Food for thought 11-2021

Finabel

3d Printing

Towards Land Force Supply Chain Modernisation

AN EXPERTISE FORUM CONTRIBUTING TO EUROPEAN ARMIES INTEROPERABILITY SINCE 1953

FINABEL
European Army Interoperability Centre

Written by
Matthias Meheust Kemp

This Food for Thought paper is a document that gives an initial reflection on the theme. The content is not reflecting the positions of the member states but consists of elements that can initiate and feed the discussions and analyses in the domain of the theme. All our studies are available on www.finabel.org

DIRECTOR'S EDITORIAL

Globalisation and the fast development of new technologies are the most important elements driving global market activity and international logistical change. Military supply chains always function alongside product delivery in this environment, whether in times of war or peace. Contemporary military logistics support presents significant challenges, from isolation problems to stock maintenance and responsiveness.

The anticipated expansion of the additive manufacturing sector might provide several benefits to the European defence community, including lower tool and component production costs, improved design, shorter time to market, and enhanced technical and commercial competitiveness. Simultaneously, 3D printing is expected to have a significant influence on military platform maintenance through the manufacturing of spare parts and equipment components. Because the underlying architecture of European air, land, and sea defence systems are complicated and unique, AM's modification capability, as well as its on-site and on-demand characteristics, are particularly appealing to the defence sector.

This paper attempts to analyse the integration of additive manufacturing in a military context by assessing the performance gains and applicability of such a technology and its limitations. AM will influence the military's responsiveness and long-term viability. Because of the number, complexity, and age of current military systems, AM has the opportunity to shorten lead times, decrease inventory, and increase operational readiness.

Mario Blokken
Director PSec

TABLE OF CONTENTS

INTRODUCTION

In 2017, US Army Chief of Staff General Mark Milley exposed his view of the future of warfare, stating: "The convergence of new developments such as ubiquitous information technology and personal communications, proliferation of precision-guided weapons, robotics and on-site 3D printing, and rapidly growing urbanization all augur a very different era of warfare".[1]

Industry 4.0 has helped companies reach their consumers' requirements in the private sector by combining modern technological solutions with creative management techniques. These developments are especially relevant to service operations, where having spare parts and components on hand for prompt maintenance and repairs is critical to minimising downtime and increasing operational effectiveness and responsiveness. Spare parts shortages, in particular, may be disastrous, as a failing component might result in protracted system outages and failures. In recent years, traditional operations management techniques, such as finding and maintaining appropriate inventory levels, have been widely implemented to address these issues.[2] However, those approaches are insufficient to solve specific issues, particularly in isolated regions where the logistical challenges remain ever-present.

Additive manufacturing (AM), commonly known as 3D printing, attempts to bring the manufacture of objects and users closer together and outlines a possible relocation of production, the likes of which is particularly interesting for military supply chains. The aerospace and defence industry are increasingly using additive manufacturing to reduce material costs, decrease labour content, and increase parts availability at the point of use. The industry sees many advantages in this, from vehicle maintenance to the repair of parts in external operations and the production of optimised, lighter objects. Integrating new functionalities such as 3D printing provides an opportunity to modernise military supply chains. This paper attempts to analyse the integration of additive manufacturing in a military context by assessing the performance gains and applicability of such technology and its limitations.

To do so, we begin our paper by examining the basic concepts associated with the technology, the current state of the AM market and some examples of its use in the military. We then expose some of the significant contemporary challenges that military supply chains face, from isolation problems to inefficiencies related to stock and supply. Based on those challenges, we assess the potential

1. Barno, David, and Nora Bensahel. "Three Things the Army Chief of Staff Wants You to Know." War on the Rocks, May 22, 2017. https://warontherocks.com/2017/05/three-things-the-army-chief-of-staff-wants-you-to-know/.

2. Xu, Xinglu, Mark D. Rodgers, and Weihong Grace Guo. "Hybrid simulation models for spare parts supply chain considering 3D printing capabilities." Journal of Manufacturing Systems 59 (2021): 272-282.

impact of 3D construction in the military. Finally, we shed light on some of the limitations mitigating its complete implementation in military supply chains.

ADDITIVE MANUFACTURING: AN OVERVIEW

Additive Manufacturing offers a wide array of solutions for the military, previously impossible with conventional manufacturing techniques. The flexibility provided by the technology can be game-changing through multi-domain integration (land, air, marine, space, and cyberspace). So, what is additive manufacturing?

3D-printed construction

AM is an umbrella term for all manufacturing processes utilising a layer by layer deposition approach, also referred to as 3D printing, Rapid Prototyping (RP), Rapid Tooling (RT), Rapid Manufacturing (RM) or Direct Digital Manufacturing.[3] A broad definition of AM is as follows: an innovative and advanced construction process, whereby objects are created by agglomerating layers of materials (polymers, metals...) from a digital model, as opposed to conventional techniques which subtract elements from solid pieces of material.[4] The process utilises elements from diverse material sciences such as architectural, mechanical, structural and software engineering to print full-scale structures and components into the real world.[5]

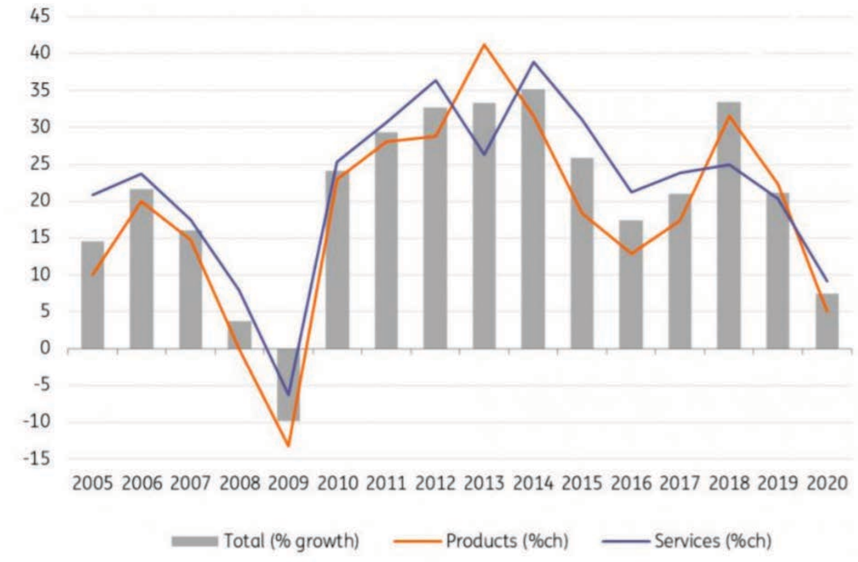
The basic model of this technology starts with a 3D Computer-Aided Design (CAD) system (a solid modelling software), outputting a 3D solid or surface representation. The software converts the 3D data into an STL file (industry standard), which will describe the external closed surfaces of the model to the AM machine and form the basis of the calculation for the slicing software. The slicing software creates different layers from the 3D representation to build the object slice by slice. The machine must then be set up based on the build parameters (i.e. material constraints, energy source, layer thickness, timings, etc.). The building phase is an automated process needing little to no supervision. Finally, once the component is manufactured, the parts are post-processed, cleaned, and treated to give an acceptable texture and finish.[6]

Three of the most common 3D printing techniques include contour crafting, a wet extrusion method using two trowels to shape the layers of material as they are extruded; powder bed fusion using either a binder, laser or elec-

3. ibid
4. Verboeket, Victor, and Harold Krikke. “Additive manufacturing: A game changer in supply chain design.” Logistics 3, no. 2 (2019): 13. P 2
5. Jagoda Jeneé, Brandy Diggs-McGee, Megan Kreiger, and Steven Schuldt, The Viability and Simplicity Of 3D-Printed Construction: A Military Case Study. Infrastructures 5 (4). 2020. doi:10.3390/infrastructures5040035. p2
6. Gibson, Ian, David W. Rosen, Brent Stucker, and Mahyar Khorasani. Additive manufacturing technologies. Vol. 17. Cham, Switzerland: Springer, 2021.

tron beam to fuse powdered materials, such as metals; and concrete printing where a wet extrusion prints both the perimeter and infill of the structure.[7]

While still in the early stages of development, AM could become a disruptive technology, changing the way we model our supply chains and the manufacture of products. In cases where additive manufacturing competes with other manufacturing processes (machining, casting, forming, assembly), several principles can guide the diffusion of 3D printing, especially for the military. First of all, the logic inherent to additive manufacturing does not lie in the reproduction of existing practices or parts but in their redesign and optimisation. This technology allows weight and performance gains, improves the geometry of complex parts and facilitates their assembly, and can both shorten manufacturing times and reduce costs. The identical copy can be chosen to avoid redesign and simplify the qualification of the part, to produce it as soon as possible. Then, additive manufacturing is associated with the idea of speed and flexibility to overcome the obsolescence of materials or production times and costs that would be exorbitant with other processes (especially for small quantities).



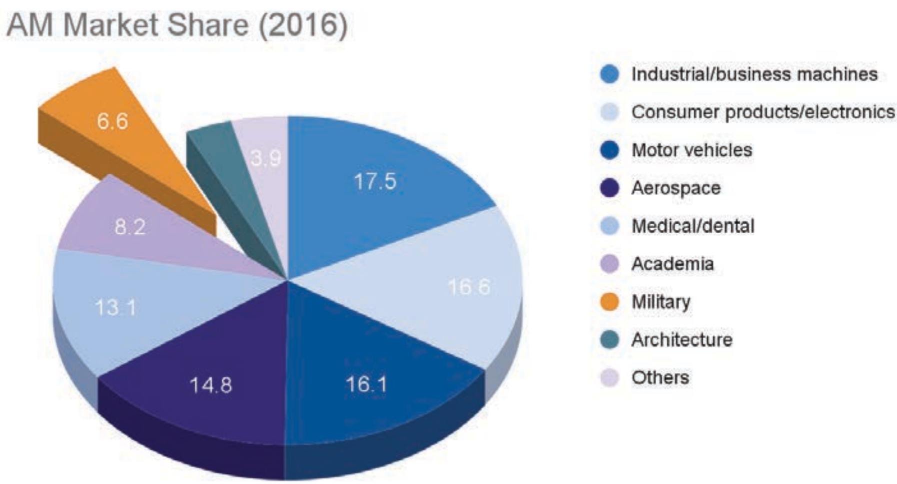
Source: Wohlers Report 2021 3D Printing and Additive Manufacturing: Global State of the Industry, Wohlers Associates

7. Ibid; Wong, Kaufui V., and Aldo Hernandez. "A review of additive manufacturing." International scholarly research notices 2012 (2012).

The state of the AM market

3D printing is progressively being used in many fields. Its development is accelerating, particularly in the health, industrial (including aeronautical), and construction sectors, while also being of growing interest to the general public through everyday consumer objects. In addition to the development of online manufacturing services and prototyping, 3D technologies are increasingly used for the mass production of parts.[8] The AM industry has seen significant growth since 1995, from a $295 million global market valuation to a $12.8 billion market in 2020.[9] Worldwide revenue growth of the 3D printing business has commonly seen 15% to 30% growth from the previous year, with the exception of the 2008-9 and COVID-19 crises.

Despite only currently accounting for 0.1% of global manufacturing, the market is forecasted to grow by 27% a year until 2030 and reach up to 5% of global goods manufacturing in the next two decades.[10] In 2016, AM's market share included industrial/business machines (17.5%), consumer products/electronics (16.6%), motor vehicles (16.1%), aerospace (14.8%), medical/dental (13.1%), academia (8.2%), military (6.6%), others (3.9%), and architectural (3.2%).



Based on: Schrand, Amanda M. "Additive manufacturing: from form to function." Strategic Studies Quarterly 10, no. 3 (2016): 74-90.

8. Taithe, Alexandre, and Bruno Lasalle. 2020. "Le Développement de l'Impression 3D Dans Les Armées : Une Innovation de Rupture ? :: DEFENSE&Industries :: Fondation Pour La Recherche Stratégique :: FRS." Www.frstrategie.org. 2020. https://www.frstrategie.org/publications/defense-et-industries/developpement-impression-3d-dans-armees-une-innovation-rupture-2020.
9. Schrand, Amanda M. "Additive manufacturing: from form to function." Strategic Studies Quarterly 10, no. 3 (2016): 74-90.
10. Leering, Raoul. 2021. "3D Printing's Post-Pandemic Potential." https://think.ing.com/uploads/reports/3D_printing_report_final_050821_RL_OT_FINAL.pdf.

THEREFORE, the AM industry is one with exponential growth and is likely to play an essential role in the years to come.

AM research and development in the military

The defence industry was an early adopter of AM technology. The history of Additive Manufacturing traces back to the early 1980s, with some companies experimenting with the technology as early as 1988.[11] One of the first uses of 3D computer-aided design (CAD) manufacturing was rapid prototyping, a way by which engineers could rapidly visualise what they had in mind.[12] Nowadays, several reasons underline the adoption of AM in the armed forces. AM can provide a promising solution for military missions abroad where supply chains are often isolated by providing parts and products close to deployment points. Furthermore, because of AM's impact on economies of scale, the technology is a perfect fit for A&D, primarily focused on customised output, unlike other mass-production businesses.

3D printing is steadily gaining ground in the armed forces around the world. In January 2021, the US Department of Defense released its first-ever comprehensive additive manufacturing strategy to implement AM solutions throughout the nation's defence programmes. In unveiling this new strategy, spokespersons for the Office of the Secretary of Defense Manufacturing Technology (OSD ManTech) and the Secretary of the Air Force for Acquisition, Technology and Logistics stated: "Additive manufacturing offers DoD unprecedented supply chain agility while enabling our developers to sustain technological dominance for our Warfighters" and "we envision AM as an effective tool that can mitigate diminished manufacturing sources of supply and long lead supply chain shortfalls".[13]

FINABEL countries have also started implementing AM in their respective militaries. In 2020, to meet the supply problems posed by COVID-19, the French Army built a farm in Bourges with 50 3D printing machines, which has already manufactured more than 60,000 parts. It now wants to make the use of this technology more permanent.[14] In 2019, the UK Ministry of Defence (MoD) identified 3D printing as essential to harnessing "new types of data about human and platform performance".[15] In 2018, Germany released a plan to use AM to redesign obsolete parts during deployment.[16] In 2017, The European Defence Agency (EDA) led efforts promoting initiatives in research and development,

11. Cotteleer, Mark, Jonathan Holdowsky, Monika Mahto, and John Coykendall. 2014. "3D Opportunity for Aerospace and Defense." Deloitte Insights. 2014. https://www2.deloitte.com/us/en/insights/focus/3d-opportunity/additive-manufacturing-3d-opportunity-in-aerospace.html.
12. Wong, Kaufui V., and Aldo Hernandez. "A review of additive manufacturing." International scholarly research notices 2012 (2012).
13. Hanaphy, Paul, Hayley Everett, and Kubi Sertoglu. "Department of Defense Unveils Additive Manufacturing Strategy." 3D Printing Industry, February 4, 2021. https://3dprintingindustry.com/news/department-of-defense-unveils-additive-manufacturing-strategy-183832/.
14. Virol, Gautier. "Pourquoi L'ARMÉE De Terre S'est Constituée UNE Ferme De 50 MACHINES D'IMPRESSION 3D." usinenouvelle.com. L'Usine Nouvelle, July 3, 2020. https://www.usinenouvelle.com/editorial/pourquoi-l-armee-de-terre-s-est-constituee-une-ferme-de-50-machines-d-impression-3d.N982136.
15. Valva, Tia. "The Authority on 3d Printing & Additive Manufacturing." 3D Printing Industry, September 11, 2019. https://3dprintingindustry.com/news/uk-ministry-of-defence-to-leverage-3d-printing-in-new-security-approach-161491/.
16. Scott, Clare. "German Armed Forces Use 3d Printing to Redesign an Obsolete Part - 3DPrint.Com: The Voice of 3d Printing / Additive Manufacturing." 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing, October 17, 2018. https://3dprint.com/227587/german-armed-forces-3d-print-obsolete-part/.

prototypes and tests of 3D printing systems including in standard containers and their transport with tactical transport aircraft.[17]

CONTEMPORARY CHALLENGES IN MILITARY SUPPLY CHAINS

Globalisation and the fast development of new technologies are now the most important elements driving global market activity, and this has a significant impact on logistical procedures. Military supply chains are always functioning alongside the delivery of products within this environment, whether in times of war or peace.[18] The analysis of supply chains is focused on discovering ways to be more efficient and productive. In that way, logisticians strive to save costs and deliver goods faster while maintaining a high quality of service. Contemporary military logistics support presents a series of significant challenges. The following section focuses on those challenges to show where AM fits in the modernisation of supply chains.

What is military logistics?

While the North Atlantic Treaty Organisation (NATO) does not mention supply chain management, it does employ the term logistics. However, logistics is increasingly interpreted as the management of supply chains.[19] The NATO definition of logistics is the "science of planning and carrying out the movement and maintenance of forces including the acquisition of services and the provision of medical and health support".[20] Military logistics are essential factors contributing to military success, epitomised in Omar Bradley's famous quote: "Amateurs talk about strategy and tactics. Professionals talk about logistics and sustainability in warfare".[21] Indeed, logistical efficiency directly increases overall fighting power in combat situations. Without engaging in direct combat, attacking enemy military logistics and supply systems can defeat an army, as has been observed throughout history.[22] Transport and energy systems are often targeted to weaken enemy forces. The Gulf War, for example, saw 90% of Iraqi oil refineries destroyed.[23]

In broad terms, military logistics can be described as the bridge between military operations and the national economy. It can be seen in a country's resources, methods, and systems

17. Schütz, Torben, and Zoe Stanley-Lockman. Smart logistics for future armed forces. European Union Institute for Security Studies., 2019.
18. Pawelczyk, Marta. "Contemporary challenges in military logistics support." Security and Defence Quarterly 20, no. 3 (2018): 85-98.
19. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.
20. North Atlantic Treaty Organisation. "NATO logistics HANDBOOK: Chapter 1: Definitions", 1997. https://www.nato.int/docu/logi-en/1997/lo-103.htm.
21. Lindley-French, Julian, and Yves Boyer, eds. The Oxford handbook of war. Oxford University Press, 2012. P376
22. Xu, Jie, Jun Zhuang, and Zigeng Liu. "Modeling and mitigating the effects of supply chain disruption in a defender–attacker game." Annals of Operations Research 236, no. 1 (2016): 255-270.
23. Xiong, Biao, Rong Fan, Shuai Wang, Bixin Li, and Can Wang. "Performance Evaluation and Disruption Recovery for Military Supply Chain Network." Complexity 2020 (2020).

for producing material and troops. Logistics, therefore, covers the following areas:

- design and development, acquisition, storage, transport, distribution, maintenance, evacuation and disposal of material;
- transport of personnel;
- acquisition, construction, maintenance, operation and disposition of facilities;
- acquisition of provision of services;
- medical and health service support.[24]

These broad areas exist at all levels of warfare (operational, tactical, and strategic). The most important aspect of logistics is connecting all the processes to provide the right services in the operational arena. Supply chain management is of vital importance for any military operation. Without it, operations cannot be carried out and sustained, especially in the case of out-of-area operations.[25]

In simple terms, a military logistic supply system is thus a complex system comprising several factories, supply storage, demand storage, and logistic devices. Nonetheless, a military supply chain network comprises the basic complex system characteristics with regular complex networks, such as complexi-

Source: https://unsplash.com/photos/6AuEoIYM4rE

Man with 3d printer, 2020
Tom Claes

24. North Atlantic Treaty Organisation. "Logistics", 2017.
https://www.nato.int/cps/en/natohq/topics_61741.htm
25. Pawelczyk, Marta. "Contemporary challenges in military logistics support." Security and Defence Quarterly 20, no. 3 (2018): 85-98.

ty and dynamic extensibility, and has unique characteristics that set it apart.[26] Unlike typical private-sector supply chain management, the decision-maker in military supply chains may have distinct objectives (e.g. maximising payoffs in the contest) or operational settings (e.g. in a war or combat) and decision options (e.g. resources allocated). As a result, military supply chain risk management may differ from regular supply chain risk management.[27] Furthermore, the military has much more at stake than traditional commercial actors: while in the commercial world, stockout can lead to loss of profits, in the military world, lack of ammunition, fuel or blood can lead to loss of life.[28]

Generalised military supply chain challenges

COVID-19 has shed light once again on the risks posed by supply chain vulnerabilities in every industrial sector. Indeed, global shortages in silicone, semiconductors or even energy have impacted consumers, industries, and the military sector in the last two years. The study of supply chain vulnerability highlights several factors which can have disruptive impacts on traditional supply chains, from the globalisation of supply chains, specialisation of factories, centralisation of distribution, increased outsourcing, reduced supplier base, increased volatility of demand and technological innovations.

However, military supply networks entail even more disruptive possibilities. The best way to outline the main logistical challenges in the armed forces is to explain the 4D formula, which includes demand, distance, destination, and duration.[29] These are the main anticipated challenges considered when formulating the logistics of an operation. However, the logistical parameters change based on the given situation, and frictions are likely to appear given the variety of actors at each level within the support chain (governmental actors, contractors, international institutions, etc.).[30]

While distance and destination are the easier parameters to assess in the logistical planning process, they represent critical challenges: the terrain or a lack of basic infrastructure can hinder accessibility, and the destination may be in a warzone.[31] Additionally, today's missions entail non-traditional military tasks such as humanitarian work or peacekeeping, and the region of conflict is often unknown until days or weeks before deployment.[32] Demand and duration are even harder to assess as many mission mandates are extended or renewed several times. Furthermore, military supply networks are vulnerable to even more disruptions, such as natural disasters, hostile strikes, or unplanned mishaps. A disruption

26. Xiong, Biao, Rong Fan, Shuai Wang, Bixin Li, and Can Wang. "Performance Evaluation and Disruption Recovery for Military Supply Chain Network." Complexity 2020 (2020).
27. Xu, Jie, Jun Zhuang, and Zigeng Liu. "Modeling and mitigating the effects of supply chain disruption in a defender–attacker game." Annals of Operations Research 236, no. 1 (2016): 255-270.
28. Wiles, Matt, and David Chinn. "Supply Chain Transformation Under Fire." McKinsey, 2010. https://www.mckinsey.com/~/media/alumni%20center/pdf/mog_supply_chain.pdf.
29. ibid
30. Major C, Strickmann E. "You Can't Always Get What You Want – Logistical Challenges in EU Military Operations." German Institute for International and Security Affairs. 2011.
31. ibid
32. Simon, Steve John. "The art of military logistics." Communications of the ACM 44, no. 6 (2001): 62-66.

may target or disable only one or a few nodes in the system at first, but its impact can quickly spread across interconnected entities.

Flexibility, adaptability, and speed characterise strategic agility, which provides a solution for fast, unexpected change. Similarly, operational agility—defined as the capacity to quickly generate solutions and switch between several solutions for a given challenge—is a response to new risks. The truth is that the military issues of the twenty-first century cannot be handled with a single solution but require the flexibility to provide several solutions. The quick rate of change may be regarded as a barrier to those who cannot adjust, but it can also be seen as a long-term advantage for those who are adaptable.[33]

Isolation problems and strategic resilience in external operations

The security of equipment, supplies, and components significantly influences strategic resilience in a deployed context. For an inherently expeditionary defence force, supply chain resilience is a crucial subset of this. Militaries must have ready and responsive access to parts, supplies, and commodities as required.[34] However, the reality of deployed contexts dictates that armed forces are often isolated from their supply chains.

The system is considered isolated when the time it takes to supply a system with the items it needs to function properly exceeds the time it takes to supply those items according to a waiting time incompatible with mission planning. In other words, a system is logistically isolated whenever external conditions rule supply operations.[35] Two types of isolation problems can arise within a military context: geographical and temporary obstruction.

Geographic isolation occurs when accessibility is hindered by a lack of communication, when the supply chain is disrupted due to the nature of the environment (high mountains, polar regions, etc.), or when the on-site risks are high (warzones, areas of natural disasters, etc.). On the other hand, temporary isolation describes a situation where the supply chain is dependent on elements likely to disappear in a given timeframe.[36]

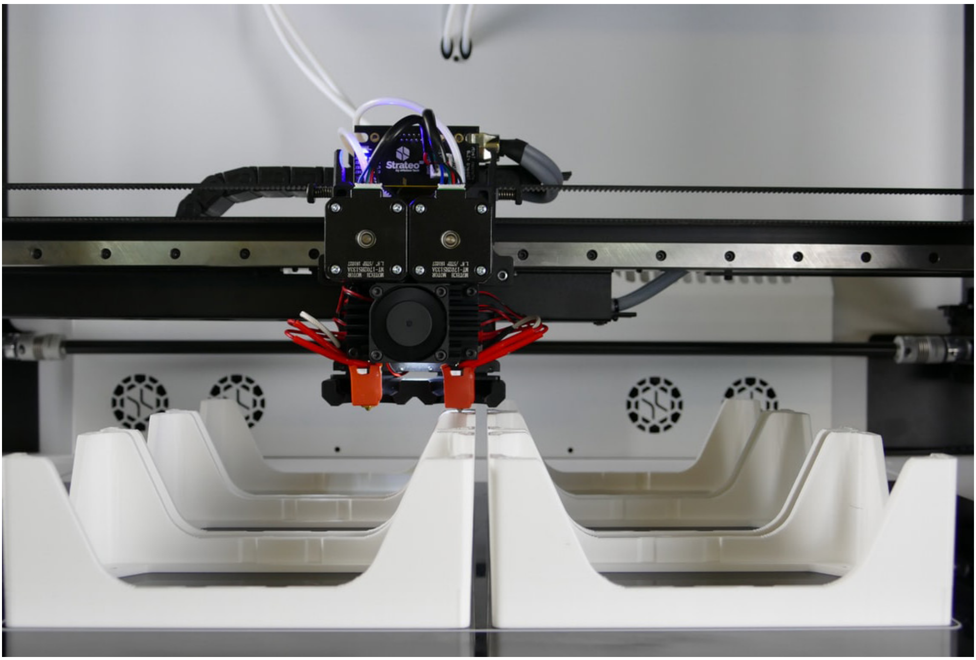
Inefficiencies related to stock and supply

Even if the cost may not be the priority in certain military supply chains, it still plays an important role. Most points of sale in the military, such as army units, ships, and air bases, are mobile and move several times a day. The range of items they need to stock and supply is more diverse than most commercial businesses—including vehicle and aircraft spare parts, heavy industrial equipment, and hospital supplies.[37] For example, a single firearm can contain hundreds of spare parts, the more

33. Schrand, Amanda M. "Additive manufacturing: from form to function." Strategic Studies Quarterly 10, no. 3 (2016): 74-90.
34. Wright, Kane, James Roberts, and Calum Stewart. "The future of army supply chains and distribution-a possible model." Australian Army Journal 16, no. 1 (2020): 79-100.
35. Pérès, François, and Daniel Noyes. "Envisioning e-logistics developments: Making spare parts in situ and on demand: State of the art and guidelines for future developments." Computers in industry 57, no. 6 (2006): 490-503.
36. ibid
37. Wiles, Matt, and David Chinn. "Supply Chain Transformation Under Fire." McKinsey, 2010. https://www.mckinsey.com/~/media/alumni%20center/pdf/mog_supply_chain.pdf.

common parts including the barrel, magazine, handguard, pistol grip, trigger and the trigger guard, springs, levers, and pistons.[38] Furthermore, in the case of fighting in confined spaces, military instructions stipulate that any equipment that cannot be repatriated must be destroyed. Given the high cost of certain types of equipment (e.g. tanks), this prompts the military to set up rear line logistics with wide ranges of spare parts.[39] As such, large swathes of stock must be kept at long lengths, resulting in efficient outcomes in the form of idle capital. [40]

This stock problem is reinforced by the fact that demand is not easily predictable in a military context. Indeed, as opposed to commercial logistics operations where peaks in demand can be predicted on reliable past experiences (product launches, holidays etc.), military demand cannot predict where or when a peak will occur in the same accurate manner, particularly with spare parts.[41]



Source: Stockvault, https://unsplash.com/photos/hfoIlAvHuPw

Professional production of parts on Strateo3D 3D printer, 2021

38. "Firearms Parts and Components." United Nations Office on Drugs and Crime, 2019. https://www.unodc.org/e4j/en/firearms/module-2/key-issues/firearms-parts-and-components.html.
39. Pérès, François, and Daniel Noyes. "Envisioning e-logistics developments: Making spare parts in situ and on demand: State of the art and guidelines for future developments." Computers in industry 57, no. 6 (2006): 490-503.
40. ibid
41. Wiles, Matt, and David Chinn. "Supply Chain Transformation Under Fire." McKinsey, 2010. https://www.mckinsey.com/~/media/alumni%20center/pdf/mog_supply_chain.pdf.

In that respect, military manufacturers are compelled to commit themselves to provide spare parts for an extended period of time after the production of the specific equipment has stopped meeting customers' requests. As such, the manufacturers must either keep their production lines active or make several parts in advance. Both of these imperious options are extremely constraining and, because of their expense, entail price increases on the customer, i.e. the armed forces.

While the Operating and Support (O&S) costs are often less discussed than acquisition costs, for instance, their share of the budget has been steadily rising since the early 2000s. The purchase price of a typical weapon system is just one-third of its total cost during its entire service life. Nearly two-thirds of the cost is spent on running and maintaining it. In the US, out of the Pentagon's annual budget, O&S is estimated to consume roughly one-third of the discretionary budget.[42] In France, the land force O&S costs represent 11.2% of the total annual military budget in 2021, at 4.4bn euros per annum.[43]

Sustainability issues

On a worldwide scale, public demand is growing for more sustainable operations, and armies are beginning to recognise the direct link between their actions during missions and their environmental and social effects. While it may seem paradoxical to talk about sustainability in the military, considering that the main aim is to establish a well-prepared and resilient defence, armed forces worldwide are starting to rethink their role in the global environmental crisis. In 2020, in the view of the EU Green Deal, France's Minister of the Armed Forces, Florence Parly, proposed steps for moving towards an energy strategy, reducing the military's carbon footprint.[44] Similarly, the US military departments introduced the concept of *sustainable operations*, taking into account the environmental cost of military readiness.[45]

3D PRINTING: A POTENTIAL GAME-CHANGER IN MILITARY LOGISTICS

Although additive manufacturing is becoming a hot issue in supply chain research, its

42. Erwin, Sandra. "Cost to Maintain Weapons Eating into Military Budgets." National Defense, 2016. https://www.nationaldefensemagazine.org/articles/2016/2/18/cost-to-maintain-weapons-eating-into-military-budgets.
43. "Budget 2021 : 39,2 Milliards d'Euros Alloués Au Ministère Des Armées." Ministère des Armées, 2020. https://www.defense.gouv.fr/actualites/articles/budget-2021-39-2-milliards-d-euros-alloues-au-ministere-des-armees.
44. Durro, Gisella. "Let's Go Green: France Is Ready to Make Its Army More Sustainable." You are being redirected..., 2020. https://finabel.org/lets-go-green-france-is-ready-to-make-its-army-more-sustainable/.
45. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.

use specifically in defence supply chains is still understudied.[46] Weapon systems and equipment in military organisations are both sophisticated and outdated. As a result, extended life cycles and substantial contracts result in supplier dependence. AM offers agility by allowing for quick and low-cost design and production of single or multiple parts to suit various mission requirements, including on-the-fly part repair and replacement. The ability to deploy printers and materials in various strategic places, including land, sea, and space, allows for on-demand product creation during the design and assembly phases, thus reducing manufacturing cycle times. There's a good argument to be made that AM can support many aspects of the defence sphere while also saving money in the long run. In this next section, we respond to the previously-mentioned challenges regarding the distinctive world of military logistics.

One site produces all: Firstly, establishing a new manufacturing site with printers is considerably easier than adding conventional production sites because the different elements of a traditional production line are almost all concentrated in one machine. As such, the use of 3D printers allows for unique supply chain configurations.[47] Supply chains for AM can either be centralised or decentralised. The centralised AM spare parts supply chain "is more suited for components with low average demand, relatively high demand volatility, and longer manufacturing lead time,"[48] as well as being more efficient when the number of parts suitable for AM is limited. The dispersed AM supply chain is ideal for various components with fluctuating demand and short production lead times. In both cases, the particularity of AM as a single organised point production facility entails a potential reduction of the cost per unit of manufactured objects without requiring expansion. As products/parts are re-organised inside a single facility, assembly lines and supply chains can be streamlined, reduced, or eliminated, lowering costs. The influence of AM in connection to supply chain position was assessed in recent research on the advantages of AM in Defence Support Services. When AM becomes mission-important on the battlefield, the impact grows, according to the findings.[49]

Reduced supply chains have a significant influence on global transportation needs. A single printer and pump, capable of being moved anywhere globally in a standard-size shipping container, replace numerous tools and pieces of heavy equipment with 3D-printed construction. Automating the building process makes it possible to decrease the need for workers to be transported and housed in remote, isolated, or expeditionary locations and the related food, fuel, and energy requirements.[50]

46. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.
47. Xu, Xinglu, Mark D. Rodgers, and Weihong Grace Guo. "Hybrid simulation models for spare parts supply chain considering 3D printing capabilities." Journal of Manufacturing Systems 59 (2021): 272-282.
48. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.
49. Busachi, Alessandro, John Erkoyuncu, Paul Colegrove, Richard Drake, Chris Watts, and Stephen Wilding. "Additive manufacturing applications in Defence Support Services: current practices and framework for implementation." International Journal of System Assurance Engineering and Management 9, no. 3 (2018): 657-674.
50. Jagoda, Jeneé, Brandy Diggs-McGee, Megan Kreiger, and Steven Schuldt. "The Viability and Simplicity of 3D-Printed Construction: A Military Case Study." Infrastructures 5, no. 4 (2020): 35.

Reduced labour demand: Increased automation, which translates to a reduction in labour demand, is a second key advantage of 3D-printed builds over conventional supply chain design. As whole workplaces are filled with AM machines conducting unmonitored, overnight builds, labour expenses will be reduced accordingly.[51]

In 2019, the US military conducted an exercise in a controlled setting where members of the US Marine Corps, Air Force, and Army Corps of Engineers showed the viability and ease of three-dimensional (3D) printed buildings by constructing anti-tank concrete dragon's teeth and other custom-designed objects. Only two people were needed at any given time to keep printing operations running during Exercise Burgeon Strike: one labourer monitored the computer and made minor manual adjustments to print speed and pump speed as needed, and the other monitored the pump and added additional bags of premixed material as required.[52]

In that respect, AM can decrease labour content or increase labour time for other tasks to be completed. This is particularly interesting in isolated or remote locations where the goal is to build structures as expediently as possible because it can improve the safety of personnel.[53]

Production at or near point of requirement: Supply chains are shaped by minimum efficient scale considerations. In that respect, AM has the ability to minimise the amount of capital needed to attain a minimum efficient scale of production, decreasing the barriers to entry into manufacturing in a certain region or location.[54] As such, one of the most significant benefits is that items can be manufactured at or close to the Point of Requirement (POR). In-Situ production is supported by the fact that (a) AM does not require object-specific tools and has a shorter supply chain with fewer nodes, (b) design creation (scanning) or storage systems allow design sharing and reuse, and (c) local raw material can be delivered from a single source.[55]

Producing out of the area at remote or isolated sites can save operating costs and improve system availability. Thus, AM becomes very useful in these scenarios, where military equipment is either geographically or temporarily isolated, one of the logistical challenges previously mentioned.[56] When considering the speed of distributed AM in relation to the possible savings in lead and transit times in the military supply chain, it's a highly appealing alternative for military operations. Furthermore, AM can improve the availability of military items due to bypassing customs and reducing potential theft, bribery, and trans-

51. Drushal, Jon R. Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030. ATLANTIC COUNCIL WASHINGTON DC BRENT SCOWCROFT CENTER ON INTERNATIONAL SECURITY, 2013.
52. Jagoda, Jeneé, Brandy Diggs-McGee, Megan Kreiger, and Steven Schuldt. "The Viability and Simplicity of 3D-Printed Construction: A Military Case Study." Infrastructures 5, no. 4 (2020): 35.
53. ibid
54. Cotteleer, Mark, Jonathan Holdowsky, Monika Mahto, and John Coykendall. 2014. "3D Opportunity for Aerospace and Defense." Deloitte Insights. 2014.
55. Verboeket, Victor, and Harold Krikke. "Additive manufacturing: A game changer in supply chain design." Logistics 3, no. 2 (2019): 13.
56. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.

portation issues.[57]

On-Demand production: AM is viewed as a way to speed up the acquisition of out-of-production parts. Because the army keeps a spare parts inventory, some parts may go unused or become outdated. On-demand production with additive manufacturing is a way to decrease these stockpiles and the dangers of obsolescence. AM can reduce supply chain inventories, which is a linked benefit. As warfighting evolves and becomes more unexpected, emergency stockpiles will grow: "these added inventory volumes increase the storage liability, as well as pressure on army logistics unit vehicles, the latter adding further to the logistics drag of a unit in the field".[58]

AM may cut down on needless parts purchases and inventory by printing replacement parts on-demand in the field. The learning curve to adopt and manage this new procedure into depot maintenance is, however, steep. Replacement engine components, for example, are now ordered, transported to the depot, inventoried, and removed when needed. Instead, the parts may be printed on-demand in the field or at maintenance and overhaul locations, eliminating the requirement for many spare parts.[59] Additionally, by efficiently minimising logistical delays through AM, mission readiness of essential warfighting assets would be increased. Because items are produced on-demand, this is genuine "just in time" logistics. Reduced inventories disrupt the conventional business strategy of decreasing prices through economies of scale in production. As a result, significant storage needs are no longer necessary, saving millions of dollars usually spent on keeping goods for traditional supply manufacturing.[60]

Maintenance, repair, operations, reverse engineering: Historically, the army's equipment fleets have been subject to tight contracts governing the usage of OEM-specific (original equipment manufacturers) repair components and the extent to which non-OEM maintainers can perform repairs (specifically, uniformed and defence contracted members). Because after-sales service and replacement parts are a profitable element of these contracts for manufacturers, defence may be constrained in its capacity to undertake the needed work using uniformed personnel. This has a severe influence on the military's capacity to maintain this equipment or, because of intellectual property limitations, have military personnel perform anything more comprehensive than operator training.[61]

In that respect, AM brings potential solutions to in-house maintenance and repair for the military. As the need for cooperation and partnerships develops, AM might play a key role in identifying and investigating co-pro-

57. Xu, Xinglu, Mark D. Rodgers, and Weihong Grace Guo. "Hybrid simulation models for spare parts supply chain considering 3D printing capabilities." Journal of Manufacturing Systems 59 (2021): 272-282.
58. Antill, Peter, and Jeremy Smith. "The British army in transition: From army 2020 to the strike brigades and the logistics of future operations." The RUSI Journal 162, no. 3 (2017): 50-58.
59. Schrand, Amanda M. "Additive manufacturing: from form to function." Strategic Studies Quarterly 10, no. 3 (2016): 74-90.
60. Drushal, Jon R. Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030. ATLANTIC COUNCIL WASHINGTON DC BRENT SCOWCROFT CENTER ON INTERNATIONAL SECURITY, 2013.
61. Wright, Kane, James Roberts, and Calum Stewart. "The future of army supply chains and distribution-a possible model." Australian Army Journal 16, no. 1 (2020): 79-100.

duction opportunities with suppliers, partners, and consumers. [62]

Furthermore, traditional postponement, whereby the production is delayed until the customer order is received, is improved by AM. Digital inventory can replace physical inventory with an AM supply chain, bringing the differentiation choice closer to the point of use. The digitised stock mechanism is made possible by (a) AM, which requires no object-specific tools, (b) raw materials from the same source, and (c) a system that stores digital designs for sharing and reuse. This enables differentiation at the last possible time, resulting in the replacement of a variety of stock-keeping units. It also increases part availability and eliminates the requirement for inventory management.

Another way AM can be used for maintenance and repair is in combination with reverse engineering to reproduce obsolete parts. Reverse engineering uses 3D scanning and AM combined as an integrated manufacturing process, reducing the design-to-manufacture development cycle time, as well as enabling old or obsolete parts to be recreated. This 3D scanning can also be employed to scan broken objects and redesign them to recreate a functional object. By doing so, the military can save on production costs and extend the life cycles of products already produced without building entirely new components.

Design flexibility and complex iteration: While changing the capital versus scale relationship could impact supply chain configurations, as we discussed above, changing the capital versus scope relationship could also have an impact on product designs. Indeed, economies of scope have an impact on how and what goods can be manufactured. The versatility of AM allows a unit of capital to manufacture a greater range of goods, lowering the costs of production changeovers and

Source: https://unsplash.com/photos/jcav1COVvOc

Warehouse, 2021
Jacques Dillies

62. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.

customisation, as well as the overall quantity of capital required.[63]

AM allows for product designs and dimensions that are difficult to achieve through traditional production, overcoming existing design and manufacturing constraints. Due to their complicated shape and design, certain topology-optimised devices cannot be built in traditional production. However, with AM, components may be designed to offer optimal performance rather than to suit manufacturing capabilities. AM can also be used to create parts with features like hollow interiors and lattice structures. While preserving the components' strength by giving support just where it is needed, the AM method may keep the parts' weight low. The weight savings made possible by additively producing such parts might have a big influence on the industry.[64]

Another product-enhancing feature is AM's ability to create numerous A&D parts as a single component, minimising assembly work. A single-component product is typically easier to alter than a system made up of several components, making demand unpredictability more manageable.[65] The use of additive manufacturing for customisation and personalisation of spare parts is another benefit. Personalisation can aid in improving the working conditions for troops. For instance, when the original (universal) face brackets for night vision goggles were defective, AM was utilised to create customised versions. The troops responded enthusiastically, stating that using night vision with the customised face bracket was more comfortable than using the original bracket.[66]

Improved sustainability: The ability to decrease negative environmental consequences caused by material waste, energy consumption and greenhouse gas emissions is another advantage of 3D-printed building over conventional construction. By design, AM's shorter and simpler supply chains, more localised manufacturing, novel distribution methods, and new non-linear partnerships all lead to more sustainable operations. Compared to traditional production, AM may save 50% of energy and up to 90% of material costs.[67] In distant, isolated, or expeditionary areas without established electrical networks, the ACES Lite 2 is an electric printer that can run on a generator or solar power, decreasing energy usage compared to traditional construction, which generally depends on diesel-powered heavy equipment.[68]

AM can also improve resource efficiency, which may be obtained in both the production and consumption phases by redesigning manufacturing processes and products for

63. Cotteleer, Mark, Jonathan Holdowsky, Monika Mahto, and John Coykendall. 2014. "3D Opportunity for Aerospace and Defense." Deloitte Insights. 2014.
64. ibid
65. ibid
66. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.
67. Drushal, Jon R. Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030. ATLANTIC COUNCIL WASHINGTON DC BRENT SCOWCROFT CENTER ON INTERNATIONAL SECURITY, 2013.
68. Jagoda, Jeneé, Brandy Diggs-McGee, Megan Kreiger, and Steven Schuldt. "The Viability and Simplicity of 3D-Printed Construction: A Military Case Study." Infrastructures 5, no. 4 (2020): 35

AM.[69] Because 3D printing is an additive process, it only utilises the materials necessary for the construction and does not require material formwork, resulting in less waste. Conventional machining can result in scrap rates as high as 80–90% of the original billet, given the fundamental difference between subtractive and additive manufacturing processes, whereas AM can reduce scrap rates to 10–20%.[70] This also has cost benefits in areas requiring expensive raw materials to manufacture parts, such as the use of titanium.

Finally, extending product life can be achieved by AM through technical techniques such as repair, remanufacture, and refurbishment, as well as more sustainable socio-economic patterns such as stronger consumer-product affinities and closer producer-consumer connections, thus improving sustainability.[71]

LIMITATIONS OF ADDITIVE MANUFACTURING

The A&D sector, which is not a mass-production industry in the traditional sense, benefits from AM's capacity to handle small volumes, generate complicated designs, and build lightweight but robust structures. However, AM currently confronts problems related to size and scalability, high material prices, a restricted variety of materials, intellectual property and cybersecurity issues.

Scalability: Traditional production and procurement techniques present A&D firms with the issue of storing huge inventories, the bulk of which may be underutilised. AM systems, on the other hand, may not be able to scale up output as needed. To satisfy the industry's bulk-production demands, AM suppliers are trying to enhance the build speed of existing AM systems. According to one AM expert, AM systems where various components may be manufactured concurrently or where production and unloading can happen simultaneously would assist increase AM's scalability.[72]

High costs: AM primarily employs a limited number of polymers and metal powders to create A&D components, and these materials are significantly more expensive than those utilised in traditional manufacturing processes. Metallic powder, for example, is 5-10 times more expensive per kilogram than the same material's equivalent bar stock. So, for material prices to be competitive, the current

69. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.
70. Cotteleer, Mark, Jonathan Holdowsky, Monika Mahto, and John Coykendall. 2014. "3D Opportunity for Aerospace and Defense." Deloitte Insights. 2014.
71. Ford, Simon, and Mélanie Despeisse. "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges." Journal of cleaner Production 137 (2016): 1573-1587.
72. Cotteleer, Mark, Jonathan Holdowsky, Monika Mahto, and John Coykendall. 2014. "3D Opportunity for Aerospace and Defense." Deloitte Insights. 2014.

part's buy-to-fly ratio (the amount of material purchased versus the amount of material in the completed part) must be at least 5:1 (or 10:1).[73] As such, material costs will need to decrease in the years to come for AM to be truly viable for wide usage. Similarly, procurement, depreciation, and maintenance can be significantly expensive with AM. Normally, machines depreciate after over ten years in traditional manufacturing, but with AM, it may take as little as three years.[74]

Intellectual property: Defence relies on original vendors for replacement components due to long-term contracts. The issue of intellectual property and royalty payment is therefore very present. The availability of design is a barrier to AM implementation: the military has just a few systems for which the manufacturer's original designs are available. Access to a digital design must be built into contracts with suppliers and developers to enable the usage of AM. The connection with the supplier varies as the position and function in the production process changes. Future tenders must include receiving the digital design, system, and/or rights to utilise them. The willingness of the supplier or developer to give designs, on the other hand, would probably be relatively low. Warranties, in particular, are a source of worry. Issues with warranties, intellectual property, and quality can be resolved when a supplier installs an AM system on-site but supervises the process remotely. The possibility of having defence personnel trained by the AM service system's provider or supplier might help with warranty issues.[75]

Cybersecurity challenges: Armed forces must anticipate that wherever data and information are transferred, utilised, or accessed, someone, somewhere, will try to exploit that data and information for personal benefit or to cause harm or damage. Recognising this tragic truth is not just a commercial requirement but possibly a matter of life and death for additive manufacturing technology. Because AM relies on digital data files and connectivity to transmit them, AM technology is vulnerable to a variety of security risks, ranging from product malfunctions to intellectual property theft, as well as other new threats that traditional manufacturers may not be aware of. The digital thread in the production cycle of an object through AM contains a wealth of technical and operational information about that product. If a digital design file is stolen or tampered with, pundits may do more than reverse engineer the item and sell it illegally. Hackers might theoretically put in failure entries in crucial components without the designer's knowledge, thus causing potential mass disruption.[76]

73. Simpson, Timothy. "Industrializing Am: A Simple Cost Equation." Additive Manufacturing. Additive Manufacturing, October 8, 2020. https://www.additivemanufacturing.media/articles/industrializing-am-a-simple-cost-equation.
74. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301
75. ibid
76. Goldenberg Simon, and Mark Cotteleer. "Cyber Risks in Additive Manufacturing Threaten to Unravel the Digital Thread." Supply Chain Navigator, April 24, 2018. http://scnavigator.avnet.com/article/april-2018/cyber-risks-in-am-threaten-to-unravel-the-digital-thread/.

CONCLUSION

AM's capabilities speak directly to the goals and problems of the A&D sector. Traditional production processes are unable to match the design complexity enabled by the technology. At the same time, AM aids in the weight reduction of parts, resulting in increased fuel economy. Complex parts can also be manufactured as single-component systems using this method. As previously said, AM decreases the amount of capital necessary to achieve economies of scale and scope, allowing businesses to improve their goods and supply chains. AM will influence the military's responsiveness and long-term viability. Because of the number, complexity, and age of current military systems, AM has the opportunity to shorten lead times, decrease inventory, and increase operational readiness. Supplier lead times of six to nine months are standard in the current world, and local stockpiles of spare parts are kept to respond swiftly to changing conditions and system breakdowns.[77] Despite certain present limitations, AM's capacity to rapidly field capabilities can revolutionise logistics and sustainment. AM can change acquisitions and redefine system qualifications and certifications due to the time and cost savings.

BIBLIOGRAPHY

"Budget 2021 : 39,2 Milliards d'Euros Alloués Au Ministère Des Armées." Ministère des Armées, 2020. https://www.defense.gouv.fr/actualites/articles/budget-2021-39-2-milliards-d-euros-alloues-au-ministere-des-armees.

"Firearms Parts and Components." United Nations Office on Drugs and Crime, 2019. https://www.unodc.org/e4j/en/firearms/module-2/key-issues/firearms-parts-and-components.html.

Antill, Peter, and Jeremy Smith. "The British army in transition: From army 2020 to the strike brigades and the logistics of future operations." The RUSI Journal 162, no. 3 (2017): 50-58.

77. den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. "Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain." Journal of Cleaner Production 257 (2020): 120301.

Barno, David, and Nora Bensahel. “Three Things the Army Chief of Staff Wants You to Know.” War on the Rocks, May 22, 2017. https://warontherocks.com/2017/05/three-things-the-army-chief-of-staff-wants-you-to-know/.

Busachi, Alessandro, John Erkoyuncu, Paul Colegrove, Richard Drake, Chris Watts, and Stephen Wilding. “Additive manufacturing applications in Defence Support Services: current practices and framework for implementation.” International Journal of System Assurance Engineering and Management 9, no. 3 (2018): 657-674.

den Boer, Jelmar, Wim Lambrechts, and Harold Krikke. “Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain.” Journal of Cleaner Production 257 (2020): 120301.

Drushal, Jon R. Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030. ATLANTIC COUNCIL WASHINGTON DC BRENT SCOWCROFT CENTER ON INTERNATIONAL SECURITY, 2013.

Durro, Gisella. “Let’s Go Green: France Is Ready to Make Its Army More Sustainable.” You are being redirected..., 2020. https://finabel.org/lets-go-green-france-is-ready-to-make-its-army-more-sustainable/.

Erwin, Sandra. “Cost to Maintain Weapons Eating into Military Budgets.” National Defense, 2016. https://www.nationaldefensemagazine.org/articles/2016/2/18/cost-to-maintain-weapons-eating-into-military-budgets.

Ford, Simon, and Mélanie Despeisse. “Additive manufacturing and sustainability: an exploratory study of the advantages and challenges.” Journal of Cleaner Production 137 (2016): 1573-1587.

Gibson, Ian, David W. Rosen, Brent Stucker, and Mahyar Khorasani. Additive manufacturing technologies. Vol. 17. Cham, Switzerland: Springer, 2021.

Goldenberg Simon, and Mark Cotteleer. “Cyber Risks in Additive Manufacturing Threaten to Unravel the Digital Thread.” Supply Chain Navigator, April 24, 2018. http://scnavigator.avnet.com/article/april-2018/cyber-risks-in-am-threaten-to-unravel-the-digital-thread/.

Hanaphy, Paul, Hayley Everett, and Kubi Sertoglu. "Department of Defense Unveils Additive Manufacturing Strategy." 3D Printing Industry, February 4, 2021. https://3dprintingindustry.com/news/department-of-defense-unveils-additive-manufacturing-strategy-183832/.

Jagoda Jeneé, Brandy Diggs-McGee, Megan Kreiger, and Steven Schuldt, The Viability and Simplicity Of 3D-Printed Construction: A Military Case Study. Infrastructures 5 (4). 2020. doi:10.3390/infrastructures5040035. p2

Leering, Raoul. 2021. "3D Printing's Post-Pandemic Potential." https://think.ing.com/uploads/reports/3D_printing_report_final_050821_RL_OT_FINAL.pdf.

Major C, Strickmann E. "You Can't Always Get What You Want – Logistical Challenges in EU Military Operations." German Institute for International and Security Affairs. 2011.

North Atlantic Treaty Organisation. "Logistics", 2017.

North Atlantic Treaty Organisation. "NATO logistics HANDBOOK: Chapter 1: Definitions", 1997. https://www.nato.int/docu/logi-en/1997/lo-103.htm.

Pawelczyk, Marta. "Contemporary challenges in military logistics support." Security and Defence Quarterly 20, no. 3 (2018): 85-98.

Pérès, François, and Daniel Noyes. "Envisioning e-logistics developments: Making spare parts in situ and on demand: State of the art and guidelines for future developments." Computers in industry 57, no. 6 (2006): 490-503.

Pérès, François, and Daniel Noyes. "Envisioning e-logistics developments: Making spare parts in situ and on demand: State of the art and guidelines for future developments." Computers in industry 57, no. 6 (2006): 490-503.

Schrand, Amanda M. "Additive manufacturing: from form to function." Strategic Studies Quarterly 10, no. 3 (2016): 74-90.

Schütz, Torben, and Zoe Stanley-Lockman. Smart logistics for future armed forces. European Union Institute for Security Studies., 2019.

Scott, Clare. "German Armed Forces Use 3d Printing to Redesign an Obsolete Part - 3DPrint.Com: The Voice of 3d Printing / Additive Manufacturing." 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing, October 17, 2018. https://3dprint.com/227587/german-armed-forces-3d-print-obsolete-part/.

Simon, Steve John. "The art of military logistics." Communications of the ACM 44, no. 6 (2001): 62-66.

Simpson, Timothy. "Industrializing Am: A Simple Cost Equation." Additive Manufacturing. Additive Manufacturing, October 8, 2020. https://www.additivemanufacturing.media/articles/industrializing-am-a-simple-cost-equation.

Taithe, Alexandre, and Bruno Lasalle. 2020. "Le Développement de l'Impression 3D Dans Les Armées : Une Innovation de Rupture ? :: DEFENSE&Industries :: Fondation Pour La Recherche Stratégique :: FRS." Www.frstrategie.org. 2020. https://www.frstrategie.org/publications/defense-et-industries/developpement-impression-3d-dans-armees-une-innovation-rupture-2020.

Valva, Tia. "The Authority on 3d Printing & Additive Manufacturing." 3D Printing Industry, September 11, 2019. https://3dprintingindustry.com/news/uk-ministry-of-defence-to-leverage-3d-printing-in-new-security-approach-161491/.

Verboeket, Victor, and Harold Krikke. "Additive manufacturing: A game changer in supply chain design." Logistics 3, no. 2 (2019): 13. P 2

Virol, Gautier. "Pourquoi L'ARMÉE De Terre S'est Constituée UNE Ferme De 50 MACHINES D'IMPRESSION 3D." usinenouvelle.com. L'Usine Nouvelle, July 3, 2020. https://www.usinenouvelle.com/editorial/pourquoi-l-armee-de-terre-s-est-constituee-une-ferme-de-50-machines-d-impression-3d.N982136.

Wiles, Matt, and David Chinn. "Supply Chain Transformation Under Fire." McKinsey, 2010. https://www.mckinsey.com/~/media/alumni%20center/pdf/mog_supply_chain.pdf.

Wong, Kaufui V., and Aldo Hernandez. "A review of additive manufacturing." International scholarly research notices 2012 (2012).

Wright, Kane, James Roberts, and Calum Stewart. "The future of army supply chains and distribution-a possible model." Australian Army Journal 16, no. 1 (2020): 79-100.

Xiong, Biao, Rong Fan, Shuai Wang, Bixin Li, and Can Wang. "Performance Evaluation and Disruption Recovery for Military Supply Chain Network." Complexity 2020 (2020).

Xu, Jie, Jun Zhuang, and Zigeng Liu. "Modeling and mitigating the effects of supply chain disruption in a defender–attacker game." Annals of Operations Research 236, no. 1 (2016): 255-270.

Xu, Xinglu, Mark D. Rodgers, and Weihong Grace Guo. "Hybrid simulation models for spare parts supply chain considering 3D printing capabilities." Journal of Manufacturing Systems 59 (2021): 272-282.

Created in 1953, the Finabel committee is the oldest military organisation for cooperation between European Armies: it was conceived as a forum for reflections, exchange studies, and proposals on common interest topics for the future of its members. Finabel, the only organisation at this level, strives at:

- Promoting interoperability and cooperation of armies, while seeking to bring together concepts, doctrines and procedures;
- Contributing to a common European understanding of land defence issues. Finabel focuses on doctrines, trainings, and the joint environment.

Finabel aims to be a multinational-, independent-, and apolitical actor for the European Armies of the EU Member States. The Finabel informal forum is based on consensus and equality of member states. Finabel favours fruitful contact among member states' officers and Chiefs of Staff in a spirit of open and mutual understanding via annual meetings.

Finabel contributes to reinforce interoperability among its member states in the framework of the North Atlantic Treaty Organisation (NATO), the EU, and *ad hoc* coalition; Finabel neither competes nor duplicates NATO or EU military structures but contributes to these organisations in its unique way. Initially focused on cooperation in armament's programmes, Finabel quickly shifted to the harmonisation of land doctrines. Consequently, before hoping to reach a shared capability approach and common equipment, a shared vision of force-engagement on the terrain should be obtained.

In the current setting, Finabel allows its member states to form Expert Task Groups for situations that require short-term solutions. In addition, Finabel is also a think tank that elaborates on current events concerning the operations of the land forces and provides comments by creating "Food for Thought papers" to address the topics. Finabel studies and Food for Thoughts are recommendations freely applied by its member, whose aim is to facilitate interoperability and improve the daily tasks of preparation, training, exercises, and engagement.

FINABEL

Quartier Reine Elisabeth
Rue d'Evere 1 box 44
B-1140 BRUSSELS

Tel: +32 (0)2 441 79 05 – GSM: +32 (0)483 712 193
E-mail: info@finabel.org

You will find our studies at **www.finabel.org**

European Army Interoperability Centre

www.linkedin.com/in/finabelEAIC @FinabelEAIC @FinabelEAIC

Responsible publisher: Mario BLOKKEN - Finabel Permanent Secretariat - QRE - Rue d'Evere,1 - B-1140 Brussels - +32 (0)2 441 79 05