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3D PRINTING – SUPPLY CHAIN REACTION

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This paper will examine limitations that would affect the integration of *additive manufacturing* (AM) into the Canadian Armed Forces (CAF) supply chain. AM will be cross-examined with the *disruptive technology* concept to inform recommendations by considering AM as an emerging technology that is at the precipice of causing a shift in the supply chain paradigm.[1] Consequences of disruptive technologies, along with industry-acknowledged limitations of AM, will be used to provide insights to better determine how and when to implement AM.[2] AM is a maturing technology that will disrupt supply chain operations, requiring the CAF to decide how to implement the technology and not if it should implement the technology. Although, this paper will focus on *parts* to facilitate discussion, the concepts are applicable to other items in the CAF supply chain.

To frame this argument, one must understand what AM is, and what existing technology it is disrupting. AM's rival is *subtractive manufacturing*, a term assigned to longstanding manufacturing methods when AM emerged. Three-Dimensional printing, formally referred to as AM, is a process by which "a machine deposits material sequentially, layer upon layer, hardening the material as it goes, until the object is finished… This layer-by-layer approach enables the transformation of a virtual, three-dimensional model into a physical object."[3] Three-dimensional virtual models, referred to as computer-aided design (CAD) files, are either created by a designer or by a three-dimensional scan of an existing part. Once a three-dimensional CAD file is created,

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[1] B. Colosimo, et al, "Opportunities and Challenges of Quality Engineering for Additive Manufacturing," *Journal of Quality Technology* 50, no. 3 (2018): 233.
[2] Michael Kidd, Angela Quinn, and Andres Munera, "Additive Manufacturing: Shaping the Sustainment Battlespace," *Joint Force Quarterly*: JFQ no. 91 (2018): 46.
[3] Steve Stark, "WHY the HYPE?" *Army AL & T* (2019): 91.

software converts the three-dimensional design into a series of two-dimensional layers. Each *pass* of the printer represents a two-dimensional layer and after thousands of passes and the *adding* of thousands of layers, a three-dimensional part is created.[4] For this reason, the process is called *additive* manufacturing. Subtractive manufacturing, by contrast, is when "the end product is created from one or many larger materials where a number of machines cut, drill or otherwise remove material from a larger initial block to manufacture a product."[5] Subtractive manufacturing, although only recently referred to as such, has been in existence for thousands of years incrementally shaping how the world's supply chain operates and engraining in us assumptions on how best to manage materiel.[6]

DISRUPTIVE TECHNOLOGY

Classifying AM as a disruptive technology is a significant step in determining how to proceed with its integration or even deciding whether to proceed with it at all. Stating that AM is more than an incremental progression in manufacturing technology implies that the ramifications of its existence go beyond how goods are manufactured to causing second and third order effects. For example, prior to AM, subtractive manufacturing underwent numerous incremental developments that only affected the manufacturing aspects of the parts supply chain. Specifically, Alan Brown, of the American Society of Mechanical Engineers, observes that despite all the ameliorations of subtractive manufacturing in the automotive industry of the 20th century, the effects were contained to the manufacturing process without forcing change in the rest of the parts

[4] *Ibid*.
[5] A. Boukhtouta, et al, *Additive Manufacturing and Repair, Support & Distribution*. Scientific Report. DRDC-RDDC-2017-R164 (Defence Research and Development Canada, 2018): 1.
[6] Steve Stark, "WHY the HYPE?" *Army AL & T* (2019): 92.

supply chain system.[7] That is to say, that warehousing, distribution and inventory management techniques were not disrupted as a result of these subtractive manufacturing technique improvements.[8]

TechTarget, a company designed to keep technology executives apprised of emerging technological innovations, states that "a disruptive technology is one that displaces an established technology and shakes up the industry or a ground-breaking product that creates a completely new industry."[9] United Parcel Service (UPS), the world's largest package delivery company and a leading global provider of supply chain management[10] sees a world where "goods will be produced in lower quantities and more frequently, closer to the point of consumption."[11] UPS predicts that AM will disrupt their supply chain paradigm and threaten their ability to maintain a relevant and competitive business despite currently being the largest provider of the service in the world.[12] "To stay ahead of the curve, UPS partnered with enterprise software giant SAP and [an] additive manufacturer … to roll out industrial 3-D printers globally, starting with its Supply Chain Solutions facility."[13]

Similarly, Investopedia, a complex financial concepts publisher, states that a "disruptive technology significantly alters the way businesses or entire industries operate. It often forces companies to change the way they approach their business for fear of

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[7] Alan S. Brown, "Chain Reaction," *Mechanical Engineering-CIME* 140, no. 10 (2018): 34.
[8] *Ibid*., 30.
[9] TechTarget, "Disruptive Technology," Last accessed 2 April 2019. https://whatis.techtarget.com/definition/disruptive-technology
[10] United Parcel Service, "UPS Company History," Last accessed 2 April 2019. https://www.ups.com/ca/en/about.page?
[11] Alan S. Brown, "Chain Reaction," *Mechanical Engineering-CIME* 140, no. 10 (2018): 34.
[12] *Ibid*., 35.
[13] *Ibid*.

losing market share or becoming irrelevant."[14] Using this definition and the 53 billion-dollar corporation UPS as a case study, it is evident that AM is a disruptive technology.[15] UPS is altering how it operates its business by transitioning physical inventory into digital inventory and by introducing 3D printers into their network of warehouses. Instead of stocking a myriad of parts, they will maintain a database of CAD files and print the part on demand within the distribution network instead of procuring the part from a manufacturer and holding inventory based on a predicted need. UPS has been forced to adapt this model to prevent entrepreneurial competitors who are leveraging 3D printing from providing a more responsive and economic service than UPS.[16] Using TechTarget's definition of a disruptive technology, where an established technology is displaced by a new one, the UPS case study shows that 3D printing is an option that is replacing traditionally sourced and manufactured parts. The second part of TechTarget's definition states that a disruptive technology creates a new industry.[17] In the case of UPS, the new industry is on-demand-manufacturing within the supply chain distribution system with an added need to procure and protect designs.[18] Therefore, as evidenced in the UPS scenario, AM fulfills the concept of a disruptive technology as defined from both a technical and commerce perspective.

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[14] Investopedia, "Disruptive Technology," Last accessed 02 April 2019. https://www.investopedia.com/terms/d/disruptive-technology.asp

[15] Diffen, "FedEx vs. UPS," Last accessed 02 April 2019. https://www.diffen.com/difference/FedEx_vs_UPS

[16] Alan S. Brown, "Chain Reaction," *Mechanical Engineering-CIME* 140, no. 10 (2018): 35.

[17] TechTarget, "Disruptive Technology," Last accessed 2 April 2019. https://whatis.techtarget.com/definition/disruptive-technology

[18] Alan S. Brown, "Chain Reaction," *Mechanical Engineering-CIME* 140, no. 10 (2018): 34.

There are, however, counterarguments that AM is not a disruptive technology and it therefore does not merit special management considerations.[19] These arguments are based on the premise that AM will not completely displace subtractive manufacturing; an argument which is reasonable. There will continue to be a niche for subtractive manufacturing when it makes economical sense and in situations where it may not be viable to additively manufacture a part.[20] To counter this perspective, Sarah Goehrke, an industrialization of AM expert for Forbes, states that "We Need To Stop Equating Disruption With Displacement… Disruption is changing workflows -- but that doesn't have to mean reinventing the wheel."[21] Goehrke refutes the counterargument on two axioms. First is that a new technology does not need to completely displace another to have disruptive affects. Second, the counterargument is confounding *displace* and *replace*.[22] Taking into consideration the rebuttal that AM will not replace subtractive manufacturing, it is reasonable to assert that AM will displace some subtractive parts sources and have disruptive affects on the supply chain as manufacturing workflows shift to within the supply chain. Therefore, the supply chain paradigm must adapt to account for this eventuality.

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[19] Siavash H. Khajavi, Jan Holmström, and Jouni Partanen, "Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration and Technology Maturity," *Rapid Prototyping Journal* 24, no. 7 (2018): 1179.

[20] Michael Kidd, Angela Quinn, and Andres Munera, "Additive Manufacturing: Shaping the Sustainment Battlespace," *Joint Force Quarterly*: JFQ no. 91 (2018): 43.

[21] Sarah Goehrke, Forbes, "We Need To Stop Equating Disruption With Displacement: Where Additive Fits Into Manufacturing," Last accessed 2 April 2019, https://www.forbes.com/sites/sarahgoehrke/2018/11/27/we-need-to-stop-equating-disruption-with-displacement-where-additive-fits-into-manufacturing/#6eb3e050168d.

[22] *Ibid.*

LIMITATIONS

The Industrial Engineering Department of Aalto University in Finland, after its multiyear analysis of the *state-of-the-technology*, has consolidated the limitations of AM into seven categories. "These limitations are related to the software, availability of materials, production finish quality, production rate, production chamber size, repeatability of production and the cost of machines and material."[23] Similarly, the United States Defense Logistics Agency has developed nine criteria that must be met for it to be viable to additively manufacture individual parts. They propose the following limitations as a minimum: "material availability, material demand, backorders, technical data availability, type of 3D printer required, manufacturing lead times, unit cost, technical complexity and quality assurance requirements."[24] These two assessments, one from an academic engineering perspective, and the other from a military supply chain management perspective, are indicative of the perception across the AM field.[25]

The purpose of this paper is not to analyse these limitations in detail, rather it is to provide a synopsis in order to inform integration and implementation recommendations. The reasons for this are twofold. First, Defence Research and Development Canada (DRDC), in concert with Australia, New Zealand, the United Kingdom and the United States under the auspices of The Technical Cooperation Program (TTCP) has already

[23] Siavash H. Khajavi, Jan Holmström, and Jouni Partanen, "Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration and Technology Maturity," *Rapid Prototyping Journal* 24, no. 7 (2018): 1179.

[24] Michael Kidd, Angela Quinn, and Andres Munera, "Additive Manufacturing: Shaping the Sustainment Battlespace," *Joint Force Quarterly*: JFQ no. 91 (2018): 46.

[25] Siavash H. Khajavi, Jan Holmström, and Jouni Partanen, "Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration and Technology Maturity," *Rapid Prototyping Journal* 24, no. 7 (2018): 1179.

provided a detailed analysis of these limitations.[26] Second, as discovered by the Aalto University's Engineering Department, "The current body of knowledge regarding [AM] is highly focused on process, material and design research" with literature gaps in how to enterprise and implement the technology.[27] To present a synopsis of these accepted limitations, the following questions will be discussed: *Can the part be 3D printed? Is it necessary to 3D print? Is it viable to 3D print?*

Can the Part be Printed?

Parts are comprised of various materials such as metals and plastics and accordingly require both different print materials and different printers. Likewise, different parts have varying complexity and higher consequences upon part failure and appropriately require varying degrees *quality control and parts certification*. Another limiting factor seldomly focussed on is the legal implications. Specifically, the legal right to reproduce a copyrighted design or scan an existing part which is not the intellectual property of the CAF. The ability to print a part has both physical and intellectual ramifications requiring equipment, consumable stocks and competencies.[28] Applying these limitations to each part generates a list of parts that are possible to print. But does it make sense to print a part just because it is possible?

Is it Necessary to 3D Print?

3D printing's primary niche is the obsolete part realm, that is, when the part demand is no longer sufficient to warrant subtractively manufacturing large numbers of

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[26] A. Boukhtouta, et al, *Additive Manufacturing and Repair, Support & Distribution*. Scientific Report. DRDC-RDDC-2017-R164 (Defence Research and Development Canada, 2018): 4.

[27] Siavash H. Khajavi, Jan Holmström, and Jouni Partanen, "Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration and Technology Maturity," *Rapid Prototyping Journal* 24, no. 7 (2018): 1180.

[28] A. Boukhtouta, et al, *Additive Manufacturing and Repair, Support & Distribution*. Scientific Report. DRDC-RDDC-2017-R164 (Defence Research and Development Canada, 2018): 16.

the part or it is no longer profitable for original and aftermarket equipment manufacturers to make or maintain inventory of the part.[29] 3D printing's secondary niche is when the time to *get* the part is longer than the time to print the part at or close to the point-of-need, particularly when it is a critical part.[30] Essentially, 3D printing is necessary when the part is simply not available or a long delivery time results in the major-assembly not being serviceable to the detriment of the business or mission; such as AOG (aircraft on ground), VOR (vehicle off road) and OOR (Out of Routine).

Is it Viable to Print?

Viability is comprised of cost and whether the AM process results in mitigating the limitations of subtractive manufacturing. For example, once a part is 3D printed, there is often a need for finishing work and certifications. Each of these steps may be sufficiently complex to require a centralised point within the supply chain to complete due to both personnel and equipment requirements. If this is the case, it is possible that the advantages of 3D printing may be nullified by the technical process and delivery time.[31] On the cost side of viability, a business case for the part may yield that the resources required, most notably time and money, results in the 3D printing option being prohibitively expensive when weighed against the demand and impacts of not having the part.

The questions *Can the part be 3D printed? Is it necessary to 3D print*? and *Is it viable to 3D print?* yield several factors relevant to the integration and implementation of

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[29] Alan S. Brown, "Chain Reaction," *Mechanical Engineering-CIME* 140, no. 10 (2018): 32.

[30] Siavash H. Khajavi, Jan Holmström, and Jouni Partanen, "Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration and Technology Maturity," *Rapid Prototyping Journal* 24, no. 7 (2018): 1182.

[31] *Ibid.,* 1180.

AM within the CAF supply chain. Location of the printers and certification can either amplify the benefits of AM or nullify them. Personnel requirements go beyond the 3D printing and certification technicians to include designers, lawyers and inventory managers. Finally. the inventory management paradigm must shift to include both physical and digital parts which in turn affects procurement.

INTEGRATION AND IMPLEMENTATION

Aalto University's Engineering Department explicitly proposes three configurations to introduce AM into a supply chain based on distributed or concentrated characteristics and implicitly suggests that outsourcing can be leveraged to varying degrees to achieve the same affects.[32] In military terms, there are four implementation options; centralised, decentralised, outsourced and a blended option. The centralised option, in the CAF construct, would equate to each element (ie. Navy, Army, and Air) having an AM location based on the proximity to the highest point-of-demand. These few locations would have the whole AM capability onsite with the requisite competencies and materiel to satisfy each of the three questions; *Can the part be 3D printed? Is it necessary to 3D print*? and *Is it viable to 3D print?* On the other hand, the decentralised option would see multiple locations established on bases throughout Canada and missions abroad. The centralised method has the benefit of a lower start-up cost due to requiring less enabling-personnel (designers, lawyers, inventory management and business case personnel) and possibly less technician-personnel (equipment operators and certification personnel). Likewise, there is a potential to require less materiel such as the quantity of

[32] Siavash H. Khajavi, Jan Holmström, and Jouni Partanen, "Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration and Technology Maturity," *Rapid Prototyping Journal* 24, no. 7 (2018): 1186.

printers, finishing machinery, print material and certification equipment. However, if the capability is centralised at a few locations, the primary benefit, which is shortened delivery time for difficult to source parts, is not fully capitalised upon.[33] These concerns are addressed by the decentralised option at the expense of additional personnel and materiel.

Aalto's study of world leaders in AM concludes that a compromise is necessary to balance resource restraints with supply responsiveness constraints.[34] Aalto emphasises that

> the annual cost of equipment and personnel can severely affect the distributed production configuration in a negative way as the number of locations with AM installation outnumber the AM hub supply chain configuration. Therefore, any small cost reduction in AM equipment can benefit a distributed setting on a larger magnitude. For the AM hub supply chain configuration, the annualized cost of equipment is as important as it can be for a centralized configuration. The reason is that in a hub configuration, the number of AM machines can be minimized through a tight calibration of AM machine production capacity and hub size with regard to demand.[35]

Industry best practices point to a hub supply chain configuration with technical-personnel and materiel close to the point-of-need with the enabling-personnel centralised.[36] For highly complex parts and parts with higher consequences upon part failure, the part can either be manufactured at a single robust hub or outsourced.[37]

Lieutenant-Commander Kidd, a supply officer at the Defense Logistics Agency, emphasises the importance of the balance between centralised and decentralised options

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[33] Alan S. Brown, "Chain Reaction," *Mechanical Engineering-CIME* 140, no. 10 (2018): 32.

[34] Siavash H. Khajavi, Jan Holmström, and Jouni Partanen, "Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration and Technology Maturity," *Rapid Prototyping Journal* 24, no. 7 (2018): 1186.

[35] *Ibid.*

[36] Michael Kidd, Angela Quinn, and Andres Munera, "Additive Manufacturing: Shaping the Sustainment Battlespace," *Joint Force Quarterly*: JFQ no. 91 (2018): 44.

[37] Jason C. Gill, "A Feasibility Study of Additive Manufacturing for Rapid Prototyping at an Air Force Depot," ProQuest Dissertations Publishing, 2019: 110.

stating that "AM and the ability to create single- or small-batch runs of parts should be managed carefully to ensure that this technology is deployed as a force multiplier versus a niche program with limited readiness impacts."[38] The inference is that if AM is implemented at the wrong scale and at the wrong point within the supply chain, that the benefits will not be worth the investment. This argument shows that the implementation of the technology is as important as the capacity of the technology itself. Kidd has also realised that although niche applications are successful throughout industry and specific applications within the Department of Defense (DOD), that "they have not yet provided enterprise solutions."[39] Equally, the Defense Systems Information Analysis Center states that the "current DOD roadmap concentrates on technology development rather than enabling factors."[40] The Aalto University Industrial Engineering Department, the Defense Logistics Agency and the Defense Systems Information Analysis Center have each researched numerous sources and reached the conclusion that the issue with integrating AM into the supply chain is not the state-of-the-technology, rather, it is the ability of institutions to adapt their paradigms to fully exploit the benefits.

DRDC's AM Report describes technical advantages and disadvantages of leveraging AM and contains technical findings on materiel and personnel requirements. Australia, the United Kingdom and the United States have also contributed their implementation plans to the report.[41] Yet, as found by a USAF feasibility study, there is

> a continued employment of often obsolete methods of design and manufacture of parts persist[ing] despite mounting evidence of the efficiencies that can be

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[38] Michael Kidd, Angela Quinn, and Andres Munera, "Additive Manufacturing: Shaping the Sustainment Battlespace," *Joint Force Quarterly*: JFQ no. 91 (2018): 40.

[39] *Ibid*., 41.

[40] Defense Systems Information Analysis Center, "DOD Releases Additive Manufacturing Roadmap," Last accessed 2 April 2019, www.dsiac.org/resources/news/dodreleases-additive-manufacturing-roadmap.

[41] A. Boukhtouta, et al, *Additive Manufacturing and Repair, Support & Distribution*. Scientific Report. DRDC-RDDC-2017-R164 (Defence Research and Development Canada, 2018): 22.

> leveraged with the adoption of AM for design, prototyping, or manufacturing processes. In light of this persistence in the use of outmoded technologies, this study sought to discover a possible business, technical, or political case for the lack of adoption of AM technologies.[42]

Brigadier-General Stewart of the 2nd Marine Logistics Group states that the inefficient incorporation is due to the fact that "the organizational structure adopted is not aligned to the technologies on the immediate horizon."[43] Along this same line of thinking, the USAF's feasibility study found that of all the limitations associated with AM, one of the greatest hindrances to capitalising on its integration was an "inability to describe a business or use case sufficient to convince leaders to commit to AM adoption"[44] because it is not instinctively incorporated into current processes in a way that proves significant benefit. This same study asserts that "an organization's ability to adopt a new or disruptive method or technology"[45] is more than simply *adding a tool to the box*. The study concludes that the main reason AM has not been fully realised within the USAF is not the maturity of the technology, rather it is the institutional capacity and framework to embrace it.[46]

Although the USAF study corroborates that AM is a disruptive technology that requires special consideration to incorporate into a supply chain, it takes a different point-of-view on the options available to overcome the limitations from that of the mainstream solutions. The first option is essentially to wait for the industry to mature and then adopt best practices in a single transformation.[47] Although this is certainly an easy option, it

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[42] Jason C. Gill, "A Feasibility Study of Additive Manufacturing for Rapid Prototyping at an Air Force Depot," ProQuest Dissertations Publishing, 2019: 102.
[43] Kevin J. Stewart, "Future Logistics Challenges," *Marine Corps Gazette* 102, no. 12 (2018): 56.
[44] Jason C. Gill, "A Feasibility Study of Additive Manufacturing for Rapid Prototyping at an Air Force Depot," ProQuest Dissertations Publishing, 2019: 104.
[45] *Ibid.,* 106.
[46] *Ibid.,* 115.
[47] *Ibid.,* 110.

risks falling behind the curve in a defense industry and does not address the fact the transformation or adaptation will still be complicated for the military in the future. The second option proposed is that "the organization can hire talent that fills the knowledge gaps required to leverage AM."[48] This option requires the hired talent to provide insight on how best to adjust the supply chain paradigm. This option, however, would still require a decision to be made on whether to centralise, decentralise or implement the hub-configuration. The third option proposed is that "the organization can outsource the requirements and requisite risks to other parties… but with those go the benefits of developing talent and new capabilities."[49] Each option has benefits and risks, but each option does not need be exclusive. Much like the blending of the centralised, decentralised and outsourced options to create the hub-configuration option as identified by Aalto's engineering department, a blended option of *adopt now* or *wait* can be made to leverage the strengths of one option and mitigate the risks of the other.

The USAF study's *adopt now* option can be blended by introducing a proof-of-concept which is then gradually expanded throughout the supply chain embracing best practices as they are identified. Currently, the DOD has conducted localised proofs-of-concept by deploying AM capabilities, but there has been little return on investment to date because it has been introduced as a new technology and not a disruptive technology.[50] A true proof-of-concept needs to acknowledge the nuances by integrating AM and not just inserting a capability. For this to happen, the ability to additively manufacture needs to be considered during materiel procurement and personnel training

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[48] *Ibid.*

[49] *Ibid.,* 110.

[50] Michael Kidd, Angela Quinn, and Andres Munera, "Additive Manufacturing: Shaping the Sustainment Battlespace," *Joint Force Quarterly*: JFQ no. 91 (2018): 41.

and incorporated into the Defence Resource Management Information System (DRMIS). Brigadier-General Stewart emphasises the significance of information technologies to enable a military to fully benefit from modern technologies.[51] For the CAF, DRMIS can be the system of record to enable satisfying each of the three questions; *Can the part be 3D printed? Is it necessary to 3D print*? and *Is it viable to 3D print?* Once the answers to these questions have been determined by enabling-personnel, technical-personnel can access this information if it is readily available CAF wide… DRMIS. Supply chain and maintenance personnel are dependant on resource management software while AM is also dependant on information from a CAD file and copyright perspective. Recognising that the supply chain must manage a digital inventory to implement AM is a fundamental shift that is necessary to expand the AM proof-of-concept. With this challenge being addressed, the hub-configuration option can be trialed either in Canada for difficult to source parts at a central location or abroad at an operational support hub where delivery timelines cause serviceability delays. As the CAF embraces AM and the technology matures, the CAF's AM capacity can be expanded upon as long as the three questions have been satisfied and the information is accessible, allowing for the CAF's equipment management and supply management systems to fully leverage AM.

Each of the referenced studies acknowledges the possible benefits of incorporating AM while recognizing its characteristics as a disruptive technology. In cross-examining AM with the disruptive technology concept, it is evident that AM is a maturing technology that will disrupt supply chain operations, requiring the CAF to integrate the technology and not simply insert a capability if it wants to fully benefit from its

[51] Kevin J. Stewart, "Future Logistics Challenges," *Marine Corps Gazette* 102, no. 12 (2018): 57.

implementation. Consequences of disruptive technologies, along with industry-acknowledged limitations of AM dictate a wholistic approach to incorporate AM including information and inventory management systems, technical-personnel, enabling-personnel and materiel. This wholistic approach is best served through an institutional proof-of-concept using the hub-configuration model from which best practices can be used to inform the expansion of the capability on a wider scale.

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