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ADDITIVE MANUFACTURING IN THE MILITARY INDUSTRY: RESILIENCE AND SUSTAINABILITY FOR SMALL STATES

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Abstract: *Military industries operate with many opportunities, but also face obstacles in the form of political, economic or security restrictions. This paper analyzes additive manufacturing, or 3D printing, as a technology which can provide more resilient production, development, and sustainability of military capability for small states. By analyzing open-source strategic reports and scientific studies, the paper identifies three interlinked dimensions in which 3D printing can contribute to sustainable military production under various political and security conditions: security resilience, economic efficiency and environmental responsibility. The findings show that additive manufacturing can reduce dependence on imports of different components, which can mitigate challenges related to international sanctions, export restrictions or supply chain disruptions. Analyzed sources indicate that 3D printing can offer greater adaptability, lower cost, and a faster development process for small scale production. It can reduce material waste, energy consumption, transportation costs and carbon emissions. The global trends, opportunities and present risks, such as patent rights, cybersecurity and arms proliferation control are taken into consideration. Policy recommendation includes establishment of 3D printing hubs, product modification strategies and the adoption of energy efficiency and ecology standards. Overall, 3D printing can provide a higher degree of autonomy and resilience in military production for small states.*

Keywords*: additive manufacturing, 3D printing, military industry, production sustainability, small states, production efficiency.*

1. INTRODUCTION

Nowadays, military industries are frequently hit by political disturbances, economic obstacles, security threats, and ecological catastrophes. These constraints are usually expressed in forms of political requests, international sanctions, weapon embargoes, or trade tariffs.

Production of military weapons and equipment in small states is usually based on massive imports of different components and spare parts. The supply is relied on long-distance supply chains, centralized supply routes, suppliers from various countries, and a long time for execution. These characteristics make the supply very sensitive to any possible constraints.

The military industry can use developed technology of additive printing (AM) or 3D printing, as a national defense strategy policy to establish operational resilience under disruptive conditions [1]. This technology offers opportunities for locally produced components, in small series with small-scale material stocks, using universal 3D printers and DIGITAL FILE models. It constructs objects by adding material layer by layer, with minimal leftover. Modern technology produces very complex components technology can produce very complicated components, consisting of different materials, depending on printing technology [2].

According to open-source strategic reports and case studies, AM contributes to the resilience of military production in small states through three areas: security resilience, economic efficiency, and environmental responsibility.

Along the positive sides of AM technology, the paper discusses critical risks, focusing on the patent rights, cybersecurity, arms proliferation control, and required precondition for locally 3D printing of spare parts [3].

In conclusion, the paper translates findings into several policy recommendations, including the establishment of regional 3D printing hubs, on-site modification workshops, and the implementation of material recycling standards in manufacturing.

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2. BASIC CONCEPTS: ADDITIVE MANUFACTURING, MILITARY INDUSTRY, AND INTERNATIONAL TRADE CONTROLS

Characteristics of AM, the production of weapon systems, and international trade conditions are in correlation to component supplies. Each domain introduces analytical categories that are essential for interpreting empirical evidence presented in subsequent sections of this paper.

2.1. Additive Manufacturing: Definition, Processes, and Characteristics

Additive manufacturing (AM) is an innovative technology where the object creation is based on layer-by-layer material addition, in contrast to conventional manufacturing, where the object creation is based on removing excess material.[2].

For small series component production, AM offers several advantages over conventional manufacturing: almost no material waste, easy fabrication, minimal human work, little post-processing, and energy efficiency. [4]

These properties make 3D printing relevant for production in the military industry, for small-scale production, where availability of components is crucial, the time of supply is essential, and the cost reduction is fundamental. The Peace Research Institute Frankfurt characterizes AM as "key for the development of future military capabilities" and notes that the technique "produces objects layer by layer according to a digital 3D model" [5].

According to the American Society for Testing and Materials (ASTM) classification, AM processes are divided into seven main categories [4]: Stereolithographic (SL), the earliest process, introduced and patented by Charles Hull in 1984; Fused Deposition Modelling (FDM), developed by Stratasys; Powder Bed Fusion (PBF), encompassing Selective Laser Sintering (SLS), Electron Beam Melting (EBM), and Selective Laser Melting (SLM); Binder Jetting, developed at MIT; Direct Energy Deposition (DED), specifically employed for repair and maintenance rather than new-part fabrication; and Laminated Object Manufacturing (LOM), commercialized by Helisys Inc. in 1991. Every AM technology has different characteristics and fields of application.

2.2. Technological Framework

Additive manufacturing is strongly connected with industrial development aligned with Industry 4.0. Raja Santhi, A. and Muthuswamy, P. [6] describe Industry 4.0 as an industry transformation based on digital connection and data-driven processes, focused on automation, interconnectivity, and real-time process optimization. In this environment, leading technologies are the Internet of Things (IoT), Machine Learning (ML), Artificial Intelligence (AI), Cyber-Physical Systems (CPS), Cloud Computing, Additive Manufacturing, Digital Twins, and Cybersecurity. All of these technologies from Industry 4.0 create a manufacturing ecosystem that is interconnected and data-driven [6].

On the other hand, military industry production has always been expensive, involved high technology, complicated product development, and secrecy. In the era of globalization, the costs of development and production have been reduced by outsourcing some work or by buying some components from the main world producer. Such a solution leads to many challenges: trade barriers, disruption of supply-chains, security challenges, time for delivery, quality control, etc. In some cases, for high-tech systems, for small-scale production, the low price is not the main goal, but the availability of components on time.

2.3. International Trade Controls, Sanctions, and Trade Barriers

Hirbu [7] provides a foundational definition: "A trade restriction is defined as any government policy that limits the free flow of goods and services across borders. The main goal of trade restrictions is to protect domestic industries from cheap imports from other countries".

Of greater relevance to the military-technological context is the author's typology of four categories of formal trade barriers: Voluntary Export Restraints, Regulatory Barriers, Anti-Dumping Duties, and Subsidies [7]. Beyond formal tariff barriers, the literature identifies non-tariff measures as increasingly central instruments of trade governance. Hirbu [7] notes that "non-tarife barriers are way to restrict trade using trade barriers in a form other than a tariff ... There are different types of non-tariff measures, such as quotas, sanctions, import deposits, licenses, embargoes, etc."

Monadjemi and Lodewijks [8] highlight the strategic, power-political dimension of trade restrictions: "There is a literature on strategic trade policy, and this appears a power play to reduce market access to improve a bilateral trade deficit." This insight is relevant for understanding how sanctions and export controls function, not merely as regulatory instruments but as tools of geopolitical competition, directly affecting the availability of advanced manufacturing technologies, including AM systems, to states subject to such measures.

3. METHODOLOGY AND ANALYSIS OF THE THREE CORE DIMENSIONS

3.1. Security Resilience

The primary utility of AM within a small state’s defense strategy is its capacity to transform a physical, vulnerable logistics pipeline into an anti-fragile, digital asset protection network.

Traditional weapons embargoes and economic sanctions rely on physical interdiction at critical geographical choke points such as maritime ports, airspace corridors, and border crossings. Additive manufacturing fundamentally alters this interdiction dynamic by digitizing the transaction layer, and they become invisible to traditional

maritime blockades and customs border checks [9].

Field data from international deployments confirms that the speed of local component execution acts as a major resilience factor during active disruptions. In expeditionary or isolated defensive settings, standard logistical transport pipelines typically feature severe vulnerabilities due to damaged local infrastructure or a lack of secured transport [2].

3.2. Economic Efficiency

Military supply chains during operations differ from civilian supply chains in ways that amplify the vulnerabilities of smaller states. Den Boer et al. [2] identify three distinguishing features: the primary focus is not on financial efficiency but on advancing the operational effectiveness of deployed troops; the circumstances in which troops operate are of considerably greater variety; and during military and humanitarian operations, the supply chain frequently encounters damaged infrastructure, lack of transport, loss of governmental functions, threat or physical violence, and the presence of many injured and traumatized individuals.

Westerweel et al. [16] conclude that on-site 3D printing can help to solve some of the biggest issues. It is presented the new model formulation in which a 3D printer can be used to resolve spare parts shortages. The benefits of on-site printing are demonstrated via a case study based on actual Royal Netherlands Army operations in Mali. The results prove that RNLA greatly benefits from on-site printing, much more than from a conventional expediting option. It shows a reduction in operational costs of 47% across 14 components, and inventory storage space for regular spare parts is reduced by 72%. Those benefits are achieved with a relatively simple general-purpose printer against small investments in on-site raw material [16].

3.3. Resource saving and recycling

The military industry is structurally optimized for weapon production, where the raw material is optimized for subtractive production, ignoring ecological costs of raw material extraction, scrap generation, and intercontinental transportation loops [10]. In conventional subtractive production, up to 80% to 90% of the raw material is ground away into unrecyclable shavings, which becomes a massive waste footprint for premium, energy-intensive materials [1].

Additive manufacturing has different material processing based on different technology [12]. 3D printers build components layer-by-layer, using the precise volume of printing powder required for the component's geometry [13]. Any unspent material powder surrounding the build chamber is vacuum-reclaimed, sieved, and recycled into subsequent production runs, capping net material waste below 5% to 10% [13]. For a small state facing import restrictions, this 90% reduction in material scrap ensures that precious stocks of national raw metals are preserved rather than lost to factory floor waste.

Official field deployment records for the Dutch troops in the UN mission in Mali indicate that over 51% of all freight cargo delivered to remote military bases consists of single-use packaging materials, polymer containers, and protective sealing foils, with less than 0.1% of these materials ever returned to the home country [2].

By deploying ruggedized shredders and compact filament extruders within the base infrastructure, single-use polymer packaging can be processed locally into technical-grade printing filaments [2]. Processing the baseline 51% packaging waste stream available on-site drops external supply dependency down to 56.65%, proving that on-site circular recycling acts as a strategic buffer [2]. This transformation turns military production into a localized, self-sustaining loop, significantly reducing the carbon footprint of transport vehicles while securing parts supply without drawing on external resources [11].

4. GLOBAL TRENDS, RISKS, AND CHALLENGES

4.1. Resilience policy trends in study cases

The case of the Royal Netherlands Army is particularly instructive as an example of how a small but technically advanced NATO member has approached the AM-logistics nexus. Den Boer et al. document that "the Dutch Army has been going through several budget cuts in the last decade. It has caused the military to be feeding off reserves, both financially and physically in spare parts and material. These budget cuts have led to situations in which availability requirements of materials and spare parts for certain units were not met, in turn affecting preparatory activities for missions and on combat power during missions themselves" [2].

The institutional response was equally significant: "As part of the government strategic plan, the Dutch Ministry of Defense is supposed to reduce primary raw material use by 50%" [2]. This commitment simultaneously addresses economic, environmental, and operational objectives, with AM as the enabling technology.

The most extreme contemporary illustration of AM as a supply chain resilience instrument under conditions of acute disruption is provided by the Ukrainian wartime context. Suckau describes how "both industrial actors and private citizens form nodes in a crowdsourced supply network that supplies the army. As such, it not only shows how lethal effects are achieved, compared to industrial applications' simpler 3D printing, but also exemplifies the professionalization and adaptation of an ad hoc innovation that initially responded to a lack of materials and supply. Besides polymer-based products, replacement parts for conventional armaments have been printed with machines provided through international military assistance".[5] This case transcends the conventional state-centric model of military logistics, demonstrating that under conditions of extreme supply chain disruption, AM enables decentralized, distributed production networks involving civil society actors.

The author appropriately notes the epistemological

limitation of this case: "It is too early to assess the impact on Ukrainian military capabilities" [5]. Nevertheless, the case provides a documented illustration of the mechanisms through which AM can substitute for or supplement conventional supply chains when those chains are partially or fully disrupted.

4.2. Intellectual Property (IP) and Legal Vulnerabilities

When there are supply chain disruptions, regardless of whether they are political isolation, embargoes, or blockades, it immediately affects military production and defense forces readiness [2]. To keep weapon production and maintenance alive by using reverse engineering and locally 3D printing components without authorization from foreign original equipment manufacturers. This can be an immediate solution for defense capabilities, but long-term it can induce problems with contractual and guarantee breachs, but also can cause additional diplomatic countermeasures.

As documented by defense logistics reviews, utilizing self-produced spare parts instead of OEM-certified components routinely invalidates overall system warranties. This can lead to intense legal disputes regarding liability if a system fails during operations [2].

The international community and companies will not look favorably on the infringement of patent rights, such as the mass production of parts without a license. This will have as a consequence secondary economic sanctions, further trade restrictions, or military actions in some cases, which can be extremely harmful for the military structures of small states.

4.3. Cyber-Physical Security Vulnerabilities

AM infrastructure is relying on digital design files, which opens up for hostile cyber operations [9], especially when the CAD software and 3D printers are usually produced by global foreign companies. In some cases, 3D printers are connected to the Internet to their producer, from whom the printing file has to be received. Adversaries can use these facts to cyber-physically sabotage.

Cyber attackers do not need to destroy a network or prevent printing components. Instead of that, the printing file can be intercepted, and the component registries can be changed. These changes can lead to small changes in design or printing quality, which can have an impact on printed component function [3].

These compromised parts will visually pass field inventory checks, only to suffer catastrophic failure under operational stress (e.g., a drone propeller snapping at high RPM or a missile casing rupturing upon ignition), rendering the weapon system ineffective at a critical moment.

4.4. Technical Omissions and Quality Control

Maintaining consistent mechanical properties across distributed, forward-deployed 3D printers remains a difficult engineering challenge. In centralized mass production, quality control is maintained through tightly regulated factory conditions [1]. On the field, however, AM systems must operate in harsh, volatile environments. Institutional reports from the U.S. GAO and the NATO STO [14] mention uncontrolled changes in humidity, and fluctuations in electrical grids, but also the quality of trained personnel.

Uncontrolled changes in humidity, ambient temperature, and dust contamination can degrade raw metal powders and technical polymers [1]. For example, nylon and advanced polyamides are highly sensitive to moisture, and poor storage conditions can lead to porous, brittle prints [2].

Fluctuations in electrical grids or rough physical handling of machines can throw off optical laser calibration or extrusion precision [1]. This can affect the precision of the production head, which can be a big problem for high-precision military systems [2].

The problem of trained personnel who are responsible for printing components or quality control is problematic because usually it’s their additional job, and the different components have different requirements. It’s difficult to train personnel for every possible situation.

4.5. Arms Control and Proliferation Challenges

Today, 3D printing is a widely spread technology, with very capable 3D printers available for a relatively low price. If CAD printing file reach a person with criminal intentions, they can easily produce components of highly capable weapon systems. Traditional arm control systems are based on tracking physical components, and they aren’t successful. Tracking digital files is much harder, and it’s dangerous.

UNIDR [3] highlights that AM deconstructs this framework by separating the design of a weapon from its material execution. Unindexed weapon designs, modular CAD frameworks for improvised explosive devices (IEDs), and components for autonomous kamikaze drones can be shared globally across untraceable digital networks.

This digital transfer makes it increasingly difficult for international bodies to enforce traditional export controls or verify non-proliferation treaties. This environment allows both non-state actors and domestic criminal enterprises to establish covert, localized manufacturing cells that bypass all conventional border and customs checkpoints [9].

5. POLICY RECOMMENDATIONS

It isn’t possible to set one solution for building resilience of military industry production in small states, considering global trade market disturbances. To get the most from AM and mitigate the system risks, the best solution for small states is to establish national policies, with the aim to build military industry, including AM as integrated technology. That will include the establishment of regional 3D printing hubs, product development aiming to design for 3D printing and required ownership of data

files, production standardization, and required procedures for material recycling, storage, and testing.

5.1. Establishment of Sovereign and Secure 3D Printing Hubs (AM Hubs)

Small states should avoid fragmented, ad-hoc adoption of AM by civilian operators and instead build a centralized network of secure, military-controlled Additive Manufacturing Hubs (AM Hubs) [3]. These installations must serve as the primary repositories for national digital inventory data, technical materials, and industrial-grade printing systems (e.g., Wire Arc Additive Manufacturing - WAAM and Selective Laser Melting - SLM) [12].

AM Hubs should be built as production facilities with big data centers and different printing material reserves. It should operate as a service center for small-scale production where other types of production would demand too many operations or be too costly. As a production line, there should be many different 3D printers for printing all kinds of materials. For military purposes, this kind of facility can be built in cargo containers, and it could be set for expeditionary purposes.

As a data center for CAD file storage, this hub has to be protected from different cyber-physical vulnerabilities, so it has to be built with high network protection from physical impact and cyberattacks.

To insulate these hubs from the cyber-physical vulnerabilities detailed in Chapter 4, they must adhere to rigid network isolation criteria.

First, all computer-aided design (or other types of digital files) stations, slicing engines, and industrial printers must be completely disconnected from public internet routing and unclassified defense networks.

Data transfer from the main digital registry to forward-deployed or mobile printing modules must utilize high-level, end-to-end encryption protocols with hardware-token validation to prevent malicious code modifications or file interception.

Hubs should establish cooperation with national technology research centers and technical universities to provide an environment for technical improvement, material development, and 3D printing localization, but also to ensure a continuous pool of certified operators and design engineers without relying on foreign technical support.

5.2. Adoption of "Design-for-AM" and Digital Procurement Protocols

3D printing requires digital files, which are usually intellectual property and should be solved before the need for printing arises. Small states must pivot toward data-centric purchasing frameworks [2].

Future procurement contracts signed by small states with foreign original equipment manufacturers (OEMs) should mandate the following provisions: contractual technical data packages (TDPs), "Design-for-AM" optimization, and certified third-party service escrows.

Tenders must require that international suppliers include fully documented CAD files, material performance criteria, and localized printing rights for non-structural, high-wear components as part of the base purchase agreement.

Domestic defense industries must design native military equipment to prioritize the use of modular, standardized components that are explicitly optimized for on-demand 3D printing, reducing the need for specialized external tooling [1].

To protect against situations where an OEM goes bankrupt or imposes a political cutoff, agreements should place critical design blueprints in secure digital escrows managed by neutral international bodies or verified domestic service providers.

5.3. Codification of Digital Quality and Ecological Standards

For decentralized designing and manufacturing components

that will meet required structural performance and quality, but also the resource efficiency and ecological standards, small states must enforce strict, standardized quality controls [15].

Any critical component printed at a forward-deployed location must undergo strict verification protocols (e.g., ultrasonic scanning or industrial computed tomography) to check for internal microstructural voids and layer alignment anomalies before field installation [1].

Mobile, containerized printing labs must be equipped with active environmental control systems to manage internal moisture, temperature, and dust levels. This ensures raw metal powders and technical polyamides do not degrade before printing [1].

Small states should mandate for hubs to use high-efficiency machinery and compulsory recycling of unspent metal powders and single-use polymer packaging within tactical zones [11]. Standardizing on-site filament extrusion processes allows small states to transform base waste streams into functional defense assets, ensuring long-term resource independence under blockade [2].

6. CONCLUSION

Additive manufacturing is a disruptive technology, which can cause a structural shift in how small states design and maintain their defense capabilities and sustain national interests under geopolitical constraints. As global supply chain disruptions, caused by international sanctions, wars, export controls, or resource constraints, threaten the continuity of military industry production and degrade the defense capabilities of small countries. Conventional centralized supply models, characterized by long lead times and high inventory dependencies, increasingly fail to guarantee operational readiness.

This paper has evaluated the impact of 3D printing on small states military industry and defense capability.

Changing from physical import to transfer of encrypted digital data protects small states from physical supply chain breaks and embargoes, effectively bypassing traditional geographical choke points. AM excludes upfront tooling costs in conventional manufacturing and enables the financially viable production of rare, customized, and small-batch components, reducing weapon system downtime by over 90%. Building components layer-by-layer cuts net raw material waste below 10%, while localized circular loops (such as converting single-use base packaging waste into raw printing filament) allow outposts to sustain manufacturing needs without drawing new external resources.

Building a military industry around AM technology, it has its negative sides. The digitalization of supply chains is an opportunity for hostile actors to change printing files to cause undetected structural weapon malfunction. Unauthorized component replications have intellectual property and warranty challenges. For security reasons, the digitalization of weapon designs can cause severe problems for non-proliferation hurdles for global arms control.

Successful implementation of AM depends on proactive public policies. By establishing AM hubs, requiring digital data rights in procurement contracts, establishing strict control standards, and recycling and ecology standards, small states can mitigate these risks. Then, AM becomes an essential, sustainable ecosystem that provides small states with the operational flexibility, economic sustainability, and long-term autonomy required to survive in a volatile global arena.

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