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# From Additive Manufacturing to Advanced Manufacturing: Evolving a CAF Joint Sustainment Concept

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# FROM ADDITIVE MANUFACTURING TO ADVANCED MANUFACTURING: EVOLVING A CAF JOINT SUSTAINMENT CONCEPT

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## AIM

1. Advanced Manufacturing (AdM) is defined as "the use of innovative technology to improve new and existing products and processes"[1]. While additive manufacturing (AM), also known as 3D printing, is the best-known AdM technique, an integrated AdM system encompasses much more including manufacturing data management and a host of automated subtractive manufacturing techniques. The purpose of this paper is to discuss why the Canadian Armed Forces (CAF) should evolve from exploring AM technologies to a joint deployable AdM capability for 3rd line sustainment.

## INTRODUCTION

2. This paper will start by discussing the changing relevance of manufacturing capabilities given lessons learned from the war in Ukraine, as well as Canada's strategic orientation towards the Indo-Pacific and the North. It will then give some doctrinal considerations, the perceived advantages of implementing AdM, and considerations to why the CAF might employ this capability. The paper will then discuss, at a high level, the technical challenges and lessons learned from CAF trials of AM as well as observations from allied nations, suggesting that current orientation towards AM alone is insufficient when compared to an AdM approach for achieving the desired effects in the contemporary environment. It will conclude with two key challenges and suggested strategies to mitigate them.

## DISCUSSION

3. The ongoing war in Ukraine has shown the importance of technological agility, innovation, and resiliency for logistics and maintenance of equipment. Videos posted online of commercial-off-the-self drones dropping bombs with 3D-printed mechanisms demonstrates the increasing importance of battlefield innovation to exploit adversary vulnerabilities when they have near-peer or overmatch[2]. Ukrainian forces have shown the ability to identify and fill capability gaps by rapidly designing and producing parts for these drones to suit the requirements, and rapidly evolving these capabilities over time to outpace their adversary. Another challenge is posed by the diverse fleet of equipment acquired by Ukraine through the donations provided by Western nations. The variety of the fleet, amount of battlefield damage, and limited repair parts and special tools which were donated with major systems has equally highlighted the importance of self-sufficiency in manufacturing parts at the point of demand to improve responsiveness of the equipment support system[3].

4. CAF must be able to similarly adapt and innovate on the battlefield and add resiliency into its sustainment system. Lessons from Ukraine suggest the next war may be fought in a contested logistics environment which doctrine defines as "an environment in which the armed forces engage in conflict with an adversary that presents challenges in all domains and directly targets logistics operations, facilities, and

[1] National Research Council Canada, 'NRC Capabilities in Advanced Manufacturing', 1 April 2019, https://nrc.canada.ca/en/research-development/research-collaboration/programs/nrc-capabilities-advanced-manufacturing.
[2] Mykhaylo Zabrodskyi, 'Preliminary Lessons in Conventional Warfighting from Russia's Invasion of Ukraine: February–July 2022' (Royal United Services Institute, 30 November 2022), https://www.rusi.org/explore-our-research/publications/special-resources/preliminary-lessons-conventional-warfighting-russias-invasion-ukraine-february-july-2022.
[3] Frank Hofmann, 'Who Repairs Ukraine's Western Weapons?', Deutsche Welle, 26 September 2022, https://www.dw.com/en/ukraine-war-how-to-repair-the-ukrainian-armys-modern-weapons/a-63215373.

activities"[4]. In such a non-permissive environment, redundancy is needed to ensure the responsiveness and self-sufficiency of the support system, however, the Canadian Forces Joint Publication (CFJP) 4-0 support principals note that redundancy is in opposition to economy[5] – a principal which Canada has favored in its equipment support systems in recent years. The CAF's low volume equipment inventory on the battlefield means that contested logistics challenges may also become compounded through competition with other nations for scarce items who have more influence with global defense industry partners. The conflict in Ukraine has highlighted the importance of the industrial base to sustain the combat capability of each nation, however, the response time of industry to state demand is not immediate[6]. Canadian industry will certainly play a role in fulfilling similar unanticipated support demands, particularly at scale, but there will be a delay while industry ramps up to respond to the CAF's demand which could be filled by flexible organic fabrication resources.

5. The Indo-Pacific Strategy in addition to increasing interest in Arctic operations means that the CAF will need to contend with both more complex lines of communication (LOCs) which will challenge supply chain responsiveness. With the CAF's limited access to lift resources, it is preferable to have options beyond the traditional supply model that give more flexibility as these new areas of operations may only permit limited access to local resources. In Canada's north, resources are in limited supply with only short windows of time and space to resupply. due to ice flows. Similarly, diplomatic considerations may make support for CAF politically sensitive in Indo-Pacific nation hosts due to pressure from China or other regional powers[7]. Consider, for example, the difficult diplomatic situation for members of Association of Southeast Asian Nations (ASEAN) who need to balance regional and global economic and security interests. With limited access to local resources, and across complex LOCs the CAF sustainment system will be tested to respond to unanticipated crises rapidly.

**CAF Manufacturing Doctrine**

6. The introduction of digital automated tools for the fabrication of defense supplies, the ability to share digital information, and proliferation of relatively low-cost manufacturing equipment now allows many items to be reproduced at low cost near the point of demand making organic manufacturing resources more desirable than ever. Some have called the availability of these new AdM tools the beginning of fourth industrial revolution, which will fundamentally change both products and manufacturing systems to be more modular, service oriented, interoperable, and decentralized [8]. Many of these tools can be employed in the production of defense supplies, either to reduce the reliance on stockpiling of rarely demanded items (such as obscure repair parts), to return battle damaged equipment to operation through expedient repair, or proving battlefield innovation through rapid prototyping. An AdM capability could consist of a combination of digitally aided manufacturing tools such as computer

[4] Michael Hugos Hazen Edward Salo, Ryan Kuhns, Ben, 'Logistics Determine Your Destiny: What Russia's Invasion Is (Re)Teaching Us about Contested Logistics', Modern War Institute, 9 August 2022, para. 1, https://mwi.usma.edu/logistics-determine-your-destiny-what-russias-invasion-is-reteaching-us-about-contested-logistics/.
[5] Canada, Department National Defence, 'CFJP - Canadian Forces Joint Publication B-GL-005-400-FP001' (Department National Defence, 2014).
[6] Sidharth Kaushal, 'The War in Ukraine, One Year On - Interactive Commentary', Royal United Services Institute, 24 February 2023, https://rusi.org/explore-our-research/publications/commentary/war-in-ukraine-one-year-on/null.
[7] Global Affairs Canada, 'Canada's Indo-Pacific Strategy', GAC, 24 November 2022, https://www.international.gc.ca/transparency-transparence/indo-pacific-indo-pacifique/index.aspx?lang=eng#a1_3.
[8] Lenny Koh, Guido Orzes, and Fu (Jeff) Jia, 'The Fourth Industrial Revolution (Industry 4.0): Technologies Disruption on Operations and Supply Chain Management', *International Journal of Operations & Production Management* 39, no. 6/7/8 (2019): 817–28, https://doi.org/10.1108/IJOPM-08-2019-788.

numerical control (CNC) mills, lathes, cutters, AM, in addition to IT equipment and software to network them together. Generally speaking, AdM tools exist as a collection of modular and scalable commercial-off-the-shelf products that can be integrated into a networked and ruggedized deployable capability to fit the need. CFJP 4-0 Sustain includes manufacturing capabilities within doctrinal joint maintenance organizations, but Canada does not currently possess a robust deployable manufacturing capability. Canada's deployable sustainment capabilities consist of 1st, 2nd line assets and purpose-built 3rd line capabilities are generally force generated from these forces with little or no specialized equipment that is described in doctrine for 3rd line sustainment organizations[9]. With the introduction of AdM technology, and the forthcoming 4th industrial revolution, it's the right time for the CAF to make investments into a new AdM capability in order to capitalize on these forthcoming technological benefits.

**The Arguments for an AM Capability**

7. Since 2019, 18 Canadian Forces College papers have advocated for the establishment of a CAF AM capability, a subgroup of AdM technologies. These papers outline potential benefits for the CAF generally summarized as: improving operational flexibility and responsiveness[10], mitigating challenges with long or complex LOCs on deployed operations[11], and improving economy and efficiency through reduced stockpiling[12]. While these advantages are significant, some note challenges with advancement of the DND/CAF Data Strategy to enable sharing, transfer, and storage of manufacturing information will limit the potential benefits[13]. Tranquilla argues that achieving significant benefits from AM implementation will require a top-down institutional change to implement structural conditions to achieve similar positive results to other military forces[14]. The United States, and particularly the Marine Corps (USMC) have implemented through an aggressive implementation strategy for AM which have produced strong early results in line with the aforementioned benefits, but also emphasizes the ability for Marines to use this tool to rapidly innovate on the battlefield[15]. There is clear agreement that AM will provide benefits to the CAF, however, the challenges to implementation in Canada, namely digitization, remain unaddressed. In some cases, the potential benefits of AM may be overstated due to present technological limitations.

**Why it is Necessary to Re-Orient towards AdM**

8. CAF experimentation with AM equipment has exposed limitations for its use in the field. Trials have been going on for several years, with the deployment of a polymer 3D printing capability to Op REASSURANCE in 2020-21 being the most notable. The equipment was used successfully within both the National Support Element and the Enhanced Forward Presence Battle Group in Latvia, demonstrating the utility of these tools in both 1st and 2nd/3rd line support organizations, however, lessons learned show

[9] Canada, Department National Defence, 'CFJP - Canadian Forces Joint Publication B-GL-005-400-FP001'.
[10] Major Allison Lucas, 'Untapped Potential: How The Use of Additive Manufacturing Could Dramatically Improve the CAF Military Deployment Supply Chain' (Joint Command and Staff College paper, Canadian Forces College, 2019).
[11] Major Shain Ronalds, 'Additive Manufacturing as a Force Multiplier in Deployed Operations' (Joint Command and Staff College paper, Canadian Forces College, 2015).
[12] Major Ryan Adams, 'Additive Manufacturing: Support to Canadian Army Sustainment' (Joint Command and Staff College paper, Canadian Forces College, 2018).
[13] Lieutenant-Commander Sebastien Fleury, 'Policy Implications for Integrating Additive Manufacturing in the Defence Supply Chain' (Joint Command and Staff College paper, Canadian Forces College, 2020).
[14] Major Nick Tranquilla, 'Additive Manufacturing Effects on Sustain Requires Formal CAF Commitment' (Joint Command and Staff College paper, Canadian Forces College, 2021).
[15] Major E J Henzler, 'Additive Manufacturing: A Canadian Imperative' (Joint Command and Staff College paper, Canadian Forces College, 2018).

that infrastructure and portability constrains which systems can be deployed tactically[16]. A key limitation encountered during the trials was materials, as only polymers could be printed with the CAF deployed equipment. While polymer AM can fill niche supply shortages and return equipment to service, organic metal manufacturing assets can alleviate a wider range of gaps in the support structure for a military organization more suitable to the challenges seen in Ukraine. Current generation metal AM equipment is even more cumbersome than traditional subtractive methods, raising questions about its utility for austere applications. The Australian Army has trialed a deployable metal AM system, yet while these trials successfully produced end-use items in the field[17], the capability only offers questionable appreciable sustainment advantages due to its size, weight, post-processing requirements, and materiel limitations for common most defense items. AM has proven to be a useful tool in the sustainment system, but subtractive AdM tools are also needed to meet the demands of the CAF in addition to digitization requirements.

9. The current limitations of AM technology require a rethinking of the capability solution being trialed by the CAF. From an equipment standpoint, a broad set of AdM manufacturing tools are already regularly used in the DND team, albeit not employed in an AdM system. For example, significant manufacturing capabilities exist to support the Canadian Army from 202 Workshop Depot, the Royal Canadian Navy from the Fleet Maintenance Facilities. These workshops employ both traditional manufacturing as well as AM techniques to support their respective elements, however, are without comprehensive digitization strategies needed to capitalize on the connectivity and scalability of AdM technologies, which permit sharing of manufacturing information with forward deployed elements for manufacturing at the point of demand. Additionally, neither facility has deployable manufacturing assets or trained personnel in order to staff forward deployed manufacturing facilities. There is similarly no formal capability or policy development assets allocated to AdM at this time. From an equipment standpoint, the British Army has shown that deployable equipment which includes a wide array of digital subtractive metal and additive manufacturing techniques can be assembled for relatively low cost, £3 million in 2022[18], demonstrating that deployable capabilities are available today. Such systems have limited tactical mobility which implies housing AdM in a 3rd line (or higher) support organization is the only viable option at present. An AdM capability could benefit any component or be used jointly between services.

10. Many allied nations have already started to pursue AdM capabilities. In addition to the US, UK, and Australia, NATO has also adapted AdM as one of its nine technology priorities[19]. Many of these capabilities are in the initial stages of fielding, and are conducting trials to standardize information within AdM systems for multinational sustainment approaches. One concept is retaining national control over manufacturing data, while the resources of other nations manufacture the item. Under this construct any nation could manufacture the items of an allied nation, provided they are able to share their manufacturing information with their partners which provides opportunities for greater economy and capacity for multinational sustainment. While desirable, this possibility also highlights two key challenges for adopting AdM for the CAF, standardization and integration.

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[16] Lieutenant Sean Menezes, 'Op REASSURANCE Additive Manufacturing Lessons Learned' (Department National Defence, 15 April 2021).
[17] Lieutenant-Colonel Kane Wright, 'The Future of Army Supply Chains and Distribution A Possible Model', *Australian Army Journal* XVI, no. 1 (2020): 79–101.
[18] Captain Tom Warner, 'British Army Advanced Manufacturing Centre of Excellence', The Craftman, July 2022, https://issuu.com/official_reme/docs/craftsman_july_2022_website_/s/17063925.
[19] NATO, 'Emerging and Disruptive Technologies', NATO, accessed 27 February 2023, https://www.nato.int/cps/en/natohq/topics_184303.htm.

**Challenges with AdM and how to Mitigate them**

11. Standardization of manufacturing equipment is challenging for several reasons. First, there are equipment limitations and specifications that prevent designs from being autonomously manufactured without significant effort to translate the information between platforms due to differences in programming the interface with the machine, differences in base materials (dimensions, properties, etc), as well as the tools used to do the manufacturing. The variety of equipment needed in an AdM capability makes overcoming this challenge from the equipment perspective difficult. Consider, for example, the variety of tools needed in a combined environment where most nations use metric tools while others use imperial. Second, there are challenges with standardization of policy, in the area of what DND calls materiel assurance, that is ensuring defense items are "safe to use… and compliant with applicable statutes, regulations, policies, instructions and directives, throughout their life cycle"[20]. Desperate governance, legal, and risk management regimes can lead to challenges with risk acceptance for using AdM parts when their failure can present a risk to personnel safety or to mission failure. This is exasperated both in a joint and combined environment. Within the CAF, an example is the Royal Canadian Air Force (RCAF) airworthiness program which imposes a strict governance and risk management regime on RCAF equipment[21]. Similar programs exist in the other services as well as in allied nations which can complicate the governance of a joint manufacturing capability.

12. Integration is also a challenge with AdM due to poor digital connectivity between information systems and differences in organizational governance. Interconnectivity of information systems is difficult to achieve due to the possibility of disparate national choices in an environment where a lack of purpose-built software for military purposes exists. Many designs needed to manufacture defence materiel are either proprietary to its creator (generally defence industry), or are designated materiel nationally which prevents easy sharing. Furthermore, intellectual property can also be a barrier – at present the legal implications are not yet fully understood due to a lack of legal precedence[22] which creates an environment of risk adversity. The complexity of integrating service and national processes for requesting manufacturing services can also not be underestimated, while AdM is a relatively new capability there is a risk that both services and allies develop processes that meet their national requirements without consideration for integrating into a multinational sustainment system.

13. The challenges of standardization and integration are significant enough that they require upfront investment to mitigate the risks these challenges pose. Most importantly, early and persistent collaboration is essential to overcoming challenges – both from a whole of government perspective as well as with allied militaries. Canada views AdM as a key high-technology investment area and has invested significantly in research and development through the National Resource Council[23], and has created opportunities to partner with Canadian Industry through two Industry Science and Economic Development Canada initiatives[24]. The CAF, being in the trial stages of developing its AdM concept could partner with these other government departments to leverage their experience and knowledge to

[20] National Defence, 'DAOD 3035-0, Materiel Assurance', policies, 11 May 2021, https://www.canada.ca/en/department-national-defence/corporate/policies-standards/defence-administrative-orders-directives/3000-series/3035/3035-0-materiel-assurance.html.
[21] National Defence, 'DND/CAF Airworthiness Program Overview', service description, 2 March 2018, https://www.canada.ca/en/department-national-defence/services/military-airworthiness/dnd-caf-airworthiness-program-overview.html.
[22] Fleury, 'Policy Implications for Integrating Additive Manufacturing in the Defence Supply Chain'.
[23] Canada, 'NRC Capabilities in Advanced Manufacturing'.
[24] Innovation Government of Canada, 'Key Industrial Capabilities', 23 April 2018, https://ised-isde.canada.ca/site/industrial-technological-benefits/en/key-industrial-capabilities; Government of Canada.

quicken its understanding of how an AdM capability concept could fit into its existing structure, and to keep apprised of the latest in technology developments. As many allied nations are advancing AdM capabilities, it is possible to advance joint research and development initiatives (through the Technical Cooperation Program and NATO Science and Technology Organization[25] for example), sharing of resources and expertise, process development, as well as combined trials and development of lessons learned. This collaboration work, and the subsequent changes to CAF and DND business practices necessitate the establishment of a project to further define the statement of operational capability deficiency and begin to work with other government departments, allies and industry partners towards establishing an AdM capability that takes full advantage of automated technology while being standardized and integrated to work across DND services and with allies.

## CONCLUSION

14. An investment into AdM to pursue a joint deployable AdM capability that incorporates subtractive manufacturing, AM, and an accessible and assured database is more desirable for the CAF than ever before. Lessons from Ukraine show that the CAF must adapt to operations in a contested logistics environment, and developing an AdM capability is one way the CAF can improve the responsiveness, flexibility, and resiliency of its support system, as well as enable battlefield innovation. Implementing an AdM capability requires overcoming the challenges of standardization and integration, which can be mitigated through early collaboration with whole of government partners as well as allies. The first step towards formalizing the initiating a project to further define the statement of operational capability deficiency and begin work towards implementing a joint capability as soon as practical.

[25] Defence Research and Development Canada, 'Partnerships and Opportunities: Allies', 17 November 2021, https://www.canada.ca/en/defence-research-development/services/partnerships-opportunities/allies.html.

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