, we used the Gigafactory model. The Gigafactory model was primarily used because UAS companies such as Anduril have recently opened their Gigafactory in the U.S. Using the Russo-Ukrainian conflict as a relevant case study, we reviewed drone selections compiled by the UAS team that assessed platforms relevant to U.S. defense needs in future conflicts (see Berg, 2025; Gonzalez, 2025; Rhodes, 2025). Component analysis was used with each platform to establish dependencies, identify vulnerabilities, and assess the feasibility of scaling production during crisis conditions.

Through the analysis of the component dependencies, sourcing vulnerabilities, and feasibility of scaled production, we created a sourcing risk framework. This chapter helps to determine whether centralized manufacturing strategies, like the Gigafactory model, can reliably sustain large-scale UAS production in the Great Power Competition.

A. SUBSYSTEM CLASSIFICATION AND FUNCTIONAL DECOMPOSITION

We used a functional decomposition approach to analyze the component requirements for each platform studied. This method organizes every part of the drone's architecture into subsystems, creating a structured assessment of cost distribution, sourcing risk, and scalability concerns about specific platforms.

Each drone was decomposed into seven subsystem categories to establish a general understanding of the preferred production method and cost constraints from a top-to-bottom and bottom-to-top perspective. Separating these categories allow for traceable mapping between component function, performance, and production feasibility under the Gigafactory model. Five classifications are used in this study:

1. Powertrain – Includes the motors, propellers, and battery components that enable lift, maneuverability, and sustained operations in UAS platforms. The powertrain components generate and deliver the mechanical thrust and energy that enable the drone to operate.

Motor: "The brushless motor consists of a permanent magnet rotor that creates a constant magnetic field and a stator wound with copper wire that forms the electromagnetic poles" (T-Drones, 2024). The controller works to stabilize the currents, creating a rotating magnetic field that causes the motor to spin. Brushless motors are preferred because maintaining brushes reduces overall efficiency and can hinder prolonged use. Figure 3 shows the brushless motor composition.

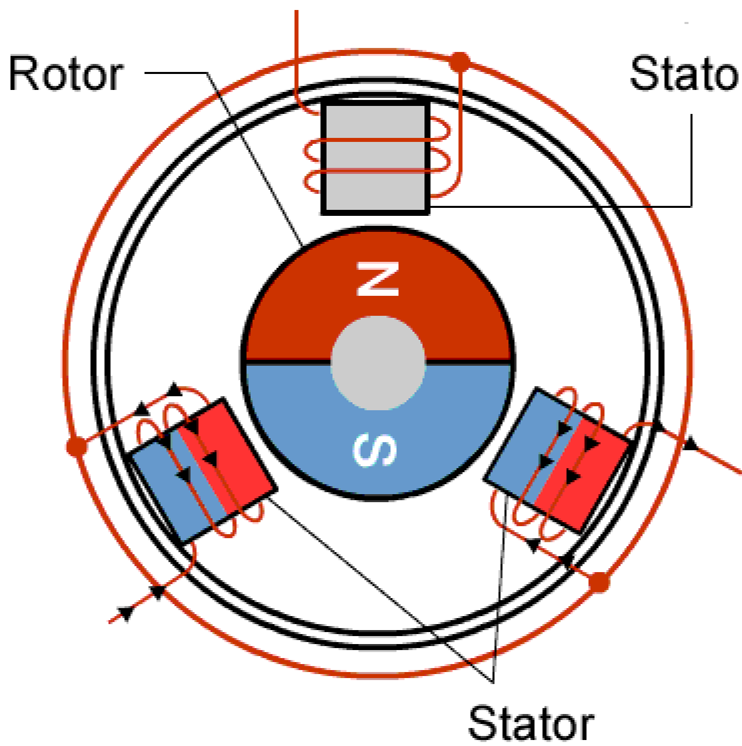

Figure 3. Brushless Motor Design. Source: T-Drones (2025).

While Brushless motors are the preferred style of motor in UAS platforms, they are much more complex than their brushed counterparts. This complexity becomes a significant cost driver when considering non-standardized scales that could be available through the Gigafactory model. When looking at production at scale, standardizing a brushless motor becomes important, as the composition and coordination of parts are similar to building a computer. For example, when building a computer, if the power supply does not match the motherboard's voltage requirements, the computer will not function properly. This is similar to the brushless motor and the Electronic Speed Controller (ESC), where the ESC's voltage rating must match or exceed the motor's current draw to ensure optimal performance and prevent overheating (T-Drones, 2024). When it comes to the production process, standardization becomes key to ensure that stamping, laser cutting, and coil tightening are consistent, reducing complexity and improving quality control standards necessary for high-rate performance.

Additionally, other methods have been used to produce brushless motors more cheaply through 3D printing using fused deposition modeling (FDM) with polylactic acid (PLA), which reduces weight, extends flight times, and increases customizability (Akula, 2024). 3D printing technology is still new in this production model, as the study is dated in late 2024. However, if it is successfully implemented, it could be incorporated into the Gigafactory model and significantly reduce the cost constraints of mass production.

Propellers: Additive manufacturing follows the basic method of slicing a three-dimensional part into thin layers. Additive manufacturing allows you to significantly reduce the quantity of raw materials required, the ability to produce usable parts from a Computer Aided Design (CAD) file in hours, and the ability to produce complex parts without the need for retooling (Rutkay, 2016). Utilizing 3D printing to create the propellers should be the primary method as once the design is created it can be produced in scale to fit the drones. Additionally, when focusing on attritable drone designs, the type of propeller will vary depending on the weight and capabilities of the platform. For this reason, 3D printing will allow for limited customization where need be to support modularity, but once the CAD is developed for mass production platforms they can be created at the scale necessary to support the desired throughput.

Batteries: Lithium-ion battery production represents one of the most complex and resource-intensive elements when producing UAS in scale. Expertise in chemistry, material handling, and environmental stability lead to a higher barrier to scaling than other subsystems. Battery production. Jack Xing with Lithium Battery Tech goes into detail on the production process from the chemistry to production. Electrodes are the starting point for battery production where raw materials such as graphite and lithium compounds are extensively cleaned as any impurities can hinder battery performance. Once the cleaning has been completed, the compounds are mixed with special solvents to create a slurry. This slurry has to be the right consistency as it links directly to the amount of energy the battery can store along with how fast it charges and discharges. The slurry is then spread onto anodes made of copper and cathodes made of aluminum in a "coating" process. At the conclusion of this process, the foils go through drying tunnels to get rid of excess solvent and then will be cut to fit the battery (Xing, 2023).

The assembly line is where the foils get a special coating of active materials designed to store and release energy. These materials do not let the folds touch, but allows the ions to pass through the foils. Next, the electrolyte is added which allows the ions to move freely and boosts the battery performance by acting as a conductor. They are then transferred to cylindrical tubes or pouches and connected to terminals and cell tabs. Finally, the batteries are subjected to an extreme quality control standards to test voltages, heat handling, and safety (Xing, 2023). This production process is further exacerbated when taking foreign export controls that are affecting primary components such as lithium that create significant bottlenecks due to availability. Additionally, the labor force required for these processes demand highly-skilled professionals which can raise labor costs.

According to industry experts most domestic battery suppliers currently operate at the kilogram-scale output level. This level of output is well suited to research and small-scale production but far below the industrial throughput that is required by the Department of Defense. This limited scale drives per-cell costs to several dollars, compared with approximately eight dollars per cell at volumes above one-hundred thousand units that can be achieved by major commercial manufacturers (Personal communication, November 3, 2025). They further emphasized that the primary constraint in scaling U.S. lithium-ion production lies in access to and processing of active materials, which must be centralized to a dedicated manufacturing base.

2. Electronics – These components include the flight controller, autonomy processor, ESCs, embedded computing units, and onboard computers. These components enable autonomous operation, real-time decision-making, and integration with C2 systems currently used in DoD organizations, which are critical to the future capabilities that warfighters will need.

Flight Controller / Autonomy Processor: "There are two types of FCs: One is more plane-oriented, while the other is more multirotor-oriented. This doesn't mean you can't use a plane FC on a multirotor or vice versa, but you will likely face more challenges." (Liang, 2024). Some FCs can incorporate the ESC into it as well and is referred to as an "all-in-one," however, those types of FCs are more suited to micro-drones and begin to lose capabilities the DoD seeks in drones. The main component of the FC is the PCB which is the "brain" of the drone, which is developed similarly across the general electronics industries. According to Wonderful PCB (2025), there are three parts to the production of PCBs: The flexible part, the rigid part, and the rigid-flex part, all three encompass similar procedures which can be viewed in Figure 4.

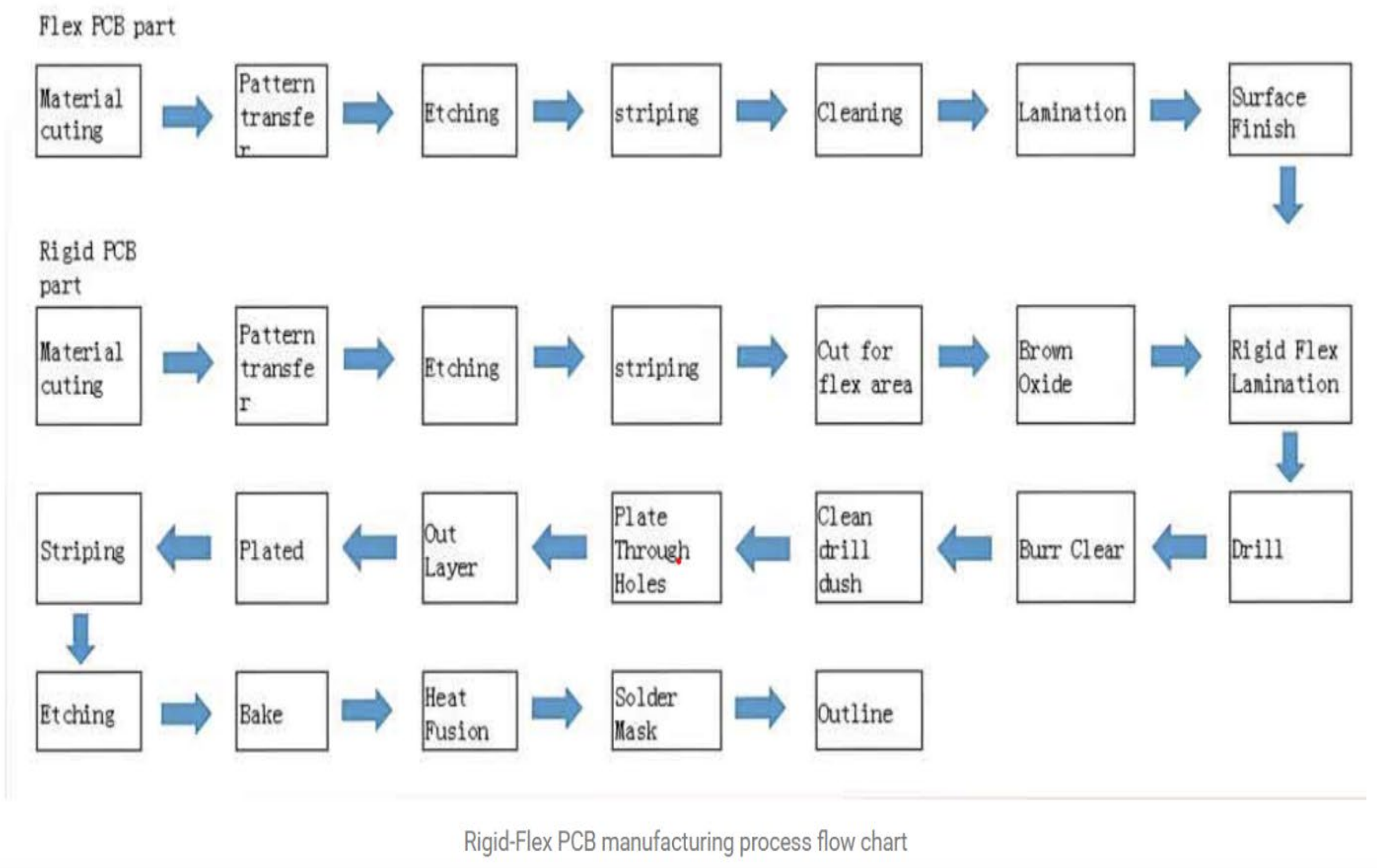

Figure 4. PCB Manufacturing Process Flow Chart. Source: Wonderful PCB (2025).

Once the fabrication of the PCB has been completed, the FC goes into the SMT phase which is the longest process in electronics production. The SMT phase involves integrating fabricated components onto PCBs through automated SMT or manual through-hole assembly. In serial production, PCBs are first coated with solder paste via stencil printing, followed by component placement with Pick and Place machines and subsequent soldering in reflow soldering machines. For through-hole components, wave or manual soldering is utilized to achieve full connectivity. Post soldering operations include AOI, cleaning, and functional testing to verify assembly before firmware programming (Feng, 2024).

The final stages of FC assembly is testing and quality control. When designing subcomponents for drones the most important tests are vibration, reliability, and thermal testing as these will halt operations immediately and cost thousands of dollars to replace. "Testing is performed through Automatic testing and Manual testing processes. In Automatic testing, testing is performed through dedicated software, whereas per the product parameters are fed and the software checks those parameters. Manual testing utilizes trained technicians to manually check the parameters (Feng, 2024). Going hand in hand with testing is quality control where the end product is sorted into the different industries it was designed for (commercial, industrial, defense, etc.) and prepared for final distribution.

Electronic Speed Controller: A typical ESC is composed of a power stage, gate driver circuitry, current and voltage sensors, and a microcontroller unit that executes the motor control algorithm and communicates with the FC (Mogensen, 2016). Additionally, Figure 4 in the TI paper illustrates the functional block diagram depicting the integration of these subsystems in a compact module to meet the requirements of UAS platforms.

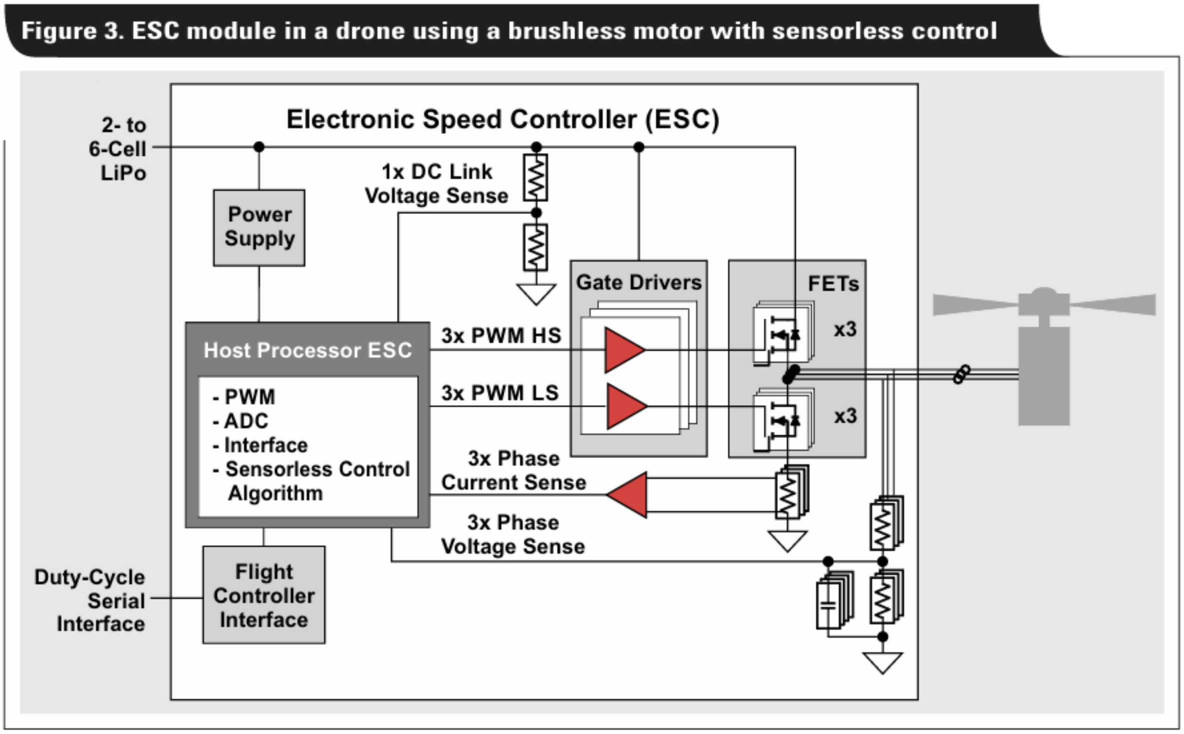

Figure 5. ESC Composition and Subsystem Integration. Source: Mogensen (2016).

When focusing on manufacturing the ESC, the processes are similar to the power-electronics module fabrication that is seen widespread in the electronics industry. Torrey Hills Technologies identifies that the traditional chip-on-board assemblies rely on manual die attach, wire bonding, and epoxy encapsulation which limits scalable throughput and thermal reliability. Contemporary ESCs instead leverage flip-chip mounting and 3D metal-post interconnect parallel plate structures (MPIPPS) that allow semiconductor dies to be mounted directly to the substrate with solder bumps or copper pillars, reducing interconnect length and electrical resistance (Torrey Hills Technologies, 2020). One of the biggest disadvantages identified by Torrey Hills Technologies is the complexity, cost, and design software for these packages. However, when looking to produce UAS in scale, these costs can be allocated across production which would reduce these constraints to a more manageable level. When looking at longevity the raw materials used to effectively solder the components together becomes important. Bare copper has a high thermal conductivity lending it ease in soldering; however, its expansion rate would cause failure after few cycles. For this reason, copper tungsten is the preferred material to provide thermal management and attachment of components without sacrificing component failure (Torrey Hills Technologies, 2020).

Embedded Computing Units / Onboard Computers: The ECUs are the interlink between the FC and the ESCs managing the drone's overall operation. The total number of ECUs relative to the drone are dependent on the capabilities current industry is pursuing in their platforms. "From a technology perspective, current UAS can perform multiple tasks such as collision avoidance, SLAM navigation, waypoint navigation, autonomous takeoff and landing, path planning and decision-making, among others, simultaneously. If we then consider the emerging drivers of BVLOS operations, airspace integration, functional safety, autonomy, multiple UAS operations, industrial internet of things and cognitive functions, the computation demands coupled with SWaP constraints of the onboard embedded computers is drawn into question" (Mejias et al., 2021). ECU's and onboard computers are created in similar fashion to the other electronics components described earlier. They following the same sequence of fabrication, surface-mount assembly, soldering, testing, and inspection. The key difference however is the integration of higher-density processors and memory modules, which require enhanced thermal management, electromagnetic shielding, and conformal coating during the final assembly. These additional considerations add to the complexity of the subcomponent, but remain compatible with the standard automated electronics manufacturing processes (Viasion Electronics, 2024; Torrey Hills Technologies, 2020).

3. Structure – Responsible for the physical framework that supports all other components of the drone. It includes the airframe assembly, and mounting fastening hardware that provide rigidity, aerodynamic form, and protection for sensitive internal components. This subsystem determines the drone's physical dimensions, structural integrity, and ability to withstand mechanical stress during flight and landing.

Airframe Assembly: "When manufacturing drones, selecting the appropriate materials is crucial for ensuring durability, efficiency, and optimal performance. Some of the most common materials used for various drone components are Carbon Fiber Reinforced Polymer, Aluminum Alloys, High-Density Foam, Polycarbonate, and Nylon" (Prototek, 2025). It's important to distinguish that materials that comprise the structure are not a one-size-fits-all approach but need to be combined in different aspects to create the product. For example, Prototek, a U.S.-based additive manufacturing and CNC machining firm, distinguishes between materials based on their intended function. Carbon fiber and aluminum alloys are typically used for the frame, fuselage, and wing structures, while nylon and polycarbonates are used for propellers and camera mounts. "Carbon fiber is the most commonly used material in drones due to their lightweight and high strength, stiffness, durability and corrosion resistance, electrical insulation, and design flexibility (NitProComposites, 2025). However, even with the benefits of carbon fiber, there are some disadvantages that make it more difficult for smaller industries to enter the market. For example, NitProComposites adds that carbon fiber is relatively expensive in comparison to other materials in drone production. Additionally, the process becomes more complex due to the brittle nature of carbon fiber which can lead to structural failure if not well designed.

"When it comes to the production process, the general overview is that the components will go through a design phase, mold creation, carbon fiber sheet preparation, layup, resin infusion, curing, trimming ,assembling, testing, and quality control" (NitProComposites, 2025). Additionally, Prototek defines five different methods for producing drones: Additive Manufacturing (3D Printing), CNC Machining, Cast Urethane, Fabrication, and Injection Molding. When the focus is on scalable production, fabrication and cast urethane is not the best approach due to significantly higher costs for smaller batches and increased labor hours to produce the drone. However, "Additive manufacturing, the standard for making drones, allows for designs that are challenging or impossible to achieve under traditional methods offering high customization, material waste reduction, and rapid prototyping (Prototek, 2025). CNC machining and injection molding are also viable for drone production and generating economies of scale and efficiency, reducing costs and increasing profitability for industry competitors.

Mounting and Fastening Hardware: One of the largest challenges in drone manufacturing is needing to balance lightweight materials with the strength and durability to allow for the drone to endure sustained operations. "In industrial drone manufacturing, achieving precise tolerances in the assembly of machining drone parts is a critical challenge. Micro-vibrations are more pronounced when machining smaller drone parts, which leads to achieving a mirror finish on smaller components being more challenging" (Kimber, 2024). There are several strategies that Kimber identifies can be employed to mitigate this risk, such as anti-vibration mounts, dampening pads, machine-tool stability, and experimental testing and vibration simulations. “The material used to manufacture these components is a titanium allow (Ti6Al4V) which can be machined on a CNC 3-axis milling machine. But there are features on almost every surface which requires multiple flipping, clamping, and positioning, posing considerable challenges to machining” (Kimber, 2024). While the CNC machining process to design these parts seem relatively straightforward and complex, significant factors can either assist or hinder the Dod from meeting their requirements. Such factors lay in decision-makers establishing universal parts through MOSA architecture so that these parts can be mass produced and installed onto a variety of platforms.

4. Software – Responsible for the digital logic, autonomy algorithms, flight control firmware, and communication protocols required for the drone to operate in an autonomous or semi-autonomous role. Software is not a physical line item in the BOM, but it is factored in the spreadsheet due to its critical nature as a subsystem and its central role in enabling mission functionality, system integration, and C2 interoperability.

Development and Architecture: “Software is an essential part of modern air vehicles, and it usually implements complex safety-critical functions. Many developers use rapid prototyping methods during their research and development and flight-testing phases. With constrained resources, a lack of knowledge and a still developing certification environment for their products, companies are looking for processes such as agile as their development cycles” (Dmitriev et al., 2020). Microsoft defines agile as an approach to software development that focuses on incremental delivery, team collaboration, and continual learning and planning. Scrum, planning poker, and continuous integration are common frameworks, but it is important to understand that it is not cowboy coding (“we’ll figure it out as we go”) or following a single plan. Team collaboration and development with specifications are key to ensuring the software being built adheres to the requirements of the end user (Mijacobs, 2022).

Dmitriev et al. (2020) mentions the use of programs such as MathWorks to automate software development and verification. As shown in Figure 6, requirements authored in Polarion are translated into Simulink and Stateflow design models, automatically converted to embedded C/C++ code using embedded coders, and verified through multi-faceted processes including static analysis, model/software/hardware-in-the-loop testing. This workflow is compliant with DO-178C and DO-331 objectives which are the safety standards of the aviation community and demonstrates how current software engineering aligns with automation, traceability, and reusability (Dmitriev et al., 2020). This flexibility is critical when integrating software into platforms that will be utilized by the DoD which requirements change to adapt to the current situations which are ever-changing.

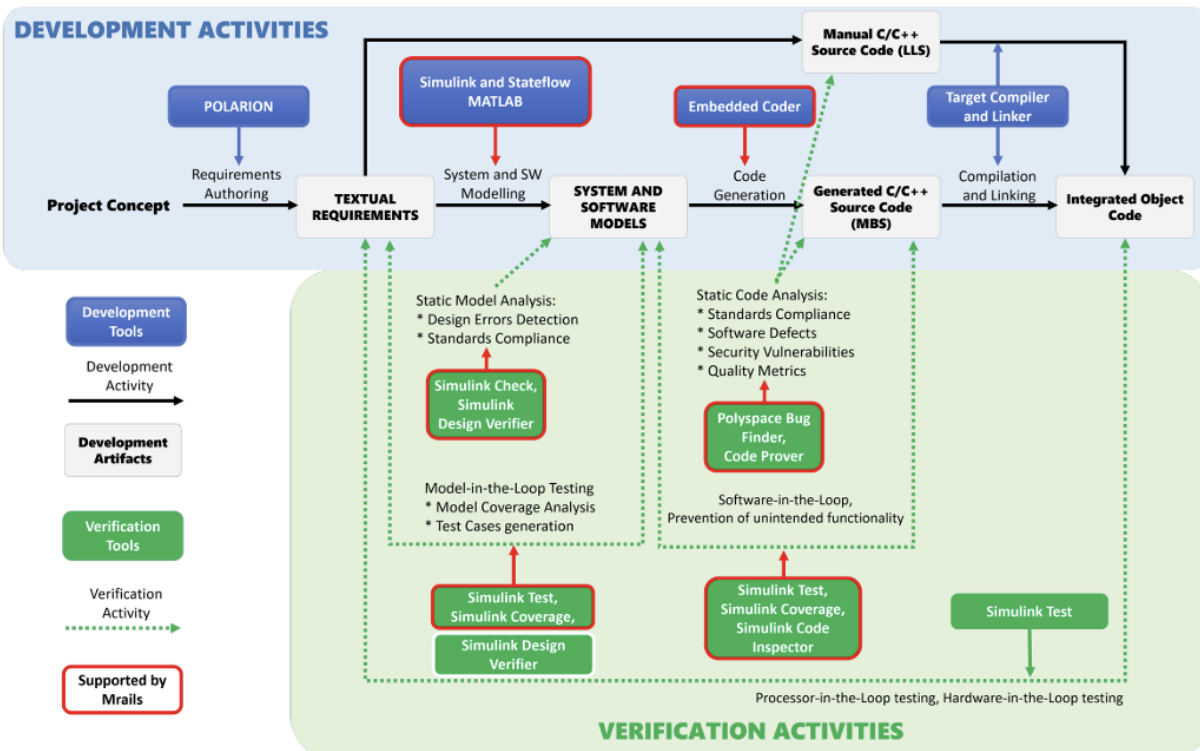

Fig. 3. Development and verification workflow using MathWorks based toolchain for safety critical systems

Figure 6. Development and verification workflow using MathWorks based toolchain for safety critical systems. Source: Dmitriev et al. (2020).

Integration and Testing: "Software testing can be divided into two main categories: static and dynamic. Static testing is a type of testing that occurs without actually using code while dynamic testing involves executing actual code and running tests with accurate data" (Kishore, 2023). Both methods of testing should be utilized in software development to ensure that programs authored are tested in controlled and uncontrolled environments to support the best product emerging for the platform. Kishore (2023) further mentions the common challenges in software testing which are led by the top three of the test environment, data management, and test automation. The test environment is the most challenging as depending on the size of the company creating the software, they may not have limited resources to set up hardware and infrastructure to manage the testing. Additionally, with data management and test automation, the biggest challenges is ensuring the data used is the most accurate and up to date so when it is implemented into automation tests the developers get the most accurate picture of performance (Kishore, 2023). When applying this in scope to the DoD, specific policy memos have been drafted to assist decision-makers and acquisition professionals in the software integration and testing process. "DevSecOps is a combination of software engineering methodologies, practices, and tools that unifies software development (Dev), security (Sec), and operations (Ops)" (Department of Defense CIO, 2024). According to the Department of Defense CIO (2024), DevSecOps is iterative in design with the primary focus being that software is never "done" and maintains a serial style delivery that makes it easier to change course as necessary. Figure 7 depicts this continuous flow of software development, further emphasizing the importance of this production style when utilizing products with heavy software dominance.

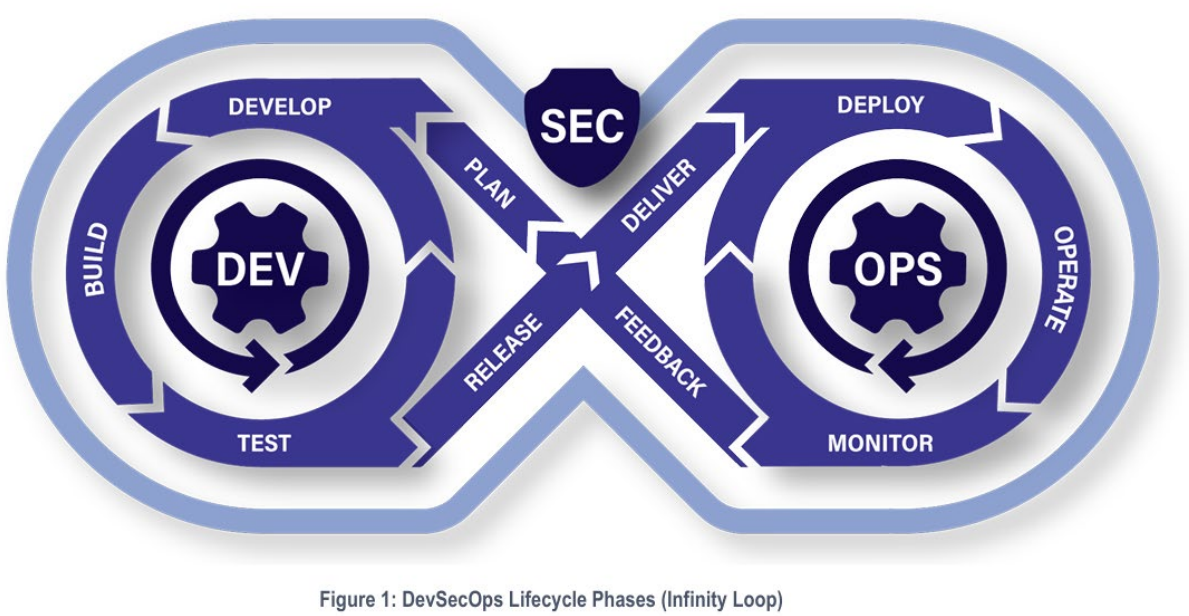

Figure 7. DevSecOps Life cycle Phases (Infinity Loop). Source: Department of Defense CIO (2024).

“To ensure success, we must radically shift our organizational culture away from traditional waterfall methodologies and processes and break down silos to foster collaboration (Department of Defense CIO, 2024). This is a fundamental shift from the “if it isn’t broken don’t fix it” mindset that is typically seen within government organizations and is a promising shift toward being able to adjust capabilities as requirements and missions change rapidly.

Sustainment and Scalability: “The digital twin can allow companies to have a complete digital footprint of their products from design and development through the end of the product life cycle. This, in turn, may enable them to understand not only the product as designed but also the system that built the product and how the product is used in the field” (Parrot et al., 2017). Parrot et al. (2017), continues to define the digital twin as being based on massive, cumulative, real-time, real-world data that can provide insights on system performance. This is different from traditional CAD in that it can provide real-time linkage in the digital and physical worlds. The use of digital twins helps to build sustainment options in long-term software contracts due to the increased construction of software data centers as well as favorable costs for storage over the past decade. When looking at production of drones at scale, having the total snapshot of software development from the beginning aids analysts in reviewing historical and current code to determine where the software falls short. Once shortfalls have been identified or new requirements been generated, the software team can run through agile production processes to implement changes to the current system and reintegrate it into a new experience for the principal user.

5. Miscellaneous – Captures the peripheral components that support the operation of the drone to include piloting and control. However, these components are typically procured rather than directly manufactured. These include handheld controllers, antennas, tablets, and other hardware essential for the drones operation.

Peripherals: “Anduril successfully integrated legacy multi-domain sensors into its Lattice operating system during exercise North Edge 23–2, providing Marines with advanced, real-time battlespace awareness and multi-domain command and control of effects across the Indo-Pacific” (Anduril, 2025). The DoD has numerous legacy systems still employed on a near constant basis, withstanding the test of time. Where acquisition professionals and industry can come together is finding linkages in which peripherals commonly used can be modified to support and sustain operations in future drone platforms. To achieve this level of interoperability and responsiveness, the DoD should utilize COTS solutions and MOSA architecture to reduce integration costs and accelerate fielding timelines (U.S. Department of Defense, 2022). Using these frameworks allows acquisition professionals to incorporate these peripherals directly into the existing digital structure without needing to develop costly and unique interfaces for each platform. The increased variety of peripheral devices allow program managers to leverage existing suppliers to ensure standardization across the variety of platforms. These implementations would minimize integration risk while ensuring the control devices can operate across each platform regardless of size or mission scope.

B. GIGAFACTORY IMPLICATIONS FOR SCALABLE UAS PRODUCTION

The preceding analysis of UAS subsystems demonstrates the diversity of production processes necessary to build a complete system. Traditionally, these components have been manufactured in distributed supply chains, where the final assembly is completed late in the production cycle. The Gigafactory model however, offers a different approach through a vertically integrated, digitally connected production model where the entire production process is completed in-house. By centralizing production and automating coordination between the subsystems, the Gigafactory enables the scalable production of drones required by the DoD with greater speed, cost efficiency, and configuration control.

Within the Gigafactory, the unique production requirements of each subsystem can be accommodated through modular production cells with a common digital infrastructure. Additive manufacturing enables rapid prototyping of structural components, CNC machining delivers precision components for propulsion assemblies, and injection molding aids in creating lightweight housing and protective casings. Meanwhile, SMT and PCB assembly lines create the critical production environment for the electronics subsystem. While these manufacturing modes are uniquely separate concepts, they are unified by shared design files and process data managed through a centralized PLM system. This allows component production to work parallel with each other rather than sequentially, therefore reducing lead times and simplifying integration in final assembly.

The Gigafactory's efficiency depends on physical co-location and digital integration. Modern production environments rely on software-defined production, where continuous feedback loops can be created between design and execution. This approach mirrors the software engineering frameworks already adopted within UAS development, such as MathWorks' model-based design and the Department of Defense's DevSecOps pipeline (Dmitriev et al., 2020; Department of Defense CIO, 2024). In a Gigafactory, these digital workflows synchronize production flow, equipment, and subsystem interfaces from a linear design to an adaptative one.

Battery industry experts emphasized that automation alone cannot close the gap between small-scale laboratory output and industrial throughput without concurrent centralization. Most current facilities rely on distributed small-batch production of electrodes and formation cycling, resulting in inconsistent quality and high cost per unit. Consolidating these stages into a single centralized manufacturing base would improve material flow, uniformity and quality control, which directly aligns with the Gigafactory principle of vertically integrated production (personal communication, November 3, 2025).

The key to success within the Gigafactory is the adoption of the digital twin which will provide a real-time, data-driven representation of each subsystem and its relation to each other. This enables engineers to trace performance from production floor to deployment, identifying defects, optimizing maintenance cycles, and feeding performance data back into design models. As Parrot et al. (2017) note, digital twins bridge the digital and physical environments, offering cumulative, real-world insight into product behavior. In application with UAS production, this enables predictive sustainment and rapid software updates in scale. These continuous upgrade iterations ensure deployed systems remain relevant and in alignment with evolving mission requirements.

However, while the Gigafactory model improves the efficiency and control through vertical integration, not every component can be produced in-house. Peripheral systems such as antennas, controllers, and tablets are better off being procured via COTS solutions. Attempting to internalize their production would divert resources away from the Gigafactory's core competencies. Instead, a hybrid model is preferred in which the Gigafactory focuses on the high-value platforms while integrating COTS peripherals through vendor-managed logistics. This model mitigates risk and maximizes agility, bringing desired platforms to the warfighter at speed and scale.

Implementing this type of model, however, is not merely hindered by ensuring technology and assets are readily available, but policy, investment, and workforce development as well. The U.S. industrial base is well-positioned to accommodate individual sections of this model, but are constrained by aligning with ongoing initiatives such as CHIPS and Science Act, DPA Title III, and the DoDs MOSA strategy. By intertwining these policy mechanisms through the Gigafactory, the DoD could create a digitally networked, high-throughput production capability capable of meeting the demands of future conflicts.

Table 1. Gigafactory vs. External Procurement Suitability by Subsystem[1]

Subsystem / Component	Gigafactory Production Suitability	Gigafactory Pros	Gigafactory Cons	Recommendation
Airframes	High	Repeatable, mold-based fabrication; automation friendly; large economies of scale; high throughput	Requires specialized composite layups; some vendors already optimized for this	Produce in Gigafactory; These costs are not atypical in the regular startup costs in developing the machinery to support optimized production in scale
Propellers	High	Easily standardized; 3D-printing compatible; very high volume; low cost	Commodity propellers are widely available commercially; outsourcing is cheap	Gigafactory or Hybrid; While incredibly easy to establish the machinery and process flow, it can be cost effective to contract with external industry
Brushless Motors	High	High standardization potential; assembly is automable; quality control improves with centralization	Requires magnet supply chain (foreign-dependent); winding tolerances require specialty vendors	Hybrid (co-produce magnets or windings externally); foreign dependency limits the viability of the Gigafactory which leads to needing some of the components to be sourced via foreign routes
ESCs	Moderate	Can be integrated into automated SMT assembly lines; benefits from co-location with FC/autonomy	Chip shortages; PCB manufacturing often cheaper offshore; requires high-volume electronics fabs	Hybrid with vendor-qualified SMT line; external lift from industry leaders will be required to create a "base model" set that can be incorporated into UAS in scale.
Flight Controllers / Autonomy Processors	Low-Moderate	Software integration benefits from proximity; some testing can be internalized	Dependence on imported chips, IMUs, MCUs, high NRE cost for in-house PCB fabrication	External procurement with in-house testing; ease of procurement favors foreign sources, but through pre-validated routes and significant QA/QC processes can ease risk of tampered equipment

[1] Table generation and formatting were supported by AI editing tools. See AI Disclosure Statement

Onboard Computers / Embedded Systems	Low	Can test firmware in-house; vertically integrates with assembly line	High specialization; chips controlled by global suppliers (China, Taiwan, Germany)	External Procurement; similar to the ESCs, DoD should work with foreign partners to produce a "basic" chipset that can provide the basic functionalities necessary for required functionalities
GPS Modules / Navigation Systems	Low	Testing can be done internally; integration QA improves	Heavily globalized supply chain; crystal oscillators and RF front-ends not domestic	External Procurement; per the cons, these components have too many specialized components to simply produce them. The most cost-effective approach is to source from industry and manage a rigorous QA/QC process
Lithium-Ion Batteries	Low-Moderate	Gigafactory can perform final QA, conditioning, and integration; co-location improves safety and throughput	U.S. cell production capacity is limited; active material processing is still globally dependent. Even ALE produces at tens-of-kg scale	Hybrid: source cells from domestic vendors where possible, supplement with allied suppliers; domestic sources have confirmed that they can meet the requirement to produce, but it is a capital intensive process
Battery Packs (final assembly)	High	Pack design, welding, BMS integration, and safety checks are highly automatable; scalability improves with centralization; co-locates with final assembly	Commodity-level packs may be cheaper externally, but high-performance military packs benefit from in-house QA	Produce packs in Gigafactory; Source cells externally but with preference to domestic suppliers; domestic sources have confirmed that they can meet the requirement to produce, but it is a capital intensive process
Wiring Harness / Connectors	High	Easily automated; identical layouts; high-volume cable cutting and crimping is ideal for Gigafactory	Some connectors require proprietary tooling	Produce in Gigafactory; These can be included in the typical startup processes of acquiring and preparing machinery for the standardization of functionality pieces
Fasteners / Mounting Hardware	High	Standardized CNC + additive manufacturing; extremely high throughput	Commodity screws/bolts are cheaper from suppliers	Hybrid (critical parts in-house); these pieces should be outsourced due to cost-efficiency purposes. However, further industry analysis should be developed to determine components susceptible to bottlenecking. Those components should be produced in the Gigafactory

Payloads (Cameras, EO/ IR, LIDAR)	Low	Integration testing only; payloads differ by mission	High specialization, export controlled, expensive optics	External Procurement; These are highly specialized components of the drone and would not be cost-efficient to produce in small scale in a Gigafactory that is more readily suited for mass produced components
Software	High	Must be tightly integrated; fast iteration cycle; supports vertical integration	None – developing externally introduces versioning and IP risk	Produce in Gigafactory; Production in the Gigafactory would be difficult to implement but the most cost-efficient as software is so iterative and upgrade heavy that a contracted team of software professionals can make a basic version that can be worked on without concerns of IP risk and being “vendor-locked”
Packaging / Shipping Kits	High	Fully automated; high standardization	Vendors can supply cheaply, but integration is easier in-house	Produce in Gigafactory; similar to the airframe and structural components, these can be included into the general machining setup costs and produced via standardized processes.

The analysis indicates that Gigafactories are most effective when applied to components with high repeatability, strong automation potential, and low dependency on foreign-owned materials. Structural components, propellers, wiring harnesses, and final assembly operations align well with vertically integrated manufacturing. Conversely, components such as GPS modules, IMUs, and autonomy processors remain constrained by global electronics and material supply chains. These constraints make external procurement the most feasible option when looking at whether to produce these components in-house or by procurement. The hybrid strategy that leaves the Gigafactory in charge of assembly and testing externally produced components provides the best balance between cost, resilience, and throughput.

C. DATA SOURCING AND SUPPLIER MAPPING

The accuracy and relevance of the BOM developed for this study depend on the availability of transparent, traceable, and publicly accessible data. The detailed component-level information we have collected comes from open-source materials, manufacturer catalogs, supplier websites, and publicly released technical documentation. The goal was to develop a defensible and repeatable methodology that DoD decision-makers could apply to additional platforms or use in future industrial base analyses.

- Primary Data Sources – Our consolidated BOM utilizes the following categories of sources to populate its drone-specific tabs:
- Commercial Vendor Catalogs: Including KDE direct, Freefly Systems, Inspired Flight, Skyfront, American Lithium Energy, and APC propellers. These sources provided technical specifications (ex., weight, voltage, dimensions) part numbers, and pricing data.
- Open-Source Teardowns and Bench Reviews: Youtube (channels focused on tested industry experts [Anduril, Shield AI, etc.]) and GitHub-based teardowns, Reddit technical threads, and drone hobbyist forums were used to validate configurations and identify likely components when manufacturer level detail was not available.

- Government Industry Reports: References included DoD Industrial Capabilities Reports, NDIA Vital Signs, Defense Production Act Title III project disclosures, and publicly released documents from DIU and DARPA programs.
- SEC Filings and Manufacturer Disclosures: For publicly traded or venture-backed firms like Anduril, AeroVironment, and Teledyne FLIR, financial filings and investor materials were reviewed to identify supplier partnerships, production trends, and sourcing risks.
- Technical Standards and Datasheets: PDF datasheets for individual components (ex., battery components, flight controllers, RF modules) were used to verify dimensions, voltage compatibility, and export control markings.

Each BOM line item includes a sourcing URL and data retrieval date to support transparency and allow future updates. In cases where exact components were unavailable, close alternates were selected based on size, function, and system weight compatibility, particularly when reverse-engineering baseline performance to match industry drone weights.

Supplier Classification Schema – To assess industrial resilience and foreign dependency, each component supplier was classified into one of four origin categories:

- U.S.-based supplier
- Allied or trusted-partner nation (ex., Japan, Germany, UK, Australia)
- Foreign – low-risk (ex., Taiwan, South Korea)
- Foreign – high-risk / PRC influenced (ex., mainland China, Hong Kong entities)

These classifications were used to flag components in the spreadsheet using conditional formatting and to support supply chain risk scoring in Chapter Six. Additionally, components were flagged for:

- Critical materials content (ex., rare earth metals, lithium, copper)
- Single-source dependency
- ITAR or export-controlled designations

D. DATA INTEGRITY CONSIDERATIONS

The goal of this analysis was to effectively break these platforms selected in the spreadsheet to their component level to determine how the Gigafactory could resolve some of the overarching material issues in surge production; however, the data referenced in the spreadsheet is limited to unclassified and open-source information that was gained along with estimations. Some part weights or costs were estimated using analog components with similar performance. Costs are treated as estimates to help DoD decision-makers with a general understanding of what you could generally be expected to spend at a minimum to procure these platforms. These costs are not representative procurement quotes or actual program data. The model was designed to compare and analyze the breakdown of today's drone needs across various capabilities, rather than detailed acquisition or budgeting.

E. SUMMARY OF FINDINGS AND PRODUCTION IMPLICATIONS

The analysis presented here and in Chapter IV demonstrate that the significant benefits in standardization, throughput, and labor efficiency through the Gigafactory model. However, this model like any other is susceptible to negative outcomes when it comes to supply chain shortages, whether due to economic means such as trade wars or simple supply and demand issues. Drone subsystems such as the powertrain and structure are heavily favored in the Gigafactory model due to their standardization and bulk manufacturability. In contrast, electronics, adhesives, and software dependencies reveal risk areas tied to foreign sourcing, material scarcity, limited domestic fabrication, or dependence on a single domestic vendor. The findings used in this analysis that continue to develop today demonstrate the importance of aligning the industrial base policy with production strategy. Aligning policy and production strategy aims to ensure that scaling is not simply an assembly line problem, but a supply chain challenge. The following chapter synthesizes these findings into strategic conclusions and actionable recommendations.

Adhesives and software dependencies reveal risk areas tied to foreign sourcing, material scarcity, limited domestic fabrication, or dependence on a single domestic vendor. The findings used in this analysis that continue to develop today demonstrate the importance of aligning the industrial base policy with production strategy. Aligning policy and production strategy aims to ensure that scaling is not simply an assembly line problem, but a supply chain challenge. Chapter VI synthesizes these findings into strategic conclusions and actionable recommendations.

VI. CONCLUSION AND RECOMMENDATIONS

This chapter presents the overarching conclusions derived from the BOM analysis and component-level supply chain assessment presented in Chapter V. While the centralized Gigafactory model offers a scalable path to high-rate UAS production, this study finds that critical constraints persist in upstream sourcing, material availability, and component manufacturability. These constraints directly impact the feasibility of sustained centralized production and require deliberate coordination between the DoD and the domestic industrial base. The following sections synthesize these findings into actionable recommendations, particularly focused on where the U.S. has postured itself to mitigate the risk of critical components and identifying where targeted DoD investment or policy intervention is most warranted.

A. U.S. INDUSTRIAL RESPONSE AND STRATEGIC INVESTMENT

The success of a defense-oriented Gigafactory model for UAS' ultimately depends on the adaptability of the U.S. industrial base. While the U.S. retains dominant manufacturing capacity across the aerospace, semiconductors, and advanced materials, they remain distributed and usually disconnected from DoD modernization objectives. Starting and sustaining high-rate UAS production will require not only physical infrastructure, but also long-term investment mechanisms that link commercial innovation with defense acquisition priorities.

Recent federal initiatives have laid the groundwork for this transformation. Programs such as the CHIPS and Science Act, DPA Title III, and the manufacturing network collectively incentivize domestic semiconductor fabrication, additive manufacturing, and workforce development. These efforts serve as the foundation to establish the vertically integrated and digitally connected Gigafactory model that can adapt to surge demands and reinforce supply chain resilience. For example, the U.S. government's partnership with Intel to expand domestic fabrication capacity under the CHIPS Act incentives illustrate the potential for aligning industrial base policy with national security objectives (Intel, 2024). Similarly, the DoEs investment in domestic lithium-ion cell production and the establishment of partnerships with firms such as American Lithium Energies demonstrate a growing commitment to securing upstream battery and energy-storage materials (Chapman, 2025).

ALEs participation in the Red River solicitation exemplifies ongoing government-industry partnerships to expand lithium-ion production capacity domestically. Battery industry experts noted that the Red River facility aims to mass produce both cylindrical and pouch cells at roughly two cells a minute per line, contributing to the gigawatt-scale capacity. The contract is valued at $41M and will establish the largest domestic electrode manufacturing operations in the world. This partnership further demonstrates how the DPA Title III can anchor critical material production within the U.S. (personal communication, November 3 2025).

However, coordination challenges persist. The DoD continues to rely on a fragmented network of prime contractors and small manufacturers that often lack digital compatibility or shared data standards (Government Accountability Office [GAO], 2025). Without a unified production environment, UAS production at scale will be slow and costly. Industry leaders such as Tesla and SpaceX have implemented vertical integration models that point to the Gigafactory model being a highly favorable production model. Additionally, new startups like Joby who specialize in aircraft have implemented vertical integration to reduce the needs of maintaining vast quantities of suppliers. CEO JoeBen Bevirt of Joby doubles down on this point by saying "When you're building hardware, there is no substitute to being vertically integrated with the rate of progress that you're able to deliver and the quality of products you're able to create" (Goldstein, 2024). However, the DoD continues to suffer from a highly fragmented manufacturing base, lacking digital integration across suppliers.

To align these industrial policies with defense objectives, the DoD must be both a strategic investor and integration catalyst. The DoD can achieve this by expanding dual-use manufacturing, establishing public-private partnerships for automated production lines, and continuing to incentivize MOSA architectures. The implementation of these measures would allow the commercial industry to integrate defense-specific requirements earlier in the design process which would cut cost and fielding timelines. As the FAR continues through its overhaul process, tools such as OTAs, rapid prototyping agreements, and digital engineering environments can accelerate Gigafactory deployment while maintaining accountability and cyber resilience.

Additionally, the readiness of the workforce is another critical factor in scaling this model. Advanced UAS production requires a hybridization of traditional manufacturing with digital competencies in automation, artificial intelligence, and model-based systems. Workforce initiatives at the federal and state level should incentivize strategic partnerships between academic and industry institutions near major defense-industrial mobilizations. This approach mirrors past successful defense-industrial mobilizations, where the proximity of technical education and production facilities led to rapid innovation.

Finally, ensuring scaled and sustainable throughput demands stronger government involvement in raw-material sourcing and component fabrication. Investments in domestic rare-earth processing, lithium-ion battery manufacturing, and electronics packaging aligns directly with the critical dependencies identified in this study's BOM analysis. Initiatives such as the Ambler Road Initiative, where the U.S. government has opened the floodgates to mine for rare-earth metals, are first steps in this process to begin severing our foreign dependence on these materials. Additional targeted investments through DPA Title III would help close these material gaps and secure the upstream inputs necessary for consistent output through the Gigafactory model.

To summarize, the U.S. possesses the technological foundation, policy frameworks, and industrial capacity to achieve success of the Gigafactory model. The challenge now is to synergize these efforts to work as a well-oiled machine that can sustain pressures of future conflicts. Aligning DoD acquisition with commercial innovated under a shared infrastructure will position the U.S. to maintain both strategic autonomy and production agility in the evolving global defense environment.

B. SUMMARY OF KEY FINDINGS

This study set out to evaluate how a centralized Gigafactory production model could support high-rate UAS manufacturing in future conflicts. The research focused on identifying the most critical subsystems in supporting scaled production, comparing current production models with a vertically integrated Gigafactory model, and assessing the cost implications of centralizing production at scale. The following sections summarize the key findings from Chapter Five as they relate to each of these core questions.

1. Which UAS components and subsystems are most critical and at risk and therefore should be a priority to enable secure U.S. production?

The analysis identified several high-risk components whose limited domestic production capacity or foreign dependency presents a vulnerability for sustained production. Components such as batteries, ESCs, FCs, and semiconductor-based subsystems led the highest risk of foreign dependency. Each of these components relies on heavily specialized materials and fabrication processes that are dominated by foreign suppliers, particularly in China and Southeast Asia. These dependencies would create critical bottlenecks when faced with a contingency scenario.

Conversely, structural components are far more readily available to adapt to U.S. production due to the existing strength of the aerospace and composite fabrication infrastructure. Prioritizing the onshoring of the electronic subsystems while maintaining flexible sourcing for structural components is the most balanced approach to securing scalable UAS production.

2. Across existing production models versus a centralized "Gigafactory" model, what are the comparative advantages, constraints, and prerequisites for scaling U.S. UAS production?

To understand how the U.S. might expand high-rate UAS production, five representative productions models were analyzed: Silicon Valley Embedded Teams, Decentralized Crowd Production, Additive Surge Manufacturing, Prime Startup Digital Consortia, the Ford Model T Paradigm and the Gigafactory model. Each offers distinct advantages in innovation, scalability, and control, but also introduces structural or policy constraints. Table 1 summarizes the comparative characteristics.

Table 2. Comparative Assessment of Six U.S. UAS Production Models.[2]

Dimension	Silicon Valley Embedded Teams	Decentralized Crowd Production	Additive Surge Manufacturing	Prime-Startup Digital Consortia	Ford Model T Paradigm	Gigafactory Model
Core Concept	Small, agile DoD-industry teams that co-locate to iterate prototypes rapidly using commercial innovation methods	Distributed network of small firms, makers, and universities collaborating via open platforms or rapid contracting	Rapid additive manufacturing of modular parts to meet surge demand	Collaborative network linking primes and startups under shared digital design and testing ecosystems	Sequential, assembly-line mass production for standardized output	Vertically integrate facility uniting design, component fabrication, assembly, and QA in on automated ecosystem
Integration & Coordination	High communication speed; low process standardization; dependent on team cohesion	Loose coordination; innovation-rich but prone to IP and QA challenges	Moderate integration through digital files and on-demand printing	Integrated digital collaboration; dependent on shared data standards	Rigid centralized process control; low flexibility	Full digital integration across design, manufacturing, and testing using digital twins and MES
Scalability & Throughput	Rapid for prototypes; limited for sustained output	Broad participation but low throughput consistency	Strong surge potential; limited sustained capacity	Scalable collaboration but dependent on network maturity	High sustained throughput; poor adaptability	Extremely high throughput and repeatability once established
Cost Efficiency	Low overhead; high per-unit R&D cost	Low entry cost; uneven efficiency across participants	Moderate cost; low material waste	Balanced; shared investment across consortium partners	High capital investment; low marginal cost at scale	High capital investment; long-term cost efficiency via automation and co-location

[2] Table generation and formatting were supported by AI editing tools. See AI Disclosure Statement

Innovation & Adaptability	Exceptional adaptability; fosters disruptive concepts	High innovation diversity; chaotic convergence	Rapid redesign capability; constrained by print certification	Balanced, structured innovation through digital engineering	Minimal adaptability; rigid process sequences	High adaptability within digital twin environment; rapid configuration updates
Supply-Chain Resilience	Moderate, depending on commercial tech imports	High diversity; difficult to govern or audit	Localized production enhances resilience; dependent on raw-material feedstock	Strong internal communication: risk distributed among members	Centralized risk dependent on global supply chains	Highly controlled supply chain with reduced vendor dependency but potential single point vulnerability
Workforce Requirements	Cross-functional, skill sets; minimal manufacturing expertise	Broad participation; variable skill quality	Skilled additive manufacturing technicians	Digitally fluent engineers and integrators	Assembly-line technicians and managers	High-skill digital manufacturing workforce
Policy & Regulatory Alignment	Enabled by flexible OTA or CSO contracting; limited scalability within FAR framework	Misaligned with current acquisition policy; best for early R&D	Enabled under rapid-acquisition authorities during crises	Compatible with modernized digital-acquisition frameworks	Traditional industrial base model; outdated for digital production	Requires modernization of acquisition and industrial policy
Best Application Context	Early-stage prototyping and concept validation	Innovation crowdsourcing, field experimentation, or low-volume customization	Contingency surge or battle-damage repair	Long-term development of multi-tiered production partnerships	Legacy model demonstrating economies of scale	Standardized, high-rate production and sustainment for mature UAS platforms

The expanded comparison shows how the Gigafactory model integrates lessons from each preceding approach. Like the Ford Model T, it achieves economies of scale through vertical integration and process automation, yet it retains adaptability through the usage of digital twins and flexible production cells. It benefits from the Prime-Startup Digital Consortia's collaborative ecosystem while increasing its efficiency through co-location and automation. While the Additive Surge and Crowd Production models favor distributed innovation and resilience, they lack the sustained throughput and standardization achievable through the Gigafactory construct. Finally, the Silicon Valley Embedded Teams remain vital for front-end prototyping but are not suited for production scenarios at scale.

Collectively, the findings suggest that a hybrid production model utilizing a Gigafactory core and supported by distributed, additive, and agile innovation networks, offer the most broad framework for U.S. production at scale.

3. What are the cost implications of moving from today's distributed/outsourced approach to a more centralized U.S.-based production approach?

The current distributed model for drone manufacturing relies heavily on global supply chains, foreign dependence, and COTS components to achieve economies of scale and lower per-unit costs in steady-state operations. While this approach typically optimizes affordability, it risks substantial long-term costs through supply-chain fragility, limited scalability, and diminished quality control visibility. In the current state of the economy, export/import constraints, tariffs, and political tensions have highlighted the critical fragility of the supply chain in the electronics and rare earth metals sectors. These supply-chain fragilities risk production halts of critical capabilities due to bottlenecks without creating a more stable source.

Transitioning to a centralized U.S.-based Gigafactory model presents a different cost profile. Capital expenditures are significantly higher due to the real estate, equipment, manufacturing infrastructure, and workforce requirements. However, these investments yield long-term savings through automation and co-location efficiencies and shortened production cycles. Digital integration across design fabrication, and sustainment enables real-time feedback loops that minimize re-engineering and life cycle maintenance costs (Parrot et al., 2017). Industry leaders such as Tesla and SpaceX's vertically integrated manufacturing demonstrate that while startup costs can be a significant factor in the decision-making process, life cycle efficiencies outweigh the initial expenditure through continuous process optimizations.

From a strategic perspective, centralization should be pursued for selective cases rather than uniformly. High-risk components should be prioritized as they benefit the most from domestic vertical integration due to security and sustainment imperatives. Peripherals should remain COTS based to preserve platform affordability and design flexibility. The DoD can leverage existing authorities such as the DPA Title III, the CHIPS and Science Act, and public-private partnerships to offset the capital intensity (Department of Defense CIO, 2024). This hybrid methodology balances resilience with cost efficiency, ensuring that the Gigafactory approach enhances readiness and industrial economy without imposing unsustainable budgetary burdens.

C. IMPLICATIONS OF SUPPLY CHAIN CONSTRAINTS

The Gigafactory case study model shows that the U.S. can scale production effectively through standardization, throughput, and cost control. Still, reliability and steady availability of components remains a challenge. Our analysis of the BOM indicated that certain subsystems are well-suited to centralized manufacturing. This is due to their physical standards, commercial availability, and ease of integration into production lines. However, these advantages do not extend universally across all critical subsystems.

The Gigafactory will have to face the current challenge of being overly dependent on foreign suppliers for raw materials, electronic subcomponents, or finished assemblies. Lithium-ion battery cells, battery management systems, microelectronics, rare-earth magnets, and adhesives/sealants/thermal shielding materials are a few of the examples. Many of these components fall into categories, such as single-source supply, non-allied vendors, long lead-times, or export restrictions. Even when domestic distributors are used, the components themselves typically trace back to non-U.S. vendors, particularly in Southeast Asia and China.

To increase the reliability of centralized production at scale, these constraints must be addressed concurrently and cannot be assumed to be resolved through economies of scale alone. In several cases, centralization may further contribute to fragility. For example, concentrating demand for constrained parts at a single production site increases the risk of line stoppage unless redundant sourcing methods have been identified and are in place.

Furthermore, the macroeconomic environment regarding shifting tariff regimes, defense budget pressures, and onshoring incentives complicates the "make vs. buy" decisions at the strategic and policy level. For example, components such as GPS receivers and RF modules are inexpensive to import in peacetime, which incentivizes firms to rely on foreign suppliers. Yet the DoD notes that supply chains dependent on foreign sources are increasingly vulnerable during crises, when export controls, political constraints, or market shocks can reduce component availability. In such environments, domestic production capacity often proves insufficient to absorb the disruption (GAO, 2025). Thus, when evaluating the Gigafactory model, the focus should not be solely on its production metrics, but also on its alignment with national defense industrial resilience priorities.

These realities suggest that a hybrid approach may be required to identify which components can be manufactured through centralization to scale without added risk, and which are globally constrained should be decentralized or buffered. Additionally, the economic and political environment reinforces the need for a deliberate "make vs. buy" analysis at the component level, addressed in the following section.

D. RECOMMENDATIONS

The findings from this study demonstrate that achieving scalable and centralized production of UAS and UUV systems is not strictly a manufacturing challenge, but rather a system-level supply chain problem. The following recommendations, derived from the BOM analysis, component-level risk assessment, and the proposed "make vs. buy" framework, are aimed at both DoD acquisition authorities and key defense industrial base stakeholders.

E. FOR THE DEPARTMENT OF DEFENSE (DOD)

1. <u>Institutionalize component-level "make vs. buy" analysis in acquisition planning.</u> To strengthen supply chain resilience, the DoD should institutionalize "make versus buy" analysis at the component-level as a routine part of the acquisition

planning. This approach should be reinforced by integrating part-level sourcing risk assessments into Program Objective Memoranda (POM), RFP language, and supply chain audits. For UAS platforms intended for high-rate production, BOM-level disclosures from vendors should be mandatory as it will distinguish cost in the relevant subsystems and apply structured sourcing risk thresholds. These assessments will help to identify high levels of foreign dependency and prepare plans to mitigate supply chain risk, particularly for subsystems dependent on rare earths, lithium, and dual-use electronics.

2. Expand use of Title III and Defense Production Act (DPA) authorities. Target DPA investments toward upstream bottlenecks, specifically on lithium-ion cell production, trusted RF component fabrication, and domestic flight controller manufacturing. Use DPA Title III not only for prototyping, but for building enduring commercial capacity in partnership with industry.

3. Incentivize supply chain transparency and BOM reporting. Require drone vendors to submit structured BOMs (to include hardware and software) with standardized categories for origin, function, and sourcing risk. Use these as a baseline for program-level risk assessments and industrial base reporting.

4. Prioritize commonality across programs of record. Where tactically feasible, platform-specific components should be avoided to retain standardization across systems. As the needs of the warfighter rapidly evolve and component life cycles for software are relatively short, common standards become critical in maintaining systems that are still viable after the first year of fielding. Promoting part commonality reduces sourcing complexity and streamlines production which ultimately increases efficiencies in the supply chain.

F. FOR INDUSTRY STAKEHOLDERS

1. Standardize components and interfaces across product lines. Internal R&D and procurement strategies must be aligned to support cross-platform interoperability. This can best be utilized by maintaining consistent communications with DoD

program managers to ensure that information and needs do not get siloed during production. Industry should prioritize COTS when possible to reduce cost and lead time for materials. To reduce disruptions and ensure long-term supply continuity, sourcing pathways for critical items should be identified and validated in advance. Standardizing widely used components like fasteners and wire harnesses can also simplify integration and streamline production across a wide range of platforms.

2. Dual-Source or Pre-Stock Non-Scalable Items. For items that are harder to scale at a quickly such as adhesives and epoxies, heavier investment should be placed in inventory buffers and the development of alternative sources of supply. Industry partners can mitigate these risks by negotiating contract provisions that clarify expectations for surge production and government-directed redirection during emergencies. Because such terms can require costly upfront investments in inventory and production capacity, firms should establish guarantees (cost sharing, minimum-order requirements, or indemnification) that protect them if the surge requirement is never met. The implementation of these will assist industry in justifying the overall financial risk associated with maintaining a readiness-oriented stock vice a more traditional just-in-time style of stockage.

3. Collaborate with Government on Industrial Scaling Plans. Industry teams should engage early with DoD counterparts to shape realistic scaling strategies. Naval Postgraduate School (NPS) for example utilizes tools such as the CRADA between student researchers and industry collaborators to help to align expectations around research and current defense requirements. Increased collaboration through not only NPS, but through the DoD as a whole will help to reduce the gray area between where our domestic requirements are currently at, and where we can invest or conduct more research to increase our domestic capabilities.

4. Automate Where Possible, Buffer Where Not. Finally, as artificial intelligence and smart machines are implemented into the workforce, automation becomes a

tool that can assist in economies of scale. At a high level, automation can help industry to decrease labor costs and achieve higher scalability, able to rapidly meet emerging requirements. Even through automation, labor will still be a cost to consider, however, industry can prioritize specialized labor rather than the typical production line labor that is easily imaginable. In cases where automation falls short of current industry capability, short-term subcontracting can help to alleviate constraints. In the meantime, further research can be aimed at how these critical parts can be implemented into automation processes and improve long-term solutions.

G. SUMMARY

Together, these recommendations aim to align future high-rate drone production efforts with the realities of supply chain limitations, fiscal constraints, and operational urgency. A Gigafactory model may streamline final assembly, but without a synchronized upstream strategy, the U.S. risks encountering friction at precisely the point it intends to scale. It is therefore essential that both DoD and industry make deliberate, risk-informed decisions today to ensure UAS availability tomorrow.

AI DISCLOSURE STATEMENT

Generative artificial intelligence tools were used in preparing this work. Specifically, AI was employed for the following purposes: improving sentence clarity, grammar, formatting, and the organization of tables. The use of these tools was approved according to institutional and faculty guidance, in alignment with NPS policy on generative AI use. ChatGPT and Perplexity were the AI models used.

All recommendations and suggestions provided by the AI were reviewed and applied at the author's discretion, and final editorial decisions were made by the author to ensure the accuracy, integrity, and originality of the content. All ideas, arguments, interpretations, and analyses presented in this work are entirely the author's own. Efforts were made to mitigate any risks related to AI-generated inaccuracies, over-reliance on automated recommendations, or misuse of field-specific terminology by verifying changes and consulting with academic resources when appropriate. All AI-generated outputs were independently verified for factual accuracy before inclusion.

THIS PAGE INTENTIONALLY LEFT BLANK

SUPPLEMENTAL: FUNCTIONAL BOM OF GROUP 2/3 UAS WITH GIGAFACTORY CONSIDERATIONS

To support the Gigafactory evaluation framework, a comprehensive spreadsheet was developed with a team studying UAS systems to organize subsystem components and their associated technical data. The document catalogs each part at the component level and includes identifiers related to the subsystem it belongs to, supplier origin, underlying materials, physical specifications, and verified sourcing information. These entries are supplemented with cost observations, comparative benchmarks, and manufacturer documentation to establish a baseline for understanding how each component contributes to overall system performance. Rather than presenting the data as a static table of inputs, the spreadsheet functions as a living analytical tool that can accommodate new sources, updated material data, or revised subsystem configurations as research progresses.

Beyond basic technical and sourcing attributes, the spreadsheet incorporates a structured set of evaluation metrics designed to align with the Gigafactory production model. Each component is qualitatively assessed against factors such as standardizable, suitability for automation, production centralization value, and estimated manufacturing time. Additional columns evaluate strategic risk dimensions including origin dependency, bottleneck potential, material criticality, and cost or supply volatility. These scores are not intended to prescribe a single definitive ranking, but rather to reveal patterns of vulnerability and scalability that may influence decision-makers considerations. The ultimate presentation of this information may evolve as the project moves toward publication, and its format will necessarily reflect the constraints of the journal and the requirements of the research sponsor. To access the supplemental material listed here, contact the Dudley Knox Library or, for publicly releasable theses and supplementals only, visit the thesis pages in the library's Calhoun database.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Aldemir, H. O. (2024). *Harnessing digital innovation for air transportation.* IGI Global.

Anduril. (2025, January 16). *Anduril building Arsenal-1 hyperscale manufacturing facility in Ohio*. https://www.anduril.com/article/anduril-building-arsenal-1-hyperscale-manufacturing-facility-in-ohio/

Anduril. (2023, August 28). *Anduril showcases Lattice C2 for U.S. Marine Corps at Northern Edge 23–2*. https://www.anduril.com/article/anduril-industries-marine-corps-northern-edge-lattice-c2/.

Askerbekov, D., Garza-Reyes, J. A., Ghatak, R. R., Joshi, R., Kandasamy, J., & de Mattos Nascimento, D. L. (2024). Embracing drones and the internet of drone's systems in manufacturing: An exploration of obstacles. *Technology in Society, 78*, 102648. https://doi.org/10.1016/j.techsoc.2024.102648

Baballe, M. A., Bello, M. I., Alkali, A. U., Abdulkadir, Z., Muhammad, A. S., & Muhammad, F. (2022). The unmanned aerial vehicle (UAV): Its impact and challenges. *Global Journal of Research in Engineering & Computer Science, 2*(3), 35–39.

Baker, T., & Welter, F. (2024). Silicon Valley entrepreneurship: Revisiting a popular dream. *Journal of Business Venturing Insights, 21*, e00466. https://doi.org/10.1016/j.jbvi.2024.e00466

Bazaluk, O., Rahman, M. A., Zayed, N. M., Faisal-E-Alam, M., Nitsenko, V., & Kucher, L. (2024). Crowdsourcing review: The crowd workers' perspective. *Journal of Industrial and Business Economics, 51*, 647–666. https://doi.org/10.1007/s40812-023-00295-9

Bird, D. T., & Ravindra, N. M. (2021). Additive manufacturing of sensors for military monitoring applications. *Polymers, 13*(9), 1455. https://doi.org/10.390/polym13091455

Bremner, R. P., & Eisenhardt, K. M. (2021). Organizing form, experimentation, and performance: Innovation in the nascent civilian drone industry. *Organization Science, 33*(4). https://doi.org/10.1287/orsc.2021.1505

Caldwell, D. T. (2024). Defense innovation at an inflection point: The rise of new primes slike Anduril and the changing military-tech ecosystem. *Open Access Cases, 1*(4), 1–15. https://oacases.com/index.php/cases/article/view/12/28

Candi, M., & Beltagui, A. (2019). Effective use of 3D printing in the innovation process. *Technovation, 80–81*, 63–73. https://doi.org/10.1016/j.technovation.2018.05.002

Chapman, M. "U.S. government taking stake in company operating massive lithium mine in Nevada." *PBS*, Public Broadcasting Service, 1 Oct. 2025, www.pbs.org/newshour/nation/u-s-government-taking-stake-in-company-operating-massive-lithium-mine-in-nevada.

Criollo, L., Mena-Arciniega, C., & Xing, S. (2024). Classification, military applications, and opportunities of unmanned aerial vehicles. *Aviation, 28*(2), 115–127. https://doi.org/10.3846/aviation.2024.21672

Cury, A. A. R. (2024). Time of war and time in war: Unmanned aerial vehicles and the changes in the warfare: An approach to recent events. *Universidade Catolica Portuguesa.* https://www.proquest.com/openview/0c2ba0de439b08a30c4627cec70e637b/1?pq-origsite=gscholar&cbl=2026366&diss=y

Department of Defense Chief Information Office. (2024). *DoD enterprise DevSecOps fundamentals (Version 2.5).* U.S. Department of Defense. https://dodcio.defense.gov/Portals/0/Documents/Library/DoD%20Enterprise%20DevSecOps%20Fundamentals%20v2.5.pdf

Dmitriev, Konstantin et al. (2020) *A lean and highly-automated model-based software development process based on DO-178C/DO-331*. ArXiv. arxiv.org/abs/2010.06505?utm_source=chatgpt.com.

El Adawy, M., Abdelhalim, E. H., Mahmoud, M., Zeid, M. A. A., Mohamed, I. H., Othman, M. M., ElGamal, G. S., & ElShabasy, Y. H. (2023). Design and fabrication of a fixed wing unmanned aerial vehicle (UAV). *Ain Shams Engineering Journal, 14*(9), 102094. https://doi.org/10.1016/j.asej.2022.102094

Elmeseiry, N., Alshaer, N., & Ismail, T. (2021). A detailed survey and future directions of unmanned aerial vehicles (UAVs) with potential applications. *Aerospace, 8*(12), 363. https://doi.org/10.3390/aerospace8120363

Eslami, A. M., Rawat, K. S., Asthana, C. B. (2023). Curriculum alignment for workforce development in advanced manufacturing. *2023 Annual Conference & Exposition,* 1–9. https://doi.org/10.18260/1-2--42853

Fareed, N., Das, A. K., Flores, J. P., Mathew, J. J., Mukaila, T., Numata, I., & Janjua, U. U. R. (2024). UAS quality control and crop three-dimensional characterization framework using multi-temporal LiDAR data. *Remote Sensors, 16*(4), 699. https://doi.org/10.3390/rs16040699

Feng, R. (2024, March 20). Viasion Technology. *Viasion*, www.viasion.com/blog/electronics-manufacturing-process-a-comprehensive-guide/

Finkhauser, J., & Larsen, M. (2021). Reliable command, control, and communication links for unmanned aircraft systems: Towards compliance of commercial drones. *DroneSE and RAPIDO '21*, 22–28. https://doi.org/10.1145/3444950.3444954

Government Accountability Office. (2025, July) *Actions needed to address risks posed by dependence on foreign suppliers* (GAO-25-107283).

Gereffi, G., Fernandez-Stark, K. (2016). Global value chain analysis: a primer. *Duke University Libraries*. https://hdl.handle.net/10161/12488

Goldstein, B. (2024, May 15). Joby versus Archer: Vertical integration strategy is a key split. *Aviation Week Network*. https://aviationweek.com/business-aviation/aircraft-propulsion/joby-versus-archer-vertical-integration-strategy-key-split

Greitemeier T., & Lux, S. (2025). The intellectual property enabling Gigafactory battery cell production: An in-depth analysis of international patenting trends. *Journal of Energy Storage, 108*, 115083. https://doi.org/10.1016/j.est.2024.115083

Haghnegahdar, L., Joshi, S. S., & Dahotre, N. B. (2022). From IoT-based cloud manufacturing approach to intelligent additive manufacturing: Industrial Internet of Things – an overview. *The International Journal of Advanced Manufacturing Technology, 119*, 1461–1478. https://doi.org/10.1007/s00170-021-08436-x

Han, X., Liu, W., & Jiang, T. (2024). Practicing future-making: Anticipation and trans local politics of Tesla's Gigafactory in Shanghai as assemblage. *Transactions of the Institute of British Geographers, 49*(2), e12645. https://doi.org/10.1111/tran.12645

Hopkins, C., & Tavares, M. (2025). Unmanned aerial vehicles: Platforms, applications, security and services. *Electronics, 9*, 975. https://doi.org/10.3390/electronics9060975

Huang, C., Chen, Y., & Harris, J. (2021). Regulatory compliance and socio-demographic analyses of civil Unmanned Aircraft Systems users. *Technology in Society, 65*, 101578. https://doi.org/10.1016/j.techsoc.2021.101578

Intel Corporation "Intel and Trump Administration Reach Historic Agreement to Accelerate American Technology and Manufacturing Leadership." 22 Aug. 2025, www.intc.com/news-events/press-releases/detail/1748/intel-and-trump-administration-reach-historic-agreement-to.

Javaid, M., Khan, I. H., Singh, R. P., Rab, S., & Suman, R. (2022). Exploring contributions of drones towards industry 4.0. *Industrial Robot, 49*(3), 476–490. https://doi.org/10.1108/IR-09-2021-0203

Jarrell, Z. (2025, July 30). Columbus Opportunity Summit: Anduril moving full speed ahead in Central Ohio. *Columbus Business First.* https://www.bizjournals.com/columbus/news/2025/07/30/anduril-columbus-opporunity-summit-recap.html

Jeans, David. (2025, April 17). Silicon Valley's military drone companies have a serious Chinese parts problem. *Forbes*. www.forbes.com/sites/davidjeans/2025/04/16/silicon-valley-drones-china-problem/.

Kamonsukyunyong, P., Katongtung, T., Srinophakun, T. R., & Sukpancharoen, S. (2025). Optimization of 3D printed drone performance using synergistic multi algorithms. *International Journal of Thermofluids, 26*, 101058. https://doi.org/10.1016/j.ijft.2025.101058

Kapustina, L., Izakova, N., Makovkina, E., & Khmelkov, M. (2021). The global drone market: Main development trends. *The 21st International Scientific Conference Globalization and its Socio-Economic Consequences 2021, 11004*, 1–8. https://doi.org/10.1051/shsconf/202112911004

Karali, H., Inalhan, G., & Tsourdos, A. (2024). Avdnaced UAV design optimization through deep learning-based surrogate models. *Aerospace, 11*(8), 669. https://doi.org/10.3390/aerospace11080669

Keagle, J. M., & Cahall, B. A. (2011). Attack of the drones: Unmanned aerial vehicles as an instrument of war. *International Conference of Scientific Paper ADASES 2011*, 1220–1230.

Kimber. (2024, July 5). Industrial drone parts manufacturing challenges and solutions with real case. *WayKen*. https://waykenrm.com/blogs/industrial-drone-parts-manufacturing-challenges-and-solutions/

Kishore, K. (2023, November 23). Software testing strategies: Protecting software from threats. *A3Logics*. https://www.a3logics.com/blog/software-testing-strategies-for-robust-software-development/

Kunertova, D. (2023). The war in Ukraine shows the game-changing effect of drones depends on the game. *Bulletin of the Atomic Scientists, 79*(2), 95–102. https://doi.org/10.1080/00963402.2023.2178180

Liang, O. (2024, May 31). Flight controller explained: How to choose the best FC for FPV drone. *Oscar Liang*. https://oscarliang.com/flight-controller/

Mahobiya, C., Iyer, S., Verma, M., Mishra, P. R., & Bohidar, S. K. (2024). *Unmanned aircraft systems.* Wiley Online Library.

Marshall, D. M. (2021). *Introduction to unmanned aircraft systems.* CRC Press.

Martins, N. (2024). Cunning tools of war: Moving beyond a technology-driven understanding of sUAS infiltration. *Military Review.* https://www.armyupress.army.mil/Portals/7/military-review/Archives/English/Nov-Dec-2024/Cunning-Tools-of-War/Cunning-Tools-of-War-UA.pdf

Mejias, L., Diguet, J.-P., Dezan, C., Campbell, D., Kok, J., & Coppin, G. (2021). Embedded Computation Architectures for Autonomy in Unmanned Aircraft Systems (UAS). *Sensors*, *21*(4), 1115. https://doi.org/10.3390/s21041115

Michaelides-Mateou, S. (2023). Challenges and trends in the aviation industry: Integrating UAVs in non-segregated airspace. In: Abdelkader, M., & Koubaa, A. (eds.). Unmanned aerial vehicles applications: Challenges and trends. *Synthesis Lectures on Intelligent Technologies.* https://doi.org/10.1007/978-3-031-32037-8_13

Mijacobs. (2022, November 29). What is agile? *Microsoft Learn.* https://learn.microsoft.com/en-us/devops/plan/what-is-agile

Miske, R. (2023). *Countering small unmanned aircraft systems with advanced data analysis and machine learning* [Master's thesis, Naval Postgraduate School]. Defense Technical Information Center. https://apps.dtic.mil/sti/trecms/pdf/AD1212947.pdf

Mogensen, K. N. (2016). *Motor-control considerations for electronic speed control in drones*. Texas Instruments. https://www.ti.com/lit/pdf/slyt692

Mohsan, S. A. H., Khan, M. A., Noor, F., Ullah, I., & Alsharif, M. H. (2022). Towards the unmanned aerial vehicles (UAVs): A comprehensive review. *Drones, 6*(6), 147. https://doi.org/10.3390/drones6060147

Mohsan, S. A. H., Othman, N. Q. H., Li, Y., Alsharif, M. H., & Khan, M. A. (2023). Unmanned aerial vehicles (UAVs): Practical aspects, applications, open challenges, security issues, and future trends. *Intelligent Service Robotics, 16*, 109–137. https://doi.org/10.1007/s11370-00452-4

Moradlou, H., Roscoe, S., & Ghadge, A. (2020). Buyer-supplier collaboration during emerging technology development. *Production Planning & Control, 33*(2-3), 159–174. https://doi.org/10.1080/09537287.2020.1810759

Mosterman, P. J., & Vangheluwe, H. (2024). When tiny is big: Design alive. *Simulation, 100*(12), 1225–1241. https://doi.org/10.1177/00375497241298648

Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2021). UAVs for industrial applications: Identifying challenges and opportunities from the implementation point of view. *Procedia Manufacturing, 55*, 183–190. https://doi.org/10.1016/j.promfg.2021.10.026

Muralidharan, N., Pratheep, V. G., Shanmugam, A., Hariram, A., Dinesh, P., & Visnu, B. (2021). Structural analysis of mini drone developed using 3D printing technique. *Materials Today: Proceedings, 46*(17), 8748–8752. https://doi.org/10.1016/j.matpr.2021.04.053

Munoz, J. A. I., Baha, E., & Muratovski, G. (2022). Radically innovating the automotive design process with immersive technologies. *International Conference on Engineering and Product Design Education,* 1–6.

Naor, M., Coman, A., & Wiznizer, A. (2021). Vertically integrated supply chain of batteries, electric vehicles, and charging infrastructure: A review of three milestone projects from theory of constraints perspective. *Sustainability, 13*(7), 3632. https://doi.org/10.3390/su13073632

NitPro Composites. (2025). *Why carbon fiber is a preferred material for making drones?* https://www.nitprocomposites.com/blog/why-carbon-fiber-is-a-preferred-material-for-making-drones

Nwaogu, J. M., Yang, Y., Chan, A. P. C., & Wang, X. (2024). Enhancing drone operator competency within the construction industry: Assessing training needs and roadmap for skill development. *Buildings, 14*(4), 1153. https://doi.org/10.3390/buildings14041153

Olanipiekun, O. A., Montalvo, C. J., Lippert, K. J., & Wade, J. T. (2024). Application of mind map and TRIZ to an advanced air mobility system for post-disaster response. *Systems, 12*(11), 508. https://doi.org/10.3390/systems12110508

Panou, E., Stathakis, I., Koutsoukos, D., Kirilov, K., & Mavrogiannakis, E. (2024). The evolving UAS threat: Lessons from the Russian-Ukrainian war since 2022 on future air defense challenges and requirements. *Integrated Air & Missile Defense Centre of Excellence.* https://iamd-coe.org/wp-content/uploads/2024/02/The-Evolving-UAS-Threat-Lessons-from-the-Russian-Ukrainian-War-Since-2022-on-Future-Air-Defence-Challenges-and-Requirements.pdf

Panwar, R., Pinske, J., De Marchi, V. (2022). The future of global supply chains in a post-COVID-19 world. *California Management Review, 64*(2), 5–23. https://doi.org/10.1177/00081256211073355

Parrot, Aaron, and Lane Warshaw. (2017, May 11). *Industry 4.0 and the Digital Twin.* Deloitte Insights, www.deloitte.com/us/en/insights/industry/manufacturing-industrial-products/industry-4-0/digital-twin-technology-smart-factory.html.

Paul, P., & Paul, L. (2023). An overview on the parachute recovery systems with additive manufacturing for UAV safe landing. *Materials Today: Proceedings, 72*(6), 3158–3162. https://doi.org/10.1016/j.matpr.2022.10.229

Prototek. (2025, June 19). *Drone manufacturing: A guide from components to production*. https://prototek.com/article/drone-manufacturing-a-guide-from-components-to-production/

Rabiu, L., Ahmad, A., & Gohari, A. (2024). Advancements of unmanned aerial vehicle technology in the realm of applied sciences and engineering: A review. *Journal of Advanced Research in Applied Science and Engineering Technology, 40*(2), 74–95. https://doi.org/10.37934/araset.40.2.7495

Ramesh, P. S., & Muruga Lal Jayen, J. V. (2021). Evaluation of design criteria for mini unmanned aircraft systems (UAS) applications. *Aircraft Engineering and Aerospace Technology, 94*(3), 327–335. https://doi.org/10.1108/AEAT-03-2021-0089

Rana, B., & Singh, Y. (2021). *Unmanned aerial vehicles for Internet of Things (IoT): Concepts, techniques, and applications.* Wiley Online Library.

Rauhala, A., Toumela, A., & Leviakangas, P. (2023). An overview of unmanned aircraft systems (UAS) governance and regulatory frameworks in the European Union (EU). *Unmanned Aerial Systems in Agriculture,* 269–285. https://doi.org/10.1016/B978-0-323-91940-1.00012-8

Rodrigues, D., Carvalho, P., Lima, S. R., Lima, E., & Lopes, N. V. (2022). An IoT platform for production monitoring in the aerospace manufacturing industry. *Journal of Cleaner Production, 368*, 133264. https://doi.org/10.1016/j.jclepro/2022.133264

Rogers, J. (2021). *Future threats: Military UAS, terrorist drones, and the dangers of the second drone age.* The Joint Air Power Competence Centre.

Rowland, M., & Karch, B. (2022). A review of technologies that can provide a "root of trust" for operational technologies. *Sandia National Laboratories.* https://www.osti.gov/servlets/purl/1861944

Salinas, J. C., & Lewandowski, T. (2024). Blue unmanned aircraft systems explained: The current drone market, flight regulations, and debunking common misconceptions. *Transportation Research Record: Journal of the Transportation Research Board, 26*(1), 1802–1813. https://doi.org/10.1177/03611981241257509

Salvador, M. A. (2023). Challenges of machine learning for eVTOL reliability and safety. *Journal of Mobile Multimedia, 19*(1), 311–324. https://doi.org/10.13052/jmm1550-4646.19116

Sanders, G., & Holderness, A. (2023). Rising demands and proliferating supply: The future of the global UAS markets. *Acquisition Management,* 190–207. https://www.dair.nps.edu/bitstream/123456789/4829/1/SYM-AM-23-060.pdf

Sarhadi, M. (2021). Robotic handling and lay-up of advanced composite materials: An overview. In: Taylor, P. M. (eds.). Sensory robotics for the handling of limp materials. *NATO ASI Series, 64*. https://doi.org/10.1007/978-3-642-75533-0_4

Shah, R. M., & Kirchhoff, C. (2025). Ukraine and the battlefield of the future. *Horizons: Journal of the International Relations and Sustainable Development, 30*, 172–189.

Sodhi, M. S., & Tang, C. S. (2022). Supply chain management for extreme conditions: Research opportunities. *Journal of Supply Chain Management, 57*(1), 7–16. https://doi.org/10.1111/jscm.12255

Tahmina, T., Garcia, M., Geng, Z., & Bidanda, B. (2022). A survey of smart manufacturing for high-mix low-volume production in defense and aerospace industries. *Flexible Automation and Intelligent Manufacturing: The Human-Data-Technology Nexus.* https://doi.org/10.1007/978-3-031-3_24

Thiessen, C. M., Van Bossuyt, D. L, & Halle, B. (2023). Reducing asymmetry in countering unmanned aerial systems. *Naval Engineers Journal, 135*(1), 83–93.

Tomasso, J. (2025). Low-cost solutions for military capabilities. *Programme Defence and High Technology Industry.* https://www.iris-france.org/wp-content/uploads/2025/09/ProgIndusDef_2025_09_Low_cost_capabilities_Note_EN-1.pdf

Torrey Hills Technologies, LLC. (2020). *Review of Power Electronics Packaging and the Use of Copper Tungsten as a Heat Sink* [White paper]. https://www.torreyhillstech.com/Documents/Power_Electronics_Packaging.pdf

U.S. Department of Defense. (2022). *Operation of the Adaptive Acquisition Framework (DoDI 5000.02).* Washington, DC: Office of the Under Secretary of Defense for Acquisition and Sustainment. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/500002p.pdf

Vanderhorst, R., H. D., Heesom, D., Suresh, S., Renukappa, S., & Burnham, K. (2023). Barriers and cost model of implementing unmanned aerial system (UAV) services in a decentralized system: Case of the Dominican Republic. *Construction Innovation, 23*(4), 833–857. https://doi.org/10.1108/CI-08-2021-0155

Vashishth, T. K., Sharma, V., Sharma, K. K., Kumar, B., Chaudhary, S., & Ahamad, S. (2024). *Unmanned Aircraft Systems.* Wiley Online Library. https://doi.org/10.1002/9781394230648.ch1

Velter Drone Brigade. (2024). Home. https://www.velterdronebrigade.co.uk/

Vrana, J., & Singh, R. (2021). NDE 4.0: A design thinking perspective. *Journal of Nondestructive Evaluation, 40*(8). https://doi.org/10.1007/s10921-020-00735-9

Waller, S. T., Qurashi, M., Sotnikova, A., Karva, L., & Chand, S. (2023). Analyzing and modeling network travel patterns during the Ukraine invasion using crowd-sourced pervasive traffic data. *Transportation Research Record: Journal of the Transportation Research Board, 2677*(10), 491–507. https://doi.org/10.1177/03611981231161622

Wang, L., Xhang, Y., Wang, Z., Chen, J., Yang, L., Xia, J., … Kong, Y. (2024). Additive manufacturing in construction using unmanned aerial vehicle: Design, implementation, and material properties. *Journal of Building Engineering, 98*, 111363. https://doi.org/10.1016/j.jobe.2024.111363

Weldon, W. T., Hupy, J., Lercel, D., & Gould, K. (2021). The use of aviation safety practices in UAS operations: A review. *Collegiate Aviation Review International, 39*(1). https://ojs.library.okstate.edu/osu/index.php/CARI/article/view/8214/7544

Wicke, T., Weymann, Neef, C., & Tubke, J. (2025). Forecasting battery cell production in Europe: A risk assessment model. *Batteries, 11*(2), 76. https://doi.org/10.3390/batteries11020076

Wonderful PCB. (2025, January 13). *PCB manufacturing and assembly process flow chart*. https://www.wonderfulpcb.com/manufacturing-process-flow-chart/

Xing, J. (2023, September 25). *The ultimate guide: How are lithium batteries made*. Lithium Battery Tech. https://www.lithiumbatterytech.com/how-are-lithium-batteries-made/

Acquisition Research Program
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net