2024-06

A WAVE OF INNOVATION: ASSESSING ADDITIVE MANUFACTURING AS A STRATEGIC INITIATIVE FOR THE BRAZILIAN NAVY'S DEFENSE LOGISTICS

do Nascimento da Silva, Diego

Monterey, CA; Naval Postgraduate School

https://hdl.handle.net/10945/73104

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

A WAVE OF INNOVATION: ASSESSING ADDITIVE MANUFACTURING AS A STRATEGIC INITIATIVE FOR THE BRAZILIAN NAVY'S DEFENSE LOGISTICS

by

Diego do Nascimento da Silva

June 2024

Thesis Advisor: Geraldo Ferrer
Co-Advisor: Kristen Tsolis

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704–0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2024	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE A WAVE OF INNOVATION: ASSESSING ADDITIVE MANUFACTURING AS A STRATEGIC INITIATIVE FOR THE BRAZILIAN NAVY'S DEFENSE LOGISTICS	**5. FUNDING NUMBERS**
6. AUTHOR(S) Diego do Nascimento da Silva	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Distribution Statement A. Approved for public release: Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This research evaluates the feasibility and potential impact of adopting additive manufacturing (AM) as a strategic initiative to improve defense logistics in the Brazilian Navy (BN). Sustaining operational readiness across Brazil's vast Blue Amazon maritime jurisdiction is strained by conventional supply chains struggling to deliver spare parts promptly to remote regions like the Amazon Basin and Antarctica. Through a qualitative case study approach analyzing literature, Brazilian naval doctrine, AM trends, and logistics contexts, the research synthesizes findings on AM's feasibility, benefits, requirements, risks, and limitations for enabling responsive on-demand parts production. Analysis reveals that AM enables simplified fabrication of customized components, reducing lead times and inventory while enhancing supply flexibility and contingency capacity. However, AM integration risks exist, due to immaturity across quality, materials, scale, cybersecurity, and workforce capabilities. A phased AM adoption roadmap is proposed, focused on infrastructure development, operational validation, digital integration, and governance to methodically realize potential benefits while controlling implementation hazards. Selective naval AM deployment supplementing conventional manufacturing is recommended, pending further cost-benefit analysis, cybersecurity assessments, maintenance studies, and performance characterization to align with modernization.

14. SUBJECT TERMS 3D printing, additive manufacturing, AM, Blue Amazon, Brazilian Navy, innovation adoption, naval logistics, readiness, roadmap, spare parts, supply chain	**15. NUMBER OF PAGES** 85
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500 Standard Form 298 (Rev. 2–89) Prescribed by ANSI Std. 239–18

THIS PAGE INTENTIONALLY LEFT BLANK

Distribution Statement A. Approved for public release: Distribution is unlimited.

A WAVE OF INNOVATION:
ASSESSING ADDITIVE MANUFACTURING AS A STRATEGIC INITIATIVE FOR THE BRAZILIAN NAVY'S DEFENSE LOGISTICS

Diego do Nascimento da Silva
Capitão de Corveta, Brazilian Navy
BNS, Brazilian Naval Academy, 2012
MBA, Universidade Potiguar (UnP), 2015
DPA, Universidade Federal do Rio de Janeiro (UFRJ), 2017

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN DEFENSE LOGISTICS MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
June 2024

Approved by: Geraldo Ferrer
Advisor

Kristen Tsolis
Co-Advisor

Harrison C. Schramm
Academic Associate, Department of Defense Management

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This research evaluates the feasibility and potential impact of adopting additive manufacturing (AM) as a strategic initiative to improve defense logistics in the Brazilian Navy (BN). Sustaining operational readiness across Brazil's vast Blue Amazon maritime jurisdiction is strained by conventional supply chains struggling to deliver spare parts promptly to remote regions like the Amazon Basin and Antarctica. Through a qualitative case study approach analyzing literature, Brazilian naval doctrine, AM trends, and logistics contexts, the research synthesizes findings on AM's feasibility, benefits, requirements, risks, and limitations for enabling responsive on-demand parts production. Analysis reveals that AM enables simplified fabrication of customized components, reducing lead times and inventory while enhancing supply flexibility and contingency capacity. However, AM integration risks exist, due to immaturity across quality, materials, scale, cybersecurity, and workforce capabilities. A phased AM adoption roadmap is proposed, focused on infrastructure development, operational validation, digital integration, and governance to methodically realize potential benefits while controlling implementation hazards. Selective naval AM deployment supplementing conventional manufacturing is recommended, pending further cost-benefit analysis, cybersecurity assessments, maintenance studies, and performance characterization to align with modernization.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
ASTM	American Society for Testing and Materials
ASTRO	Applied Science & Technology Research Organization
BN	Brazilian Navy
CAD	computer-aided design
CDLP	continuous direct light processing
CF	Constituição Federal Brasileira (Brazilian Federal Constitution)
CLIP	continuous liquid interface production
DED	directed energy deposition
DED-arc	directed energy deposition-arc
DEVCOM	U.S. Army Combat Capabilities Development Command
DGN	Diretoria-Geral de Navegação da Marinha (Brazilian Navy's General Directorate of Navigation)
DLP	direct light processing
DMLS	direct metal laser sintering
DOD	drop-on-demand
EBAM	electron beam additive manufacturing
EBM	electron beam melting
EACF	Estação Antártica Comandante Ferraz (Comandante Ferraz Antarctic Station)
FDM	fused deposition modeling
FFF	fused filament fabrication
GDP	gross domestic product
IAEA	International Atomic Energy Agency
IP	intellectual property
ISO	International Organization for Standardization

JDMC	Joint Defense Manufacturing Council
LENS	laser engineered net shaping
LOM	laminated object manufacturing
NAsH	Navio de Assistência Hospitalar (Hospital Assistance Ships)
NSF	U.S. National Science Foundation
NPJ	nano particle jetting
NPS	Naval Postgraduate School
OPERANTAR	Operação Antártica (Operation Antarctica)
PBF	powder bed fusion
PETG	polyethylene terephthalate glycol-modified
PLA	polylactic acid
PMBOK®	Project Management Body of Knowledge
PPE	personal protective equipment
PROANTAR	Programa Antártico Brasileiro (Brazilian Antarctic Program)
ROI	return on investment
SLA	stereolithography
SLM	selective laser melting
SLS	selective laser sintering
STL	Standard Tessellation Language

ACKNOWLEDGMENTS

My deepest gratitude to those responsible for making my dream come true:

To God, for blessing us greatly and taking care of us in every detail throughout our journey in the United States.

To my beloved wife, Ayda, for her love, patience, and endless care. This achievement would not have been possible without your continuous support and words of encouragement. If it hadn't been for you, I wouldn't have had the strength and courage to volunteer to study at NPS. I love you deeply. Thank you for dreaming this dream together. With you, I feel that all things are possible … this thesis is proof.

To my parents, Jorge and Lígia, my sister, Juliana, and my nephew, Guilherme, for their unconditional love, prayers, and support, even at a distance. Since before I joined the Brazilian Navy, you have always trusted me, cheered me on, and done everything you could to help me achieve great things in my career and life. Who would have thought that I could have come so far? Well, you certainly would!

Lastly, I would especially like to thank my advisor, Professor Geraldo Ferrer, and co-advisor, Professor Kristen Tsolis, for their invaluable support throughout my research. Their exceptional knowledge, unwavering commitment, and precise guidance have significantly enhanced the quality of my work, and I was able to overcome obstacles and achieve a result of which I am genuinely proud.

Never give up on what you really want to do. The person with big dreams is more powerful than one with all the facts.

—*H. Jackson Brown Jr., Life's Little Instruction Book*

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

The Brazilian Navy (BN) faces logistical challenges sustaining the readiness and capability of vessels conducting critical missions across Brazil's vast maritime jurisdiction. Operations in remote domains like the Amazon Basin and Antarctica have revealed vulnerabilities in conventional supply models reliant on centralized, forecast-driven warehousing and distribution. Unpredictable breakdowns and spare parts delays degrade fleet combat resilience, undermine maritime patrols, and risk interruptions to riverside population assistance. As the importance of operational logistics intensifies, strategic initiatives enabling responsive on-demand manufacturing warrant consideration.

Additive manufacturing (AM), also known as three-dimensional (3D) printing, appears well-suited to mitigate naval supply risks by enhancing the agility, resilience, and self-sufficiency of military logistics. This research seeks to answer this question: What is the feasibility and potential impact of adopting AM as a strategic initiative to improve defense logistics in the BN?

To evaluate this issue systematically, the following subsidiary lines of inquiry guide the investigation:

1. What AM technologies and applications are relevant for naval spare parts supply?
2. What infrastructure, systems, and process changes are required to enable AM adoption?
3. What are the risks and limitations associated with AM adoption?
4. How can the BN strategically implement AM to improve naval logistics?

The research methodology adopts a qualitative case study approach utilizing comprehensive literature analysis, a review of Brazilian naval doctrine, an examination of AM adoption trends, and an evaluation of logistics operations contexts.

The study examines potential BN applications. The analysis will not encompass detailed technological aspects, such as AM-printed parts' physicochemical properties and performance characteristics, because that would require specialized materials engineering expertise. Additionally, the research does not include a Return on Investment (ROI) or cost-benefit analysis, as the goal is to provide an informed starting point to assist the BN leadership in evaluating AM's operational benefits and limitations for enabling resilient and responsive supply chains. Finally, cybersecurity and intellectual property (IP) considerations will be only briefly touched upon because the emphasis is on supply chain logistics rather than information security or legal issues. Areas for future research will be identified and highlighted among these subjects.

Research limitations include the scarcity of existing academic work and data on the costs of adopting AM, the difficulty in assessing the impacts of AM integration on the reliability of naval military platforms and quantifying the potential benefits of AM for these platforms. Additionally, Brazil's official policies and implementation guidelines regarding AM are still in the early development stages.

Following this introduction, Chapter II reviews relevant background on Brazilian naval priorities, operating environments, and logistical challenges. Chapter III analyzes the literature on AM advancement and applications in defense logistics. Chapter IV assesses the feasibility, infrastructure and process requirements, risks, limitations, and strategic implementation opportunities of adopting AM for naval spare parts supply. Chapter V proposes an AM capability development roadmap to guide the BN in harnessing AM benefits through a deliberate, phased process that manages risks and that is aligned with modernization. Finally, Chapter VI provides a summary of the key findings and identifies areas for future research.

II. BACKGROUND

This chapter establishes the need for efficient military logistics to enable the operational readiness of the BN throughout the country's sovereign maritime domain and in its subsidiary activities while presenting opportunities for adopting AM as a strategic logistics initiative.

The chapter outlines the Brazilian Navy's institutional priorities per the Federal Constitution, complementary law, military doctrine, and the vision of the 2040 Brazilian Navy Strategic Plan to equip a modern naval force to defend national sovereignty and interests. It introduces the Blue Amazon concept, underscoring the geostrategic, economic, and environmental significance of Brazil's extensive maritime jurisdiction. Moreover, it presents some challenges in sustaining operations in Antarctica and the Amazon, where climate extremes, lack of infrastructure, and vast distances strain conventional logistics capabilities. As Brazil asserts sovereignty through naval missions spanning critical domains, AM may enable an increase in the operational readiness level where conventional supply chains present points of inefficiency.

The BN's mission, established in 2016 based on article 142 of the Brazilian Federal Constitution (CF) (1988) and Complementary Law no. 97/99 (Lei Complementar, 1999), is "to prepare and employ Naval Power, to contribute to the Defense of the Homeland; to guarantee the constitutional powers and, on the initiative of any of them, the law and order; to fulfill the ancillary attributions provided for by law; and to support Foreign Policy."[1] Additionally, the Future Vision of the Navy, according to the *Strategic Plan of the Navy 2040* (Marinha do Brasil, 2017), is to be "a modern, equipped and motivated Force, with a high degree of technological independence, of a size compatible with Brazil's political-strategic stature in the international scenario, capable of contributing to the defense of the Homeland and safeguarding national interests, at sea and in inland waters, in tune with society's aspirations" (p. 51).

1 This thesis contains material that was originally written in the Portuguese language. Throughout the thesis, translation into English was performed by the author as needed.

According to the Brazilian Naval Military Doctrine (EMA, 2017), operational readiness is "the capacity of the Armed Forces to respond promptly to situations that may occur in a combat environment" (p. 2–8). The Brazilian Navy Standards for Supply Execution (SGM, 2020) adds that this capacity is strongly linked to the development and operation of an adequate Logistics Support System. Thus, the Brazilian Navy's Supply System aims to be ready to meet the demands of combat forces, both in peacetime and wartime, with efficient logistical operations to guarantee the highest level of operational readiness.

A. THE BLUE AMAZON

The Blue Amazon is a crucial national priority for Brazil with significant geopolitical, socioeconomic, and environmental importance. The BN introduced the term in 2004 to raise public awareness of the importance of the vast maritime areas under Brazilian jurisdiction, rich in biodiversity and natural resources, and with significant environmental value. However, it is as vulnerable as the Amazon rainforest, also known as the "Green Amazon," whose importance is widely recognized by Brazilian society and the whole world.

When the term was first used, the idea was to value, preserve, sustainably use, and protect Brazilian jurisdictional waters, which cover 5.7 million square kilometers (2.2 million square miles), where more than 95% of the country's oil is produced, 85% of natural gas, and 95% of foreign trade takes place, thus supporting more than 20 million jobs (Agência Marinha de Notícias, 2023).

According to the Brazilian Navy's General Directorate of Navigation (DGN), the ocean's current contribution to the national economy already exceeds R$1.74 trillion (US$ 350 billion), corresponding to 19% of the 2022 Gross Domestic Product (GDP). Similarly, approximately 45% of the fish consumed in the country comes from the sea, and submarine cables that transmit more than 95% of internet data are installed on the Brazilian continental shelf. In addition, the marine subsoil has extensive reserves of polymetallic nodules that can be exploited sustainably (Agência Marinha de Notícias, 2023). Fernandes and de Souza (2022) argue that as the utilization of Brazilian waterways increases, so does the perceived value of the Blue Amazon. Consequently, they emphasize the necessity of comprehending the potential threats that could jeopardize the continued exploitation of these aquatic resources to effectively manage all assets within Brazilian jurisdictional waters.

Among the potential threats to Brazil's sovereignty and national security is illegal fishing by foreign vessels, which could deprive Brazil of important natural resources and tax revenues. Maritime drug trafficking also poses major challenges, as criminal groups try to use Brazilian waters to transport narcotics. Piracy and terrorist threats cannot be ruled out, given the strategic location along international maritime routes. Other potential threats include illegal arms trafficking, human trafficking, smuggling, and maritime accidents such as oil spills. A comprehensive strategy is essential to protect the Blue Amazon and its contributions to Brazil's economy, food security, and global trade.

As a result, ensuring the protection of the Blue Amazon emerges as an imperative task for Brazil to uphold its sovereignty and maintain absolute control. For the BN to fulfill its mission and achieve its vision based on its institutional values, it is necessary to rely on a high level of operational readiness to act in a deterrent manner or as an instrument of action during patrols, defending the Brazilian jurisdictional waters from threats to national sovereignty.

B. LOGISTIC DIFFICULTIES IN THE AMAZON REGION'S RIVERS

The logistical challenges faced by ships navigating the Amazon region are significant, given the area's environmental, climatic, and infrastructure factors. As revealed by Trompowsky (2023), regardless of the size of the vessel, all suffer restrictions on cargo capacity when the levels of the Amazon River fall below 14 meters in depth during drought periods. He further notes that navigation risks increase considerably for depths less than 9.5 meters, impacting maneuverability and ship performance.

The ships operating in the region also need to deal with the effects of climate phenomena such as El Niño, which has contributed to the early onset and worsening of drought periods in the Amazon region. In 2023, the beginning of the drought already showed warning signs in September, two months earlier than usual (Trompowsky, 2023).

The BN operates Hospital Assistance Ships (NAsH), also known as “Ships of Hope,” that provide medical and dental care to remote communities along the Amazon rivers. However, keeping these ships in service is a major logistical challenge due to the difficulty in supplying spare parts. The ships operate far from seaports and naval repair facilities, with poor transportation infrastructure making it challenging to deliver spare parts quickly. Resupply from coastal naval depots takes days or even weeks, and local sourcing of spare parts is nearly impossible due to the lack of manufacturing capabilities in remote regions.

To maintain operational readiness, the NAsHs must carry considerable spare parts inventories and try to forecast their needs between infrequent big port calls. However, unpredictable breakdowns still occur, risking lengthy assistance service interruptions while waiting for spare parts delivery.

“U16 Doutor Montenegro” (Figure 1) is one of the NAsHs that aids the needy riverside populations of the Amazon region.

Figure 1. U16 Doutor Montenegro supporting the riverside population on the Amazon. Source: Marinha do Brasil (2019).

The vastness of these regions is one of the main obstacles faced by the NAsHs since the riverside communities are spread over a large geographical area. In addition, the difficulty of access hinders the work of these ships since many riverside communities can only be reached via rivers and streams, representing a logistical challenge for the militaries and health professionals (Júnior & Curto, 2020).

Kadri et al. (2019) highlight that transporting and storing temperature-sensitive medical supplies can be a significant challenge due to the hot, humid conditions and the need for steady electricity access on ships that operate for weeks or months between resupply stops. The storage space on these ships is limited, which means that rationing fuel and water is necessary. The authors state that proper waste disposal is challenging, as options are limited onboard and ashore, which could contribute to pollution and disease transmission if not correctly managed. They also emphasize that internet connectivity is non-existent or very limited in remote areas, restricting telemedicine options and transmitting service data until the vessel returns to municipal headquarters.

Investing in regional warehousing capabilities, transportation infrastructure, and timely and efficient resupply mechanisms is necessary to minimize operational disruptions and uphold high readiness across the naval fleet. Addressing these logistical limitations can help expand vital assistance to underserved populations across the Amazon region.

C. LOGISTICAL CONSTRAINTS IN THE ANTARCTIC ENVIRONMENT

Antarctica plays a vital role in global climate systems and ocean currents that impact the entire planet. The frozen continent is Earth's most tremendous single ice reservoir, containing 90% of the planet's freshwater supply. At about 5.4 million square miles, Antarctica is also the fifth largest continent. Changes occurring there significantly influence sea levels, weather patterns, ocean circulations, and ecosystems worldwide (Kennicutt et al., 2019).

Recent insights underscore that Antarctica is fundamental to understanding humanity's future. Melting land ice could cause sea levels to rise 200 feet over centuries, submerging major coastal cities and infrastructures globally (DeConto & Pollard, 2016; Golledge et al., 2015). Emerging evidence also shows Antarctica plays a crucial role in regulating atmospheric carbon dioxide and mitigating the pace of climate change impacts (Rintoul et al., 2018; Kennicutt et al., 2019).

1. The Importance of Antarctica for Brazil

Antarctica's role in influencing global climate, ocean currents, and ecological systems gives the frozen continent heightened significance for Brazil's scientific community and policymakers. Situated in the Southern Hemisphere, not distal to Antarctica, Brazil experiences impacts from the related atmospheric and marine processes. Studying the phenomena occurring in Antarctica allows greater comprehension of the effects on Brazilian territory—critical knowledge for agriculture, fishing, disaster planning, and other national priorities. In addition to pursuing research for practical applications, Antarctica's remote and untouched setting provides a unique natural laboratory for interdisciplinary testing. The continent may contain exploitable mineral and energy resources for the future (Marinha do Brasil, 2020).

Geopolitically, establishing a presence in Antarctica allows cooperation and soft power projection on this global commons for Brazil as an emerging economy. Moreover, significant investment sustains Brazil's Antarctic Program not solely for practical impacts but because the remote icy laboratory drives innovation and supports global environmental stewardship (Marinha do Brasil, 2020).

2. Brief History of OPERANTAR

After acceding to the Antarctic Treaty in 1975 alongside the founding consultative nations, Brazil laid the groundwork for participating in scientific activities on the frozen continent. The 1980s saw the creation of the Brazilian Antarctic Program (PROANTAR) to systematize policy and practical efforts for reaping the benefits of Antarctic knowledge while protecting the fragile polar environment. PROANTAR plans and executes the annual Operation Antarctica (OPERANTAR), which oversees the movement of Brazilian ships and aircraft in support of seasonal scientific expeditions as well as the permanent base: the Comandante Ferraz Antarctic Station (EACF) (Marinha do Brasil, 2020).

The activities encompass the practical logistics of transporting personnel and materials over long distances and the coordination with governmental and research institutions collaborating on the Antarctic missions. Over 30 successful years, OPERANTAR has become a highlight for the Brazilian Navy, Air Force, and scientists developing institutional expertise for the harsh conditions.

3. Comandante Ferraz Antarctic Station

Opened in 1984, Brazil's station, occupying a peninsula on King George Island in the South Shetlands, allows for year-round habitation. Built modularly from shipping containers, it served for decades as an advanced base to study regional climate, glaciers, geosciences, biology, and other topics while connecting Brazilian researchers to international cooperation networks.

The clustered modules provided accommodation, storage, vehicle garages, laboratories, and infrastructure for operations, power, water treatment, and communications. The EACF underwent reconstruction in 2020, increasing its capacity to 4,500 sq meters. The facility now boasts a modern and functional design that meets strict environmental standards, making it an avant-garde structure that can set an example for sustainable architecture in Antarctica (Marinha do Brasil, 2020).

4. The Role of the Ships Almirante Maximiano and Ary Rongel

The maritime backbone for OPERANTAR's success in connecting Brazil with Antarctica is the Navy ships Almirante Maximiano and Ary Rongel. Their robust polar capabilities provide access and flexibility by leveraging the brief summer activity window. Since Antarctica has no permanent ports or airfields, these vessels furnish the fundamental logistics bridge between Brazil and remote field locations like Brazil's station.

According to Marinha do Brasil (2020), the oceanographic support ship Ary Rongel (Figure 2) takes charge of bulk transport duties, ferrying vital fuel and supplies required to sustain the EACF station through the long winter isolation. Spacious cargo holds carry everything from food staples to spare parts, maintaining critical systems operations for several months without any aerial resupply. The polar ship Almirante Maximiano

(Figure 3) plays a more active role in fostering Brazil's Antarctic science agenda by operating as a floating laboratory platform to deploy and retrieve scientists along the peninsula coastline. Teams use the ship as a staging base for expeditions onto land or ice caps while launching small boats or helicopters to access spots the vessel cannot approach.

As a workhorse fuel tanker, the Ary Rongel's 1-million-liter diesel tanks support electricity, heating, and transport needs for the remote EACF. The vessel's two 6-cylinder Krupp-Mak main engines, bow, and stern thrusters provide 4,500 horsepower. This translates into speeds of 14 knots, allowing the crew to navigate through packed ice fields and deliver critical supplies to the skeleton winter crew, who must survive months of total darkness (Marinha do Brasil, 2020).

Figure 2. Ary Rongel in an ice field. Source: Marinha do Brasil (2020).

The polar ship deploys two onboard helicopters, small boats, and scientists across the peninsula. At the same time, its enlarged hangar and five specialty laboratories support studying glaciers and collecting geophysical, biological, and climatic observations otherwise impossible without this mobile base sustaining exploration teams in the harsh environment (Marinha do Brasil, 2020).

Figure 3. Almirante Maximiano during research support. Source: Marinha do Brasil (2020).

5. OPERANTAR Logistical Challenges

Navigating Antarctica poses severe logistical difficulties stemming from its extreme remoteness and climate. Maritime access depends on a brief summer window from November to April when pack ice marginally recedes before encircling waters refreeze into impassable terrain (Marinha do Brasil, 2020). This isolates Brazil's base for the long dark winter, heavily reliant on risky C-130 Hercules airlifts operating at the edge given unpredictable polar weather (Figures 4 and 5). Antarctica's infrastructure is limited, and transportation of fuel, supplies, and equipment from South America over thousands of kilometers only adds to the strain. This situation is made even more difficult by environmental protections and the lack of emergency backup for self-sufficient operations. (Bender & Goulait, 2016; U.S National Science Foundation [NSF], 2023).

Figure 4. The moment the cargo is released. Source: Marinha do Brasil (2020).

Figure 5. Brazilian military personnel from the base group collecting the launched cargo. Source: Marinha do Brasil (2020).

The challenges include long lead times working around minimal transportation options, stringent customs bureaucracy through Chilean staging points, narrow delivery windows, and restricted cargo volumes—any single breakdown threatening the Antarctic mission's integrity (NSF, 2023).

A comprehensive approach to effective logistics planning is required to address these challenges, considering all the variables involved in transporting materials to and from Antarctica. This includes selecting transportation modes, contingency planning for unexpected events, and close collaboration with logistics providers and customs agencies.

Regardless, Brazil's Navy and Air Force have persisted for three decades through adversity and delays cultivating specialized polar prowess.

D. CONCLUSION

Brazil's Blue Amazon domain highlights the geostrategic importance of maritime territories, requiring naval forces ready to uphold sovereignty across vast distances. However, the remote and extreme conditions posed by specific operating environments strain conventional logistics capabilities.

The naval challenges supplying Hospital Assistance Ships along the Amazonian rivers and the EACF and polar ships in Antarctica demonstrate vulnerabilities in sustaining fleet readiness at the far reaches of Brazil's jurisdiction. These regions present distinct difficulties regarding the timely delivery of fuel, spare parts, and vital cargo. Limited warehousing, deficient infrastructure, extensive transit routes, narrow activity windows, and harsh climates accumulate to restrict conventional supply lines for vessels deployed for months from central logistics nodes. Unpredictable breakdowns force ships to carry excessive inventories, constraining capacity. Delays in obtaining spare parts directly threaten readiness.

As maintaining readiness emerges as an institutional priority, evaluating strategic initiatives to increase logistics agility and resilience for ships deployed far from robust supply lines is prudent. Additive manufacturing has shown promising potential to enhance responsiveness and self-sufficiency by enabling digital on-demand production near points of use. Nevertheless, assessing operational viability requires further analysis of capability tradeoffs and data from naval contexts. The next chapter will review AM technology maturity along with developments in defense and naval logistics applications to gauge strategic suitability. Examining these case studies and academic literature can help determine whether AM adoption could address some current naval logistics limitations and consequently improve the logistics efficiency of the BN.

III. LITERATURE REVIEW

A. INTRODUCTION

According to the Joint Defense Manufacturing Council (2021), "Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a process of joining materials to make parts from 3D model data, usually layer by layer. AM creates the part and material at the same time" (p. 4).

AM has developed rapidly since the 1980s, beginning with polymers for prototyping uses (Cordle et al., 2022). Now, AM encompasses a range of methods, from material extrusion to powder bed fusion for an expanding array of polymers, composites, ceramics, and metals (Praneeth et al., 2023). Applications have grown beyond rapid prototypes to end-use parts as system sizes, materials, accuracy, and repeatability have improved significantly (Höller et al., 2022). By 2030, the global AM market is projected to exceed $75 billion with over 20% annual growth. (Holmes, 2023).

Industry leaders and defense organizations recognize AM's advantages in complexity, customization, distributed production, sustainability, and supply chain consolidation (Holmes, 2023; Javaid et al., 2021; Mohr & Khan, 2015). AM disrupts conventions in design, manufacturing, logistics, and business models. It enables innovative lightweight structures, rapid repairs, decentralized spare part fabrication, and on-demand production while simplifying warehousing, assembly, and tooling (JDMC, 2021; Öberg & Shams, 2019). Though still maturing, multi-material AM capabilities are advancing from the lab toward industrial-scale platforms—unlocking novel functional integration opportunities (Höller et al., 2022).

Furthermore, AM facilitates significant reductions in development cycles, lead times, and inventories while increasing flexibility, productivity, and service levels (Félix, 2017; Rinaldi et al., 2021). This unique combination earns AM appellations as the "next industrial revolution" that will soon become integral across supply chains (Deshmukh et al., 2022; Höller et al., 2022). However, organizations must address upfront capability investment requirements, workflow integration, consistency improvements, and IP protection to navigate AM's rapid ascent (De Brito et al., 2021). Understanding AM's transformative potential, the following review outlines its evolution, applications in logistics and defense, and strategic promise for naval supply chain resilience.

B. EVOLUTION OF ADDITIVE MANUFACTURING TECHNOLOGY

Cordle et al. (2022) explain that the origins of AM technology can be traced to Japan in 1981, when Dr. Hideo Kodama published some of the earliest accounts of using photopolymers, ultraviolet light, and layer-based fabrication to produce solid objects—the process we now know as "stereolithography." That same year, according to Cordle et al., three French engineers patented stereolithography principles for photo-induced polymerization. The same authors write that in 1984, Charles "Chuck" Hull coined the term "stereolithography" and filed foundational patents, including a patent for the invention of the ".STL" file format. According to Cordle et al., this precipitated the 1987 launch of the first commercial 3D printing system, the SLA-1, by Hull's new startup company, 3D Systems, Inc.

Initially, AM methods were restricted to polymers and slower build processes aimed at concept modeling and prototyping applications rather than end-use parts. However, over decades of technological improvements, AM has expanded across industry sectors as speeds increased 100-fold, multi-material capabilities emerged, and fused metal methods achieved finer resolution, superior mechanical properties, and larger calibrated build volumes (Dow, 2022). Key patent expirations have underpinned market growth, spurring competition and accessibility by lowering printer costs (Johnston et al., 2018).

Currently, AM encompasses seven international standard categories with distinct material and binding mechanisms suited to metals, polymers, ceramics, or composites (Chiujdea & Cănănău, 2021). Though frequently associated with plastics, metal AM methods are advancing rapidly from single-laser research platforms towards industrial-scale production of end-use components for aerospace turbines and automotive applications based on enhanced understanding of powder microstructures, thermal deformations, and alloy-specific print processing requirements (Blachowicz et al., 2023).

The seven international standard categories of printers for AM are classified based on the process type, material type, and energy source. The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) define the types of technology processes used today in the ISO/ASTM 52900:2021:

1. **Sheet Lamination**: This process involves fusing or laminating layers of plastic or paper together using heat and pressure. These layers can then be cut into the desired shape with a computer-controlled laser or blade. This category includes Laminated Object Manufacturing (LOM).
2. **Directed Energy Deposition (DED)**: This process involves melting powder material as it is deposited. DED mainly uses metal in the form of powders or wire. Two key technologies are in this category: Laser Engineered Net Shaping (LENS) and Electron Beam Additive Manufacturing (EBAM). The difference between the two is the heat source used to melt the material. LENS uses a laser head, while EBAM uses an electron beam.
3. **Material Extrusion**: This process involves melting a plastic filament and depositing it layer by layer to create the final object. This is the most common type of 3D printers. This category includes Fused Deposition Modeling (FDM, which is trademarked) and Fused Filament Fabrication (FFF, which is not trademarked). FDM and FFF use strings of solid thermoplastic material, which are pushed through a heated nozzle that melts the material. The printer then moves the nozzle, extruding the material at precise locations. Simultaneously, another nozzle extrudes a dissolvable secondary material to support the part as it cools, which may be necessary in cases where the model has suspended areas that could collapse without adequate support. As the part is printed, the platform moves down, which allows the material to cool and solidify and build the part, layer by layer.
4. **Material Jetting**: In this process, inkjet printheads apply the melted build and support material directly onto the build platform. The materials used in this process can be plastic, metal, or wax. Once the materials have cooled and solidified, the build platform is lowered, and new layers are added until the part is complete. Material is deposited in droplets in lines as opposed to points. Material Jetting requires support structures to be printed simultaneously with the part from a dissolvable material and removed afterward. Apart from Material Jetting itself, two other technologies are included in this category: nano particle jetting (NPJ) and drop-on-demand (DOD).
5. **Binder Jetting**: This process involves an adhesive binding agent dispensing into a thin layer of powder material to build the part layer by layer. These layers bind together to form a solid component. After printing, the parts require additional post-processing before they can be

used. The most common materials used in the post-processing stage are sand and metal.

6. **Vat Photopolymerization**: This process involves exposing a light-activated polymer resin to a specific wavelength, causing it to solidify through a chemical reaction.
   Three different heat sources are available when using this technique:
   - Stereolithography (SLA) utilizes a laser to dissolve and cure the liquid plastic selectively, tracing the cross-section progressively and building up the part layer by layer.
   - Direct Light Processing (DLP) uses a projector to flash all layer voxels simultaneously.
   - Continuous Direct Light Processing (CDLP), also known as Continuous Liquid Interface Production (CLIP—which is trademarked), uses the build plate's continuous Z-direction motion to flash melt each layer.
7. **Powder Bed Fusion (PBF)**: This process involves using a heat source that causes plastic or metal powder particles to fuse, sinter, or melt together one layer at a time. The manufacturing techniques in this category vary according to the energy source used and the base material.
   The PBF category includes:
   - Selective Laser Sintering (SLS) is perhaps the most widely known AM technology and uses a laser to sinter thin layers of powder material.
   - Selective Laser Melting (SLM) fully melts, and Direct Metal Laser Sintering (DMLS) near-melts the powder material, meaning it is used with metals and alloys. Since the material is melted, SLM requires a support structure.
   - Electron Beam Melting (EBM) uses a high-energy electron beam rather than a laser to fuse particles. It requires a vacuum build environment and can only be used with conductive materials. (International Organization for Standardization [ISO], 2021)

The dimensional accuracy and surface finish of 3D printed parts are influenced by various factors, including the specific AM technology, manufacturer, equipment model, serial number, and build parameters employed during the printing process (Ngo et al., 2018; Schmelzle, 2022). The tolerance levels and precision achievable through AM processes are not absolute values but rather general ranges that can vary significantly based on the specific machine, materials, and settings utilized (Ngo et al., 2018). However, post-processing techniques, such as surface finishing, heat treatment, and infiltration, can be utilized to enhance the precision and surface quality of the printed components, thereby improving dimensional accuracy, surface smoothness, and mechanical properties (Gao et al., 2015; Ngo et al., 2018; Vaezi et al., 2013). Table 1 illustrates the relative accuracy levels of the processes mentioned above, ranging from least to most accurate:

Table 1. Accuracy of AM processes. Source: Adapted from Schmelzle (2022).

Greatest Precision ↕ Least Precision	Process	Tolerance	Materials
	Material Jetting	Satisfies tolerances of less than .004 in	Polymers
	Vat Photopolymerization		Polymers, Resins
	Powder Bed Fusion		Metals, Polymers
	Binder Jetting		Metals, Polymers, Ceramics
	Sheet Lamination	Satisfies tolerances of less than .012 in	Paper, Metal Foils
	Direct Energy Deposition		Metals
	Material Extrusion		Polymers

Overall, AM has progressed exponentially from nascent polymer prototyping in the 1980s, towards increasingly mainstream manufacturing integration across industries today (Öberg & Shams, 2019). It enables simplified fabrication of complex, customized products on-demand without dedicated tooling or molds. AM can produce parts with intricate internal features, lightweight cellular lattice structures, and consolidated sub-assemblies directly from digital models in a "complexity for free" approach (Johnston et al., 2018).

According to the Wohlers Associates' Report of 2023, the global AM industry revenue grew by 18.3% in 2022. This marks a trend of double-digit growth for the industry, which has been ongoing for 25 of the past 34 years. This growth is depicted in billions of dollars in Figure 6. The report focuses on the extension of AM into end-use production applications, the development and adoption of standards, and the delivery of more significant and critical parts across multiple industry sectors (including large-format AM applications in aerospace and construction). The report is based on the input of 119 service providers, 128 manufacturers of AM systems, and 28 producers of third-party materials. It also includes the expertise of a worldwide network of professionals and nearly three decades of data and market intelligence (Wohlers Associates, 2023).

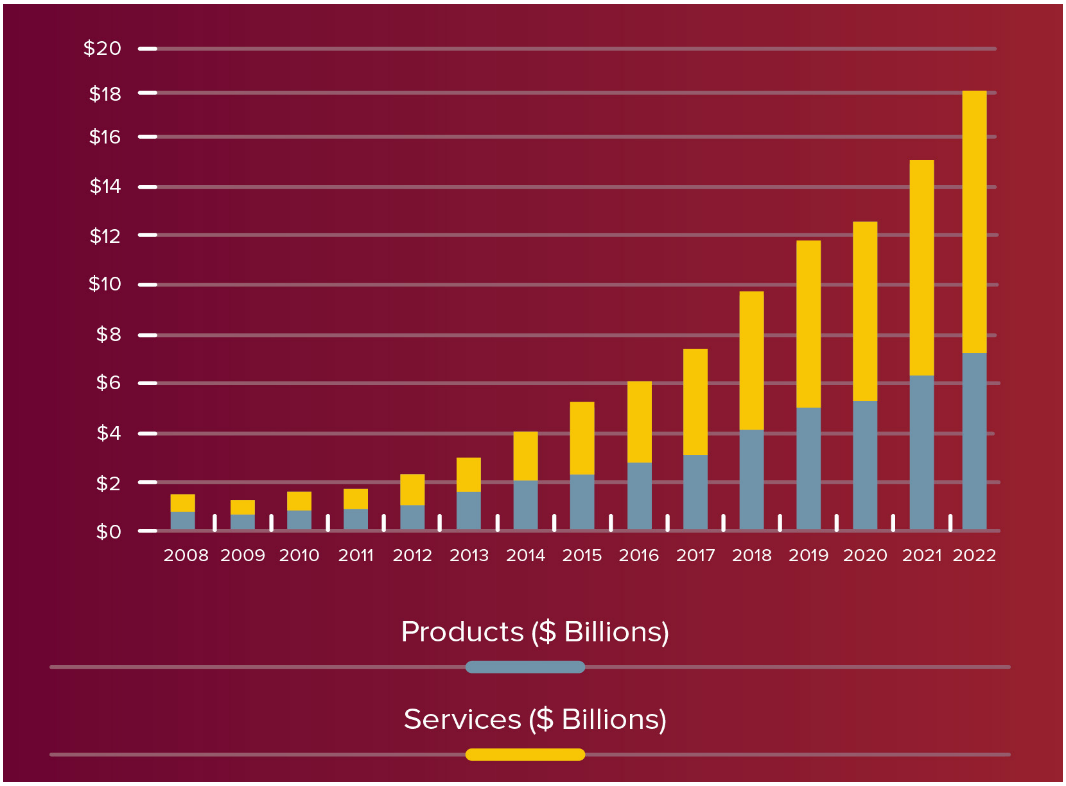

Figure 6. Global revenue for AM products and services. Source: Wohlers Associates (2023).

Recent projections predict exponential expansion in global AM adoption over the next decade. Analyses indicate that as AM equipment and materials costs decrease, improved process repeatability and part quality will increase reliability—making AM more competitive for end-use production applications (Félix, 2017; Höller et al., 2022). This rapid growth in technology maturity alongside capacity scalability is expected to enable a paradigm shift, where AM disrupts conventional centralized manufacturing models and enables more distributed, flexible supply chain strategies across sectors (Félix, 2017; Kandukuri et al., 2019). The localization and digitization afforded by maturing AM methods provide an excellent opportunity for organizations to regain responsive, resilient production capacity.

C. ADDITIVE MANUFACTURING IN LOGISTICS AND SUPPLY CHAIN MANAGEMENT

1. Disrupting Traditional Logistics Models

Several analyses highlight AM technologies' potential to fundamentally transform supply chain strategies across contexts by enabling distributed on-demand manufacturing near points of use (Félix, 2017; Khajavi et al., 2020; Salman & Mushtaq, 2018). Traditional logistics models rely on forecast-based mass production, warehousing, and transportation from centralized factories to downstream inventories or distributors. However, localized AM production using compact systems presents a paradigm shift by compressing multiple links in the chain to create individualized parts on-location efficiently (Kostidi & Nikitakos, 2018).

These disruptive AM capabilities promise game-changing logistics agility unshackled from months-long resupply lead times for maritime platforms and remote bases. With AM capacity onshore or aboard ships, critical spare parts can be fabricated in days or hours, mitigating reliance on distant vendors while enhancing responsiveness (Adrezin & Haliscak, 2017; Félix, 2017). One of the significant advantages of adopting a distributed infrastructure for AM is the provision of redundancy. This redundancy allows for faultless adaptation in the event of damaged nodes, congested passageways, and other unforeseeable contingencies. The distribution of the infrastructure across multiple locations ensures that the system can continue to function even if a particular node is compromised, making it more resilient and reliable.

2. Optimizing Inventory Levels

Additionally, as AM systems deposit material layer-by-layer only where needed for each unique part design, they facilitate major reductions in warehouse inventory sizes, logistics footprint, and losses from part obsolescence across contexts (Akmal et al., 2022; Félix, 2017; Valtonen et al., 2022). By minimizing waste, AM enables leaner supply chains. Parts can also be stored indefinitely as digital files rather than physical items with concerns about shelf life or room conditions, for example. The ability to efficiently produce small, customized batches further reduces the inventory risks associated with uncertain fluctuations in demand.

3. Enhancing Transportation Efficiency

The design freedom of AM simplifies the consolidation of complex assemblies into single parts, saving space and diminishing weight. Lightweight multi-material components optimized via AM reduce cargo weight and fuel consumption during transit downstream—trimming transportation budgets significantly (Holmes, 2023). Kandukuri et al. (2019) agree that AM provides the capability to reduce weight or volume through greater design freedom. The authors further state that, coupled with part integration, these lightweights deliver major space savings aboard weight-constrained ships, enhancing cargo capacity.

Even fractional density improvements accumulate substantial fuel, time, and cost advantages for naval convoys transiting vast distances. By reducing solid waste volumes through parts integration while trimming cargo weight via optimization, maturing AM techniques offer compounded transportation efficiency benefits for dispersed maritime missions. The prospect of almost unlimited geometrical complexity without additional production costs positions AM as an attractive avenue for next-generation maritime component design.

4. Implementation Challenges

Quantifying total cost tradeoffs requires further modeling to accurately weigh upfront AM infrastructure build-out against reliability risks and integration costs for legacy defense systems (Adrezin & Haliscak, 2017; Busachi et al., 2018). Moreover, maximizing AM benefits demands upskilling workforces, adapting quality methods and partnerships, reconsidering IP policies, and transforming paradigms.

Another field of AM that still requires improvement is the area of metrology. Tofail et al. (2018) explain that "metrology, the science and act of measuring, is required for AM not only from a technological confidence point of view but also due to the market pull for consistent and reliable performance of AM-built parts" (p. 30). The same authors anticipate that, in the near future, there will be legal and financial mandates for AM products to be commercially available.

According to Tofail et al. (2018), new tools are needed to measure and inspect AM components accurately and rapidly during the manufacturing process (in situ), as well as for quality assurance after manufacturing (offline). In their research, the authors note that nondestructive testing is essential, given the complex geometries and hybrid materials that AM can produce. Robust metrological benchmarks and standards that ensure dimensional, textural, mechanical, and chemical integrity still need to be developed for AM. This will give industries like defense, aerospace, and medical devices the confidence in quality, reproducibility, and performance to move AM from prototyping into functional production.

This monumental shift towards digitally fed distributed manufacturing networks compels changes to workflows, supplier roles, access controls, and equipment maintenance still being charted (De Brito et al., 2021; Khajavi et al., 2020). Nevertheless, maturing AM capabilities promise enhanced resilience and self-sufficiency for naval fleets while increasing commercial supply chain responsiveness.

D. ADDITIVE MANUFACTURING IN THE MILITARY SECTOR

1. Recognizing Strategic Advantages

In recent years, defense departments and forces worldwide have recognized the immense potential of AM technologies for vehicles, shelters, protective equipment, and other defense systems. This growing traction is reflected in projections approaching $2 billion for defense AM applications by 2027 (3Dnatives, 2022). The unique benefits of agile on-demand digital manufacturing align closely with military needs for responsiveness, operational resilience, and self-sufficiency in deployed locations across air, ground, and naval domains.

AM enables the creation of customized, geometrically complex components at the point of need, which is ideal for forward operating bases and naval vessels where resupply of spare parts using traditional methods can take weeks or months (Adrezin & Haliscak, 2017; Holmes, 2023). Using computer-aided design (CAD) files to fabricate maintenance parts near equipment sites precisely when required, rather than forecasting parts inventory, AM helps mitigate logistics delays and enhance mission readiness (3Dnatives, 2022; Johnston et al., 2018). These capabilities have garnered significant investments. For instance, the U.S. Department of Defense believes in the benefits of AM. In 2021, it announced the decision to install the largest metal AM system in the world. 3Dnatives (2022) states that a collaborative effort is underway involving the U.S. DEVCOM Army Ground Vehicle Systems Center, ASTRO America, Ingersoll Machine Tool, Siemens, and MELD Manufacturing Corporation to construct a large-scale metal 3D printer at the Rock Island Arsenal – Joint Manufacturing and Technology Center. The aim of this project, known as the Jointless Hull Project, is to utilize AM technology to produce monolithic (one-piece) hulls for combat vehicles. Once operational, this massive printer will have the capability of fabricating metal components measuring up to 30 feet in length, 20 feet in width, and 12 feet in height (3Dnatives, 2022).

2. Optimizing Naval Platform Serviceability

For naval vessels conducting months-long autonomous missions, localized AM production capacity means fewer spare parts must be stocked onboard, as specialized components can be manufactured during extended deployments unmatched by any land-based platforms (Adrezin & Haliscak, 2017). AM creates lighter, optimized component designs by consolidating complex sub-assemblies, integrating lattice structures, and removing unnecessary material from structural load paths (3Dnatives, 2022; Holmes, 2023). Such AM-enabled lightweighting directly benefits naval vessels by providing increased speed, range, maneuverability, survivability, and payload capacity—critical performance factors for sea control, deterrence, and power projection.

Moreover, the digital design flexibility of AM permits rapid iteration of components to cost-effectively incorporate battle damage repairs and capability upgrades rather than waiting months for conventionally manufactured delivered parts (Cordle et al., 2022; Holmes, 2023). AM offers militaries potentially asymmetric advantages by adapting more quickly than adversaries by facilitating responsive recovery and modernization efforts. Nevertheless, delays persist due to size limits in defense-suitable metal AM systems, essential capability lack for large components, reliability testing needs using nascent standards, and cultural adoption issues being actively addressed (3Dnatives, 2022; Cordle et al., 2022).

E. ADDITIVE MANUFACTURING IN NAVAL DEFENSE LOGISTICS

1. Enhancing Operational Resilience

Within naval defense logistics, current supply models reliant on fixed land-based nodes with temporary maritime payload staging, combined with just-in-time delivery, accumulate risk and degrade combat resilience in contested environments. However, distributed AM presents a pivotal pathway to reconstitute flexible manufacturing ability, both afloat and ashore, aligned with evolving naval strategies emphasizing dispersed agile platforms over consolidated assets (Shields, 2023).

Analysis shows that utilizing modular AM capacity for only 0.5% of naval component orders could provide a 10% lead time reduction across the enterprise (Shields, 2023). Localized digital production of spare parts and consumables is projected to slash logistics response times from months to days, increasing fleet readiness and serviceability (3Dnatives, 2022; Adrezin & Haliscak, 2017). As AM productivity improves, on-demand fabrication may even enable self-sufficient battlefield repairs, obviating some reliance on tender vessels (Kostidi & Nikitakos, 2018; Valtonen et al., 2022).

2. Transforming Parts Supply Strategies

Additionally, distributed AM infrastructure provides inherent contingency capacity across domains if land-based nodes face threats. Naval budgets could also benefit over the long-term from AM's reductions in both required warehoused inventory as well as losses from part obsolescence across ships with multi-decade life cycles outlasting contracted original equipment manufacturers (Akmal et al., 2022; Shields, 2023).

Nevertheless, uncertainty persists. Quantitative cost-benefit tradeoffs weighing AM implementation expenses against reliability risks, decommissioning of legacy infrastructure, digital security vulnerabilities, and requisite workforce skills development remain unclear presently (Adrezin & Haliscak, 2017; Busachi et al., 2018; De Brito et al., 2021). Resolving data gaps around material properties, quality assurance, system interoperability, and part approval workflows pose challenges for naval AM integration (Coyle, 2019; Shields, 2023). Nevertheless, maturing metals AM capabilities are projected to provide naval supply chains with increased flexibility and manufacturing self-sufficiency over the next decade if challenges are addressed judiciously (Adrezin & Haliscak, 2017). Further research must synthesize quantitative models, empirical fleet data, and field demonstrations to evaluate the operational viability and cost-efficiency of widespread naval AM adoption.

F. CONCLUSION

This review outlined AM technology's rapid evolution and transformative potential to enhance logistics agility, resilience, and self-sufficiency across civilian and defense contexts (Adrezin & Haliscak, 2017; Félix, 2017; Khajavi et al., 2020). As AM methods mature improving accuracy, speed, scale, and materials, adoption is accelerating with projections of over 20% annual growth up to a $75 billion market by 2030 (Holmes, 2023; Wohlers Associates, 2023). However, quantifying AM's benefits against risks and integration costs remains unclear for naval supply chains presently (Adrezin & Haliscak, 2017; Busachi et al., 2018).

Localized and flexible AM production promises enhanced contingency capacity and reduced reliance on fixed nodes for naval missions (Félix, 2017; Shields, 2023). This could slash logistics delays from months to days, increasing fleet readiness and serviceability (3Dnatives, 2022). As materials science research expands the list of certified alternatives beyond polymers, metal AM will likely transform conventional forecast-driven supply strategies over the next decade (Cordle et al., 2022; JDMC, 2021).

In essence, maturing AM systems are positioned to provide naval forces with increased manufacturing self-reliance and logistics agility. However, further modeling using empirical defense data is vital to evaluate operational viability and guide enterprise integration investments (Adrezin & Haliscak, 2017; Shields, 2023). Adopting AM can bring immense strategic potential, but prudent and detailed planning is necessary to maximize its benefits.

IV. ANALYSIS

The analysis in this chapter demonstrates that AM offers notable opportunities to enhance naval logistics agility and readiness, but it currently remains an immature technology with lingering deficiencies like quality variability, materials limitations, production scale constraints, post-processing needs, and cybersecurity vulnerabilities. While selective AM adoption shows potential, staged assimilation aligned to a transition roadmap can help the Brazilian Navy methodically harness benefits while controlling attendant implementation hazards across multiple organizational dimensions. The adoption of AM at a strategic level should be intended to partially supplement traditional manufacturing, improving flexibility and the speed of response to unforeseen and emergency demands of the service. The analysis documented in this chapter shows that by combining AM with conventional manufacturing, the Brazilian Navy can leverage complementary strengths while mitigating isolated weaknesses in either approach.

A. METHODOLOGY

This research adopted a qualitative case study approach to evaluate the potential benefits of adopting AM as a strategic initiative for BN defense logistics.

1. Data Collection

The research involved the review of existing academic papers, government documents, industry analyses, and authoritative media sources on AM and military logistics. As a result, the study synthesized the literature to establish the setting and identify themes relevant to evaluating AM adoption for Brazilian naval logistics.

The literature review provided a comprehensive analysis of AM technology and its commercial applications, as well as its military defense context applications, benefits, limitations, potential costs, and integration requirements. The background examined BN logistics operations cases and challenges, including a thorough examination of two BN logistics operations cases and highlighted the challenges associated with them.

The research on AM for military logistics applications covered several pertinent sources. These included peer-reviewed journal articles and conference papers focused on AM usage for commercial and defense logistics operations, as well as published graduate theses from institutions such as the Naval Postgraduate School (NPS). Official publications from the Brazilian Navy outlining logistics doctrine and procedures provided additional insights. Market research reports on AM adoption trends, applications across industries, and future outlooks helped establish contexts. Finally, media articles documenting military use cases and advancement of AM technologies supplied supplemental perspectives on the state of the field. In total, these sources encompass technical findings, institutional frameworks, industry analytics, and expert projections to broadly examine the role of additive manufacturing in transforming military supply chains and sustainment activities.

2. Data Analysis

The research utilized qualitative content analysis to extract and categorize information from the literature about the feasibility, benefits, potential costs, limitations, and implementation requirements of adopting AM. The analysis focused on critical factors such as technical maturity, supply chain integration, operational impacts, and strategic considerations. The aim was to assess the potential of AM to address Brazilian naval logistics challenges mentioned in the background section.

The obtained data were interpreted to determine AM's viability and value proposition as a strategic initiative to enable resilient and responsive logistics for critical BN missions that require on-demand fabrication when robust supply lines are absent.

B. ANALYSIS AND FINDINGS

Multiple studies highlight the capability of AM techniques to reduce costs, enhance readiness, and solve longstanding issues faced in defense procurement and contracting. AM devices simplify the fabrication of complex geometries that are impossible through conventional methods and consolidate sub-assemblies into single printed parts (Chiujdea & Cănănău, 2021; Khajavi et al., 2020). As highlighted in a recent International Atomic Energy Agency (IAEA) article, the nuclear industry is beginning to utilize AM technologies to print components like pump impellers and fuel assembly brackets (Ashton, 2023). The BN could similarly apply AM methods in its naval nuclear propulsion program, allowing the manufacture of lightweight components for next-generation vessels like nuclear-powered submarines. Ashton (2023) adds that components printed with AM can be designed with intricate shapes while reducing weight, waste, and potential for error. As a result, AM can provide the BN's potential for more responsive, mission-driven logistics by enabling distributed digital manufacturing of strategic spare parts.

Providing military units with compact, robust AM systems offers deployable in-theater production capacity, mitigating risks like disrupted maritime shipping (JDMC, 2021). In this context, Forces could sustain combat readiness through on-site printing of spare components otherwise prone to expensive, lengthy external procurement. Considering the large size of Brazil's jurisdictional waters and offshore assets, such flexible AM implementation would support force projection across the resource-rich Blue Amazon.

According to Roach (2021), the United States Marine Corps has utilized AM innovations, like building a full-scale concrete bridge printed in just 14 hours by a joint Army-Marine team, compared to days using conventional casting methods. Additionally, Oak Ridge National Laboratory manufactured a Mk 8 Mod 1 SEAL Delivery Vehicle hull at greatly reduced size, weight, and delivery time. Rather than 5 months for conventional fabrication, AM built an equivalent hull in under 4 weeks at a fraction of the cost.

Roach (2021) adds that the United States Navy has also applied AM techniques to manufacture components like obsolete Tomahawk missile circuit card clips and custom oil line wrenches for MH-60R Seahawk helicopters. For the wrenches, AM consolidation of sub-assemblies cut production time by 80 labor hours per oil change. On a larger scale, AM enabled a 30% cost reduction and 10% faster fabrication of a V-22 Osprey hydraulic manifold by lowering weight 70% compared to the traditional manifold (Roach, 2021).

In the Amazon environment, the NAsHs, like the U16 Doutor Montenegro, serve a critical mission, bringing medical care, dental treatment, and health education services to isolated communities deep along Amazon basin rivers and tributaries (Kadri et al., 2019). Maintaining operational readiness across prolonged multi-week deployments poses major logistical impediments (Júnior & Curto, 2020). The immense distances from coastal naval bases prevent rapid delivery of spare parts when critical equipment fails. In addition, carrying excessive inventories is costly and strains the limited storage capacity of ships serving numerous small riverside villages.

Recent research has presented AM with promising medical applications, such as surgical instruments, customized implants, and external supports fabricated from patient anatomy data (Salmi, 2021). Patient-specific implants and tools manufactured from medical scans could facilitate complex treatments otherwise infeasible given equipment limitations.

Sakib-Uz-Zaman & Khondoker (2023) report the potential of AM for orthotic and prosthetic devices and highlights key benefits including lower costs (56-95% less than traditional devices), the ability to use plastic/polymer materials like ABS, PETG and PLA to match the characteristics of traditional materials such as polycarbonate, and improved design and fabrication efficiency compared to conventional methods that are wasteful and hazardous. The authors emphasize that sufficient structural strength and better or similar functionality and patient satisfaction to conventional devices based on upper-limb prosthetics. Given these advantages, AM presents a promising opportunity for the Brazilian Navy Hospital Assistance Ships operating in remote Amazon regions to fabricate customized orthotic and prosthetic devices on-demand for the riverside populations they are supporting. The technology's lower costs and distributed manufacturing capabilities could increase access and personalization of medical care.

Meyer et al. (2020) analyzed that vulnerabilities in the spare parts supply chain can jeopardize the reliability and timeliness of assistance efforts. Hence, equipping the NAsHs with compact AM printers and materials could mitigate such risks with the on-demand fabrication of replacement parts that are otherwise difficult to obtain rapidly, given regional infrastructure limitations. This could help ensure assistance continuity despite breakdowns needing unforeseen components. Nonetheless, the hot, humid environment's effects on polymer printing materials require research to confirm that naval AM employment withstands Amazonian operating constraints (Despeisse et al., 2017).

The ships that support Brazilian operations in EACF and other Antarctica regions contend with immense logistical difficulties stemming from the extreme remoteness and harsh polar climate (Marinha do Brasil, 2020). The transportation of fuel, supplies, equipment, and spare parts in the required quantity and an appropriate manner over long distances from South America remains complex, risky, and expensive. According to Adrezin and Haliscak (2017), the use of additive manufacturing systems on polar ships could significantly reduce the required inventory of replacement parts, which would otherwise require large storage facilities. By fabricating strategic, critically needed components in situ, the Brazilian Antarctic missions would gain flexibility in responding to unpredictable events, like blizzard damage, through timely local printing without costly disruptions awaiting external resupply.

Equipping the EACF and the ships with 3D printers of various categories could be a viable option. This would support Brazilian scientific research in Antarctica, the EACF's needs, and it would cater to the demands of the ships Almirante Maximiano and Ary Rongel, which are constantly on the move during OPERANTAR. Further possibilities for 3D printing applications, such as lightweight replacement parts for drones, could contribute to Antarctic reconnaissance activities based on the demands of evolving missions. However, Kravcov et al. (2020) indicate that harsh marine environments impose many challenges for naval AM because it is difficult to achieve controlled factory conditions at sea. As a result, it is expected that providing the EACF with AM technology rather than the ships is the most viable option for improving supply chain management in that area. This would enable the station to meet its demands and those of the researchers and ships during OPERANTAR when the vessels will be near the EACF.

Alongside its formidable benefits, adopting AM poses limitations due to Brazil's current naval infrastructure and technologies. As Coyle (2019) and Deshmukh et al. (2022) determined, small-batch AM production continues struggling to match the economic cost efficiency and speed of conventional high-volume manufacturing. Jung et al. (2023) propose that distributed AM only proves economically competitive up to small-batch thresholds before conventional mass manufacturing's scale efficiencies dominate, arguing for selective AM application. Traditional external sourcing and warehousing may remain lower-risk options for the low-demand legacy spare parts still prevalent in Brazilian naval inventories.

While AM streamlines complex fabrication, initial surface finish and material integrity issues currently mandate extensive, costly post-processing for specific cases (Despeisse et al., 2017; Chiujdea & Cănănău, 2021). Hence, naval AM adoption would suit small-run fabrication of customized or intricate components where precision overrides production maximization, accepting higher costs per part to gain unique and strategic capabilities like performance enhancements from weight reduction or the considerable need for lead-time reduction. By combining AM, traditional methods, and hybrid systems, the Brazilian Navy can benefit from complementary strengths while mitigating weaknesses.

Höller et al. (2022) reveal that AM quality assurance through rigorous part testing remains critical before operational integration, lest unknown flaws or vulnerabilities propagate unchecked into naval vessels or other sensitive systems. Moreover, Lube Filho et al. (2024) argue that the mechanical properties of materials used for 3D printing parts vary depending on the chosen materials. Therefore, it is crucial to select the most suitable materials from a technical standpoint during the product design stage. The authors also propose that this selection should consider the thermal and mechanical properties based on the application scenario, as well as the technical and economic feasibility of the material.

AM adoption's limitations center on its current immaturity, including inconsistent part quality, materials constraints, limited sizes and production volumes, post-processing requirements, and lack of standards (Gallinaro, 2023; Salman & Mushtaq, 2018). Overcoming these limitations likely requires staged investment scaling up expertise, equipment, testing, and naval infrastructure modernization across the shore-to-ship support continuum. Brazilian officials should also focus AM implementation first on low-risk applications while strategically expanding capability and operational integration over successive technology generations until full cost-benefit realization.

Beyond its inherent drawbacks, transitioning towards naval AM implementation could also face political, economic, and organizational challenges within Brazil, necessitating coordinated resolution. Vested interests and bureaucratic inertia tend to inhibit major institutional transformations like revamping naval supply chains around AM production concepts (Espadinha-Cruz et al., 2023). As Priyadarshini et al. (2022) discuss, installing reliable AM capacities requires large, sustained equipment expenditures and specialized technician training, which may conflict with Brazil's current fiscal difficulties, risking delays or resource shortfalls.

Moreover, a lack of change management could strangle effectiveness since full-scale AM adoption compels redesigning maintenance routines, contracting procedures, and inventory practices optimized for conventional manufacturing paradigms (Öberg & Shams, 2019). Therefore, it is crucial to recommend the implementation of AM based on a well-planned roadmap. This approach enables the governing entities to work together in a coordinated manner to secure the necessary funds and legislative and regulatory changes required to make the process effective.

Another obstacle to proper AM adoption is that policymakers must address early IP protections as the Brazilian Navy encompasses increased AM integration for applications like deployable in-theater spare parts production. Since AM relies on the digital transfer of 3D model files, uncontrolled data proliferation risks the unauthorized replication of proprietary component designs by third parties. Without governance guardrails, unsecured AM systems could enable reverse engineering of sensitive military technologies (Colorado et al., 2023).

According to the discussions of Javaid et al. (2021) and Gallinaro (2023), firms adopting open business models like distributed AM platforms must regulate file usage rights between equipment owners and external clients, printing components on demand. The BN could require similar data conventions ensuring manufacturers retain control over digital assets for naval inventory items while permitting certified third-party AM capacity for surge production needs. Clear contractual protocols allowing controlled AM capacity sharing while securing sensitive defense IP would expand resilience options, balancing IP protection and flexibility.

Furthermore, AM's digitally connected nature relies on unfettered data access across the production life cycle, from design to fabrication. This increased connectivity from networked AM devices heightens exposure to cyber intrusions compared to closed legacy manufacturing equipment (Aguariavwodo, 2023). Since digital continuity across AM design, production, and quality confirmation depends on reliable data flows between systems, file corruption could fatally undermine fabrication integrity. Breaches during offshore naval missions might strand ships awaiting delayed conventional spare part replacement and make them unable to trust AM output.

Rodríguez et al. (2022) note that decentralized AM configurations compound vulnerabilities, thus requiring coordinated standards, access governance, and expansion of the cybersecurity workforce to neutralize potential threats. Proactively embedding security controls and best practices into Brazilian Navy AM engineering processes could reduce attack surfaces and mitigate operational risks in dealing with inevitable cyber incidents. This resiliency focus aligns with modernization initiatives for the Future Vision of the Brazilian Navy (Marinha do Brasil, 2017), such as enhanced Command and Control systems.

Jagoda et al. (2020) and Markforged (2022) state that essential requirements need to be addressed proactively, such as the development of AM expertise, tailored procurement structures that allow for the local printing of legacy and new components, and security certifications that enable reliable integration of printed parts into operational platforms. Through coordinated efforts aligned with a strategic transition roadmap, the BN can methodically harness AM's latent potential while controlling attendant implementation hazards across organization, personnel, training, equipment, facilities, governance, doctrine, and policy considerations. While mass-scale AM assimilation remains premature before resolving lingering deficiencies, a calibrated implementation may offer the Brazilian Navy logistical upgrades that align with its modernization vision.

Additionally, forming strategic partnerships with academic institutions and industry leaders could offer numerous advantages and benefits for the successful implementation of AM in the BN. These collaborations could provide access to cuttingedge research, expertise, and real-world manufacturing scenarios, accelerating the adoption of AM technologies and enhancing supply chain resilience.

Collaborating with academic institutions could facilitate knowledge transfer and provide access to innovative applications, virtual reality simulations, digital workflows, advanced materials, and precision manufacturing processes (PUC-Rio, n.d.). Moreover, these partnerships could contribute to the development of talent through specialized training programs, fostering in-house skills and expertise in AM technologies.

Engaging with industry partners could offer invaluable experience in transitioning 3D printing methods into volume production. Partnering with companies that possess extensive capabilities across various AM technologies could facilitate the comprehensive evaluation and validation of different processes against operational requirements. These partnerships could provide localized support and access to certified large-scale metal printing solutions, enabling the production of complex and heavy-duty components for maritime applications (Brazil Metal Parts, n.d.; Wakefield, 2024).

In conclusion, analyzed findings reveal tangible but conditioned benefits from naval AM assimilation. Officials should weigh case-specific costs and risks against prospective readiness enhancements and map targeted AM adoption opportunities with constrained fiscal resources. Further applied research measuring Brazilian naval AM prototype performance could illuminate advantageous applications for prioritized development.

THIS PAGE INTENTIONALLY LEFT BLANK

V. AM ADOPTION

Roadmaps have emerged as helpful tools to anticipate possible scenarios, maintain a competitive position, accelerate digital transformation, and summarize key elements around technology adoption (Fernandes et al., 2023). According to Despeisse et al. (2017), roadmaps unite diverse experts to facilitate communication and cooperation in building shared visions and plans. They suggest that roadmaps provide flexibility to customize timeframes and components based on organizational contexts and intents.

Fernandes et al. (2023) agree that a roadmap provides a strategic framework to guide the adoption and integration of new technologies and capabilities. It maps out a phased approach, aligning technical and operational requirements while considering enablers such as infrastructure, skills, policies, and partnerships needed for successful implementation (Despeisse et al., 2017; Ghobakhloo, 2018).

Suggested uses of roadmaps highlight their applicability for AM adoption. They can serve as strategic guides for integrating and innovating AM across operations (Fernandes et al., 2023). Tailored AM roadmaps help manufacturers undertake a deliberate, phased transition embracing AM concepts (Ghobakhloo, 2018). They also enable the consideration of sustainability implications on product life cycles beyond supporting identifying and prioritizing business opportunities, enablers, and implementation actions (Despeisse et al., 2017).

Therefore, the roadmap for AM implementation suggested in this research intends to take a strategic, phased approach to align AM capabilities with the Brazilian Navy's operational needs. The holistic view of common steps following project management best practices can help manage risks and realize benefits by thoughtfully integrating AM into doctrine, training, and supply chains to enable successful adoption and implementation.

The roadmap sections were structured in an order based on standard practices for strategic project planning and change management. While there is no single mandated approach or one-size-fits-all strategy that suits all businesses and industries, the outlined flow aims to take Brazilian Navy leaders, planners, and project managers through a logical progression of building the foundations, conducting analysis, defining the implementation plan, addressing risks/concerns, and establishing governance. The flowchart shown in Figure 7 seeks to present the stages of the roadmap in visual form.

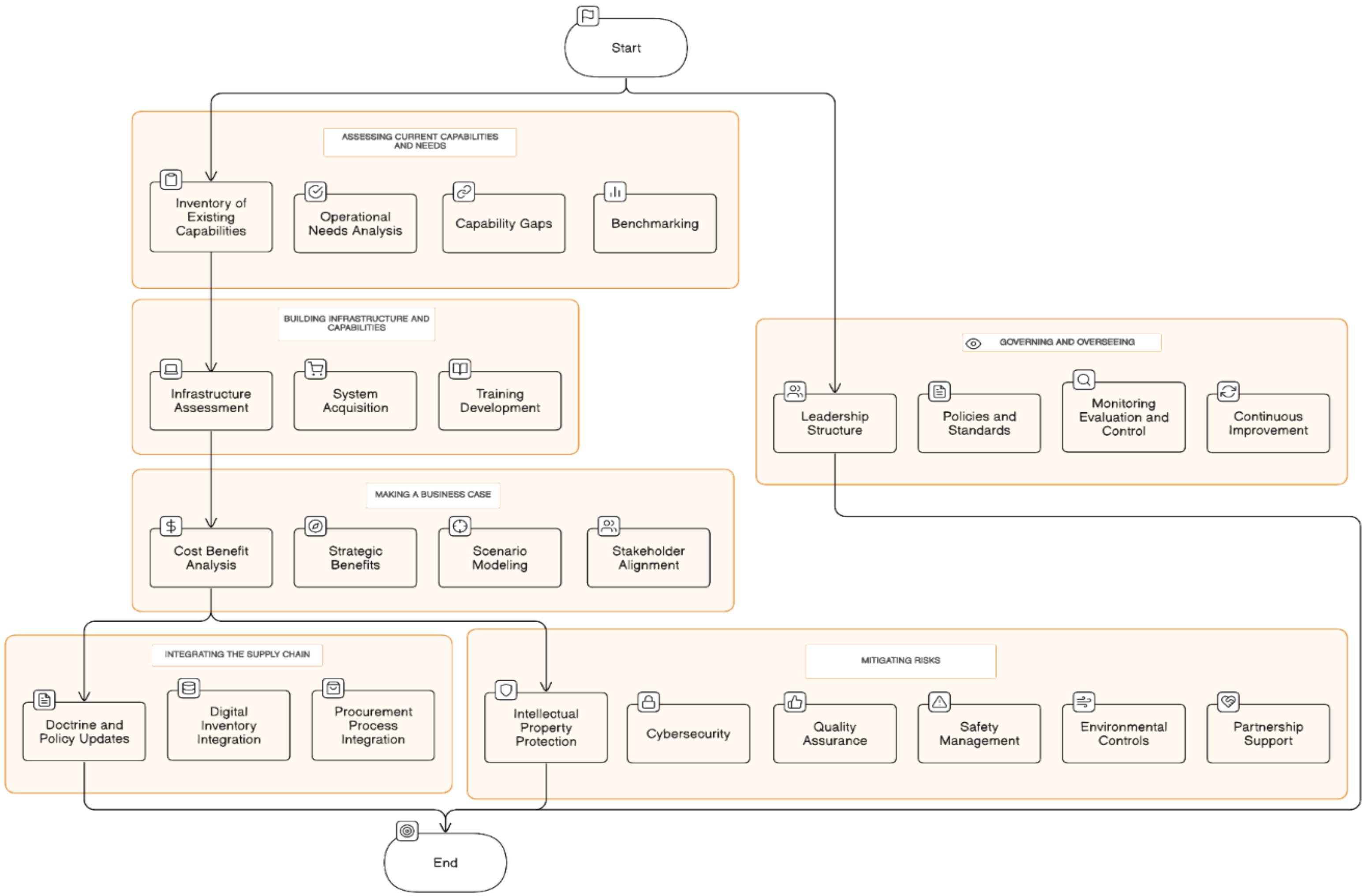

Figure 7. Flowchart of the roadmap

The strategic project development frameworks that informed the proposed high-level structure come from a few well-recognized sources on organizational change management and project governance.

John Kotter's 8-Step Process for Leading Change outlines critical actions for driving successful transformation, like establishing a sense of urgency, building a strong guiding coalition, creating short-term wins, effectively communicating the vision, and institutionalizing changes (Kotter, 2012). Similarly, McKinsey's Transformation Roadmap emphasizes assessing the current state, clearly defining the future vision, methodically bridging the gaps between them, and rigorously tracking progress against targets (Catlin et al., 2017). It also stresses the importance of securing management buy-in, investment funding, and cultural and behavioral change management, with the 7-S model (examining structure, strategy, systems, shared values, skill, style, and staff) providing an integrated diagnostic and alignment tool for organizational change.

Additionally, the Project Management Institute's Project Management Body of Knowledge (PMBOK®) offers standardized guidelines, processes, and best practices for planning, executing, controlling, and closing projects across key knowledge areas like scope, time, cost, quality, risk, project integration, and stakeholder management (Project Management Institute, 2021).

Lastly, Gartner's Hype Cycle provides a reality check on the typical rise and fall of expectations for new technology innovation and adoption life cycles. It starts with an innovation trigger that sparks inflated hype. This reaches a peak before failing to meet those lofty expectations, leading into a trough of disillusionment where interest and adoption slows. With enlightenment about real-world applications and limitations, adoption accelerates again, finally reaching a plateau of productivity as the now widely adopted innovation delivers value. Understanding this cycle permits organizations to take a measured approach to adoption, setting realistic milestones over an extended timeline. Tracking progression allows data-driven priority and resource allocation toward viable use cases rather than seeking overnight transformation (Gartner, n.d.).

With these collective insights in mind, the proposed strategic roadmap intends to take a phased, goals-driven approach that first assesses needs, develops a plan to bridge gaps, and then governs adoption, which aligns well with the change management and project governance best practices from these renowned sources.

A. THE ROADMAP FOR AM IMPLEMENTATION

1. Assessing Current Capabilities and Needs

Conducting a thorough assessment of existing capabilities and operational needs aims to provide the baseline data needed to support the AM adoption planning.

a. Inventory of Existing Capabilities

- Survey personnel to identify any AM systems, materials, and spare parts inventories currently in use;
- Document details like system manufacturers, materials supported, year acquired, and operating status;
- Compile information on personnel with AM experience or training; and
- Inspect existing systems to evaluate condition, maintenance records, and reliability.

b. Operational Needs Analysis

- Interview personnel at all levels to gather input on logistics pain points and AM solution ideas;
- Review maintenance records to identify frequent part replacement needs that AM could address;
- Assess lead times and costs for procuring spare parts that impact readiness; and
- Prioritize near-term AM applications based on operational impact and feasibility.

c. Capability Gaps

- Map current AM infrastructure and skills against projected initial adoption goals;
- Identify gaps in key enablers like facilities, training capacity, and network infrastructure; and
- Develop a plan to upgrade infrastructure and skills aligned with the roadmap timeline.

d. Benchmarking

- Research AM adoption best practices by allied navies and commercial maritime operators. Analyze their performance data from the first operational AM part installations;
- Connect with early adopters to learn lessons and accelerate capability maturation; and
- Attend naval conferences and working groups focused on AM repairs, supply chain resilience, and future manufacturing.

2. Building Infrastructure and Capabilities

A purposeful strategy for developing infrastructure, capabilities, and skills may enable the Brazilian Navy to safely implement AM at scale over time.

a. Infrastructure Assessment

- Conduct site surveys to map available space, power supply, cooling, and ventilation needed for AM systems environments;
- Identify locations accommodating system size, weight, vibrations, and safety zones;

- Evaluate options for infrastructure upgrades to support AM requirements; and
- Develop plans for storing and handling raw AM materials and waste products.

b. System Acquisition

- Conduct market research to identify AM technologies suited for the Brazilian Navy's applications and operating environments;
- Develop procurement criteria balancing capability, reliability, and cost-effectiveness;
- Explore leasing options to enable flexible adoption amid rapid AM advancements; and
- Phase in systems aligned with roadmap priorities like pilot facilities, shore infrastructure, and ships.

c. Training Development

- Partner with AM equipment vendors to provide operator and maintenance training;
- Work with universities to develop curriculum for part design, digital workflow, and quality assurance;
- Start with core AM familiarization programs across engineering, technician, and logistics roles; and
- Expand training portfolio over time as adoption and expertise increase.

3. Making a Business Case

A data-driven business case combining financials, strategic impacts, and adoption scenarios will help secure buy-in and funding concerns for the AM initiative.

a. *Cost-Benefit Analysis*

- Analyze upfront system procurement costs versus long-term inventory, transportation, and maintenance savings;
- Consider training costs, materials, and upgrades over the system's life cycle;
- Model total cost of ownership under different adoption scenarios; and
- Estimate return on investment (ROI) timeline as capabilities mature over time.

b. *Strategic Benefits*

- Highlight hard-to-quantify benefits like enhanced operational readiness, reduced logistics delays, and improved supply chain flexibility;
- Emphasize critical national security and defense capabilities enabled by AM adoption;
- Design the expanded mission potential and sovereignty protection of national priorities like the Blue Amazon; and
- Assess technology leadership and talent development in advanced manufacturing.

c. *Scenario Modeling*

- Develop optimistic, moderate, and conservative projections for AM cost savings and benefits realization;
- Identify inflection points where benefits accelerate as capabilities scale; and
- Conduct sensitivity analyses to quantify risks like delayed adoption or cost overruns.

d. Stakeholder Alignment

- Communicate the analysis with naval force commands, logistics and finance leaders, engineers, and operators to build support;
- Solicit input to strengthen arguments and data tied to stakeholder priorities; and
- Tailor messaging and highlight distinct benefits for each influencer group.

4. Integrating the Supply Chain

The goal is to fully incorporate AM capabilities into supply chain doctrine, systems, and processes—from parts design to production to end use. This will allow AM to integrate with traditional logistics seamlessly.

a. Doctrine and Policy Updates

- Revise logistics doctrine to enable distributed AM production as an alternative to centralized warehousing and distribution;
- Update technical manuals to include AM design principles and specifications for suitable parts;
- Develop policies for digital library management, AM system access control, and cybersecurity; and
- Institute protocols for tests and quality assurance, materials handling, and system maintenance.

b. Digital Inventory Integration

- Create a comprehensive digital library of 3D design files for parts approved for AM production;
- Integrate this library into corporative logistics systems for online access across the Brazilian Navy;

- Enable automated workflows to send files to printers once orders are placed; and
- Implement access controls in the library to prevent unauthorized printing.

c. *Procurement Process Integration*

- Streamline contracting procedures to rapidly acquire AM materials and consumables;
- Institute justification requirements for when AM production should be used versus traditional methods (relevant and detailed parameters for the Make-or-Buy decision);
- Develop programs to guarantee budget and human resources to sustain AM system operations, maintenance, and materials; and
- Create new maintenance routines and exclusive identification codes for AM printed parts to track and analyze usage.

5. Mitigating Risks

A proactive approach to risk management will enable the safe and sustainable adoption of AM capabilities.

a. *Intellectual Property (IP) Protection*

- Implement digital rights management controls on 3D design files to prevent unauthorized distribution;
- Watermark design files before sharing on networks to identify source and ownership; and
- Institute non-disclosure agreements for personnel working with Brazilian Navy part designs.

b. Cybersecurity

- Follow Brazilian Navy cybersecurity standards when procuring AM systems to ensure strong access controls;
- Conduct regular cyber audits and penetration testing on AM hardware, software, and networks; and
- Develop contingency plans for AM system operations if the Brazilian naval networks are compromised.

c. Quality Assurance

- Define quality testing protocols for printed parts to validate properties and conformance to specifications;
- Implement audit and inspection requirements at all stages—before, during, and after the printing process; and
- Institute certification programs for AM system operators and maintenance technicians.

d. Safety Management

- Conduct hazard analyses to identify risks associated with materials handling, system operation, and post-processing;
- Develop extensive training on operating procedures and safety protocols for AM technology; and
- Enforce strict personal protective equipment (PPE) requirements when interacting with AM systems.

e. Environmental Controls

- Institute engineering controls like ventilation, spill containment, and waste management to manage particle emissions; and

- Monitor air quality and operator exposures to quantify and mitigate health risks.

f. Partnership Support

- Maintain service contracts with AM equipment vendors to provide adequate and timely troubleshooting and emergency maintenance; and

- Develop relationships with universities and industry partners for research collaboration and technical assistance if needed.

6. Developing the Roadmap

The roadmap builds capabilities in a deliberate progression focused on priority needs. It allows learning, validation, and policy development to guide scaled adoption long-term, as shown in Figure 8.

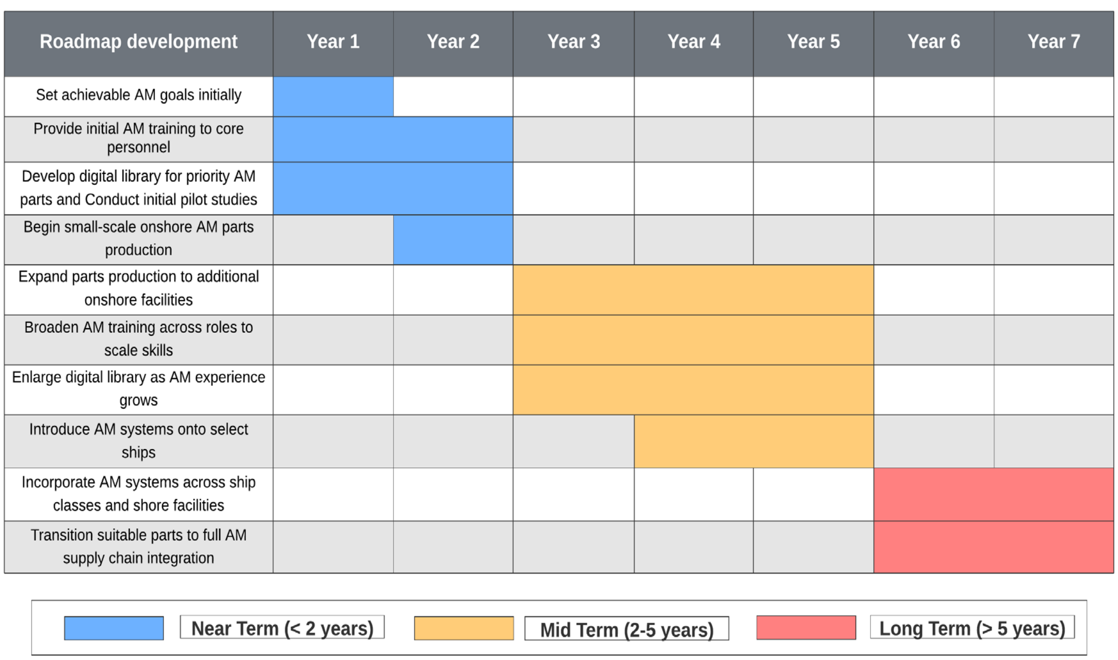

Figure 8. Notional Gantt chart of the roadmap development.

a. ***Near Term (<2 years)***

- Set achievable goals for the initial applications of AM products. New innovations like AM often start with a "Peak of Inflated Expectations," so it is crucial to manage the expected benefits so that they are not overestimated;
- Provide initial AM training to core personnel to establish knowledge base;
- Develop preliminary digital library of design files for priority parts suited for AM production;
- Conduct initial pilot studies to validate technical feasibility and operational integration for high-priority applications. This will provide data to refine longer-term plans;
- Focus initial adoption on low-risk, high-value components to demonstrate benefits and gain stakeholder buy-in;
- Begin small-scale AM parts production at select onshore naval facilities to build capabilities and gather lessons learned; and
- Anticipate the "Trough of Disillusionment": If the early AM pilots fall short of revolutionary expectations, interest may dip considerably. Being prepared for this trough will help continued funding and prevent abandonment until capabilities mature.

b. ***Mid Term (2-5 years)***

- Emphasize this phase as an opportunity to focus on practical integration, incremental improvements, and proof-of-concept studies across priority use cases. The "Slope of Enlightenment" suggests emphasizing tangible incremental progress vs. Long-term transformation during initial adoption. Early successes build confidence;

- Expand parts production to additional onshore facilities based on the success of initial adoption;
- Broaden training programs across engineering, technician, and logistics roles to scale up skills;
- Enlarge digital library with more component design files as AM experience grows;
- Introduce AM systems onto select ships for at-sea manufacturing once viable in maritime conditions; and
- Refine AM quality, data security, and access control policies and procedures as capabilities mature.

c. Long Term (>5 years)

- Discuss the long-term outlook realistically. Frame AM as an enabler augmenting rather than replacing traditional manufacturing. Set expectations for a "Plateau of Productivity" rather than a revolutionary transformation overnight;
- Incorporate AM systems throughout shore infrastructure and across multiple ship classes;
- Transition suitable parts from traditional to AM production for full integration into the supply chain;
- Digitize design files for a high percentage of suitable spare parts inventory;
- Establish AM instruction across professional development programs, from basic training to the most advanced applications fostered by innovation in strategic project design; and

- Update naval logistics doctrine to fully leverage AM capabilities for on-demand, decentralized parts production.

7. Governing and Overseeing

Strategic oversight via a dedicated governance structure will enable the BN to scale AM adoption while maximizing benefits safely.

a. Leadership Structure

- Create an AM steering committee with senior leaders from the General Management Body and Sectoral Management Bodies responsible for naval operations, logistics, finances, engineering, IT, and personnel training;
- Designate an AM program office to provide dedicated oversight and coordinate efforts; and
- Assign AM implementation managers within each command to drive adoption locally.

b. Policies and Standards

- Institute policies on AM system authorization, access control, data protections, and quality assurance;
- Develop AM-specific protocols and checklists for system operation, maintenance, and materials handling; and
- Set Naval-wide standards for AM printed part certification, quality audits and inspections, and operator training.

c. Monitoring, Evaluation, and Control

- Define metrics to track AM usage, cost, reliability, inventory impacts, and operational benefits;

- Implement a lessons-learned program to collect feedback on AM adoption across the Brazilian Navy; and
- Conduct periodic audits and performance reviews to identify issues and promote best practices.

d. Continuous Improvement

- Leverage pilot studies, user feedback, and audits to refine AM implementation plans;
- Provide ongoing training to operators and maintenance techs as AM technology evolves; and
- Fund research projects with universities and industry to expand AM capabilities over time.

This roadmap outlines a phased approach as a management tool option for the Brazilian Navy to strategically adopt AM capabilities. It includes assessing needs, developing infrastructure and skills, building a business case, integrating AM into supply chains, mitigating risks, defining a timeline for scaled implementation, and governing the transition. This deliberate process aims to transform naval logistics to be more resilient and responsive through on-demand part production.

B. CONCLUSION

The presented roadmap provides a strategic framework for the Brazilian Navy to adopt AM capabilities in a phased, managed approach to enhance naval logistics and operational readiness. It outlines the critical elements required, from assessing current capabilities and needs to defining implementation plans while integrating into supply chains, mitigating risks, and governing the transition.

Following this deliberate roadmap may enable the Brazilian Navy to implement AM in alignment with operational needs. The ability to produce spare parts on demand will help overcome logistics delays during critical missions across Brazil's vast maritime territory, in the Amazon area and Antarctic. AM adoption has the potential to significantly improve the readiness, agility, and sustainability of naval forces.

However, realizing these benefits requires rigorous validation through AM pilots, cost-benefit analysis, and securing stakeholder buy-in. Therefore, this roadmap aims to provide a starting point pending the finalization of implementation details. Lessons from the initial phases will inform the expansion of AM capabilities across shore facilities, ships, and future platforms.

Cultivating AM expertise throughout the BN will facilitate knowledge sharing as this technology advances rapidly. Strategic partnerships with academia, industry, and allies could enable the Force to stay at the forefront in leveraging AM to enhance national defense capabilities. Integrating academic and industry collaborations into the naval AM ecosystem could improve technology transfer and strengthen domestic capabilities aligned with economic development priorities. This combination of localized support and global perspective has the potential to accelerate AM adoption for enhanced naval logistics and sovereignty protection.

With careful change management, AM can transform naval supply chains to be more resilient and responsive to evolving operational needs. This roadmap presents an adaptive strategy for adoption, setting the stage for the Brazilian Navy to lead in applying advanced technologies to better protect national interests and sovereignty.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. SUMMARY

This research aimed to evaluate and answer the question: What is the feasibility and potential impact of adopting AM as a strategic initiative to improve defense logistics in the BN?

To address this question systematically, several subsidiary research questions were investigated:

1. What AM technologies and applications are relevant for naval spare parts supply?
2. What infrastructure, systems, and process changes are required to enable AM adoption?
3. What are the risks and limitations associated with AM adoption?
4. How can the BN strategically implement AM to improve naval logistics?

The analysis revealed tangible but conditional benefits possible from thoughtful naval AM assimilation. While still an emerging capability, AM enables simplified fabrication of complex, customized components on-demand without dedicated tooling or molds. This facilitates reductions in lead time and inventory alongside enhancements in supply flexibility and contingency capacity. Equipping ships and shore facilities with compact AM printers and materials mitigates reliance on distant vendors, increasing self-sufficiency. These benefits closely align with BN priorities concerning readiness and sovereignty protection across the Blue Amazon and support its critical missions.

However, the research also demonstrated that AM remains an immature technology, with lingering deficiencies like quality variability, size and materials constraints, limited production volumes, post-processing requirements, lack of standards, and cybersecurity exposure. Mass integration appears premature before resolving such deficiencies. Challenges around upfront infrastructure costs, system interoperability, workforce skills, and cultural adoption add complexity. While selective naval AM adoption seems promising, staged assimilation aligned to a capability roadmap can help the BN methodically harness AM's latent potential while controlling attendant implementation risks.

The analysis indicated that the BN could improve logistics agility and component supply resilience by combining AM and conventional manufacturing strengths in a hybrid approach. This underscores the feasibility of limited, deliberate AM adoption for small batches of customized or critical parts needing lead time reductions and inventory optimizations. Strategic AM implementation also offers a pathway to reconstitute flexible manufacturing ability afloat and ashore over long-term capability maturation.

A. RECOMMENDATIONS

This research suggests that BN adopt a coordinated, phased approach outlined in Chapter V's AM transition roadmap focused on infrastructure development, operational validation, and risk mitigation. This roadmap could allow learning, incremental improvements, and policy maturation to guide scaled assimilation in the long term. Near-term efforts should emphasize modest goals, pilot studies, and low-risk applications.

Over 2–5 years, after proving feasibility, the BN can pragmatically expand AM across shore facilities and onto ships. Concurrently, the BN could address risks regarding data protection, quality control, workforce skills, and cyber vulnerabilities. Beyond five years, the roadmap envisions fuller integration, with suitable parts shifting from conventional to AM production through updated logistics doctrine and enterprise digitization. This methodical transition can ultimately equip the BN with increased manufacturing self-reliance and logistics responsiveness.

B. FUTURE WORK

As AM research remains limited regarding defense contexts, further studies focused on naval applications would provide invaluable quantitative insights to guide adoption decisions. Suggested areas for future research include:

- **Cost-benefit and ROI analysis:** Conduct an economic feasibility study weighing the upfront and recurring costs of AM infrastructure, materials, training, and maintenance against projected logistics improvements like lead time reductions, transportation savings, and inventory optimizations. This analysis may factor in AM reliability risks and account for uncertainty, given the technology's relative immaturity in defense contexts. Detailed cost modeling and sensitivity analysis would aid leadership decisions on justified investment levels, cost targets, and maturation timelines.

- **AM cyber vulnerability assessments:** Perform an in-depth cybersecurity evaluation focused on naval AM infrastructure encompassing printers, controllers, networks, data storage, and information flows. Assess attack vectors, data corruption/theft risks, best practices for secure system architectures, and policies to ensure quality controls and configuration management in distributed manufacturing environments. Develop naval-specific cyber protection protocols to mitigate risks as integration advances.

- **Make-or-Buy Decision analysis:** Conduct a quantitative spare parts analysis to determine criteria, parameters, and break-even points for in-house AM production compared to conventional sourcing. Exploration areas can include part criticality, operational impact, lead time sensitivity, customization needs, IP restrictions, volume demands, and maintenance workflows. Establishing guidelines for an optimal make-or-buy balance can help focus naval AM applications on the highest payoff component categories.

- **AM reliability studies:** Develop studies to test the consistency and reliability of the physicochemical properties and AM processes of relevant parts based on usage data. Assess key influences like build orientation, layer thickness, environmental exposures, surface finishes, operator variables, and maintenance needs. Statistical process controls should demonstrate repeatability within acceptable tolerances before fuller adoption.

LIST OF REFERENCES

3Dnatives. (2022, June 30). *The use of additive manufacturing in the Defense Sector*. https://www.3dnatives.com/en/the-use-additive-manufacturing-defense-sector300620224/

Adrezin, R. S., & Haliscak, N. (2017). Additive manufacturing potential on United States Coast Guard cutters for resilience in the Arctic. *Naval Engineers Journal*, *129*(4), 111–121. https://www.ingentaconnect.com/content/asne/nej/2017/00000129/00000004/art00023

Agência Marinha de Notícias. (2023, November 15). *Mais de 20 milhões de empregos dependem da Amazônia Azul* [More than 20 million jobs depend on the Blue Amazon]. Marinha do Brasil. https://www.marinha.mil.br/agenciadenoticias/mais-de-20-milhoes-de-empregos-dependem-da-amazonia-azul

Aguariavwodo, J. (2023). *Additive manufacturing adoption for supply chain resilience: An empirical investigation*. [Master's thesis, Norwegian University of Science and Technology]. https://hdl.handle.net/11250/3089833

Akmal, J. S., Salmi, M., Björkstrand, R., Partanen, J., & Holmström, J. (2022). Switchover to industrial additive manufacturing: dynamic decision-making for problematic spare parts. *International Journal of Operations & Production Management*, *42*(13), 358–384. https://doi.org/10.1108/ijopm-01-2022-0054

Ashton, L. (2023, November 2). *Embracing the promise of additive manufacturing for advanced nuclear reactors*. International Atomic Energy Agency. https://www.iaea.org/bulletin/embracing-the-promise-of-additive-manufacturing-for-advanced-nuclear-reactors

Bender, B. M., & Goulait, C. (2016, August 28). *Supplying the ends of the Earth*. Defense Logistics Agency. https://www.dla.mil/About-DLA/News/News-Article-View/Article/935463/supplying-the-ends-of-the-earth/https%3A%2F%2Fwww.dla.mil%2FAbout-DLA%2FNews%2FNews-Article-View%2FArticle%2F935463%2Fsupplying-the-ends-of-the-earth%2F

Blachowicz, T., Ehrmann, G., & Ehrmann, A. (2023). Recent developments in additive manufacturing of conductive polymer composites. *Macromolecular Materials and Engineering*, *308*(7). https://doi.org/10.1002/mame.202200692

Brazil Metal Parts. (n.d.). *Industry Partnerships*. Retrieved February 1, 2024, from https://www.brazilmetalparts.com/about-us/partnerships/index.html

Busachi, A., Erkoyuncu, J. A., Colegrove, P. A., Drake, R. R., Watts, C., Martina, F., Tapoglou, N., & Lockett, H. (2018). A system approach for modelling additive manufacturing in defence acquisition programs. *Procedia CIRP*, *67*, 209–214. https://doi.org/10.1016/j.procir.2017.12.201

Catlin, T., Lorenz, J.-T., Sternfels, B., & Willmott, P. (2017, March 1). *A roadmap for a digital transformation*. McKinsey & Company. https://www.mckinsey.com/industries/financial-services/our-insights/a-roadmap-for-a-digital-transformation

Chiujdea, C., & Cănănău, S. (2021). A review of additive manufacturing technologies. *Journal of Research and Innovation for Sustainable Society*, *3*(1), 25–32. https://doi.org/10.33727/jriss.2021.1.4:25-32

Colorado, H. A., Cardenas, C. G., Gutierrez-Velazquez, E. I., Escobedo, J. P., & Monteiro, S. N. (2023). Additive manufacturing in armor and military applications: research, materials, processing technologies, perspectives, and challenges. *Journal of Materials Research and Technology*, *27*, 3900–3913. https://doi.org/10.1016/j.jmrt.2023.11.030

Cordle, J., Baur, J., Pecota, M., & Lunday, J. (2022). The Navy can use additive manufacturing to improve warfighting readiness. *Naval Engineers Journal, 134*(2), 9–15.

Coyle, D. M. (2019). Analysis of additive manufacturing for sustainment of naval aviation systems. *Defense AR Journal, 26*(4), 425. https://libproxy.nps.edu/login?url=https://www.proquest.com/scholarly-journals/analysis-additive-manufacturing-sustainment-naval/docview/2312776496/se-2

De Brito, F. M., Da Cruz, G., Frazzon, E. M., Basto, J. P. T. V., & Alcalá, S. G. S. (2021). Design approach for additive manufacturing in spare part supply chains. *IEEE Transactions on Industrial Informatics*, *17*(2), 757–765. https://doi.org/10.1109/tii.2020.3029541

DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. *Nature, 531*(7596), 591–597. https://doi.org/10.1038/nature17145

Defense Logistics Agency. (2022). *DLA additive manufacturing implementation plan for DoDI 5000.93 Use of Additive Manufacturing in DOD*. https://www.dla.mil/Portals/104/Documents/InformationOperations/Research%20and%20Development/DLA%20Additive%20Manufacturing%20Implementation%20Plan_01Jun2022.pdf

Deshmukh, K., Pasha, S. K. K., & Sadasivuni, K. K. (2022). Environmental impact, challenges for industrial applications and future perspectives of additive manufacturing. In K. Deshmukh, S. K. Khadheer Pasha, & K. K. Sadasivuni (Eds.), *Nanotechnology-Based Additive Manufacturing*. John Wiley & Sons, Incorporated. https://doi.org/10.1002/9783527835478.ch24

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S., Garmulewicz, A., Knowles, S. O., Minshall, T., Mortara, L., Reed-Tsochas, F., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change*, *115*, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Despeisse, M., Yang, M., Evans, S., Ford, S., & Minshall, T. (2017). Sustainable value Roadmapping framework for additive manufacturing. *Procedia CIRP*, *61*, 594–599. https://doi.org/10.1016/j.procir.2016.11.186

Dow, C. (2022). *Simplifying 3D printing with OpenSCAD: Design, build and test OpenSCAD programs to bring your ideas to life using 3d printers*. Packt Publishing, Limited.

Espadinha-Cruz, P., Neves, Â., Matos, F., & Godina, R. (2023). Development of a maturity model for additive manufacturing: A conceptual model proposal. *Heliyon*, *9*(5), e16099. https://doi.org/10.1016/j.heliyon.2023.e16099

Estado-Maior da Armada (EMA). (2017). *Doutrina Militar Naval* (EMA-305 – DMN, 1ª Edição) [Brazilian Naval Military Doctrine] (1st edition). Marinha do Brasil.

Félix, L.A.G. (2017). Potencial disruptivo da manufatura aditiva – influência nas cadeias de suprimentos e uma aplicação na Marinha do Brasil [Disruptive potential of additive manufacturing – influence on supply chains and an application in the Brazilian Navy]. [Master's thesis, Pontifícia Universidade Católica do Rio de Janeiro]. https://www.maxwell.vrac.puc-rio.br/30104/30104.PDF

Fernandes, F., & de Souza, F. A. (2022). The potential benefits of adopting the single fuel concept at sea in the Brazilian Navy. [Master's thesis, Naval Postgraduate School]. NPS Archive: Calhoun. https://hdl.handle.net/10945/71458

Fernandes, V., Matos, F., Oliveira, J., Neves, Â. N., & Godina, R. (2023). Identifying strategic opportunities through the development of a roadmap for additive manufacturing: The example of Portugal. *Heliyon*, *9*(9), e19672. https://doi.org/10.1016/j.heliyon.2023.e19672

Gallinaro, S. (2023). Additive manufacturing-based supply chain configurations. In A. Sharma (Ed.), *Advances in 3D printing*. IntechOpen. https://doi.org/10.5772/intechopen.110174

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C., Shin, Y. C., Zhang, S., & Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, *69*, 65–89. https://doi.org/10.1016/j.cad.2015.04.001

Gartner. (n.d.). *Gartner Hype Cycle*. Retrieved January 9, 2024, from https://www.gartner.com/en/research/methodologies/gartner-hype-cycle

Ghobakhloo, M. (2018). The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management*, *29*(6), 910–936. https://doi.org/10.1108/jmtm-02-2018-0057

Golledge, N. R., Kowalewski, D. E., Naish, T., Levy, R. H., Fogwill, C. J., & Gasson, E. (2015). The multi-millennial Antarctic commitment to future sea-level rise. *Nature*, *526*(7573), 421–425. https://doi.org/10.1038/nature15706

Höller, C., Karanovic, S., Wiltsche, M., & Klug, A. (2022). Value creation through insourcing – Additive manufacturing as efficient in-house production technology. *Procedia CIRP*, *107*, 1391–1396. https://doi.org/10.1016/j.procir.2022.05.163

Holmes, L. R., Jr. (2023). Additive technology revolutionizes defense manufacturing. In *National Defense, 108*(836), 14–16. https://www.proquest.com/docview/2836029428

International Organization for Standardization. (2021). *ISO/ASTM 52900:2021 Standard terminology for additive manufacturing – General principles – Fundamentals and vocabulary*. ISO. https://www.iso.org/standard/74514.html

Lei Complementar no 97, de 9 de junho de 1999. Dispõe sobre as normas gerais para a organização, o preparo e o emprego das Forças Armadas brasileiras [Provides for the general rules for the organization, preparation and employment of the Brazilian Armed Forces].

Jagoda, J. A., Diggs-McGee, B. N., Kreiger, M. A., & Schuldt, S. J. (2020). The viability and simplicity of 3D-printed construction: a military case study. *Infrastructures*, *5*(4), 35. https://doi.org/10.3390/infrastructures5040035

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Rab, S. (2021). Role of additive manufacturing applications towards environmental sustainability. *Advanced Industrial and Engineering Polymer Research*, *4*(4), 312–322. https://doi.org/10.1016/j.aiepr.2021.07.005

Joint Defense Manufacturing Council. (2021). *Department of Defense additive manufacturing strategy* (1st ed.). Office of the Under Secretary of Defense for Research and Engineering. https://www.cto.mil/dod-additive-manufacturing-strategy/

Johnston, T., Smith, T. D., & Irwin, J. L. (2018). *Additive manufacturing in 2040: powerful enabler, disruptive threat*. RAND Corporation. https://www.rand.org/pubs/perspectives/PE283.html

Jung, S., Kara, L. B., Nie, Z., Simpson, T. W., & Whitefoot, K. S. (2023). Is additive manufacturing an environmentally and economically preferred alternative for mass production? *Environmental Science & Technology*, *57*(16), 6373–6386. https://doi.org/10.1021/acs.est.2c04927

Júnior, A. J. de J., & Curto, L. de B. (2020). Os Navios de Assistência Hospitalar da Marinha do Brasil e a efetividade no atendimento às comunidades ribeirinhas do Pantanal e da Amazônia [The Brazilian Navy's Hospital Assistance Ships and their Effectiveness in Serving the Riverine Communities of the Pantanal and the Amazon]. *Revista GeoPantanal*, *15*(29), Article 29. https://periodicos.ufms.br/index.php/revgeo/article/view/11880

Kadri, M. R. E., Santos, B. S. D., De Sousa Lima, R. T., Schweickardt, J. C., & Martins, F. M. (2019). Unidade Básica de Saúde Fluvial: um novo modelo da Atenção Básica para a Amazônia, Brasil [Floating Primary Health Center: a new approach to Primary Care in the Amazon, Brazil]. *Interface*, *23*. https://doi.org/10.1590/interface.180613

Kandukuri, S., Ibrahim, I., Osman, S., Danwatte, T., Qin, X. D., Feng, L., & Ang, W. (2019). *Additive manufacturing market feasibility study with Singapore perspective* (Report no. 2019-9172P, Rev. 1). DNV GL. https://www.mpa.gov.sg/docs/mpalibraries/mpa-documents-files/ittd/key-mint-fund-projects/additive-manufacturing-market-feasibility-study_public-version.pdf

Kennicutt, M. C., Bromwich, D. H., Liggett, D., Njåstad, B., Peck, L. S., Rintoul, S. R., Ritz, C., Siegert, M. J., Aitken, A., Brooks, C. M., Cassano, J. J., Chaturvedi, S., Chen, D., Dodds, K., Golledge, N. R., Bohec, C. L., Leppe, M., Murray, A. E., Nath, P., . . . Chown, S. L. (2019). Sustained Antarctic research: a 21st century imperative. *One Earth*, *1*(1), 95–113. https://doi.org/10.1016/j.oneear.2019.08.014

Khajavi, S. H., Ituarte, I. F., Jaribion, A., An, J., Chua, C. K., & Holmström, J. (2020). Impact of additive manufacturing on supply chain complexity. In *Proceedings of the 53rd Hawaii International Conference on System Sciences*, 4505–4514. https://hdl.handle.net/10125/64293

Kostidi, E., & Nikitakos, N. (2018). Is it time for the maritime industry to embrace 3D printed spare parts? *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, *12*(3), 557–564. https://doi.org/10.12716/1001.12.03.16

Kotter, J. P. (2012). *Leading change*. Harvard Business Review Press.

Kravcov, A., Svoboda, P., Štoller, J., Pokorný, Z., Małachowski, J., Płatek, P., Baranowski, P., Kruszka, L., & Vasilis-Vasiliauskas, A. (2020). Development of innovative solutions for intelligent inspection of products of additive manufacturing for navy supply. *Challenges to National Defence in Contemporary Geopolitical Situation*, *2020*(1), 300–309. https://doi.org/10.47459/cndcgs.2020.39

Lube Filho, R., Silva, A. H. M. F. T. da, Mendes, V. B., & Lima de Deus, P. A. (2024). Análise da influência de defeitos nas propriedades mecânicas de materiais poliméricos utilizados em peças fabricadas por impressão 3D [Analysis of the influence of defects on the mechanical properties of polymeric materials used in 3D printed parts]. *The Journal of Engineering and Exact Sciences*, *10*(1), 17193. https://doi.org/10.18540/jcecvl9iss10pp17193

Marinha do Brasil. (2017, May 11). *Missão e Visão de Futuro* [Mission and Future Vision]. https://www.marinha.mil.br/content/missao-e-visao-de-futuro-da-marinha

Marinha do Brasil. (2019, February 20). *Navios de Assistência Hospitalar* [Hospital Assistance Ships]. https://www.marinha.mil.br/navios-de-assistencia-hospitalar

Marinha do Brasil. (2020, July 15). *Programa Antártico Brasileiro* [Brazilian Antarctic Program]. Secretaria da Comissão Interministerial para os Recursos do Mar (SECIRM). https://www.marinha.mil.br/secirm/pt-br/proantar

Markforged. (2022). *How the U.S. military uses 3D printing technologies*. https://markforged.com/resources/blog/how-are-different-branches-of-the-us-military-using-additive

Meyer, M. M., Glas, A. H., & Eßig, M. (2020). Systematic review of sourcing and 3D printing: make-or-buy decisions in industrial buyer–supplier relationships. *Management Review Quarterly*, *71*(4), 723–752. https://doi.org/10.1007/s11301-020-00198-2

Mohr, S., & Khan, O. (2015). 3D printing and its disruptive impacts on supply chains of the future. *Technology Innovation Management Review, 5*(11), 20–25. https://doi.org/10.22215/timreview/942

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

Öberg, C., & Shams, T. (2019). On the verge of disruption: rethinking position and role – the case of additive manufacturing. *Journal of Business & Industrial Marketing*, *34*(5), 1093–1105. https://doi.org/10.1108/jbim-10-2018-0293

Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio). (n.d.). NEXT Núcleo de Experimentação Tridimensional [NEXT Tridimensional Experimentation Center]. *NEXT*. Retrieved February 7, 2024, from https://next.dad.puc-rio.br

Praneeth, J., Venkatesh, S., & Krishna, L. S. (2023). A review on additive manufacturing processes. *E3S Web of Conferences*, *430*,1282-. https://doi.org/10.1051/e3sconf/202343001282

Priyadarshini, J., Singh, R. K., Mishra, R., & Bag, S. (2022). Investigating the interaction of factors for implementing additive manufacturing to build an antifragile supply chain: TISM-MICMAC approach. *Operations Management Research*, *15*(1–2), 567–588. https://doi.org/10.1007/s12063-022-00259-7

Project Management Institute. (2021). *A guide to the Project Management Body of Knowledge* (PMBOK® Guide) (7th ed.). Project Management Institute. https://www.pmi.org/help-marketplace/books-and-pmi-logo-items-help

Roach, T. (2021, July 1). *Expeditionary Fabrication in the Marine Corps*. U.S. Naval Institute. https://www.usni.org/magazines/proceedings/2021/july/expeditionary-fabrication-marine-corps

Rodríguez, J. N., Sosa, H. H. A., Villarreal-Archila, S. M., & Ortíz, Á. (2022). The impact of additive manufacturing on supply chain management from a system dynamics model—Scenario: Traditional, centralized, and distributed supply chain. *Processes*, *10*(12), 2489. https://doi.org/10.3390/pr10122489

Rinaldi, M., Caterino, M., Manco, P., Fera, M., & Macchiaroli, R. (2021). The impact of additive manufacturing on supply chain design: a simulation study. *Procedia Computer Science*, *180*, 446–455. https://doi.org/10.1016/j.procs.2021.01.261

Rintoul, S. R., Chown, S. L., DeConto, R. M., England, M. H., Fricker, H. A., Masson-Delmotte, V., Naish, T., Siegert, M. J., & Xavier, J. C. (2018). Choosing the future of Antarctica. *Nature*, *558*(7709), 233–241. https://doi.org/10.1038/s41586-018-0173-4

Sakib-Uz-Zaman, C., & Khondoker, M. a. H. (2023). Polymer-based additive manufacturing for orthotic and prosthetic devices: Industry outlook in Canada. *Polymers, 15*(6), 1506. https://doi.org/10.3390/polym15061506

Salman, M., & Mushtaq, W. (2018). *Impact of additive manufacturing on supply chain network structure*. [Master's thesis, Norwegian University of Science and Technology (NTNU)]. http://hdl.handle.net/11250/2567034

Salmi, M. (2021). Additive manufacturing processes in medical applications. *Materials, 14*(1), 191. https://doi.org/10.3390/ma14010191

Schmelzle, J. (2022). *Additive manufacturing—the advantages and the challenges*. DAU Defense Acquisition University. https://www.dau.edu/index.php/datl/b/additive-manufacturing

Secretaria-Geral da Marinha (SGM). (2020). *Normas para a execução do abastecimento* (SGM-201, 7ª Revisão) [Brazilian Navy standards for supply execution] (7th review). Marinha do Brasil.

Shields, W. E. (2023). Simulating consumable order fulfillment via additive manufacturing technologies [Master's thesis, Naval Postgraduate School]. NPS Archive: Calhoun. https://hdl.handle.net/10945/72054

Tofail, S. A. M., Koumoulos, E. P., Bandyopadhyay, A., Bose, S., O'Donoghue, L. M., & Charitidis, C. A. (2018). Additive manufacturing: Scientific and technological challenges, market uptake and opportunities. *Materials Today*, *21*(1), 22–37. https://doi.org/10.1016/j.mattod.2017.07.001

Trompowsky, M. (2023, October 5). *A seca do Rio Amazonas e os impactos logísticos e econômicos para a região Norte* [The Amazon River drought and the logistical and economic impacts for the northern region of Brazil]. Guia Marítimo. https://www.guiamaritimo.com.br/especiais/logistica/a-seca-do-rio-amazonas-e-os-impactos-logisticos-e-economicos-para-a-regiao-norte

U.S. National Science Foundation. (2023). *Packing and Shipping Instructions* (TL-MAN-0002). https://www.usap.gov/logistics/documents/TL-MAN-0002.pdf

Vaezi, M., Chianrabutra, S., Mellor, B., & Yang, S. (2013). Multiple material additive manufacturing – Part 1: A review. *Virtual and Physical Prototyping*, *8*(1), 19–50. https://doi.org/10.1080/17452759.2013.778175

Valtonen, I., Rautio, S., & Lehtonen, J. M. (2022). Designing resilient military logistics with additive manufacturing. *Continuity & Resilience Review, 5(1)*, 1–16. https://doi.org/10.1108/CRR-08-2022-0015

Wakefield, E. (2024, January 16). *MX3D and SENAI Institute give Brazilian market access to WAAM*. VoxelMatters. https://www.voxelmatters.com/mx3d-and-senai-institute-give-brazilian-market-access-to-waam

Wohlers Associates. (2023). *Wohlers Report 2023: Analysis. Trends. Forecasts. 3D printing and additive manufacturing state of the industry*. https://wohlersassociates.com/product/wr2023

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Fort Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California