ISSN 2669-2023 (print) / ISSN 2538-8959 (on-line) / DOI 10.3849/cndcgs.2024.612

Advancements in Additive Manufacturing Technologies for Enhancing Efficiency and Sustainability in Military Logistics Operations

Aidas VASILIS VASILIAUSKAS[1]*

[1] *General Jonas Žemaitis Military Academy of Lithuania, Silo g. 5A, LT-10322 Vilnius*

*Correspondence: *aidas.vasilisvasiliauskas@lka.lt*

Abstract

This research aims to present a well-rounded analysis of additive manufacturing technologies in the context of military logistics by systematically identifying their potential applications, examining the barriers to adoption, and providing actionable solutions. By highlighting the transformative potential of additive manufacturing technologies in military logistics, this study will contribute to a deeper understanding of how emerging technologies can be connected to improve the efficiency, flexibility, and resilience of military supply chains in the 21st century. The conducted study highlights that overcoming these challenges requires strategic managerial interventions, including aligning the perceived and actual benefits of additive manufacturing, fostering inter-organizational cooperation, and addressing legal and technological limitations. Through targeted decision-making strategies, organizations can mitigate the negative impacts of these issues and leverage the disruptive potential of additive manufacturing to improve efficiency, cost-effectiveness, and operational resilience. By doing so, they can enhance overall performance and position themselves to thrive in a rapidly evolving technological landscape.

KEY WORDS: *Additive manufacturing, 3D printing, military logistics, Lithuanian Armed Forces, technology integration, readiness enhancement.*

Citation: Vasilis Vasiliauskas, A. (2024). Advancements in Additive Manufacturing Technologies for Enhancing Efficiency and Sustainability in Military Logistics Operations. In Proceedings of the Challenges to National Defence in Contemporary Geopolitical Situation, Brno, Czech Republic, 11-13 September 2024. ISSN 2538-8959. DOI 10.3849/cndcgs.2024.612.

1. Introduction

In the current era, we are approaching the dawn of the Fifth Industrial Revolution, driven by breakthrough innovations in advanced artificial intelligence, robotics, nanotechnology, and biotechnology [1-3]. These emerging technologies are expected to confer unprecedented advantages in the contemporary business landscape. Nevertheless, we are still in the critical phase of integrating and testing key innovations from the Fourth Industrial Revolution, which are foundational to modern logistics systems [4,5].

Globally, logistics remains a critical sector for efficiently managing the flow of goods, ensuring timely deliveries, and optimizing costs to maintain high levels of customer satisfaction [6]. To further enhance these logistics processes, innovations under the banner of "Logistics 4.0" are gaining traction. These involve the integration of cutting-edge digital and information technologies, including the Internet of Things (IoT), big data analytics, artificial intelligence (AI), block chain, additive manufacturing, cloud computing, and cybersecurity [7,8]. However, the adaptation of these trends is not uniform across industries, with the military sector being one example where adoption may be slower, particularly in military logistics systems [9-11].

Given these circumstances, it becomes imperative to explore the potential application of "Logistics 4.0" technologies within military logistics. According to NATO's science and technology trends for the years 2023–2043, additive manufacturing technologies (AMT) hold a high significance coefficient and are classified as disruptive technologies [12, 13]. These technologies have the capacity to radically alter traditional manufacturing processes and supply chain operations [14, 15]. By enabling the on-demand production of complex parts and components, AM provides considerable advantages in flexibility, cost-effectiveness, and shorter lead times.

In military contexts, additive manufacturing could enable rapid prototyping, customization, and the repair of critical equipment, leading to improved operational readiness and resilience [16, 17]. These technologies have already reached an advanced development stage and have been demonstrated in relevant environments. It is projected that between 2025 and 2030, the full potential of additive manufacturing will be realized in military logistics operations (NATO Science & Technology Organization, 2023) [18,19].

Peer-review under responsibility of General Jonas Žemaitis Miltitary Academy of Lithuania and University of Defence, Czech Republic

This paper delves into the role of additive manufacturing technologies—commonly referred to as 3D printing—within military logistics. The military environment presents unique complexities, which pose both challenges and opportunities for the application of "Logistics 4.0" innovations, particularly in terms of implementing additive manufacturing technologies.

2. Conducted Research Design

The object of this research was chosen the additive manufacturing technologies (AMT), widely known as 3D printing. These technologies represent a cutting-edge approach to manufacturing that constructs objects layer by layer from digital models. The range of materials used in additive manufacturing, from polymers to metals, allows for the creation of highly complex, custom components. AMT is revolutionizing various industries, offering key benefits such as rapid prototyping, reduced production time, minimized waste, and the ability to produce highly customized parts on-demand. The adaptability and decentralized nature of 3D printing make it particularly attractive in contexts where traditional supply chains face significant constraints—such as in military operations and logistics.

Notable, the military logistics environment is characterized by its need for flexibility, efficiency, and the ability to operate under time-sensitive and resource-constrained conditions. Also, AMT, with its ability to produce spare parts, components, or even entire structures on-site and on-demand, offers a disruptive opportunity for military logistics to become more self-sufficient and responsive in the face of changing operational demands. So, the overarching purpose of this study was to critically evaluate the feasibility and potential of additive manufacturing technologies in the field of military logistics. This study was focused on identifying how these technologies can modernize logistical processes, reduce supply chain weaknesses, and enhance the overall readiness of military forces by enabling rapid part production in the field. By evaluating existing applications and exploring potential future implementations, the study directed to clarify how AMT can be integrated into military operations to increase operational efficiency and flexibility.

To reach mention study goals there were raised up a few tasks: (i) identify the application possibilities of 3d printing in military logistics; (ii) identify the problem areas of applying 3d printing in military logistics: (iii) provide reasonable solutions for the application of additive manufacturing technologies in military logistics.

The first task was focused on the possible uses of additive manufacturing within the complex domain of military logistics. This task involved the examining current and prospective applications, such as the production of spare parts for military equipment, customized tools, and the ability to create specialized components for mission-specific needs. Additionally, the research explored the potential for AMT to enable on-site production of critical supplies, which could substantially reduce dependence on traditional supply chains, especially in forward-operating bases or remote areas. Through this task, the study built a comprehensive framework that categorizes the various ways in which 3D printing can be employed to enhance military logistics processes. Also was included exploration how these technologies can complement existing logistical infrastructure, providing flexibility, cost reduction, and enhanced responsiveness.

The second task was focused on how to identify and analyze the barriers and challenges that may impede the successful application of additive manufacturing in military logistics. While AMT offers numerous benefits, its implementation within military contexts is not without challenges. These may include technical issues, such as material limitations (e.g., availability of durable, high-performance materials suitable for military environments), production speed limitations, quality control, and ensuring the reliability of printed parts in harsh conditions. Moreover, logistical challenges such as integrating AMT into existing military supply chains, training personnel, and overcoming organizational resistance to adopting new technologies must also be considered. Through a detailed analysis of these problem areas, the study was able offer a realistic assessment of the obstacles to widespread adoption and suggest potential ways to mitigate these issues.

The final task involved developing practical, evidence-based solutions to address the challenges identified in the previous task and proposing strategic application cases for additive manufacturing in military logistics. These solutions will be based on a thorough evaluation of the current state of AMT and best practices from both civilian and military sectors. The study was also exploring how logistics processes could be optimized to integrate AMT efficiently, offering a roadmap for military organizations seeking to implement these technologies into their logistical frameworks.

Finally, the research process was divided into three phases. In the first phase of the study, expert interviews were carried out to identify the applicability of 3D printing in military logistics. In the second phase of the study, a root- cause analysis was applied to identify problem areas and to provide valid suggestions for the application of 3D printing in military logistics. The third stage of the study was aimed at identifying applications of additive manufacturing technologies in LC logistics and formulating managerial solutions.

1. **Expert interviews**. Semi-structured, individual, expert (informant) interviews were conducted in order to meet the first research objective and to fill the gaps in the analysis of secondary data for the application of 3D printing in military logistics. The interviews were conducted anonymously, with the informants answering individually the pre-defined questions asked of them, but with the possibility of additional questions not included in the interview schedule, if these could enrich the research. At any point during the interview, the informants could refuse to answer the questions asked and could terminate the interview process.
2. **Analysis of the origins of the problems.** A root-cause analysis was carried out to address the second objective of the study and to summarise the information obtained from the secondary data and interviews. "The 'fishbone' diagram is a graphical representation of the causes of problems. "The fishbone diagram can be used to group individual problems into problem areas and is therefore useful in the initial stages of 3D printing integration to

prepare for potential risks that may arise and can be used for managerial decision making. "The 'fishbone' diagram visually represents hierarchical structures with a central element (the main problem) and distinct smaller lines representing sub-elements (problem areas and causes of problems). It simplifies complex information and reveals hierarchical relationships [20]. The analysis of the root causes of the problems allows for the formulation of valid suggestions for the application phases of 3D printing in LC logistics.

3. **Practical applications and decisions**. In order to meet the third objective of the study, specific applications of additive manufacturing technologies in Lithuanian Military Logistics (LML) were identified and sound managerial solutions were presented. Based on the LML and NATO doctrinal publications, specific applications of additive manufacturing technologies in LML were identified. Based on the root cause analysis data, informants' responses and secondary data collected from the authors [21-25], valid managerial solutions for the application of additive manufacturing technologies in military logistics were formulated.

3. The Study Results

3.1. Root Cause Analysis Interpretation

As was mention in the methodology section the root cause analysis was used to identify problem areas for the application of additive manufacturing (ADM) technology in military logistics (ML). The conducted analysis helped to clarify three main problem areas: (i) the lack of correlation between the potential of additive manufacturing and the benefits generated, (ii) the lack of cooperation in the application of additive manufacturing technologies, and (iii) the technological and legal constraints of additive manufacturing. The study let to look deeper into the problem areas that can appear and to identify their specific causes (see Fig. 1).

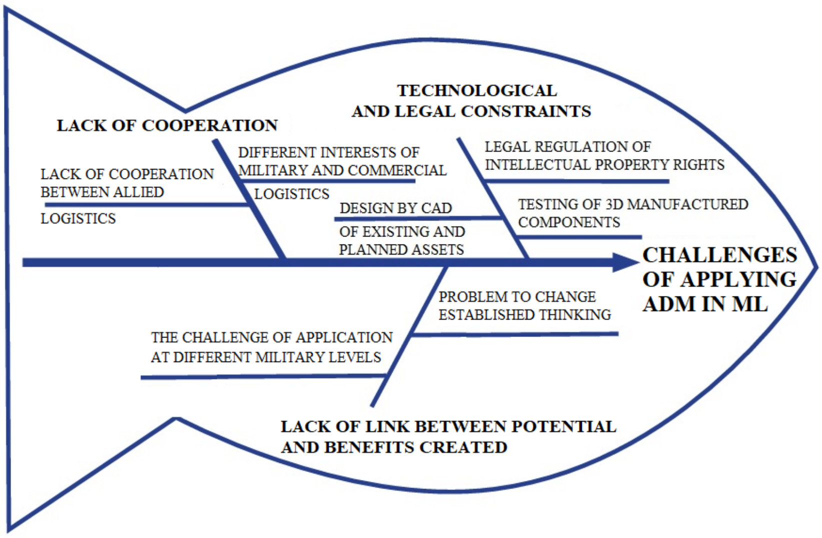

Fig. 1. Root cause analysis diagram of the problems in the application of additive manufacturing (ADM) in military logistics (ML).

The identified three main causes can be clarified more detailed. The identified "*Technological and Legal Constraints of Additive Manufacturing*" foundations can be explained by the slow integration of additive manufacturing technologies (AMT) in military logistics. As was recognized the 3D is slowed down by several technological and legal constraints, which create specific challenges for its widespread adoption.

The first cause in this group is the need for testing of 3D-Printed Components. A critical challenge is the reliability and safety of 3D-printed components in mission-critical military operations. While additive manufacturing offers flexibility in producing parts on-demand, military-grade components must adhere to strict standards regarding durability, strength, and performance. This necessitates extensive testing and validation procedures to ensure that printed parts meet military specifications and can withstand the extreme conditions often encountered in the field. The testing process adds time, cost, and complexity to the use of AMT in military settings, potentially offsetting the on-demand benefits. The challenge here is not just about testing individual parts, but also developing standardized testing protocols that ensure uniformity across different types of military equipment and across different branches of the military.

The second cause in this group is stringent intellectual property rights (IPR) requirements for additive manufacturing. Many parts and components used in military equipment are protected by patents or other forms of IPR. So, IPR is a significant legal barrier to the use of additive manufacturing in military logistics. Reproducing these components through 3D printing without proper legal clearance can lead to IP infringements, limiting the ability of military forces to leverage AMT for spare parts production. Navigating the complex landscape of licensing agreements for 3D printing technology and proprietary parts requires specialized legal frameworks and processes. Moreover, military organizations may need to establish collaborative agreements with private-sector manufacturers to secure the rights to produce proprietary components using additive manufacturing, which could slow down the adoption of this technology.

The third cause is CAD development of existing and planned assets. Notable, the additive manufacturing relies seriously on Computer-Aided Design (CAD) models to create 3D-printable components. One of the key technological challenges is the development and digitization of CAD models for both existing military assets and newly planned systems. Many older military systems were designed long before CAD technology became standard, meaning there may not be readily available digital files to replicate parts. Creating CAD models of these legacy systems requires reverse engineering, which can be a time-consuming and resource-intensive process. Even for new systems, designing parts with additive manufacturing in mind necessitates a shift in design philosophy, which poses a challenge for military engineers and manufacturers accustomed to traditional methods.

"Lack of link between the potential for additive manufacturing and the benefits generated" can be represented as one more important cause group. This situation can be represented as a significant barrier to the adoption of additive manufacturing in military logistics is the discrepancy between the potential of the technology and the concrete benefits it can provide. This cut off demonstrates in several ways, but it is important to mention main two:

- The complexity of changing established thinking that can be explained as traditional conservative of military in adopting new technologies, especially those that challenge established logistical processes. The shift toward additive manufacturing requires a fundamental change in mindset and operational procedures. Military leaders and logisticians must overcome the entrenched belief in traditional manufacturing processes and supply chain methodologies. This resistance to change stems not only from institutional inertia but also from the perceived risks associated with adopting a relatively new technology in critical operations. For additive manufacturing to be fully integrated, there needs to be broader cultural and organizational acceptance within military logistics, which requires education, training, and demonstrable success stories.
- Also, the challenge of adapting additive manufacturing at different military levels can be seen as a cause. Because the application of additive manufacturing technologies is not uniformly beneficial across all levels of military operations. While frontline units may benefit from the on-site production of spare parts and tools, higher-level strategic logistics functions may see less immediate value. For example, central supply depots that already operate with efficient traditional logistics systems may not see a significant return on investment from adopting AMT. This discrepancy in the perceived utility of additive manufacturing at different levels of military operations complicates its widespread adoption. There is a need for tailored strategies that account for the specific logistical needs and capabilities of different military units, from tactical to strategic levels.

"Lack of cooperation in the application of additive manufacturing technologies" can be characterized as important cause group. Remarkable, the successful integration of additive manufacturing technologies in military logistics also depends on cooperation between different military entities and allied nations. However, several issues arise in this area are:

- Lack of cooperation between allied military logistic systems (LS). Effective military logistics often depend on joint operations and standardization across allied forces. The lack of coordinated efforts to implement additive manufacturing across different military forces creates fragmentation in how the technology is applied. Allied military forces may have different priorities, logistical needs, and approaches to integrating AMT, which leads to inconsistencies in application and missed opportunities for collaboration. This lack of cooperation hinders the potential for shared resources, such as joint 3D printing facilities or common AMT protocols, which could reduce costs and improve efficiency across allied forces.
- Different interests between KLS and military logistics. Within the military, different entities may have divergent interests when it comes to the application of additive manufacturing technologies. For instance, Key Logistic Stakeholders (KLS) may prioritize long-term investments in centralized 3D printing facilities or focus on the development of highly specialized components, whereas field units may emphasize the need for mobile, deployable 3D printers for immediate on-site use. These differing priorities can create a disconnect between strategic goals and operational needs, further complicating the adoption of AMT within the broader military logistics framework. For AMT to be effectively integrated, there must be alignment between strategic, tactical, and operational stakeholders.

By addressing these challenges, military logistics can harness the transformative potential of additive manufacturing technologies to improve efficiency, flexibility, and resilience in complex, dynamic operational environments. Through strategic solutions that tackle both technological and organizational barriers, the military can position itself to benefit from the disruptive advantages that additive manufacturing offers.

3.2. Strategic Managerial Solutions

Overcoming the identified challenges that complicate the adoption of Additive Manufacturing Technology (AMT) within the broader military logistics framework requires a multi-faceted approach involving strategic managerial interventions. These interventions are essential to addressing the key obstacles: the misalignment between the perceived and actual benefits of additive manufacturing, the lack of inter-organizational cooperation, and the legal and technological limitations that hinder its broader application.

One of the primary challenges in integrating AMT into military logistics is the disconnect between the perceived and actual benefits of the technology. Established mindsets within military organizations may resist change due to uncertainty about how AMT can enhance efficiency and improve mission outcomes. Strategic managerial intervention in this context involves an educational and awareness campaign that emphasizes the tangible benefits of AMT. This can include case studies that demonstrate cost savings, improved operational readiness, reduced lead times, and enhanced capabilities for on-demand manufacturing in mission-critical situations. Managers must facilitate knowledge sharing across military levels, from tactical units to strategic decision-makers, to ensure a unified understanding of the technology's potential. Regular training programs, workshops, and simulations can also be used to familiarize personnel with the practical applications of 3D printing in military logistics. The mention solutions are presented in the Table 1.

Table 1.

Lack of link between the potential for additive manufacturing and the benefits generated

Cause	Losses	Solutions
The complexity of changing established thinking.	- Slow process of adapting additive manufacturing to military logistics. - Untapped potential of additive manufacturing.	- Develop a three-phase roadmap for the application of additive manufacturing in military logistics. - Start with simplified additive manufacturing equipment in the first phase.
The challenge of adapting additive manufacturing at different military levels.	- Different interpretations of the benefits of additive manufacturing and the dissatisfaction of lower levels	- Re-promoting and re-imagining the benefits of additive manufacturing through visualisation and hands-on approaches

A second significant challenge is the lack of cooperation between allied military logistics systems and the divergent interests between civilian and military logistics sectors. Inter-organizational collaboration is crucial for unlocking the full potential of AMT. This requires creating platforms for open dialogue and joint projects between military allies to align logistics strategies, standardize 3D printing technologies, and share knowledge on best practices. Establishing joint training programs, shared research initiatives, and cross-functional task forces can foster cooperation and help overcome the siloed nature of military logistics operations. By pooling resources and expertise, allied military forces can collectively develop more robust and responsive logistics systems powered by additive manufacturing. Moreover, cooperation between military and civilian sectors is also essential, as civilian industry often drives innovation in AMT. Military organizations can benefit by forming partnerships with industry leaders to accelerate the adoption of cutting-edge technologies (see Table 2).

Table 2.

Lack of cooperation in the application of additive manufacturing technologies

Cause	Losses	Solutions
Lack of cooperation between allied military logistic systems (LS).	- No exposure to allied good practices in the application of additive manufacturing in military logistics.	- Provide opportunities for logistics professionals to attend international courses/seminars on additive manufacturing.
Different interests between KLS and military logistics.	- Unprofessional maintenance of additive manufacturing equipment and unplanned failures.	- To launch a call for tenders for the selection of a professional additive manufacturing KLS company (for the purchase, ongoing maintenance and troubleshooting of equipment).

The legal and technological limitations of AMT, such as intellectual property (IP) issues and the need for advanced Computer-Aided Design (CAD) models, present another layer of complexity. Addressing these constraints requires a comprehensive strategy to streamline regulatory compliance and protect sensitive information. Military organizations must collaborate with legal experts to develop frameworks that facilitate the secure use of AMT while respecting IP rights and preventing dual-use technology risks. Technologically, investments must be made to develop or acquire the necessary infrastructure for high-quality 3D printing, such as deformation testing equipment, motion sensors, and CAD development tools. By fostering partnerships with professional companies that specialize in these technologies, military organizations can ensure that components produced through AMT meet stringent quality standards. Additionally, military institutions should explore the use of optical 3D scanning technologies to create accurate digital models of existing components, reducing the dependency on original equipment manufacturers (OEMs) for spare parts.

Table 3.
Technological and Legal Constraints of Additive Manufacturing

Cause	Losses	Solutions
The need for testing of 3D-printed components.	- Limited use of 3D-printed components. - Lack of information on the resistance of 3D-printed parts to deformation and temperature changes.	- Perform deformation testing of critical equipment components produced with a 3D printer. - Purchase 3D motion and strain sensing equipment.
The challenge of adapting additive manufacturing at different military levels.	- Possible legal infringements due to the use of the CAD created.	- To take into account the CAD intellectual property rights (IPR) credentials of CAD-ready components for military logistics in peacetime and wartime for equipment in use or planned for acquisition.
Creating a CAD for existing and planned assets.	- Limited use of additive manufacturing in military logistics.	- Use optical 3D scanning equipment to create original CAD. - Exploit the potential of additive manufacturing experimentation and CAD prototyping.

Based on this study results of the in-depth interview study, it can be specified that it takes time and effort to solve the all stated causes. But in summarizing the managerial decisions related to the integration of additive manufacturing technologies (AMT) into military logistics, four key strategic actions can be preferred. These decisions are aimed at overcoming operational challenges and maximizing the benefits of AMT within the context of military supply chains and logistics operations. The following four managerial decisions are pivotal for the successful application of additive manufacturing in this domain:

1. Development of a three-phase implementation plan. A structured, phased approach is critical for the gradual integration of additive manufacturing into military logistics systems. This three-phase plan should begin with pilot testing of 3D printing technologies in controlled environments to assess operational feasibility. The second phase should involve scaling-up production to include more complex components and broader logistics operations, with continuous monitoring and adjustments. The final phase focuses on the full integration of AMT into standard military logistics procedures, enabling real-time, on-demand manufacturing of critical components, thereby enhancing supply chain resilience and flexibility.

2. Facilitating access to international additive manufacturing courses for logistics professionals. Knowledge acquisition and continuous training are essential for the effective application of emerging technologies such as additive manufacturing. Logistics professionals must be empowered to attend international training programs and courses focused on additive manufacturing to stay abreast of the latest advancements and operational methodologies. These courses provide insights into best practices, technological innovations, and global trends that can be adapted to military logistics, ensuring that personnel are equipped with the necessary skills to implement and manage AMT effectively.

3. Mandatory deformation testing for critical components. Ensuring the structural integrity and reliability of 3D-printed components is of paramount importance in military operations, where equipment failure can have severe consequences. Therefore, all critical components produced using 3D printing must undergo rigorous deformation testing to verify their durability and performance under stress. This testing can be outsourced to professional firms specializing in component testing, or alternatively, military organizations can invest in 3D motion and deformation sensing equipment to conduct in-house testing, ensuring compliance with safety and performance standards.

4. Utilization of optical 3D scanning technology for CAD development. The adoption of optical 3D scanning equipment is critical for the creation of accurate Computer-Aided Design (CAD) models, both for the replication of existing components and the design of experimental prototypes. This technology enables the precise capture of physical objects' dimensions and geometries, which can then be used to develop original CAD models or improve existing designs. By integrating optical 3D scanning into the workflow, military logistics can streamline the reverse engineering process, enhance the customization of parts, and expedite the development of prototypes that are fit for purpose in military applications.

Together, these four managerial decisions form a cohesive strategy that addresses both the technological and operational aspects of additive manufacturing in military logistics. By developing a phased implementation plan, promoting continuous education, ensuring rigorous testing, and leveraging advanced scanning technologies, military organizations can fully realize the potential of AMT. These actions not only improve logistics efficiency but also increase the flexibility, responsiveness, and resilience of military supply chains in the face of evolving operational demands.

4. Discussions

Summing up the research conducted, it can be said that the responses provided by the experts align with most of the scientific literature discussed. When defining the concept of innovation, the primary focus is on performance improvement, which corresponds with the definitions provided by Paksoy [26]. The innovations related to "Logistics 4.0" from the KLS (Key Logistics Systems) are also applicable in military logistics. However, based on the experts' responses, greater emphasis is placed on innovations related to the functional logistics field. The functional logistics field is responsible for the execution of direct logistics activities, as discussed by Shi [27]. The experts' opinions also coincide with Paksoy's [26] discussions on the innovations of "Logistics 4.0," specifically that innovation should consistently enhance military capabilities and efficiency, though the main drawback is the time required for adaptation.

The experts consistently agree that in the adaptation of "Logistics 4.0" innovations, significant attention is also given to innovations in the supporting logistics field. For instance, they mention the development of the "Logistics IT System," which aims to integrate allied military logistics systems into a unified network to improve interaction. This aligns with Paksoy's [26] definition. However, experts' opinions differ when discussing the challenges arising from the application of "Logistics 4.0" innovations in military logistics. These challenges include issues with cooperation between allied military logistics systems and conflicting interests with KLS. Moreover, according to Rahman [28], challenges in the application of "Logistics 4.0" also include concerns about data security, costs, and realizing the full potential of the innovations.

This study experts' views also align regarding additive manufacturing technology (AMT) and its implications for military logistics. They believe that 3D printing will essentially change the approach to military logistics by offering a more decentralized capability. This innovation disrupts the traditional logistics model by introducing decentralized, on-demand production, reducing the need for storing unnecessary parts at military bases [29]. Experts recommend that 3D printing has the potential to reduce the logistical footprint and enhance international operations, such as deploying a container with a 3D printer and storing designs on a universal USB flash drive, a perspective that matches the understandings of Thong [31].

Additionally, study experts mostly agree on the potential applications of additive manufacturing in military logistics, including the production of replacement parts for temporary battle damage repairs, components that are no longer manufactured (old-fashioned parts), experimental prototypes, and UAV components. These uses are consistent with the perspectives of Valtonen et al. [30]. However, some of the experts raised points that diverge from the scientific literature, such as the need for pre-production CAD planning for military equipment or encouraging OEMs (Original Equipment Manufacturers) to prepare CAD files. This aspect is crucial in military logistics due to the time and procurement delays involved in purchasing equipment, which necessitates having CAD files ready for part manufacturing alongside the equipment itself.

The scientific literature does not extensively discuss the primary challenges of integrating additive manufacturing into military logistics systems (MLS). Experts identified several key challenges, such as the complexity of changing traditional mindsets and the difficulty of implementing additive manufacturing across different military levels. They suggested that the adoption of additive manufacturing in military logistics should follow a phased approach, starting with experimentation and prototyping at military academies and progressing to political decisions regarding the incorporation of these innovations into military logistics systems. This step-by-step approach echoes Thong's [31] recommendations. However, experts did not emphasize Mattox's [32] statement regarding the prevention of dual use of 3D printing technology.

Finally, this study experts' understanding on the future scenarios of 3D printing largely coincide with the existing literature. The increasing availability of metal 3D printing enhances the possibilities for additive manufacturing in military logistics, a view that corresponds with Srivastava's [33] conclusions. However, one future vision not discussed in the scientific literature is the adherence to the European strategy for the extraction of critical raw materials by changing solid metals into innovative polymers. Additive manufacturing technologies could play a vital role in this process, as suggested by the experts.

5. Conclusions

This study proved, the three main problem areas delaying the application of additive manufacturing technology in military logistics are interconnected. Technological and legal constraints, such as testing, IP rights, and the need for detailed CAD models, pose foundational challenges. The lack of correlation between additive manufacturing's potential and its perceived benefits highlights the difficulty in changing established mindsets and adapting to various military levels. Finally, the lack of cooperation between allied military logistics systems and the divergent interests between civilian and military logistics further complicates the technology's integration into military operations. Addressing these areas requires strategic managerial decisions, cross-functional collaboration, and ongoing education on the potential benefits of additive manufacturing.

Study highlights the tactical potential of additive manufacturing within the logistics framework of the Lithuanian Armed Forces (LAF), with future prospects for its application at the operational level and during international operations. Integration of 3D printing technology into LAF logistics operations aligns with principles of rationality, efficiency, and the 4T approach, offering the promise of providing high-quality equipment to combat units and enhancing their operational effectiveness. Specific applications of additive manufacturing in military logistics within the LAF encompass a range of critical functions, including expedient repair of battle damage, production of spare parts, prototyping and experimentation, addressing component obsolescence issues, and the fabrication of UAV components. These applications signify the diverse capabilities of additive manufacturing to address logistical challenges and ensure the readiness of military units.

Moreover, the adoption of additive manufacturing by LAF logistics units has the potential to catalyze the development of a more decentralized logistics approach, thereby reducing logistical footprint and enabling a shift from a traditional "push" model to a more responsive "pull" approach as necessitated by operational demands.

Based on the formulated managerial decisions, military logistic system can adopt and plan the course of action for the application of additive manufacturing technologies, assess the potential risks and develop solutions to the problems that arise. To facilitate the effective implementation of additive manufacturing in military logistics, a comprehensive three-phase plan or project should be developed. Such a plan would outline the necessary steps and milestones for the successful integration of additive manufacturing technologies into LAF logistics operations, ensuring seamless adoption and maximizing the technology's benefits for military readiness and operational efficiency.

In summary, the strategic adoption of additive manufacturing holds significant promise for enhancing logistic capabilities of the Lithuanian Armed Forces, enabling them to adapt to evolving operational requirements and maintain a high level of readiness in dynamic security environments.

References

1. **Ziatdinov, R., Atteraya, M. S., & Nabiyev, R.** The Fifth Industrial Revolution as a transformative step towards society 5.0. Societies, 2024. 14(2), 19.
2. **Yadav, R., Arora, S., & Dhull, S.** A path way to Industrial Revolution 6.0. Int. J. Mech. Eng, 2022, 7(1), 1452-1459.
3. **Ali, S. H., Al-Sultan, H. A., & Al Rubaie, M. T.** Fifth industrial revolution:(New perspectives). International Journal of Business, Management and Economics, 2022, 3(3), 196-212.
4. **Peerally, J. A., Santiago, F., De Fuentes, C., & Moghavvemi, S.** Towards a firm-level technological capability framework to endorse and actualize the Fourth Industrial Revolution in developing countries. Research Policy, 2022, 51(10), 104563.
5. **Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T.** Intelligent manufacturing in the context of industry 4.0: a review. Engineering, 2017, 3(5), 616-630.
6. **Akıl, S., & Ungan, M. C.** E-commerce logistics service quality: customer satisfaction and loyalty. Journal of Electronic Commerce in Organizations (JECO), 2022, 20(1), 1-19.
7. **Krishnan, R., Perumal, E., Govindaraj, M., & Kandasamy, L.** Enhancing Logistics Operations Through Technological Advancements for Superior Service Efficiency. In Innovative Technologies for Increasing Service Productivity, 2024, pp. 61-82. IGI Global.
8. **Ng, T. C., Lau, S. Y., Ghobakhloo, M., Fathi, M., & Liang, M. S.** The application of industry 4.0 technological constituents for sustainable manufacturing: A content-centric review. Sustainability, 2022, 14(7), 4327.
9. **Καραμπουρνιώτης, Δ.** Logistics 4.0: technologies, trends, applications and challenges, 2018.
10. **Bamigbala, T., Onkamo, M., Safonova, I., & Rahman, S. T.** Towards Adoption of Autonomous Mobile Cobots in Intralogistics Picking Process: Review of Current Development. Lappeenranta–Lahti University of Technology LUT: Lahti, Finland, 2022.
11. **Malik, M., Gahlawat, V. K., Mor, R. S., & Hosseinian-Far, A**. Towards white revolution 2.0: challenges and opportunities for the industry 4.0 technologies in Indian dairy industry. Operations Management Research, 2024, 1-22.
12. NATO Science & Technology Organization. Science & Technology Trends 2023-2043 Across the Physical, Biological, and Information Domains. Brussels. 2023
13. **Friedrich, A., Lange, A., & Elbert, R.** Make-or-buy decisions for industrial additive manufacturing. *Journal of Business Logistics*, 2022, *43*(4), 623-653.
14. **Roscoe, S., Cousins, P. D., & Handfield, R.** Transitioning additive manufacturing from rapid prototyping to high-volume production: A case study of complex final products. *Journal of Product Innovation Management*, 2023, *40*(4), 554-576.
15. **Colorado, H. A., Cardenas, C. A., Gutierrez-Velazquez, E. I., Escobedo, J. P., & Monteiro, S. N**. Additive manufacturing in armor and military applications: research, materials, processing technologies, perspectives, and challenges. *Journal of Materials Research and Technology*. 2023.
16. **Debnath, B., Shakur, M. S., Tanjum, F., Rahman, M. A., & Adnan, Z. H**. Impact of additive manufacturing on the supply chain of aerospace spare parts industry—a review. *Logistics*, 2022, *6*(2), 28.
17. **Hult, G., Almbladh, T., Dansarie, M., Granholm, J., Lagg, E., Silfverskiöld, S., & Thenander, D**. Technology Forecast 2022–Military Utility of Future Technologies. 2022.
18. **Seet, P. S., Klarin, A., Jones, J., Johnstone, M. N., Wilk, V., Meek, S., & O'Brien, S.** Expanding Australia's defence capabilities for technological asymmetric advantage in information, cyber and space in the context of accelerating regional military modernisation: A systemic design approach. 2024.
19. **Soare, S. R.** European military AI: Why regional approaches are lagging behind. In The AI Wave in Defence Innovation, 2023, pp. 80-111. Routledge.

20. .**Ilie, G., & Ciocoiu, C. N.** Application of fishbone diagram to determine the risk of an event with multiple causes. *Management research and practice*, 2010, *2*(1), 1-20.
21. **Fey, M.** 3D Printing and International Security, Risks and Challenges of an Emerging Technology, 2017, 1-41.
22. **Karakurt, I., & Lin, L.** 3D printing technologies: techniques, materials, and post-processing. Current Opinion in Chemical Engineering, 2020, 28, 134-143.
23. **Srivastava, M., Ammons, J., Peerzada, A. B., Krovi, V. N., Rangaraju, P., & Walker, I. D**. 3d printing of concrete with a continuum robot hose using variable curvature kinematics. In 2022 International Conference on Robotics and Automation (ICRA), 2022, May, pp. 3216-3222. IEEE.
24. **Samu, R. T.** Legal Aspects of Additive Manufacturing in the Military Logistics. Security Dimensions, 2022, 40, 154-195.
25. **Valtonen, I., Rautio, S., & Lehtonen, J. M.** Designing resilient military logistics with additive manufacturing. *Continuity & Resilience Review*, 2023, *5*(1), 1-16.
26. **Paksoy, T., Koçhan, Ç., & Ali, S. S**. Logistics 4.0. Digital transformation of supply chain management. 2021.
27. **Shi, H. W**. Research on Military Logistics based on Big Data. Advances in Computer Science Research, 2019, 87, 231-237.
28. **Rahman, A. R.** Agility and Digitalization Competancy in Logistics 4.0 in Military Setting: the Challenge, Risks and Opportunities. Asian Journal of Social Science Research, 2019, Volume 1, Issue 2.
29. **Stanley-Lockman, Z**. Revisiting the revolution in military logistics: Technological enablers twenty years on. Disruptive and Game Changing Technologies in Modern Warfare: Development, Use, and Proliferation, 2020, 197-222.
30. **Valtonen, I., Rautio, S., & Lehtonen, J. M.** Designing resilient military logistics with additive manufacturing. Continuity & Resilience Review, 2023, 5(1), 1-16.
31. **Thong., C. S.** 3D Printing – Revolutionising Military Operations. JOURNAL OF THE SINGAPORE ARMED FORCES, 2016, 42(2), 35-46.32
32. **Mattox, J. M.** Additive Manufacturing and its Implications for Military Ethics. Journal of Military Ethics, 2013, 12(3), 225-234. doi:http://dx.doi.org/10.1080/15027570.2013.847534
33. **Srivastava, M. R.** A review of various materials for additive manufacturing: Recent trends and processing issues. Journal of Materials Research and Technology, 2022, 22, 2612-2641.