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EXPANDING THE DIGITAL THREAD FOR ADDITIVE MANUFACTURING (AM): ARCHITECTING A DIGITAL TWIN (DT) META-MODEL (MM) FRAMEWORK

by

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Additive Manufacturing (AM) is an innovative technology gaining interest across various industries, including the Department of Defense (DOD). However, numerous uncertainties regarding its efficacy and necessary technological improvements persist, making AM a challenging alternative to traditional manufacturing methods. To address these uncertainties, the tri-maritime service is exploring the value of AM by employing an Additive Manufacturing Digital Twin (AMDT). This capstone design project focuses on creating a DT framework that encapsulates the seven AM types in support of the DOD AM strategy. The AMDT, developed in Magic System of Systems Architect (MSOSA), follows the DOD digital engineering initiative by transforming traditional system engineering approach to a Model-Based Systems Engineering (MBSE) one. The deployed Additive Manufacturing Digital Twin Meta-Model (AMDTMM) will serve as a centralized repository for current and future AM research, with a foundational framework that can evolve into a full-fledged DT to ultimately enhance the tri-maritime service's ability to harness AM's potential effectively.

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ABSTRACT

Additive Manufacturing (AM) is an innovative technology gaining interest across various industries, including the Department of Defense (DOD). However, numerous uncertainties regarding its efficacy and necessary technological improvements persist, making AM a challenging alternative to traditional manufacturing methods. To address these uncertainties, the tri-maritime service is exploring the value of AM by employing an Additive Manufacturing Digital Twin (AMDT). This capstone design project focuses on creating a DT framework that encapsulates the seven AM types in support of the DOD AM strategy. The AMDT, developed in Magic System of Systems Architect (MSOSA), follows the DOD digital engineering initiative by transforming traditional system engineering approach to a Model-Based Systems Engineering (MBSE) one. The deployed Additive Manufacturing Digital Twin Meta-Model (AMDTMM) will serve as a centralized repository for current and future AM research, with a foundational framework that can evolve into a full-fledged DT to ultimately enhance the tri-maritime service's ability to harness AM's potential effectively.

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List of Acronyms and Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
AMDTMM	Additive Manufacturing Digital Twin Meta-Model
CAMRE	Consortium for Additive Manufacturing Research and Education
CSM	Cameo Systems Modeler
DE	Digital Engineering
DED	Direct Energy Deposition
DMLM	Direct Metal Laser Melting
DMLS	Direct Metal Laser Sintering
DOD	Department of Defense
DODAF	Department of Defense Architecture Framework
DoN	Department of the Navy
DT	Digital Twin
EBAM	Electron Beam Additive Manufacturing
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
INCOSE	International Council on Systems Engineering
IoT	Internet of Things

JCAs	Joint Capability Areas
LCD	Liquid Crystal Display
LDW	Laser Deposition Welding
LOM	Laminated Object Manufacturing
MBSE	Model-Based Systems Engineering
MJF	Multi Jet Fusion
MM	Meta-Model
MODAF	Ministry of Defence Architectural Framework
MSOSA	Magic System of Systems Architect
NAF	NATO Architecture Framework
Naval IME	Naval Integrated Modeling Environment
NPS	Naval Postgraduate School
OQE	Objective Quality Evidence
PBF	Powder Bed Fusion
PLA	Polylactic Acid
POR	Program of Record
RIMPAC	Rim of the Pacific
RUL	Remaining Useful Life
SE	System Engineering
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SM	Subtractive Manufacturing

SME	Subject Matter Expert
SysML	Systems Modeling Language
UAF	Unified Architecture Framework
UAM	Ultrasonic Additive Manufacturing

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Executive Summary

Additive Manufacturing (AM), a groundbreaking and rapidly evolving technology, has captured the attention of various industries, including the Department of Defense (DOD). Commonly known as 3D printing, AM offers unparalleled flexibility and customization, with potential benefits such as cost savings, reduced lead times, and improved sustainability. However, uncertainties remain regarding the efficacy, integration challenges, and required technological advancements for AM to become a viable alternative for the U.S. tri-maritime service. To address these challenges, the tri-maritime service is exploring the benefits of employing Digital Engineering (DE) to aid in the capability development, deployment, and maintenance of AM technologies. This System Engineering (SE) capstone project supports the tri-maritime service in their research by employing DE heuristics to create an AM Digital Twin (DT) Meta-Model (MM) (Additive Manufacturing Digital Twin Meta-Model (AMDTMM)). Collaboration between various stakeholders, such as researchers, manufacturers, and decision-makers, is crucial for the successful development and implementation of the AMDTMM, with the Naval Postgraduate School (NPS) and its Consortium for Additive Manufacturing Research and Education (CAMRE) at the forefront of evaluating AM potential usage in the tri-maritime service.

The CAMRE at the NPS aimed to develop a DT MM for AM using Model-Based Systems Engineering (MBSE) and the Magic System of Systems Architect (MSOSA) system modeling tool. This project commenced with a research phase centered on AM and DT technologies, laying the foundation for the design process. The resulting AMDTMM framework consists of a DT for seven different types of printers. To demonstrate how to use the tool, an instantiation of the Xerox ElemX was developed. The framework is versatile, modular, and scalable, designed to evolve with future contributions and support the ongoing advancement of AM research and applications.

Through future collaboration with CAMRE and industry partners, the AMDTMM can grow to encapsulate more AM printer instances. As more printer information becomes available and is incorporated into the model, the AMDTMM's capabilities will further expand. Potential future improvements include integrating external simulations and models, adding information regarding time needed to print a part, environmental behaviors, maintainabil-

ity concerns, and enhancing compatibility with the Internet of Things (IoT) to facilitate data transfer between the physical and digital models. The AMDTMM offers a significant opportunity for CAMRE and the tri-maritime services to better understand complex AM system component functionalities and select the most adequate printer for specific purposes, requirements, and environments. Its ongoing development and expansion will continue to benefit the research community and support the advancement of AM technology.

CHAPTER 1: Introduction

This chapter defines the problem statement, objectives, system engineering process, and the report structure for this System Engineering (SE) capstone project. Additionally, this chapter explains the methodology the capstone project followed to develop the Additive Manufacturing Digital Twin Meta-Model (AMDTMM) tool and how the model will be used by stakeholders and future researchers.

1.1 Problem Statement

Additive Manufacturing (AM), a groundbreaking and rapidly evolving technology, has captured the attention of various public and private industries, including the Department of Defense (DOD). Commonly known as 3D printing, AM has the potential to significantly transform the manufacturing sector by enabling cost-effective and efficient production. Defined as "the process of joining materials to create objects from 3D model data, usually layer upon layer, as opposed to Subtractive Manufacturing (SM) methodologies, such as traditional machining" [1], AM offers unparalleled flexibility and customization. Recognizing the strategic importance of this innovation, the DOD developed an AM strategy to provide guidance in harnessing this technology. The strategy highlights AM as "a rapid, on-demand, and customizable manufacturing tool that enables the logistical and operational reforms outlined in the Summary of the 2018 National Defense Strategy" [2]. The potential benefits of adopting AM technology in the tri-maritime services could include cost savings, reduced lead times, and improved sustainability.

In response to the transformative potential, numerous uncertainties remain regarding the efficacy, integration challenges, and required technological advancements for AM to become a viable alternative for the U.S. tri-maritime services. The tri-maritime service is exploring the benefits of employing Digital Engineering (DE) to aid in the capability development, deployment, and maintenance of AM technologies. Specifically, this capstone project is aiding the tri-maritime services aim to create an AM Digital Twin (DT) to identify and exploit the undetermined potential. This SE capstone project will support the tri-maritime service in their research by employing DE heuristics defined by the DOD to create an AM DT Meta-Model (MM). To successfully develop and implement the AMDTMM, collaboration between various stakeholders, such as researchers, manufacturers, and decision-makers, is crucial. The Naval Postgraduate School (NPS) is a key researcher and partner in AM technological integration, with their Consortium for Additive Manufacturing Research and Education (CAMRE) being on the forefront in evaluating AM potential usage in the tri-maritime service.

The U.S. Navy must assess and facilitate the replacement of tri-maritime components on U.S. ships to keep up with the evolving technological landscape. Research is ongoing to determine how AM can be deployed for the tri-maritime service following NPS's AM organization, CAMRE, recent experiment of Xerox ElemX 3D printer. As of July 18, 2022, the Xerox ElemX 3D printer was installed on board the USS Essex (LHD 2), followed by at-sea trials [3], marking a significant milestone in the integration of AM technology within Naval operations. The ElemX 3D printer measures approximately nine feet long, four feet wide, and seven feet tall, and reaches an internal temperature of over 1,500 degrees Fahrenheit. It produces custom metal components that can be used to repair defective equipment while underway [4], offering the potential to significantly enhance operational efficiency. Figure 1.1 provides an example of what the ElemX looks like. In addition to arrangements and spacing requirements, interfaces with supporting equipment and materials must also be considered for AM implementation and processes on board ships. This includes, but is not limited to, water-cooling, structural load, electrical power, wire spool, and replacement parts. By addressing these challenges and leveraging the benefits of DE and DT, the Navy can accelerate the adoption of AM technology, ultimately revolutionizing the manufacturing sector within the maritime domain.

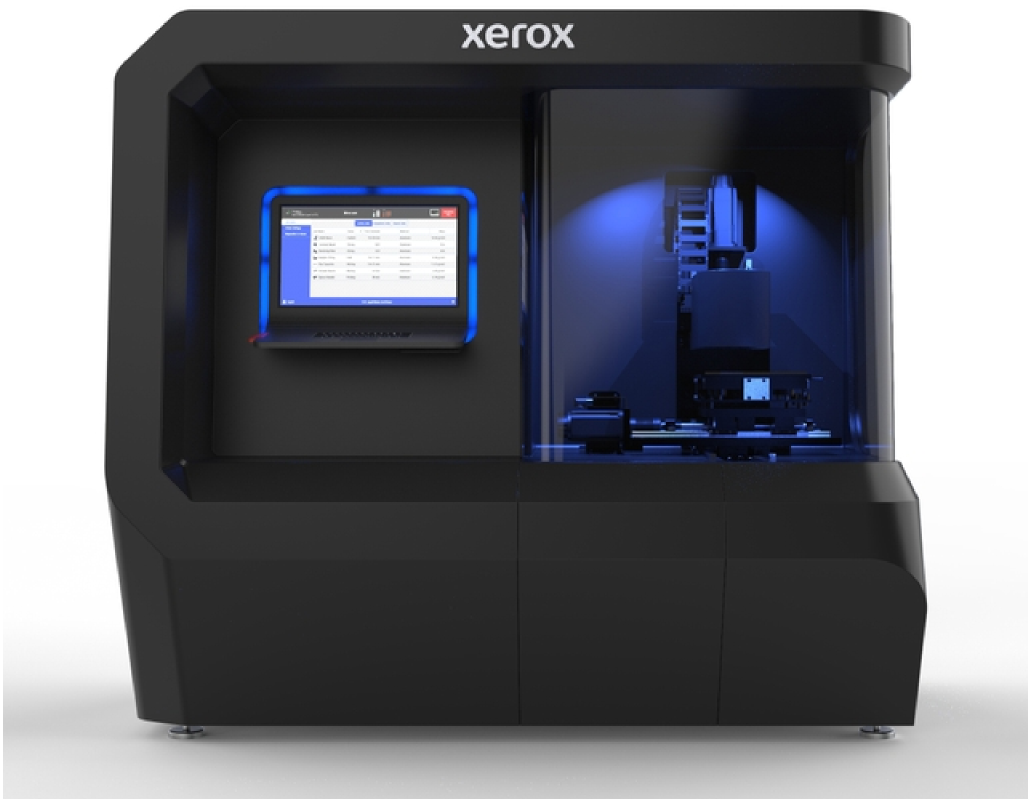

Figure 1.1. XEROX ElemX 3D Metal Printer Source: [5]

The DOD's DE Strategy describes DE as "an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support life-cycle activities from concept through disposal" [6]. This definition permits the development of models from conceptual design to disposal, as long as the data in the model comes from trusted sources. The strategy also provides an outline to guide the planning, development, and implementation of the digital engineering transformation across the DOD. [6]. In 2020, the Department of the Navy (DoN) introduced its own strategy, which shares similar objectives with the DOD version. The DoN Strategy aims to "transform systems engineering capabilities by using common, composable, interactive, model-based systems to store and exchange data, models, and information within and across programs" [7]. The

DoN strategy identifies five key objectives:

1. Formalize the development, integration, and use of models.
2. Establish a lasting authoritative knowledge source.
3. Leverage technological innovation to enhance engineering practices.
4. Create the supporting infrastructure and environments for DE practices.
5. Cultivate a culture and workforce that embraces and supports DE throughout its life cycle.

DE plays a crucial role in the development of a DT, which is essential for the advancement of AM technology. Since the definition of a DT varies among leading researchers and professionals, for the scope of this capstone project, the definition of a DT will be "a model that helps stakeholders answer specific questions by providing a readily available, rapidly testable digital analog to the system of interest" [8]. The research presented in this document develops a DT for AM to support this definition and the DOD digital engineering initiative, aiming to address the challenges and uncertainties surrounding AM technology.

The proposed AMDTMM is structured to serve as a DT template for AM. This AMDTMM functions as a centralized repository for AM research, providing a modular framework that can evolve into a comprehensive DT in the future. Moreover, the AMDTMM tool applies the Model-Based Systems Engineering (MBSE) methodology using a tool called Magic System of Systems Architect (MSOSA), which is essential for streamlining the integration and adoption of AM DT into existing systems and processes. MSOSA is a product line by Dassault Systems, offering the most robust standards-compliant including Department of Defense Architecture Framework (DODAF) 2.0, Ministry of Defence Architectural Framework (MODAF), NATO Architecture Framework (NAF) 3, NAF 4, and Unified Architecture Framework (UAF) 1.0 via a UAF standardized solution [9]. MSOSA is the de facto MBSE tool of choice for the DON via the Naval Integrated Modeling Environment (Naval IME), highlighting its importance in facilitating the adoption of AM DT across various naval applications [7]. MSOSA relies on the Systems Modeling Language (SysML), which is defined as, "a general-purpose modeling language designed to support the specification, analysis, design, verification, and validation of complex systems," [10] which makes it ideal for modeling AM processes and equipment .

1.2 Objectives

The objective of this study is to expand the current research performed in the DT AM space and provide a centralized repository of curated data for stakeholders. This digital expansion of 3D printing in conjunction with generating a MM will collectively provide a single source of truth for the tri-maritime services and serve as a repository to store and maintain models within the AMDTMM. By creating a DT for each 3D printer, the physical and functional characteristics for each printer can be highlighted and shown in various SysML diagrams. Performance data for each printer will have a designated section in the AMDTMM for post-mission analysis. The expected outcomes of this project include a more informed selection process for 3D printers, increased efficiency in deploying AM technologies in the tri-maritime services and a foundation for further advancements in the field.

Due to the complexity of developing a full operational DT, this capstone project will focus on making a partial DT with the goal of creating the foundational model utilizing DE strategies and heuristics to support the additional expansion. The overall intent of the AMDTMM is to centralize the current research performed in the AM area of study with the goal to facilitate both future works and provide accessibility to decision-making stakeholders. The motivation for this research is to further the DE domain for AM to help decision-makers select the right 3D printer for the war-fighter to bring on deployment. The AMDTMM will collectively serve as a one-stop-shop for collected information related to all instantiated 3D printers developed in the tool.

The Xerox ElemX 3D metal printer will be the first utilized AM printer that will be incorporated into the AMDTMM and serve as the initial case study to demonstrate how a 3D printer can be instantiated using MSOSA. Previous work will be leveraged as much as possible and used as a starting point for this project, and ideally, converted to a modular component that can be integrated within the AMDTMM. The potential scalability of the AMDTMM allows for the integration of additional 3D printers and AM technologies as they become available.

Challenges were expected during the development of the partial DT, such as data acquisition and research, model validation, and technology limitations. The team employed strategies such as thorough literature reviews, expert consultation, and iterative model refinement to address these challenges. Consequently, the DT portion of the AMDTMM is a partial DT due to the capstone design team not having immediate access to a Xerox ElemX 3D printer or any other 3D printer available to support data acquisition. Furthermore, this DT is designed to be modular to allow for continued future development and research in the DT space. Future development of the AMDTMM can be used to read in real-time data to update and fine-tune each printer instance for more accurate results and live feedback on performance.

The AMDTMM will be designed and developed within MSOSA, as it is the official digital engineering tool of the Navy. Within the AMDTMM, the structure of the model will be at the forefront of this design project to ensure the architecture supports the various diagrams, views needed. This AMDTMM model consists of physical (structural) and functional (behavioral) characteristics stored for different types of printers. The physical data can include aspects such as the print bed, extruder, feeder, filament, frame, and display. The functional data may encompass printer head position, average raw material used, temperature differential control, time to print, maximum size, and/or quantity of part(s) being printed, among others. The combination of both the physical and functional models will collectively form the DT of that specific printer.

1.3 System Engineering Process

To successfully execute the planned project deliverable, the team implemented a tailored SE approach. As part of the SE approach, the team performed an initial stakeholder analysis by breaking down the initial CAMRE broad area research study proposal. The bulk of this capstone design project is centered around a software-driven modeling effort, which favors the use of the SE spiral model approach. However, given the time constraints on this capstone project, the team incorporated elements of the Agile method, which favors rapid iterative design [11], and modified the traditional spiral method as necessary.

The benefits of using a hybrid agile-spiral approach include faster development cycles, better adaptation to changing requirements, and improved collaboration among team members. This approach aims to strike a balance between the thoroughness of the spiral method and the speed and adaptability of the Agile method, ultimately increasing the likelihood of a successful project outcome. A detailed overview and comparison between SE processes can be found in Section 2.4: *Systems Engineering Processes Review*. By adopting this hybrid agile-spiral approach and focusing on the structure of the AMDTMM, the team aimed to efficiently develop a comprehensive and flexible model that can accommodate various types of 3D printers, supporting the decision-making process for stakeholders and future research in the AM domain.

1.4 Report Structure

In Chapter 2: *Background and Literature Review*, a review of prior work is discussed in respect to the problem introduced in Chapter 1: *Introduction*. The literature review focuses primarily on past NPS thesis and capstone projects on DTs as well as other relevant topics to provide improved understanding of the technology and applications. Additionally, this chapter investigates current capabilities of DTs both in the DOD and in industry.

In Chapter 3: *Design and Development*, the focus is on designing and developing the architecture for the AMDTMM by building off the foundation of discussed in Chapter 1: *Introduction*, and Chapter 2: *Background and Literature Review*. This chapter begins by introducing the stakeholders, then transitioning the stakeholder needs to requirements. The AMDTMM functional and physical description is explained. The system decomposition continues through to developing the AMDTMM framework, including functional allocation.

In Chapter 4: *Implementation, Instantiations and User Guide*, the functionality of the AMDTMM is discussed along with a summary of use cases. How the user uses the AMDTMM is answered along with showcasing a user guide that is built directly in the DT meta-model.

Finally, Chapter 5: *Recommendations and Conclusions* covers recommendations for the AMDTMM architecture and framework, including suggestions for areas of future work. Additionally, this chapter serves as the conclusion of the report and a recap of the capstone project.

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CHAPTER 2:
Background and Literature Review

This chapter serves to detail the review of previous work regarding the problem introduced in Chapter 1: *Introduction*. It comprises of a review of journal articles, standards, and NPS theses and capstones, focusing on what AM is, the novelty and complexity of DTs, and contrasting different SE processes. The literature review covers four main topics: Section 2.1: *The History of Additive Manufacturing*, where the emphases is directed to the seven main types of AM technologies and how AM is used in the DOD; Section 2.2: *Digital Twin Technological Capability*, where DT are used for AM and developing DT in a MBSE environment; Section 2.3: *MBSE Frameworks*, where three different frameworks are presented; Section 2.4: *Systems Engineering Processes Review*, where the Vee, Waterfall, and Spiral models are compared; and lastly a recap of the section is presented Section 2.5: *Conclusion*.

2.1 The History of Additive Manufacturing

AM is defined as "a process of joining materials to make objects from three-dimensional model data, usually layer upon layer, as opposed to SM methodologies" [1]. In contrast, SM is defined as "making objects by removing material (e.g., milling, drilling, grinding, carving) from a bulk solid to leave a desired shape" [1]. AM offers a novel and unique alternative to traditional manufacturing approaches. The origins of AM can be traced back to the 1960s, when researchers at Battelle Memorial Institute first attempted to create solid objects using photopolymers and lasers [12]. However, the technology was not sufficiently mature at the time, and it took until the late 1980s for the first commercially available AM devices to emerge. These early AM devices utilized a technique called stereolithography, "which involves creating three-dimensional objects by solidifying thin layers of ultraviolet light-sensitive liquid polymer using a laser" [12]. This groundbreaking technology paved the way for the technological revolution that has become modern-day AM. Over time, AM technology has evolved and diversified, encompassing a variety of processes and transforming traditional manufacturing by enabling the production of parts and products with greater efficiency, customization, and design freedom. The primary advantages of using AM over traditional SM includes an abundance of benefits such as:

- *Rapid prototyping:* AM allows for the swift creation of functional prototypes, significantly reducing the time and cost associated with traditional manufacturing methods.
- *Low-volume production:* With its ability to produce small quantities of parts with minimal waste, AM serves as an ideal solution for low-volume or customized production.
- *Complex geometries:* AM enables the fabrication of intricate internal structures and geometries that are otherwise unachievable with conventional manufacturing techniques.
- *Customization:* AM facilitates the production of unique, tailored parts and products designed to meet specific customer needs.
- *Reduced tooling costs:* By eliminating the necessity for expensive tooling and molds, AM proves to be a more cost-effective option for small-scale production runs.

The academic article "3D Metal Printing Technology" [13] serves as a valuable reference and introduction to the field of AM. Focusing on metal printing technology, the article presents an overview of "3D Printing technologies, materials, applications, advantages, disadvantages, challenges, economics and applications of 3D metal printing technology" [13]. It also introduces the two most well-known 3D metal AM processes - Powder Bed Fusion (PBF) and Direct Energy Deposition (DED). A comprehensive comparison between these two technologies, along with an informative overview of their critical components, offers a strong foundation for understanding the intricacies of specifically metal AM printing processes.

AM is transforming the manufacturing industry by offering new opportunities for innovation, increased efficiency, and improved sustainability. While traditional SM methods are still widely used, AM is expanding the capabilities and flexibility of manufacturing, and is becoming an increasingly popular solution for a variety of applications. These benefits have led the DOD to become interested in utilizing AM to enhance war-fighter capabilities. A comprehensive AM strategy was developed, culminating in the formal DOD Additive Manufacturing Strategy, released in 2021 by the Office of the Deputy Director for Strategic Technology Protection and Exploitation. The strategy aims to incorporate AM into the supply chain to improve mission readiness, reduce costs, and increase innovation [2]. Key objectives from the DOD's AM Strategy showcase the these benefits such as:

1. *Rapid Prototyping:* The DOD aims to use AM to rapidly prototype and test new designs and technologies, reducing the time and costs associated with traditional manufacturing methods.
2. *Sustainment:* The DOD intends to use AM to produce replacement parts and components on-demand, reducing the need for large inventories and improving supply chain efficiency.
3. *Supply Chain Resilience:* The DOD is exploring the use of AM to create alternative supply chains and reduce dependence on foreign suppliers.
4. *Modernization:* The DOD is investing in AM to modernize its manufacturing processes and capabilities, enabling the production of more advanced and innovative products [2].

The DOD is working with industry and academic partners to advance AM technology and promote its adoption across all branches of the military. The strategy includes initiatives to improve the training and education of DOD personnel in AM, develop and implement AM standards, and invest in research and development to advance the technology [2]. Specifically, in the context of this capstone project, the tri-maritime services are exploring the use of AM in shipboard applications. Overall, the DOD's AM strategy recognizes the importance of AM technology for national security and is actively pursuing initiatives to integrate AM into the DOD supply chain.

2.1.1 Seven Types of AM Technologies

The technology used for AM continues to evolve rapidly, incorporating various materials and printing methods such as vat photopolymerization, PBF, binder jetting, material jetting, sheet lamination, material extrusion, and direct energy deposition. Each 3D printing method has advantages and disadvantages, including factors such as materials used, applications, challenges, costs, and overall implementation. Within the DOD AM Strategy, these seven broad types of AM techniques are defined, which will be incorporated within this capstone project's AMDTMM. These seven types of AM processes are listed in Figure 2.1.

Figure 2.1. Seven industry recognized types of additive manufacturing processes. Source: [2]

2.1.1.1 Binder Jetting

Binder Jetting is defined as, "an AM process in which a liquid bonding agent is selectively deposited to join powder materials" [1]. This process is typically accomplished by utilizing a print head to deposit a liquid binder material onto a powder bed, layer by layer, to build a solid object. The liquid binder material adheres the powder particles together, forming what is known as a green part, which are parts that have not undergone any post processing and treatment [14]. In this state, the parts are structurally weak, porous and sensitive, and in order to achieve the desired structural integrity, it is necessary to subject the part to further processing, such as sintering or infiltration, to increase structural integrity.

"A wide variety of materials including polymers, metals, and ceramics can be processed successfully with binder jetting" [14]. An overview of the different components of the Binder Jetting printing process is shown in Figure 2.2.

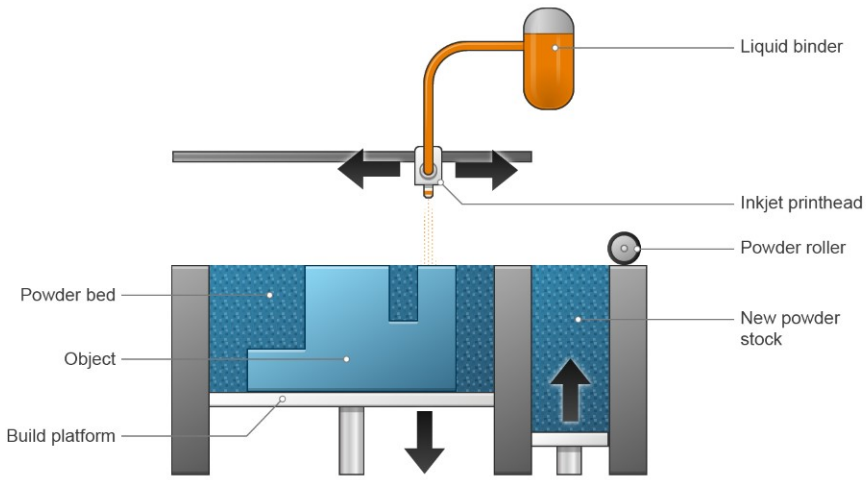


Figure 2.2. Binder Jetting AM Process. Source: [15]

2.1.1.2 Material Extrusion

Material Extrusion is defined as, "an AM process in which material is selectively dispensed through a nozzle or orifice" [1]. In material extrusion, "a spool of material, typically thermoplastic polymer, is pushed through a heated nozzle in a continuous stream and selectively deposited layer by layer to build a 3D object" [16]. The thermoplastic is heated in a chamber until it becomes melted and is forced out of the nozzle, forming a continuous filament. This melted material is then placed onto a build platform and the print head moves over the platform, depositing the melted material as needed to construct each layer [15]. Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and Nylon thermoplastics are commonly used in material extrusion, which is prized for its affordability, ease of use, and ability to create parts with polished surfaces, making it one of the most popular processes for hobbyist 3D printing. Two examples of material extrusion technology are Fused Filament Fabrication (FFF) and Fused Deposition Modeling (FDM) [16]. An overview of the different components used in Material Extrusion can be found in Figure 2.3.

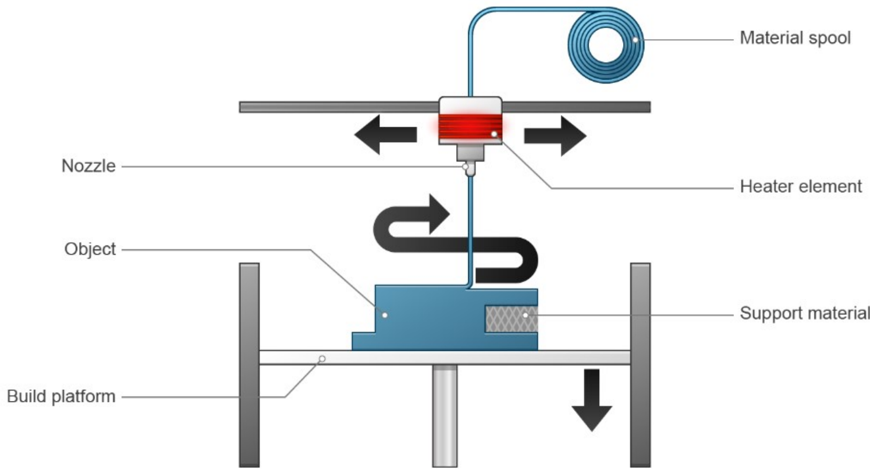


Figure 2.3. Material Extrusion AM Process. Source: [15]

2.1.1.3 Material Jetting

Material Jetting is defined as, "an AM process in which droplets of build material are selectively deposited" [1]. This AM process creates objects like a traditional ink-jet printer. Liquid photopolymer "material is jetted onto a build platform using either a continuous drop on demand approach" through a small nozzle onto a build platform [17]. Using this process, "material layers are then cured or hardened using ultraviolet light" [17]. Material Jetting has several advantages, including the ability to produce highly detailed and accurate parts, a wide range of available materials, and the ability to produce parts with multiple materials and colors in a single build. However, the parts are brittle and have poor mechanical properties [18]. An overview of the different components used in Material Jetting is shown in Figure 2.4.

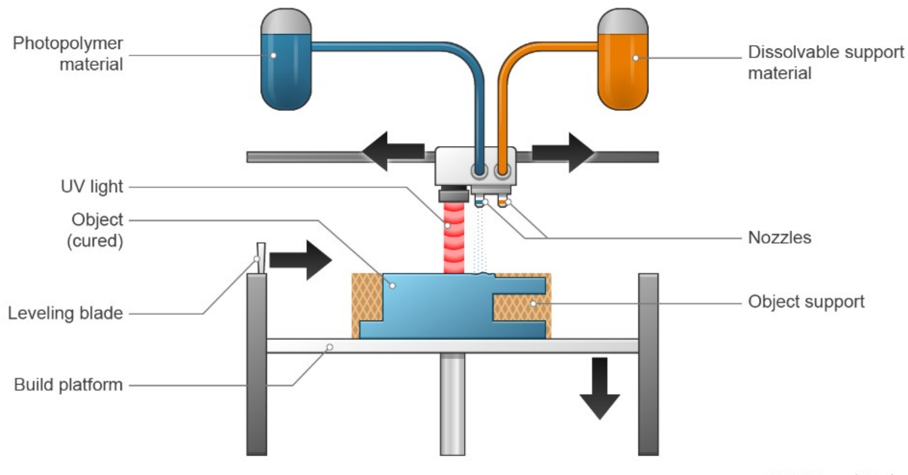


Figure 2.4. Material Jetting AM Process. Source: [15]

2.1.1.4 Sheet Lamination

Sheet Lamination is defined as, "an AM process in which sheets of material are bonded to form an object" [1]. Sheet Lamination is an AM technology that utilizes Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM) printing techniques. UAM makes use of "metal sheets or ribbons that are bound using ultrasonic welding" [19]. However, additional machining is required and any unbound metal needs to be removed during the welding process. On the other hand, "LOM uses a similar layer-by-layer approach, but instead of welding, it uses adhesive to bond paper layers together" [19]. During the printing process, a cross-hatching method is used to facilitate removal of the object after the build is complete. LOM produced-objects are mainly used for aesthetic or visual purposes and are not suitable for structural applications. Sheet lamination can utilize sheet material that can be rolled, such as paper, plastic and a few sheet metals [19]. An overview of the different components used in the Sheet Lamination process is depicted in Figure 2.5.

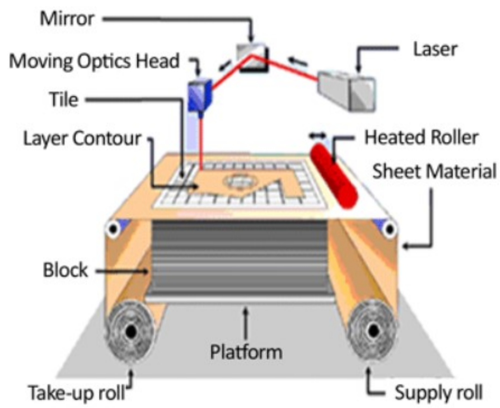


Figure 2.5. Sheet Lamination AM Process. Source: [20, Figure 2]

2.1.1.5 Vat Photopolymerization

Vat Photopolymerization is defined as, "an AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization" [1]. Photopolymerization-based 3D printing technology involves several different processes that all utilize the same basic principle. This principle involves curing a liquid photopolymer, which is stored in a vat or tank, using a heat source. By repeating this process layer by layer, a physical 3D object is eventually created. There are multiple types of curing devices, with the original technique using lasers. However, digital light processing projectors and Liquid Crystal Display (LCD) screens are now commonly used for Photopolymerization due to their low cost and high resolution. These two techniques have the advantage over lasers in that they can cure an entire layer of resin at once, whereas lasers have to illuminate the whole surface by drawing it [15]. An overview of the different components of the Vat Photopolymerization process is shown in Figure 2.6.

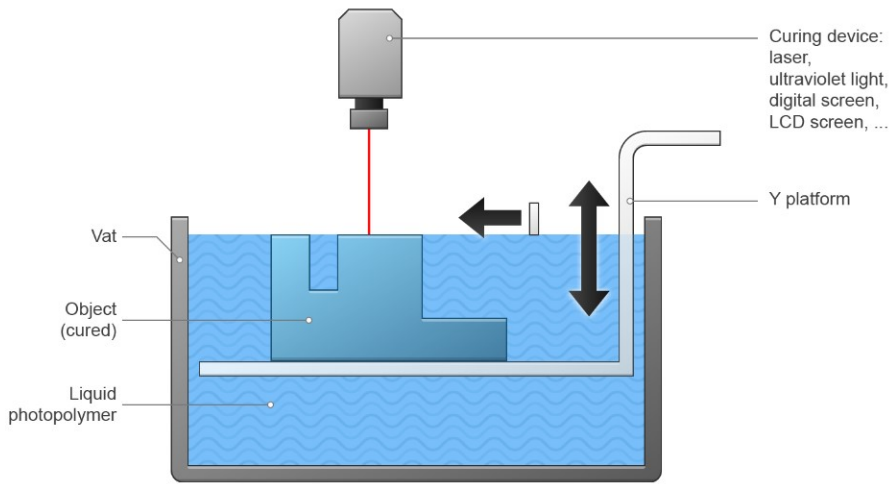


Figure 2.6. Photopolymerization AM Process. Source: [15]

2.1.1.6 Powder Bed Fusion

PBF is defined as, "an AM process in which thermal energy selectively fuses regions of a powder bed" [1]. PBF is a highly precise 3D printing technology that can generate a wide range of complex shapes by fusing particles of powder layer by layer using a heat source, typically a laser or electron beam [15]. The different types of PBF include Selective Laser Sintering (SLS), Selective Laser Melting (SLM) also known as Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), and Multi Jet Fusion (MJF). SLS lasers merge powders, while SLM and DMLS only uses this method for metal components. EBM is similar to SLS, but uses less energy and has less residual stress, making it ideal for high-value industries such as aerospace and defense. MJF uses an inkjet array instead of a laser to apply fusing and detailing agents, which are then solidified into a layer, allowing the production of lifelike objects with improved resolution [15]. An overview of the different components of Powder Bed Fusion is shown in Figure 2.7.

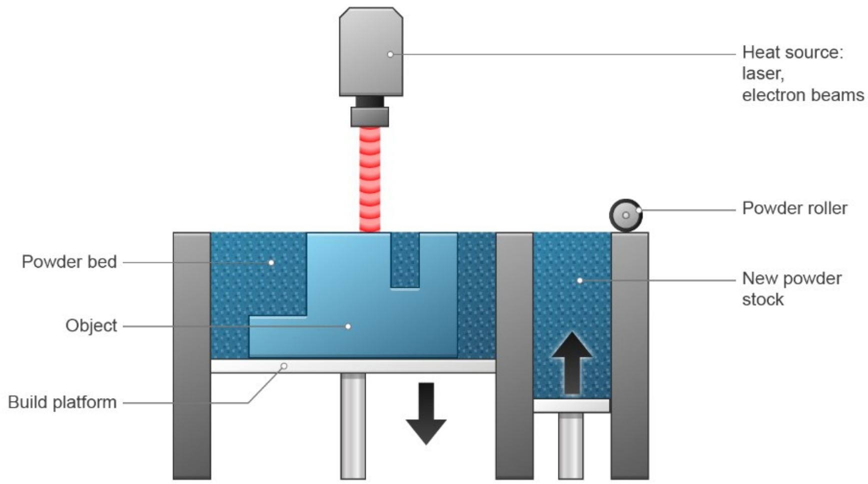


Figure 2.7. Powder Bed Fusion AM Process. Source: [15]

2.1.1.7 Directed Energy Deposition

DED is defined as, "an AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited" [1]. The DED process uses focused thermal energy to fuse and deposit materials layer by layer to create 3D parts. It primarily uses metal powders or wire source materials. Other names for DED include, "laser engineered net shaping, directed light fabrication, direct metal deposition, Laser Deposition Welding (LDW), and 3D laser cladding" [15]. DED not only allows for building new parts, but also repairing components. These 3D printers are industrial machines that require a controlled environment and consist of a nozzle attached to an arm that deposits melted material onto the part [15]. There are various DED techniques, including LENS (laser-based), Aerosol Jet, Electron Beam Additive Manufacturing (EBAM), and LDW, each with its own capabilities and limitations [15]. An overview of the different components of Directed Energy Deposition is shown in Figure 2.8.

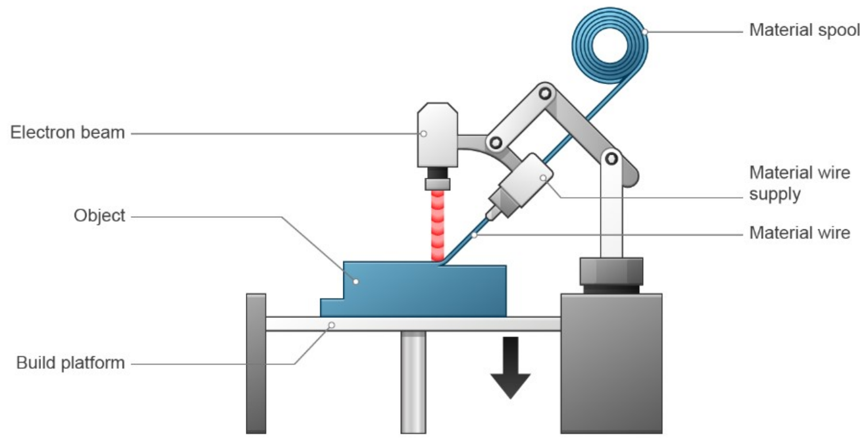


Figure 2.8. Directed Energy Deposition AM Process. Source: [15]

2.1.2 Use of Additive Manufacturing in the DOD

The DOD has been interested in AM due to the vast potential in benefiting the tri-maritime services. The study titled "Navy Expeditionary Additive Manufacturing (NEAM) Capability Integration" [21] focuses on current and future use of AM technologies within the DOD. This research examines the capability of the 3D printing systems available in the market and a selective approach of the system for each Navy ship category or existing environment. This analysis includes material and printing methods used, such as vat photopolymerization, PBF, binder jetting, material jetting, sheet lamination, material extrusion, and direct energy deposition. The research also considered the number of parts being printed, as well as finishing quality, with a focus on the maintainability and usability of the system.

The Navy recently installed a 3D printer, the Xerox ElemX, onboard the Wasp-class amphibious assault ship Essex during the Rim of the Pacific (RIMPAC) 2022 event, which was located at Joint Base Pearl Harbor-Hickam, Hawaii [22]. The purpose of this installation was to test the new printing technology at sea [22]. This exercise aimed to demonstrate the potential for sailors to print and replace defective, worn, or damaged ship parts anywhere in the world. The general manager of Xerox quoted, "The military supply chain is among the most complex in the world and putting the ElemX on USS Essex means that sailors can now bypass that complexity and print parts when and where they need them" [22]. Successful implementation of this new process could significantly benefit the tri-maritime fleet.

A thorough understanding of the environmental behaviors and capabilities of AM is essential for the successful implementation of 3D printers on maritime vessels. In order to combat these environmental behaviors, there needs to be a way of comprehending the effects of the expected operational environment on the usability of printed components. Maritime vessels are exposed to both man-made and natural environmental factors that can impact the performance and quality of 3D-printed parts. For example, man-made environmental effects include vibrations, temperature fluctuations, shock, and angle-of-list. These performance impacts can result from events such as weapons launches, vessel maneuvering, dive/surface angles (for submarines), or vibrations caused by onboard machinery, such as running engines or motors. Natural environmental effects encompass sea motion, which can vary from calm to rough depending on current trends and weather conditions. Nonetheless, both man-made and natural environmental effects should be analyzed and, when applicable, mitigated concerning their implications for the use of 3D printers and the quality of the finished printed parts. By addressing these factors, the implementation of AM technology on maritime vessels can become more viable and effective, contributing to the overall efficiency and success of shipboard operations.

2.2 Digital Twin Technological Capability

DT technology has the potential to be an effective tool in modeling and simulation due to its cost-effective simulation of complex systems that would otherwise be expensive to implement. DTs are used heavily in fields such as building design, manufacturing system design, and automotive design, among others. This capstone project intends to capitalize on the efficacy of DT by creating a modular AMDTMM. To assist in the design of this AMDTMM, the capstone team conducted research on pertinent scholarly articles and previous CAMRE capstone design projects.

The research article "Digital Twin for Additive Manufacturing: A State-of-the-Art" [23] examines the present utilization of DT within the AM industry. Zhang et al. address the existing challenges in additive manufacturing, such as the time and cost required to produce high-quality parts with desirable mechanical properties. DT is proposed as a solution to mitigate these issues in future development and research. The article's objective is to review the ongoing work in the AM DT domain.

Similarly, the report "Building Blocks for a Digital Twin of Additive Manufacturing" [24] focuses on the quality and defects of printed parts, aiming to support a DT manufacturing process that predicts variables affecting the structure and properties of the parts being printed. These variables include temperature, cooling rate, solidification parameters, and metal deposit geometry. Understanding how these variables affect part quality could improve 3D metal printing processes and reduce the percentage of defective parts produced by AM.

The article "The Use of Digital Twin for Predictive Maintenance in Manufacturing" [25] showcases a DT model used to calculate the Remaining Useful Life (RUL) of machinery equipment. The authors explain the process of gathering data for modeling and simulation, using machine controllers and external sensors. A case study is presented to demonstrate the functionality of their design approach. Successful DT strategies can provide significant benefits to the user. The benefits of a successful implementation of the DT concept are already visible in other industries and include benefits ranging from process improvement, tighter cost control, more accurate production forecast. Some early examples of DT implementation happened in the year 1970 when NASA engineers used a simulator, a DT of the command system, and a separate DT of the electrical system to save Apollo 13 astronauts. This successful implementation of the DT facilitated the process and reduced the process to under two hours and saved the lives of the three astronauts on board [26].

The articles mentioned prior provide a solid foundation for the capstone design team to understand DT and their applications. However, they fall short in accurately representing AM printers, such as the Xerox ElemX printer, and lack a focus on the application of DTs in military contexts. The missing military contexts presents an opportunity to extend the research to the tri-maritime fleet through the development of this AMDTMM. Overall, the literature on DTs demonstrates their potential to significantly enhance efficiency and, consequently, reduce costs. By adopting this technology within the additive manufacturing space, substantial return on investment can be achieved for the tri-maritime services.

2.2.1 Digital Twin for Additive Manufacturing

DT implementation offers significant benefits, including reduced costs and downtime by enabling on-site part production, eliminating the need for third-party suppliers or waiting for availability and shipment. Providing an organization the capability of rapidly producing replacement components can result in shorter overall system repair times, which ultimately increase mission readiness. DTs help decrease uncertainty related to the final printed product's quality. Using data collected from a physical AM's lifetime functioning, the DT allows sailors to simulate various printing scenarios, selecting the one with the highest fidelity. This cost-effective process minimizes waste from traditional AM processes. Furthermore, DTs are environmentally friendly due to their efficiency, eliminating the need for a designated area for defective printed parts.

The article "Case for Digital Twins in Metal Additive Manufacturing" [27] provides an in-depth analysis of AM, outlining its capabilities and limitations. It presents DTs as a valuable and secure simulation model that guides decision-makers in determining when a system should be examined and employed for various scenarios. A notable limitation of AM is its single-scenario usage at a given time. To address this, the DT model is developed using collected data, field experiments, sensor-monitored critical parameters, and a feedback loop for continuous improvement and learning. The use of a DT model helps prevent inconsistencies related to the final product quality, allowing decision-makers to simulate different production scenarios and implement their preferred choice.

The article "Scalable Digital Platform for the Use of Digital Twins in Additive Manufacturing" [28] discusses the operation of an AM system, emphasizing the benefits and drawbacks of the manufacturing process. Moreover, the article highlights the variability of the AM process as a primary incentive for introducing the DT concept to optimize component production. The digital platform is defined as " a network of manufacturing equipment, data storage systems, and computation capabilities" [28]. The authors also employ relational databases as storage for metadata during implementation, while data is stored within indexed file systems.

The development of DT for AM is ongoing since both technologies have not reached their full potential yet. From the articles discussed, one can see that initial development of the combined technology of AM and DT have been primarily in academia. Although the articles discuss the application of DT for AM by highlighting the advantages, disadvantages, capabilities, limitations, and variances, they lack a DT model of a 3D metal printer, such as the Xerox ElemX, which presents a valuable case study for this capstone team to build upon.

2.2.2 Fusing DT with MBSE

MBSE can play a significant role in the advancement of DT design by providing a structured and systematic approach to developing and designing complex systems. The International Council on Systems Engineering (INCOSE), the governing body of MBSE, defines MBSE as “the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” [29]. One area in which DTs can benefit from a MBSE developmental approach is in inclusion of iterative development cycles. Iterative development is a crucial aspect of MBSE, promoting continuous improvement and refinement of system designs. Engineers can test and validate their designs at various stages, identifying issues and potential improvements early in the development cycle, which can reduce the risk and impact of potential redesign. Additionally, MBSE encourages the creation of reusable and scalable models, which can be leveraged for similar or related systems, increasing efficiency, reducing development time, and improving knowledge management.

The successful integration of MBSE principles into a DT design enables stakeholders to effectively simulate and analyze various aspects of the systems they represent. MBSE supports traceability and integration, linking system elements, requirements, and design decisions throughout the system’s lifecycle. The integration of core MBSE concepts can help identify and manage dependencies, as well as mitigate potential risks and challenges. MBSE allows for the simulation and analysis of system behavior, performance, and other key attributes, leading to data-driven decision-making and optimization.

This fusion of MBSE and DT technologies fosters increased synergy, leading to optimization, enhanced understanding, and overall technological advancement. In the context of this capstone research project, the team will concentrate on the relationship between MBSE and DT development, integrating the two to develop the AMDTMM. By focusing on this relationship, the project aims to contribute valuable insights and findings to the growing body of knowledge surrounding DT design and implementation in various industries, particularly AM.

To begin bridging the gap between MBSE and DT design, the capstone team leveraged existing work done in this research domain, specifically, the CAMRE-sponsored capstone project "Architecture for a CBM+ and PHM Centric Digital Twin for Warfare Systems" [30]. This capstone design project focuses on integrating MBSE with digital analysis to provide printer health status and improve maintenance aspects by transitioning from time-based maintenance to condition-based maintenance. A Direct Metal Laser Melting (DMLM) 3D printer was utilized to identify pertinent data for the DT architecture. The team further developed both black box and white box representations of the 3D printer, facilitating the formulation of perspectives and scenarios within the DT.

The research article, "Requirements and a Meta Model for Exchanging Additive Manufacturing Capacities" [31], guides the reader through the process of drafting requirements for constructing a meta-model for exchanging additive manufacturing capacities. The report outlines the criteria for screening potential stakeholders to interview, the process of selecting questions to ask during the interview, and the methodology employed for analyzing the collected data. The article concludes by presenting the resulting set of requirements for capacity exchange and a schematic of the meta-model for exchanging additive manufacturing capacities.

In alignment with the MBSE approach throughout the development of the project, the team will utilize the research article co-authored by Professor Douglas Van Bossuyt, titled "Operationalizing Digital Twins Through Model Based Systems Engineering Methods" [8], as a foundation to establish a proper system engineering process and MBSE approach. The article examines the application of a DT for analyzing, "a live system's performance, reliability, suitability, remaining usable life, or other factors that stakeholders may deem necessary during initial system fielding" [8]. Additionally, the article underscores the benefits of DTs in preventing component failure, as simulations can provide a realistic view of system performance. The aforementioned articles emphasize the importance of MBSE, as it constitutes a crucial aspect of this project. This capstone project focuses on demonstrating the application of an MBSE process during the development of a project using the MSOSA modeling tool.

2.2.3 Data Analysis and DT Model

The works listed above equip the team with the necessary background and foundational information required for the development of this capstone project. The selected reports serve a specific purpose in facilitating the understanding of DT, AM, and their intersection. However, a crucial aspect of DT technology not yet addressed is the significance of *data* in the entire AMDTMM. Data, in the context of this the AMDTMM, is defined as SysML structure, behavior or requirement elements and diagrams along with the collection of human readable performance information from sensors onboard the physical AM printer, simulation results (not run in Cameo), and SysML activity results (run in Cameo).

In an article published by Forbes, titled "Care and Feeding of Digital Twins: How to keep good data flowing" [32], Andy Bane emphasizes the importance of data in DTs. He asserts that companies should seek vendors with strong partnerships and notes that organizations are increasingly utilizing powerful analytical tools to expedite DT development and enhance effectiveness with contextualized and governed metadata. Ensuring accurate metadata results in more reliable and easily maintainable analytics, ultimately leading to improved operations. Bane further explains that the data captured by industrial information management systems now could be used later to examine and enhance the system's efficiency [32]. However, it is essential to provide the DT with relevant, contextual data to generate the most useful and accurate insights. This capstone project will take these considerations into account, integrating the importance of data quality and governance in the development of the AMDTMM.

2.3 MBSE Frameworks

While developing the AMDTMM, the capstone team researched the most common MBSE frameworks to use as a focal point in designing the DT. The team understood that the AMDTMM needed to be flexible enough to encompass the seven types of printers, as mentioned in Section 2.1.1: *Seven Types of AM Technologies*, yet rigid enough to support a consistent arrangement of aggregate information for each of these types. The team inspected the feasibility of adopting the UAF, the DODAF, and the MagicGrid framework to fulfill this need. The following subsections provide a brief description of each framework, highlighting the advantages one may have over the others.

2.3.1 UAF

The UAF is essential in addressing the growing need for architecture-based decision-making in various sectors, as they adopt architecture-based digital engineering transformations. This change enables smooth information sharing across enterprises. UAF is a versatile and commercially-focused architecture framework derived from the Unified Profile for DODAF and MODAF, which allows stakeholders to focus on particular aspects of an enterprise while preserving an overarching perspective of the entire system. UAF accommodates the "business, operational and systems-of-systems integration needs of commercial and industrial enterprises as well as the U.S. DOD" [33]. Utilizing UAF, users can create architectures for diverse complex systems (comprising hardware, software, data, personnel, and facilities), maintain coherence in system-of-systems architectures, facilitate the analysis, specification, design, and verification of intricate systems, address cybersecurity analysis and risk reduction, and improve architectural information exchange between SysML-based tools and those reliant on other standards [33]. An illustration showing the different views supported by this framework is shown in Figure 2.9.

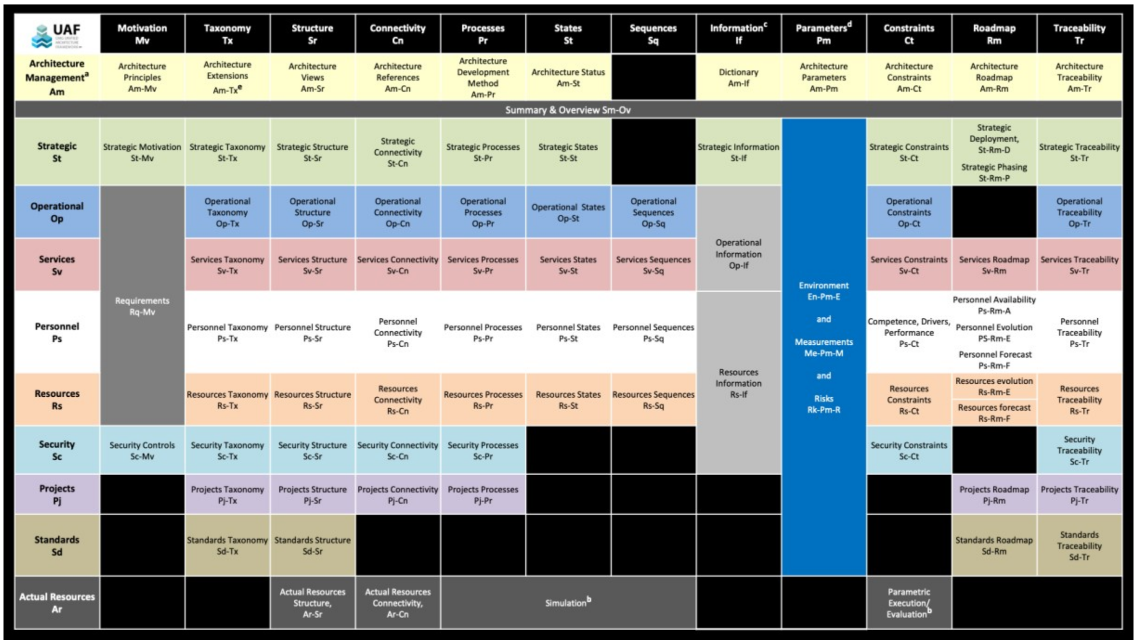


Figure 2.9. Unified Architecture Framework (UAF). Source: [34]

2.3.2 DODAF

The DODAF is a framework developed by the U.S. DOD to facilitate the creation and management of enterprise architectures [35]. DODAF enables managers at all levels within the Department of Defense (DOD) to make well-informed decisions by promoting an "organized information sharing across the department, Joint Capability Areas (JCAs), mission, component, and program boundaries" [36]. The DODAF framework comprises eight viewpoints and fifty-two models. DODAF offers a standardized structure for creating, "architectural views and capturing and presenting architectural data that supports systems engineering and the sharing of technical information among stakeholders across systems of systems and the DoD Enterprise" [36]. Figure 2.10 provides a visual representation of the various viewpoints supported by DODAF.

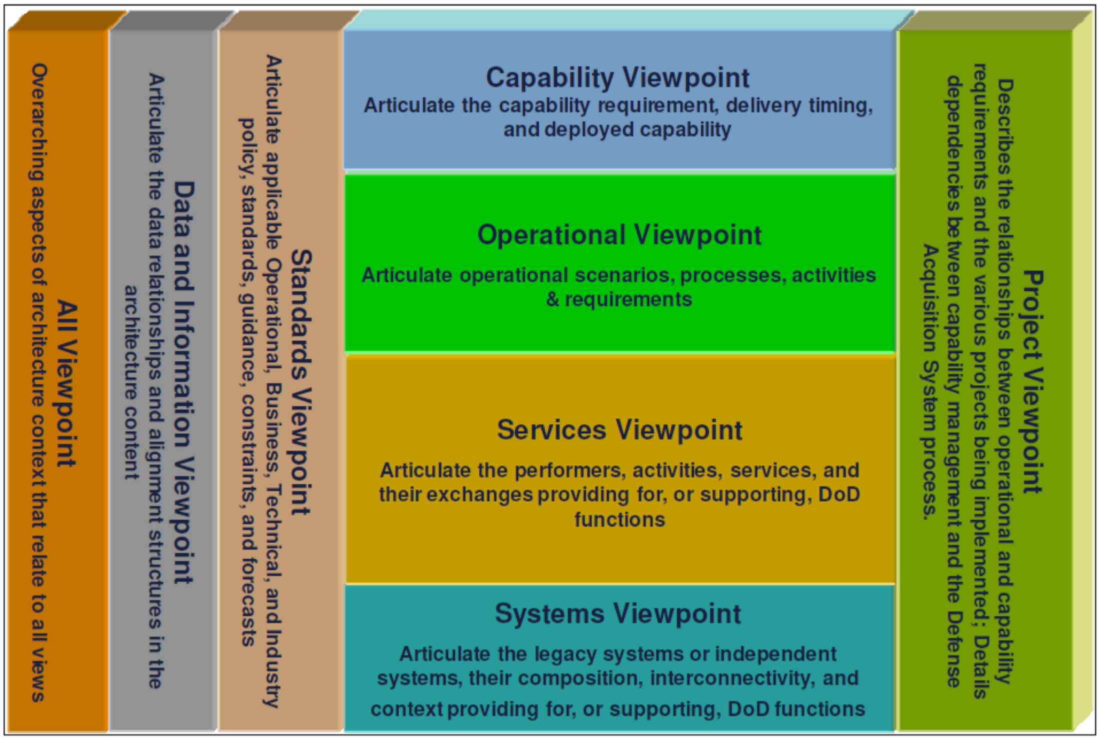


Figure 2.10. DOD Architecture Framework (DODAF). Source: [35]

2.3.3 MagicGrid

The MagicGrid MBSE framework employs a modular, grid-based approach to model complex systems [37]. This framework presents a visual representation of both the system and its individual components, allowing for a multifaceted analysis that offers stakeholders various perspectives on the system in question. MagicGrid facilitates the integration of multiple models and simulations, resulting in a comprehensive understanding of the system's behavior and architecture. Furthermore, the framework supports the identification of relationships between system components and the management of system design and development. The grid-based approach of MagicGrid delivers a clear and organized method for modeling complex systems. An illustration displaying the different views and their interrelationships within the MagicGrid framework is shown in Figure 2.11.

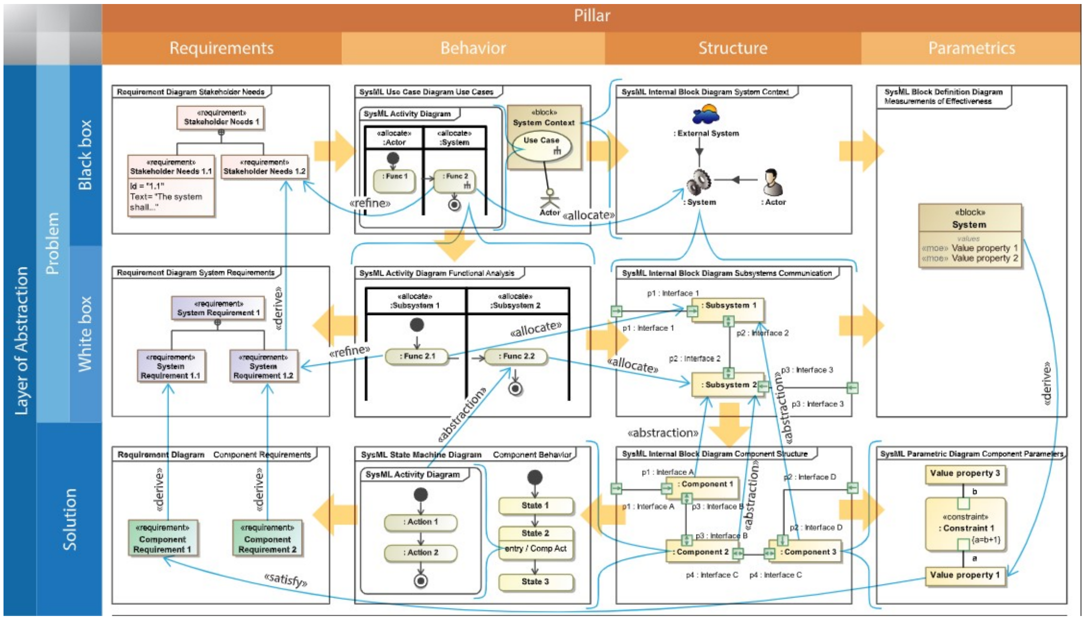


Figure 2.11. MagicGrid Framework for MBSE. Source: [37]

2.4 Systems Engineering Processes Review

The successful implementation of following a SE process throughout the project's development is crucial in determining its success. SE processes are designed to guide a development team in executing tasks traced to stakeholder needs and transforming those tasks into tangible and executable requirements that help build a robust and desirable deliverable. The SE process consists of several steps that enable project developers to ensure proper stakeholder identification, clear and concise design requirements, and the development of the system architecture during the project's initial phase. There are multiple approaches to the system engineering method, including the VEE model approach, the Spiral model, and the Waterfall model. The following subsections offer a brief description of each method, as the team conducted a study to determine the most suitable approach for this project.

2.4.1 Vee Model

The traditional VEE model is widely used across industries, particularly within the DOD, serving as the foundation for most government Program of Record (POR) project development plans. Many variations of the VEE model exist in articles and books, but they all originate from the original VEE model developed by Forsberg and Mooz [38]. As illustrated in Figure 2.12, the VEE model resembles the letter "V," with the left-hand side representing the project definition component of system design, and the right-hand side encompassing the project test and evaluation phases. The middle section of the VEE Model highlights the continuous testing process throughout development, ensuring that system components meet the specifications detailed in the system requirements document. Nonetheless, the VEE model requires testing to be conducted after the requirement and architecting of the design, which presents a limitation to the team's design approach for the AMDTMM. The traditional VEE model's inflexibility and rigidity make it less suitable for software-oriented projects, such as this capstone design model, despite its strengths in large system design projects.

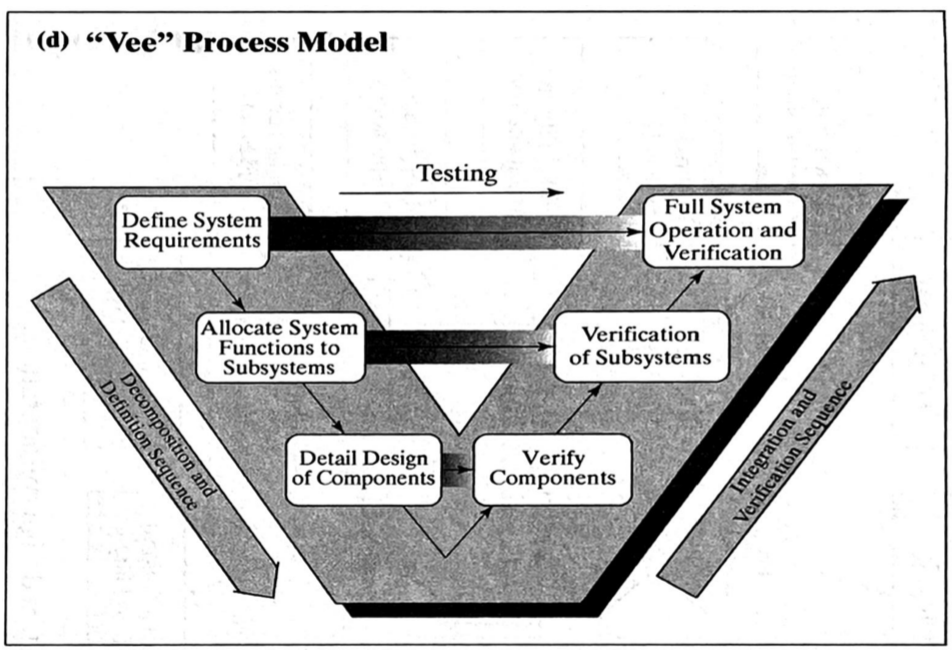


Figure 2.12. SE Process: VEE Model. Source: [38, Figure 2.5 (Sheet 2)]

2.4.2 Waterfall Model

The waterfall model, introduced by Winston Royce in the 1970s, was initially employed for software development [38]. This model comprises a series of sequential steps or phases for system engineering or software development, following a linear progression. The structure dictates that one step must be completed before the next can begin, ensuring a clear and well-defined path for project progression. Contradictory to its linear progression, it lacks the ability to iterate each step. A feedback loop is only present at the start and end as shown in Figure 2.13. Applying this process to this capstone project would have been challenging due to the constraints and limitations inherent to the project. The waterfall model, while offering a clear structure, lacks the flexibility required to accommodate changes or evolving requirements that may arise during the project's development. This rigidity may result in difficulties addressing unforeseen challenges or incorporating stakeholder feedback, ultimately affecting the project's success.

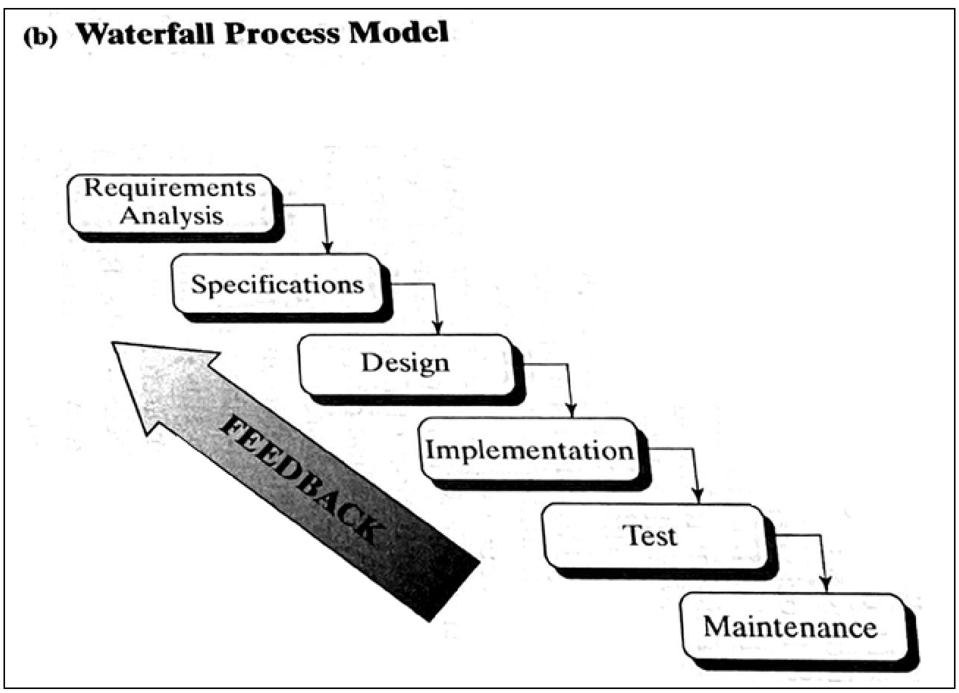


Figure 2.13. SE Process: Waterfall Model. Source: [38, Figure 2.5 (Sheet 1)]

2.4.3 Spiral Model

The spiral process model for the development life cycle, introduced by Boehm in 1986, offers a flexible and risk-driven approach to system development. This model is an adaptation of the waterfall model, but the spiral process does not direct the use of prototypes [38]. The spiral model incorporates features from other models, such as feedback loops and iterative development, allowing for continuous improvement and adaptation throughout the development process. As illustrated in Figure 2.14, in a spiral model, development progresses through several phases, with each phase culminating in the creation of a new prototype build. These iterative phases enable the incorporation of lessons learned and stakeholder feedback, ensuring that the final product or system is more closely aligned with needs and expectations. A key strength of the spiral model is its adaptability in response to changes in requirements. In the event of requirement changes, this process model enables system designers to perform risk assessments and make informed decisions with the stakeholders before transitioning to the next design phase. This built-in flexibility makes the spiral model particularly well-suited for projects rapidly innovating with evolving technologies or uncertain requirements, as it allows for ongoing adjustments and improvements throughout the development cycle.

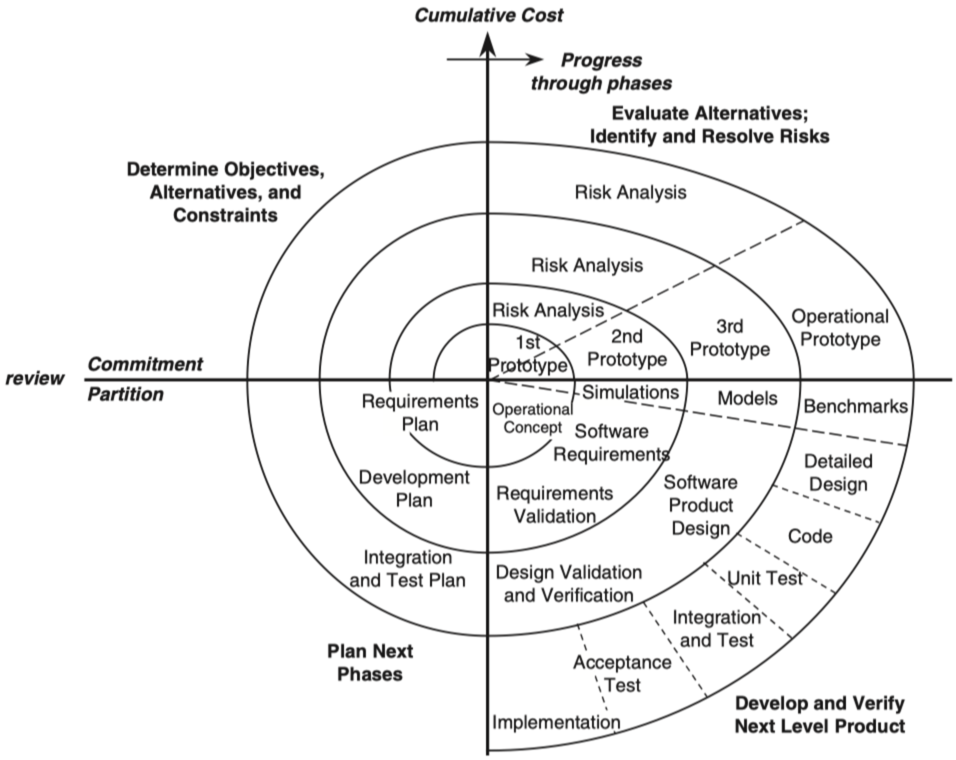


Figure 2.14. SE Process: Spiral Model. Source: [39, Figure 1.9]

2.5 Conclusion

In Chapter 2: *Background and Literature Review*, a comprehensive literature review summarizes the history of AM, the benefit of adopting DTs design, and a comparison of different types of SE processes. This research lays the foundation upon which the capstone design team can begin developing the AMDTMM. The literature covered provides pertinent information that will be used in Chapter 3: *Design and Development*, which will be employed to supplement the SE capstone project. Despite the vast research covered, the research falls short in linking the integration of all these topics by not converging the use of DT specifically for AM in a MSOSA environment with the initial AM DT of the Xerox ElemX. This SE capstone will expand the current research performed in the DT AM space and provide a centralized repository of curated data for stakeholders. This digital expansion of AM in conjunction with generating a meta-model will collectively provide a single source of truth for the tri-maritime services, and the broader DOD, to serve as a repository for storing and maintaining DTs within the AMDTMM framework.

CHAPTER 3:
Design and Development

This chapter explains the design and development approach used to create the AMDTMM. Stakeholder needs, expectations, and development goals are discussed along with a complete requirement analysis used to translate the stakeholder into top-level requirements and then eventually into system requirements. The development of the underlying architecture used to create the AMDTMM is discussed, including profile development in MSOSA and the DT framework. Finally, a summary of the chapter is provided to showcase the development aspects and how the team developed the AMDTMM tool in a timely and efficient manner.

3.1 Overview

This capstone design project followed a systems engineering approach, employing a tailored version of the spiral model to streamline the software development process. The first step in the team's development of the AMDTMM tool involved conducting a stakeholder needs analysis based on the broad area research on DT, presented by NPS, which set the foundation for this capstone project. The stakeholder needs generated in the previous step were then used to develop a set of top-level requirements, which were further decomposed into system requirements. A preliminary architecture for the AMDTMM template was developed using the output from these steps.

From this point on, the process followed an iterative approach in line with the tailored spiral model. The team's design process consisted of identifying necessary capabilities, developing the functionality in MSOSA, and finally testing for performance and validation. Although this phase of development was continuous, it considered the physical and functional architecture of metal 3D printers, serving as the adaptive framework to integrate with external models. Furthermore, the underlying methodology used to architect the AMDTMM was developed, showcasing the use of MSOSA profiles and the team's developed DT framework.

3.2 System Engineering Development Process

After evaluating various system engineering approaches, the capstone team opted for a tailored version of the spiral development model as shown in Figure 3.1. This customized hybrid agile-spiral approach simplified the development of the MSOSA model while facilitating the integration of stakeholder feedback throughout the entire development cycle. This iterative process allowed the team to generate an initial set of requirements based on feedback from the project advisor(s) and CAMRE representatives. Additional requirements were developed by examining the CAMRE broad area research study and extracting further stakeholder needs and capabilities. As the model evolved and the team better defined its capabilities, requirements were modified and incorporated within the model.

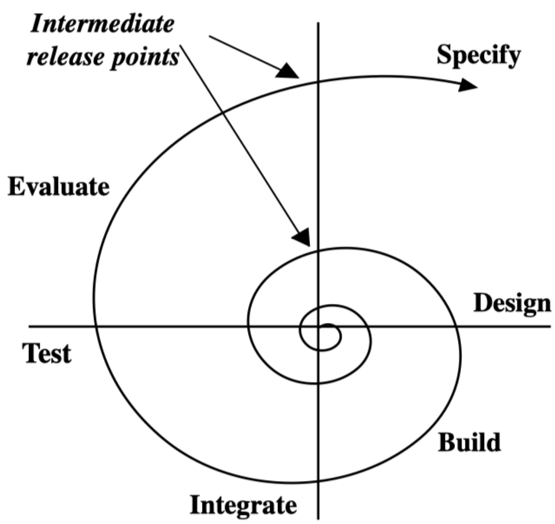


Figure 3.1. SE Process: Hybrid Agile-spiral Model. Source: [11, Figure 1.5]

3.3 Stakeholder Identification

The first step during the initiation of any project is to understand who the stakeholders are and what their varying levels of responsibility, accountability, and impact are to the overall project. Although this might not seem important at first, knowing each stakeholder's wants and needs from their perspective can help the developers immensely during the entire system development process. Stakeholders can be formally defined as "individuals and organizations who are actively involved in the project, or whose interests may be positively or negatively affected as a result of project execution or successful project completion" [40]. Common examples of stakeholders in engineering projects include project managers, end-users, team members, suppliers, operators, and sponsors.

Stakeholder analysis is crucial for defining engineering project requirements and aligning them with the needs and expectations of all involved parties. By utilizing various techniques and tools, stakeholder analysis aids the capture of expectations from stakeholders related to the project. Ultimately, effective stakeholder analysis is key for a successful project and ensuring that the product delivered meets the stakeholders' needs [40]. A stakeholder analysis was conducted for the AMDTMM to identify stakeholder needs, roles, influences, issues, and concerns. The information gathered from this analysis was used to define the system's requirements and to understand and document stakeholder expectations. The primary stakeholders identified for this project are NPS, CAMRE, and the tri-maritime service.

CAMRE was the sponsoring activity for this research into DT within AM. Existing research has been performed by CAMRE within the AM branch of study, which was provided to the capstone team. The main focus of the research was to assess a DT AM usefulness to support the U.S. tri-maritime services in their missions.

3.3.1 Stakeholder Needs

Identifying and understanding stakeholder needs is a critical phase in any SE project. Stakeholder needs provide the foundation for generating decomposed top-level and system requirements. The capstone team utilized the provided CAMRE broad area study as an initial stakeholder description of needed capabilities. The CAMRE broad area study is depicted in Figure 3.2. Key objectives from the broad area study was colorized to emphasize important details related to the capstone effort.

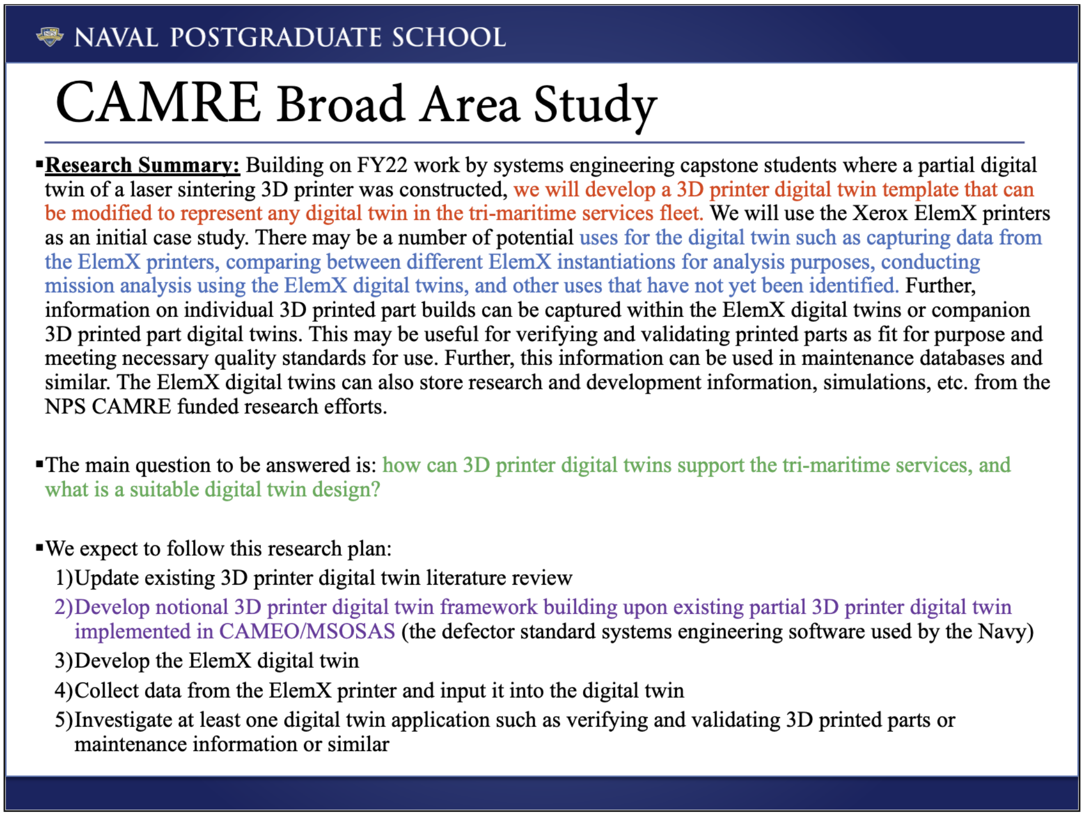


Figure 3.2. CAMRE Broad Area Study

Given the CAMRE broad area study, the team then transitioned the summary into each needed capability by thoroughly decomposing and breaking down the summary. Addressing interrogative questions such as *who, what, where, when* and *why* was used as a way to further understand the primary functions needed. This approach aids in understanding the primary functions required by the model to best meet the stakeholder's required capability. The elements defined by these questions played a crucial role in the development of the AMDTMM project. The capstone team formulated high-level objectives, which are depicted in Figure 3.3.

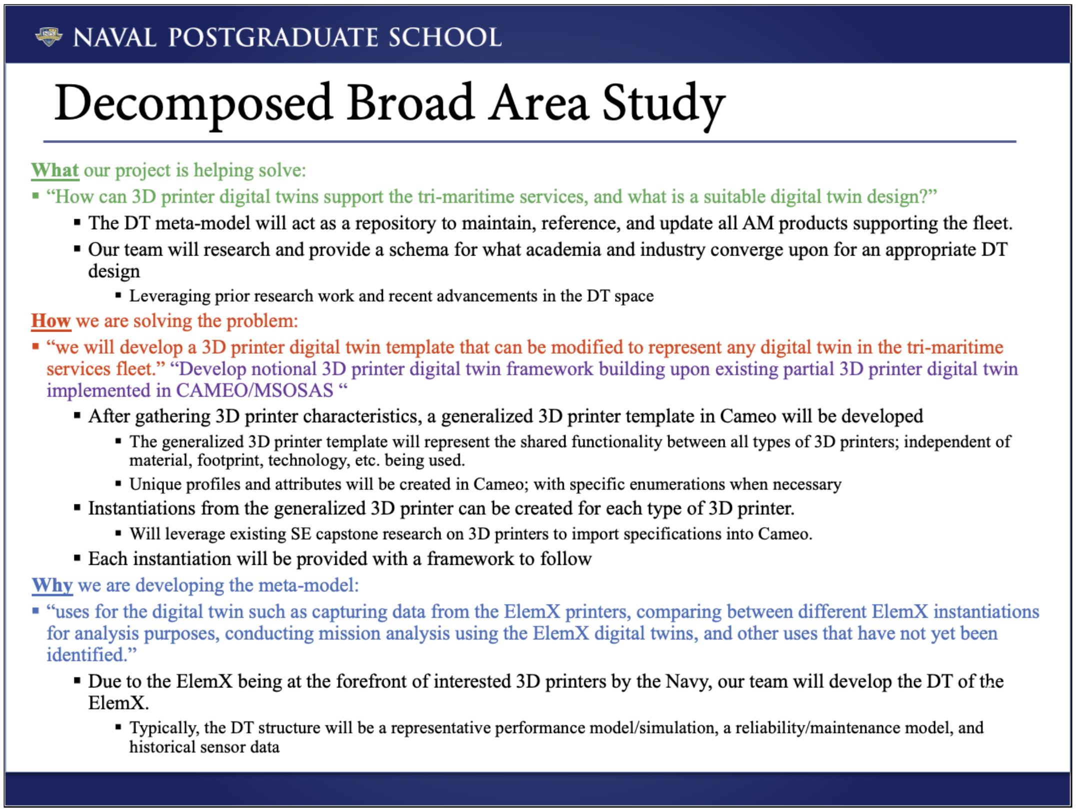


Figure 3.3. Decomposed Broad Area Study

The decomposed broad area study proved to be a valuable asset that the team referenced throughout the AMDTMM development. With this initial understanding of the functionality that the AMDTMM needed to perform, the team developed five stakeholder needs statements:

1. *DT Template:* Develop a 3D printer digital twin template that can be modified to represent any digital twin in the tri-maritime services fleet.
2. *Instance of Xerox ElemX:* Provide the ability to create instances of any 3D printer and use the Xerox ElemX printer as an initial case study.
3. *Capture Data:* Capture data from the ElemX printers.
4. *Model Management:* Create central repository for models.
5. *Printer Comparison:* Comparing different printers for analysis purposes.

These five stakeholder needs were also created in MSOSA, as shown in the SysML requirement table in Figure 3.4. It is important to note that it was a customer requirement to use MSOSA for the AMDTMM development. Thus, the team intuitively captured the stakeholder needs in MSOSA due to the provided traceability ability needed to flow down stakeholder needs to top-level and system requirements effectively. Furthermore, SysML requirement attributes such as *ID, name, text,* and *documentation* were used to adequately capture the stakeholder needs digitally.

#	Id	Name	Text	Documentation
1	SN-1	SN-1 DT Template	Develop a 3D printer digital twin template that can be modified to represent any digital twin in the tri-maritime services fleet.	CAMRE Research Summary
2	SN-2	SN-2 Instance of Xerox ElemX	Provide the ability to create instances of any 3D printer and use the Xerox ElemX printer as an initial case study.	CAMRE Research Summary
3	SN-3	SN-3 Capture Data	Capture data from the ElemX printers	CAMRE Research Summary
4	SN-4	SN-4 Model Management	Create central repository for models	CAMRE Research Summary
5	SN-5	SN-5 Printer Comparison	Comparing different printers for analysis purposes	CAMRE Research Summary

Figure 3.4. Stakeholder Needs Table

3.4 Requirements Decomposition

Requirement analysis is an essential process in the field of systems engineering, as it involves examining the previously defined stakeholder needs and effectively transforming them into requirements that are necessary, achievable, measurable, and verifiable. Throughout this process, requirements are synthesized in order to sufficiently define and bound the capabilities that meet the stakeholder's needs. This section presents the requirements for the AMDTMM, which are organized into two distinct levels: top-level requirements and system requirements. Top-level requirements are characterized by their high-level, generalized nature and are subsequently refined into more specific, detailed system requirements that pertain to individual aspects of the system's capabilities. The following subsections provide a summary of the decomposing and tracing stakeholder needs into top-level requirements and system requirements. The tractability from parent requirements to child requirements is illustrated in Figure 3.5.

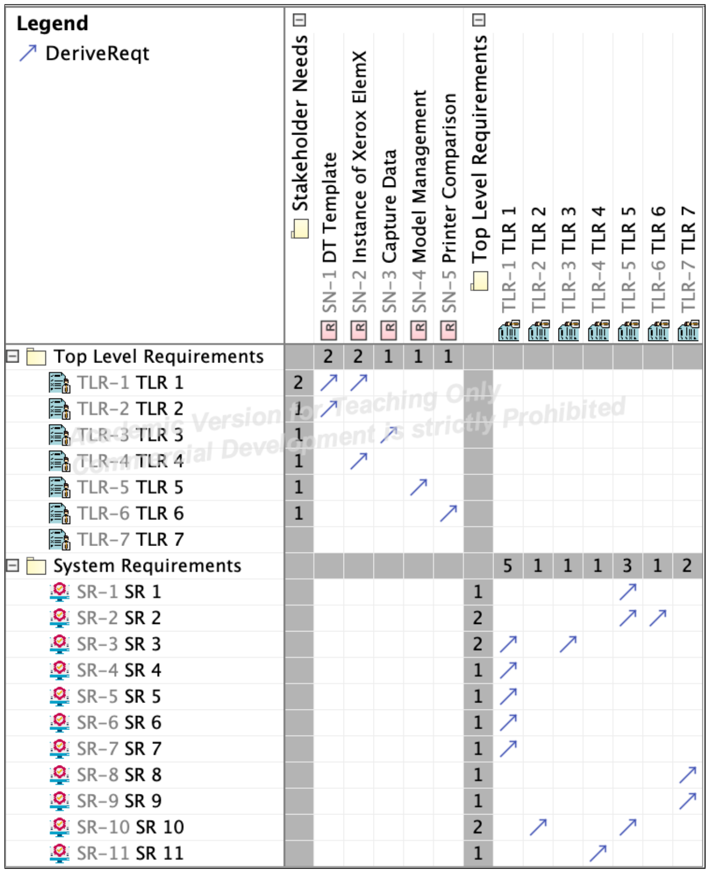


Figure 3.5. Requirement Tractability Matrix

3.4.1 Top Level Requirements

Top-level requirements are focused on the capability of the DT to fulfill the stakeholder need as discussed in Section 3.3: *Stakeholder Identification*. These top-level requirements helped the team understand the objectives that the AMDTMM needed to provide. A total of seven top-level requirements were defined based on the stakeholder need analysis. The seven top-level requirements are:

1. TLR-1: The DT meta-model shall provide the user the ability to:
   - Create new printer instantiations
   - Modify existing DT instantiations

    - Duplicate existing DT instantiations
    - Delete existing DT instantiations
2. TLR-2: The DT meta-model shall develop a framework that is suitable to the tri-maritime service fleet.
3. TLR-3: The DT meta-model shall receive 3D printer data (i.e. from inboard sensors).
4. TLR-4: The DT meta-model shall create an instance of a partial DT for the Xerox ElemX printer.
5. TLR-5: The DT meta-model shall maintain and organize models.
6. TLR-6: The DT meta-model shall provide the user to view different printers attributes concurrently.
7. TLR-7: The DT meta-model shall adhere to the United States Navy and Marine Corps Digital Systems Engineering Transformation Strategy, signed 10 June 2020.

Similar to the stakeholder needs, the top-level requirements were brought into MSOSA and traced to stakeholder needs. Six of the seven top-level requirements were traced to stakeholder needs using the SysML relationship <*derived from*> relationship, while the last one was traced to a standard using the <*conforms to*>. Figure 3.6 illustrates how a SysML requirements table diagram shows this traceability in MSOSA.

#	Id	△ Name	Text	Derived From	Conforms To
1	TLR-1	TLR-1 TLR 1	The DT meta model SHALL provide the user th to: • create new printer DT instantiations • modify existing DTs instantiations • duplicate existing DTs instantiations • delete existing printer DT instantiations	SN-1 DT Template SN-2 Instance of Xero	
2	TLR-2	TLR-2 TLR 2	The DT meta-model SHALL develop a framework that is suitable for the tri-maritime services fleet.	SN-1 DT Template	
3	TLR-3	TLR-3 TLR 3	The DT meta-model SHALL receive 3D printer data. For example, from on-board sensors.	SN-3 Capture Data	
4	TLR-4	TLR-4 TLR 4	The DT meta-model SHALL create an instance of a partial DT for the Xerox ElemX printer.	SN-2 Instance of Xero	
5	TLR-5	TLR-5 TLR 5	The DT meta-model SHALL maintain and organize models.	SN-4 Model Managem	
6	TLR-6	TLR-6 TLR 6	The DT meta-model SHALL provide the user the ability to view different printers attributes concurrently.	SN-5 Printer Compari	
7	TLR-7	TLR-7 TLR 7	The DT meta-model SHALL adhere to The United States Navy and Marine Corps Digital Systems Engineering Transformation Strategy, signed 10 June 2020.		The United States Navy and Marine Corps Digital Systems Engineering Transformation Strategy, signed 10 June 2020.

Figure 3.6. Top Level Requirements Table

3.4.2 System Requirements

The last decomposition of requirements is identifying system requirements for the AMDTMM. The system requirements are focused on the particular capabilities that the AMDTMM must adhere to. The benefit of developing system requirements is to capture performance criteria in a testable format. A total of eleven system requirements were derived from the seven top-Level requirements defined as:

1. SR-1: The system shall provide an interactable GUI
2. SR-2: The system shall allow the user to navigate to any existing instantiation of a 3D printer loaded into the system .
3. SR-3: The system shall allow entry of numerical data from 3D printers.
4. SR-4: The system shall provide the ability to create new DT instantiation that follows a predetermined template.
5. SR-5: The system shall provide the capability to modify existing 3D printer DT parameters.
6. SR-6: The system shall provide the ability to duplicate existing 3D printer DT instantiations. This includes all data parts of existing 3D printer DT.
7. SR-7: The system shall be capable of deleting existing 3D printer instantiations from meta-model repository.
8. SR-8: The system shall use Cameo Systems Modeler (CSM) as the SysML MBSE tool to develop the DT meta-model.
9. SR-9: The system SHALL provide the ability to develop SysML diagrams.
10. SR-10: The system SHALL be capable of storing external data within each DT instance.
11. SR-11: The system SHALL incorporate the Xerox ElemX as the initial DT instance within the DT meta-model.

The system requirements were generated and imported into MSOSA, similarly to how the top-level requirements were. The system requirements were labeled with identifiers using a traditional nomenclature and taking advantage of the traceability offered by MSOSA with the <*derived from*> relationship. Each system requirement was traced to a top-level requirement, as shown in Figure 3.7.

#	Id	Name	Text	Derived From
1	SR-1	SR-1 SR 1	The system SHALL provide an interactable GUI.	TLR-5 TLR 5
2	SR-2	SR-2 SR 2	The system SHALL allow the user to navigate to any existing instantiation of 3D printer loaded into the system.	TLR-6 TLR 6 TLR-5 TLR 5
3	SR-3	SR-3 SR 3	The system SHALL allow entry of numerical data from 3D printers.	TLR-1 TLR 1 TLR-3 TLR 3
4	SR-4	SR-4 SR 4	The system SHALL provide the ability to create new DT instantiations that follow a predetermined template.	TLR-1 TLR 1
5	SR-5	SR-5 SR 5	The system SHALL provide the capability to modify existing 3D printer DTs performance data.	TLR-1 TLR 1
6	SR-6	SR-6 SR 6	The system SHALL provide the ability to duplicate existing 3D printer DT instantiations. This includes all data part of the existing 3D printer DT.	TLR-1 TLR 1
7	SR-7	SR-7 SR 7	The system SHALL be capable of deleting existing 3D printer instantiations from meta-model repository.	TLR-1 TLR 1
8	SR-8	SR-8 SR 8	The system SHALL use CSM, as the SysML MBSE tool, to develop the DT meta-model.	TLR-7 TLR 7
9	SR-9	SR-9 SR 9	The system SHALL provide the ability to develop SysML diagrams.	TLR-7 TLR 7
10	SR-10	SR-10 SR 10	The system SHALL be capable of storing external data within each DT instance.	TLR-5 TLR 5 TLR-2 TLR 2
11	SR-11	SR-11 SR 11	The system SHALL incorporate the Xerox ElemX as the initial DT instance within the DT meta-model.	TLR-4 TLR 4

Figure 3.7. System Requirements Table

3.5 AMDTMM Tool Development

During the initial stages of model architecture development, the team developed a high-level system overview, which was essential in identifying the various components of the AMDTMM system architecture. As illustrated in Figure 3.8, there are four main areas that influenced the development of the AMDTMM architecture. These include identifying existing AM work, developing the AMDTMM in MSOSA, standards, and researching AM printer characteristics. The following subsection will describe the development of the AMDTMM in MSOSA, emphasizing the underlying schema used and modeling methodology.

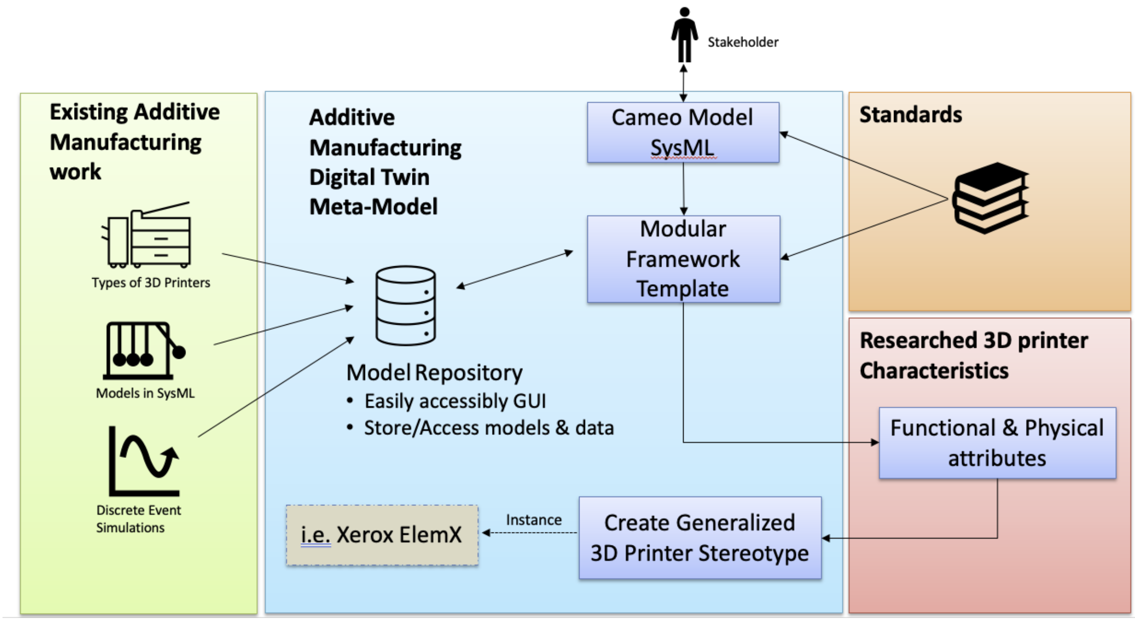


Figure 3.8. High-level System Overview

3.5.1 Profile Development

The initial phases of development for the AMDTMM led the team to create two profiles within MSOSA. One profile would support the development of custom stereotypes for requirements, while the other would facilitate the development of unique elements for the seven types of AM printers. The team was aware that due to the inherent nature of using profiles, the main AMDTMM would import the profiles with "read-only" privileges. This approach was employed to ensure that no user could accidentally change or modify the underlying element definitions within the AMDTMM tool itself. However, if any modifications to the stereotypes were needed in the future, one could simply open the individual profiles in MSOSA, implement the changes, and update the AMDTMM tool accordingly. This open architecture style was deemed beneficial by the team, and although it took longer to implement, developing this concept, later on, would be much more tedious and time-consuming.

3.5.1.1 Requirements Profile

The team aimed to integrate concepts used in standardizing MSOSA models, particularly those in the DOD. One of the initial challenges faced was capturing requirements appropriately in the AMDTMM and determining if a standard existed. As mentioned in Chapter 1: *Introduction*, the DON Digital Transformation strategy established the Naval IME to help federate and standardize model development by providing schemes, templates, and methodologies. The Naval IME's Requirements Profile was of particular interest to the team given the similarities. Due to the team's prior experience with the Naval IME Requirements Profile and the unavailability of the Naval IME during AMDTMM development, a scaled-down version of the profile was created. However, if the Naval IME Requirements Profile needs to be integrated in the future, it can be done by removing the AMDTMM's unique profile and replacing it with the Naval IME's, since the underlying development approach established could easily adopt the new profile.

There are three types of custom requirement elements available in the AMDTMM tool, which are known as *system requirement*, *top-level requirement*, and *printer requirement*. The *system requirement* element was created for the development of the AMDTMM tool to identify specific requirements as shown in Section 3.4.2: *System Requirements*. The *top-level requirement* element was created to distinguish requirements traced from stakeholder needs to top-level requirements as previously shown in Section 3.4.1: *Top Level Requirements*. Lastly, the *printer requirement* element was designed to follow the AMDTMM framework. All three types of requirements were built by extending the underlying SysML *extended requirement* class, as illustrated in Figure 3.9.

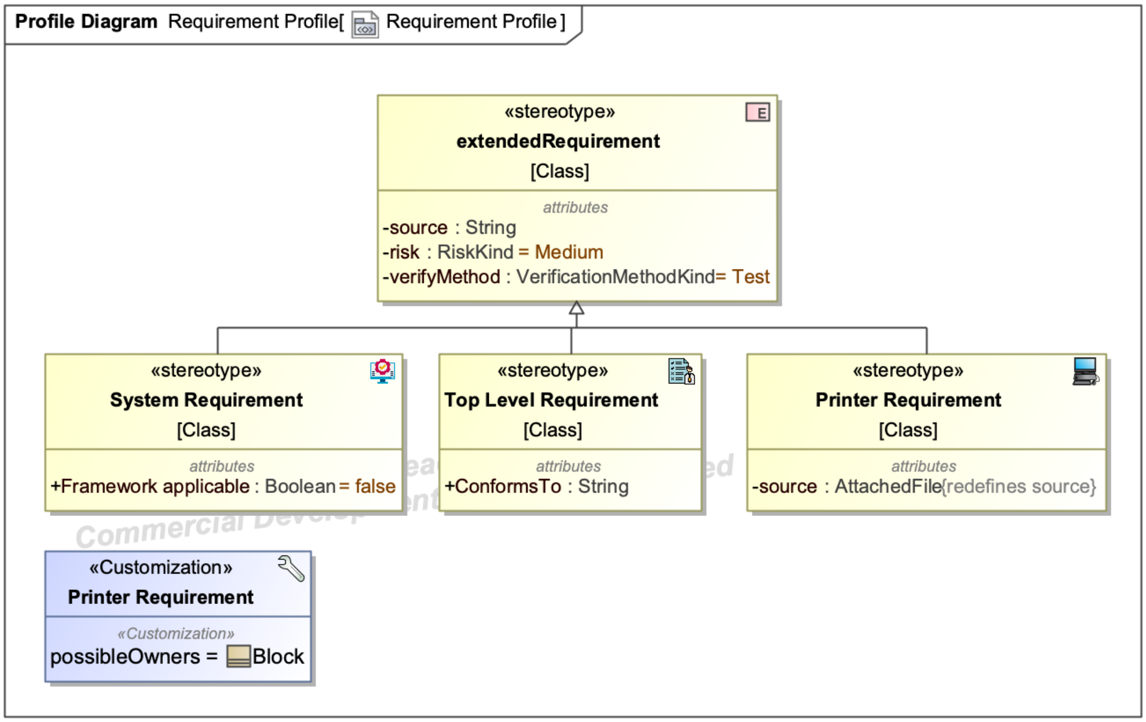


Figure 3.9. Custom Requirements Profile

The three types of requirement classes incorporate additional new attributes. The *system requirement* class includes a framework applicable attribute, of *Boolean* type, to determine if a system requirement was applicable to a framework. The *top-level requirement* class features a *conforms to* attribute, of *string* type, allowing traceability from top level requirements to a governance or standard documents. Finally, the printer requirement class has a source attribute, of *attached file* type, to indicate the origin of the requirement. If the file containing the printer requirements is imported into the AMDTMM tool (e.g., a PDF file), the printer requirement element's source attribute can link the requirement to its origin. This approach helps bridge the gap between traditional "paper-based" methods and a more modern "digital" strategy, all being accomplished within the AMDTMM tool.

3.5.1.2 AM Profile

Following the same philosophy as used when developing the requirements profile, the AM profile was created to identify the seven printer types from the DOD AM Strategy, which were Binder Jetting, Material Extrusion, Material Jetting, Sheet Lamination, Vat Polymerization, Powder Bed Fusion, and Directed Energy Deposition as unique elements in the AMDTMM tool. However, unlike the requirements profile rational, there was no federated or standard way to model AM processes using MSOSA. Nonetheless, the team used the same heuristics as in the requirements profile in the AM profile by extending the SysML *block* element as illustrated in Figure 3.10. This created the *AM printer* stereotype. The *AM printer* stereotype provided the ability to add common attributes to each printer stereotype before identifying the seven unique printer stereotypes. The *AM printer* added four new attributes: *manufacturer, part number, build volume, technology type, and print bed*. Next, all seven printer types were created by extending the *AM printer* and its associated new attributes. It is noted that the *technology type* attribute was added as a default value for each of the seven types of printers to correspond with the printer type. For example, the *binder jetting* stereotype was set a default value of "binder jetting" to *technology type*. Furthermore, the seven customizations, one for each printer type shown in Figure 3.10, enable the ability to change the element icon picture and allow the element to be selected in MSOSA's drop down menu when creating new elements.

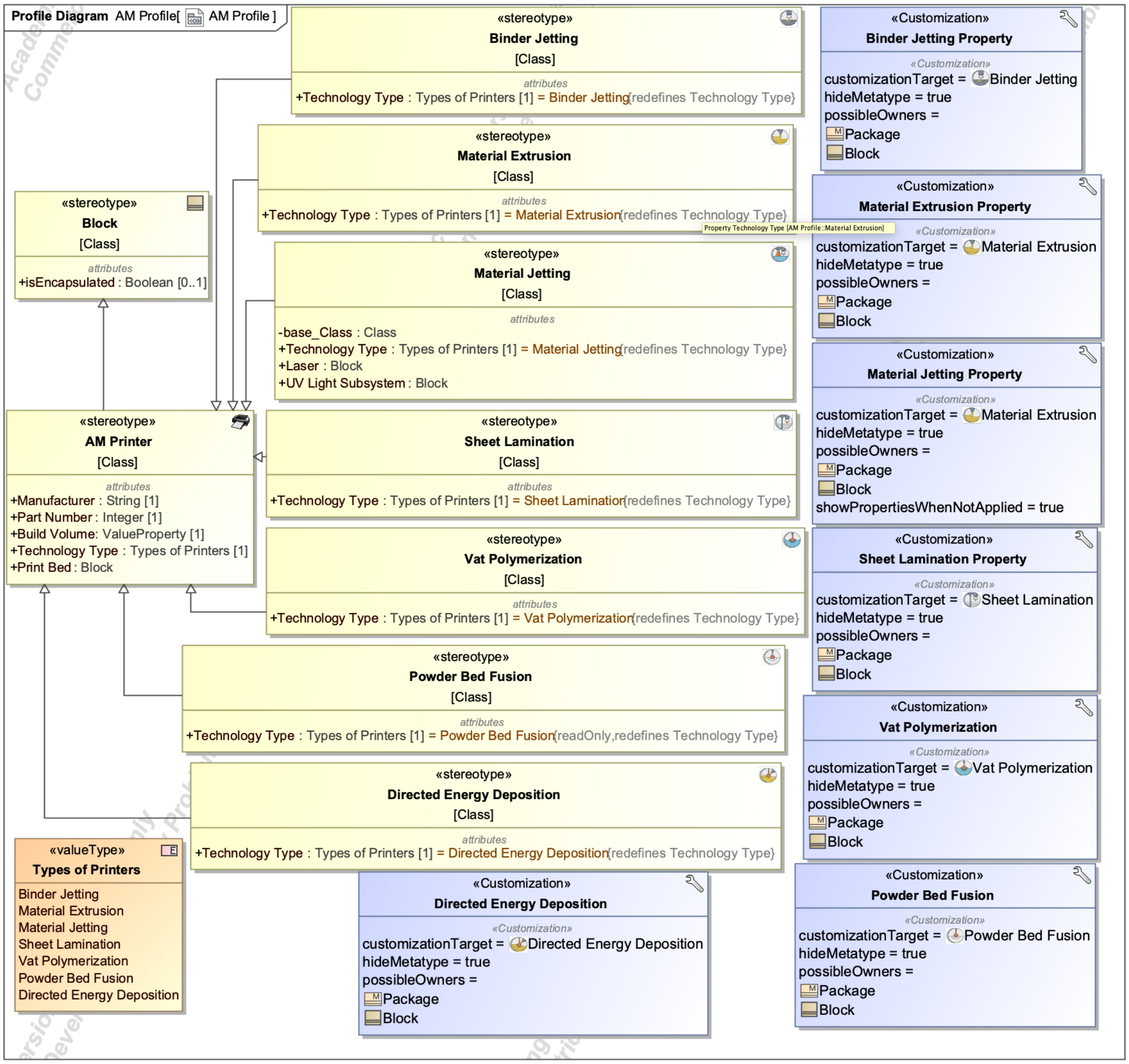


Figure 3.10. Custom AM Profile

3.5.2 AMDTMM Framework

One of the initial steps in developing a model is to understand the various factors that must be included to ensure that the AMDTMM accurately reflects the physical AM system. The framework of the AMDTMM should account for requirements of each printer type, providing the ability to capture the printer's capability and performance. Additionally, the framework should incorporate the hierarchical structure of the physical AM system, which entails creating a hierarchy representation of subsystems and parts within the printer. Furthermore, the DT needs to mimic the behavior of the physical system by capturing simulation results from other modeling tools and even SysML behavior diagrams of the printer. Lastly, the framework should include parameters of the printer as measured data off physical sensors on the printer. To offer a more comprehensive overview of the model framework, Chapter 4: *Implementation, Instantiations and User Guide* will focus on the development of one particular printer, the Xerox ElemX. The image depicted in Figure 3.11 illustrates the framework used in the AMDTMM tool.

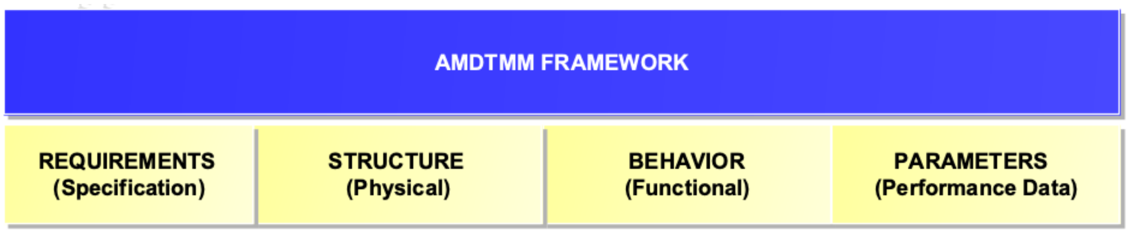
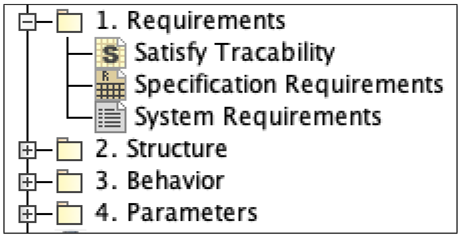


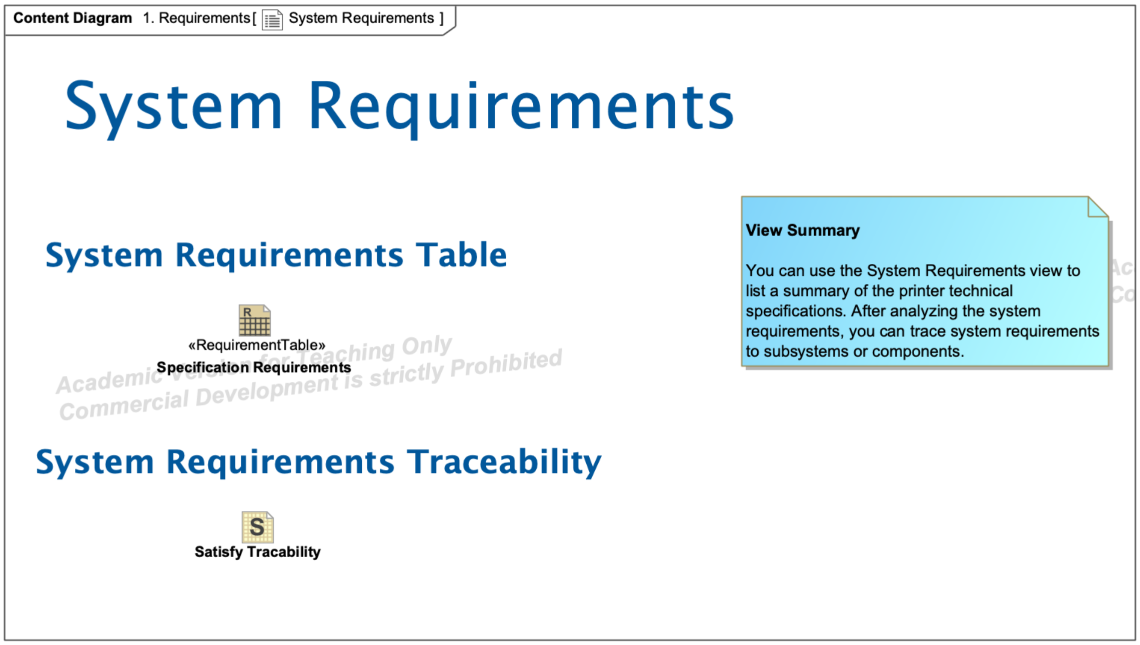
Figure 3.11. AMDTMM Framework

3.5.2.1 Requirement

The first cornerstone of the AMDTMM framework is the *Requirements*. Within the Requirements section of the AMDTMM Framework, the user is greeted with a system requirements content diagram that functions as an overview page to hold all generated views of the AM requirements, along with any notes and pertinent information, as shown in Figure 3.12. The default views provided are *system requirements table*, ready to add *printer requirements* as discussed in subsubsection 3.5.1.1, and a *system requirements traceability matrix*, built to show the satisfy relationship from requirements to SysML *blocks* (when developed as part of the printer structure). Although these are the default views, the AMDTMM tool would permit for additional views to be created as necessary. Within the *system requirements table*, the user can either add new *printer requirements*, or for a more advanced look, change the scope within the table to show requirements from multiple printers. The user can also add in specification documents of the printer to the repository. In the *system requirements traceability* view, the user is offered similar flexibility to either search existing traceability matrices or to create a SysML<*satisfy*> relationship to trace structural elements that satisfy each individual requirement.



(a) AMDTMM Framework: Requirement Repository

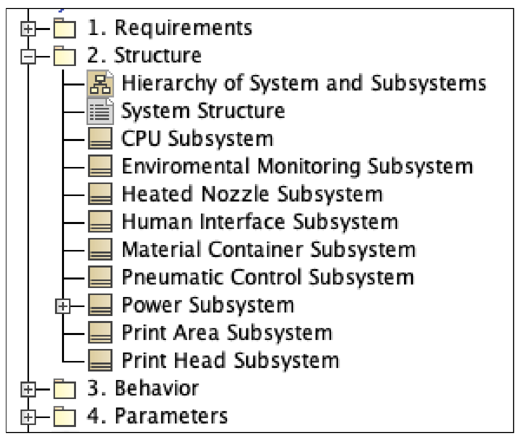


(b) AMDTMM Framework: System Requirements Overview Page

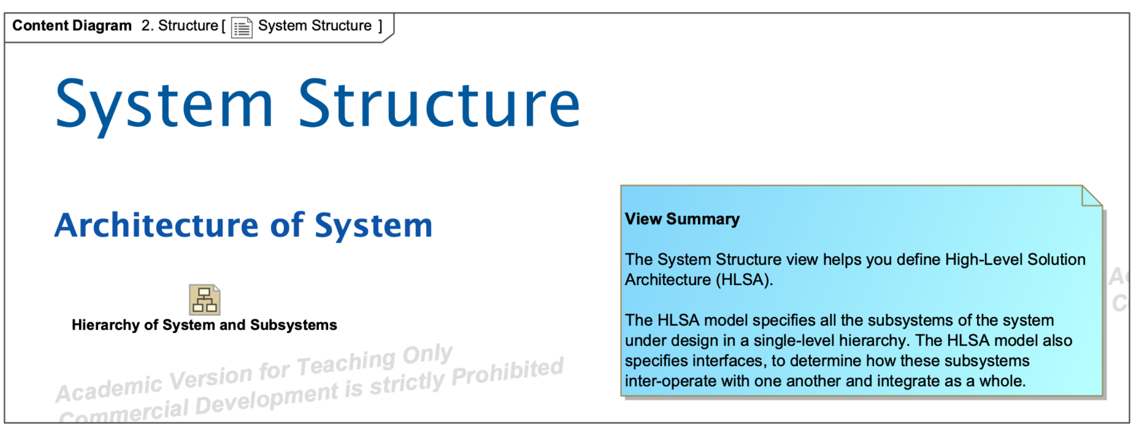
Figure 3.12. Handling Requirements Under the AMDTMM Framework

3.5.2.2 Structure

Continuing with the AMDTMM framework, the next pillar of the framework is the *Structure*. Unique structures were created for each of the seven types of AM printers, offering a high-level distinction between their various subsystems. An example of the structure built in the containment tree along with the system structure overview page developed is illustrated in Figure 3.13. This structure established in the framework can be further developed in the future to define individual subsystems and components of the specified printer. Within the *Structure* view, an AM printer's physical architecture can be decomposed into subsystems, which are represented as blocks. These subsystem blocks can be assigned specific properties. The relationships between these blocks are also defined, illustrating how each block interacts with one another to form the encapsulating system.



(a) AMDTMM Framework: Structure Repository

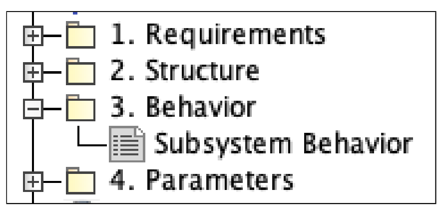


(b) AMDTMM Framework: System Structure Overview Page

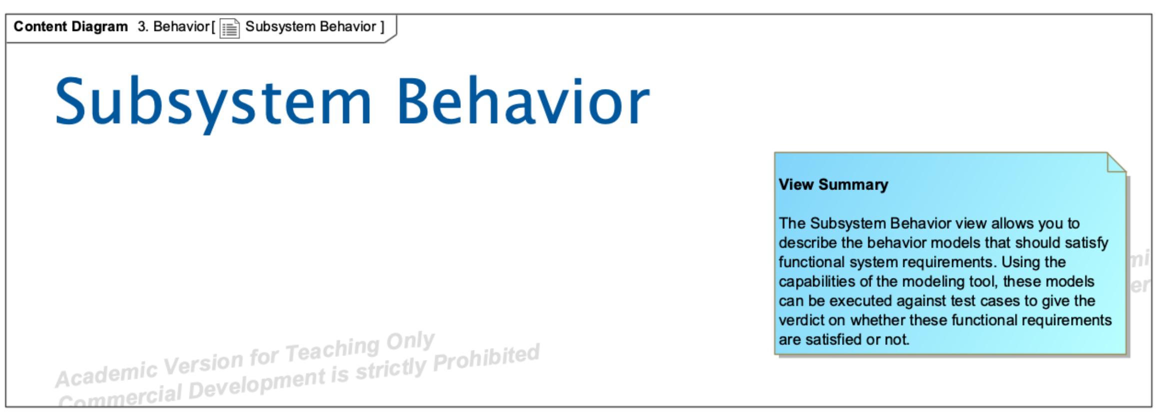
Figure 3.13. Handling Structure under the AMDTMM Framework

3.5.2.3 Behavior

The next pillar of the AMDTMM framework is the *Behavior*, which is used to characterize individual system functionality. Behaviors are specific to the overall printer and/or specific functions that make up the printer. The *Subsystem Behavior* view allows the user to visualize system behavior either through SysML diagrams, such as activity, sequence, and state machine diagrams, or by importing results from external stochastic analysis tools like MATLAB and ExtendSim into the AMDTMM. The external files can also live directly inside the AMDTMM tool, which provides the benefit of allowing the system behavior overview to serve as a method of configuration management as shown in Figure 3.14. Furthermore, behavior models built inside MSOSA have the added benefit of running simulations and against test cases to generate objective quality evidence that the requirements are being satisfied.



(a) AMDTMM Framework: Behavior Repository

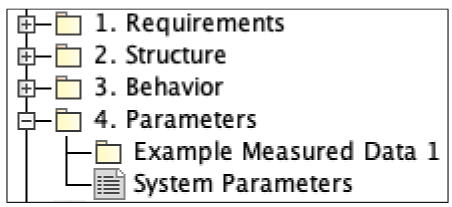


(b) AMDTMM Framework: System Behavior Overview Page

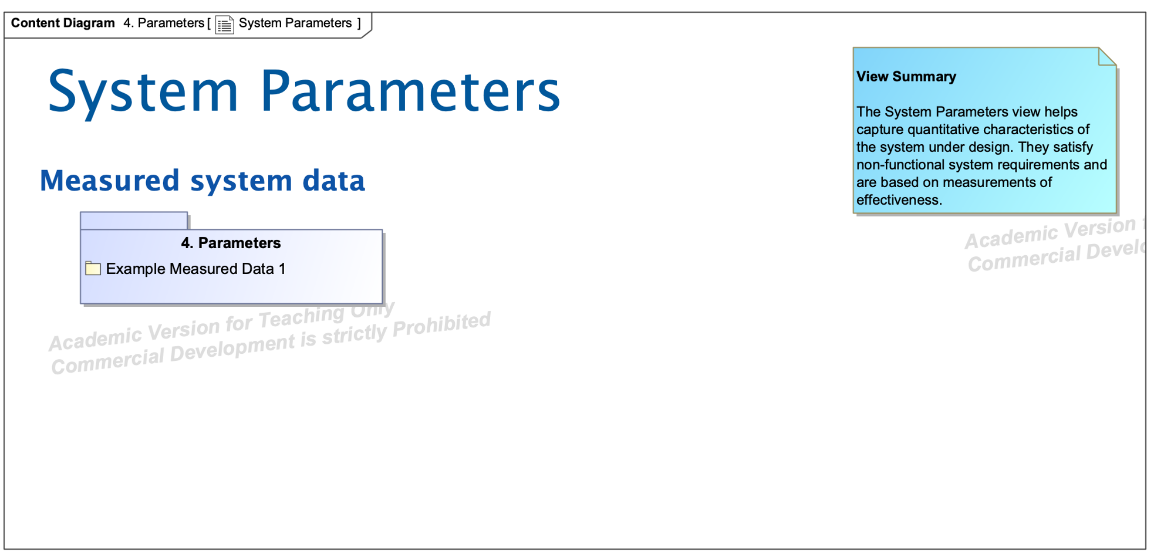
Figure 3.14. Handling Behavior under the AMDTMM Framework

3.5.2.4 Parameters

The final component of the AMDDTMM framework is the *Parameters*. Similar to the system behaviors, parameters are specific to each individual AM printer. Within the *System Parameters* content diagram, printer-specific data views can be uploaded to the AMDTMM, as seen in Figure 3.15. Stakeholders and end users can customize the parameter views as needed, incorporating external modeling and simulation results into the repository. Some examples of data that were compiled to demonstrate the model's capability include the ElemX print head acceleration, provided to the capstone team by CAMRE. Further discussion on the ElemX *Parameters* is discussed in Chapter 4. Once the model is deployed, end users can continue to add additional modeling and simulation data to the AMDTMM parameter section.



(a) AMDTMM Framework: Parameter Repository



(b) AMDTMM Framework: System Parameters Overview Page

Figure 3.15. Handling Parameter under the AMDTMM Framework

3.6 Conclusion

In Chapter 3: *Design and Development*, a detailed overview of the development approach used to create the AMDTMM was showcased, which will be used to instantiate DTs in Chapter 4: *Implementation, Instantiations and User Guide*. The development started with a stakeholder needs analysis that evolved into a complete requirements analysis, decomposing stakeholder needs into top level requirements and system requirements. Using the tailored systems engineering approach, which was iterative by design, the team's development process consisted of identifying necessary capabilities, developing the functionality in MSOSA, and testing the implementation to see if it was suitable for the proposed DT design. During the development process, a requirements profile and an AM profile was created along with a unique DT framework which served as the underlying schema in the AMDTMM tool. Coupling the AM and requirements profiles with the AMDTMM framework produced the DT design suitable for the capstone team's interpretation of the objectives of the capstone project.

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CHAPTER 4: Implementation, Instantiations and User Guide

This chapter outlines the use of the AMDTMM tool for instantiating different printers by following the detailed framework. The Xerox ElemX was the first AM DT printer instantiated using the AMDTMM tool, followed by the Concept M2 Series-5 printer. This chapter provides an overview of the AMDTMM usage, including pre-developed templates and navigation of the containment tree within the tool. Additionally, a user guide was developed to streamline the learning process for users adopting the AMDTMM.

4.1 Using the AMDTMM

There are two main use cases for utilizing the AMDTMM tool. The first involves adding a new printer type DT instance to the AMDTMM repository within one of the seven predefined printer types. The second primary use of the AMDTMM is to view or make changes to an existing printer DT already in the repository. Changes may include updating, modifying, deleting or expending existing printer information in the repository as it becomes available from resources or data gathered from experiments. To facilitate users learning how to use the AMDTMM efficiently, a user guide was built directly within MSOSA and illustrated in Appendix B: *AMDTMM User Guide*.

One of the initial findings when implementing the AMDTMM was the need for organizing each DT instance of printers in the model, including the corresponding framework. The team settled on a hierarchy of SysML *packages* to organize and structure each DT by the type of printer. The AMDTMM Containment Tree is the primary method of navigating throughout the model and serves as the organizational structure that contains all of the model's contents. It also provides a visual of the different packages, elements, diagrams, etc. contained in the AMDTMM tool. Through the containment tree, users can navigate throughout the model and reach the desired printer DT. The seven types of printers shown inside the red box in Figure 4.1 show the categorizing approach used in organizing the printer DTs. This organization approach is intuitive and yet adheres to the DOD's AM Strategy. Furthermore, after development of the AMDTMM, the team created a landing page, outlined in blue in Figure 4.1, as a way to mimic a traditional cover page and executive page in a report.

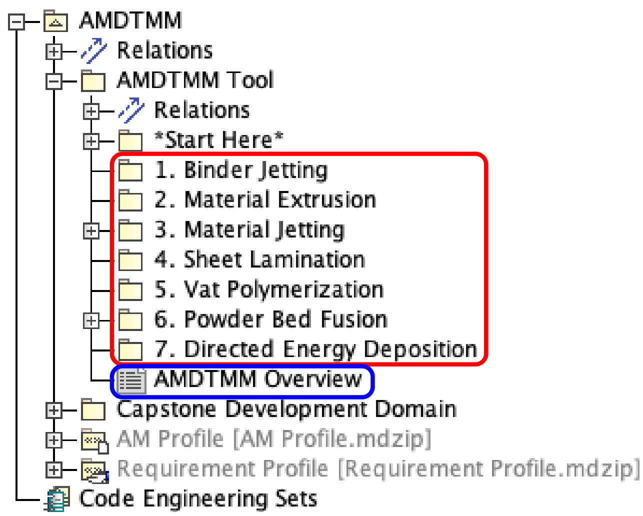

Figure 4.1. AMDTMM Containment Tree - Overview

The landing page is an important part of the model, as it provides an upfront overview of the entire model and provides helpful links that encapsulate the overall purpose of the AMDTMM tool. This landing page, illustrated in Figure A.4 in Appendix A, functions as the centralized hub of the tool and provides the user with an overview of currently instantiated DTs, which have been currently developed and modeled while providing an overview of the project. An area to point out on the landing page is the bottom seven packages. These packages will dynamically expand when new DT printer instantiations are added to the AMDTMM tool, making the landing page a versatile resource showing new additions in the AMDTMM tool.

When adding a new printer DT to the AMDTMM tool, the team provided a template to facilitate the integration of the DT framework for each of the seven types of AM. In order to provide this template, the team created seven unique "start here" *packages* that allow the user to copy and paste as a starting point when developing a new DT instantiation. The developed template provides the necessary framework, SysML elements, and diagrams needed while providing a way to standardize the data being brought into the AMDTMM in an organized fashion. Figure 4.2 illustrates how the containment tree is organized with the blue box outlining the seven AM types and the cyan box outlining the pre-developed generic framework of AM type Material Jetting, as an example.

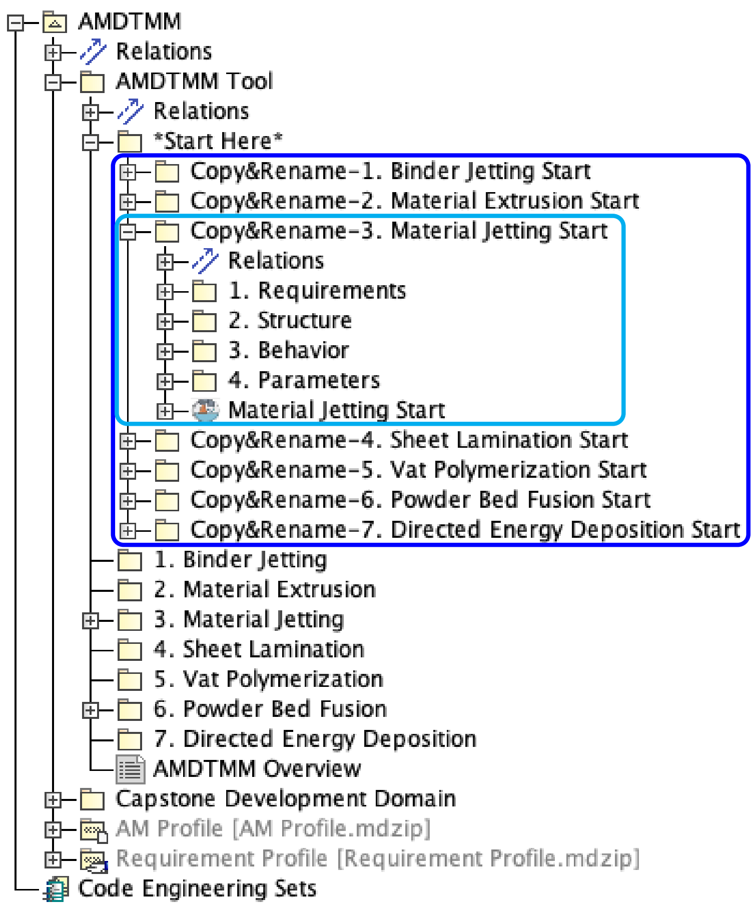

Figure 4.2. AMDTMM Containment Tree - Seven Pre-Developed Templates

4.2 Xerox ElemX Instance

As described earlier in Chapter 1: *Introduction*, the Xerox ElemX was used as an initial case study and first DT instance in the AMDTMM. The team created an instantiation of the ElemX based on information gathered from CAMRE and from online sources covered in

Chapter 2: *Background and Literature Review*. Taking into consideration limited resources for available information on the Xerox ElemX, the instantiation is considered partial and not complete, but still covers the four pillars of the AMDTMM framework. The intent is that it will serve as a foundation medium for future CAMRE work for not only the Xerox ElemX, when available, but for other 3D printer DTs to further describe aspects not already covered in the AMDTMM tool. Specifically, the *Structure*, *Behavior* and *Parameter* sections can be further refined with more information, data and experimentation-provided insight and measured data from Subject Matter Experts (SMEs).

When first creating a DT for the Xerox ElemX, the ElemX was matched with one of the seven 3D printer types defined by the DOD AM Strategy. Based on the AM Strategy, the Xerox ElemX best fit the type of Material Jetting. The next step in creating an individualized printer instance is to use the pre-developed DT shown in blue in Figure 4.3 and copy the "Copy&Rename-3. Material Jetting Start" *package* to the light blue *package* called "3. Material Jetting." Once there, rename the *elements* and *packages* inside the "Copy&Rename-3. Material Jetting Start" to the ones shown in the red box. Once complete, the outline and instance for the Xerox ElemX has been developed.

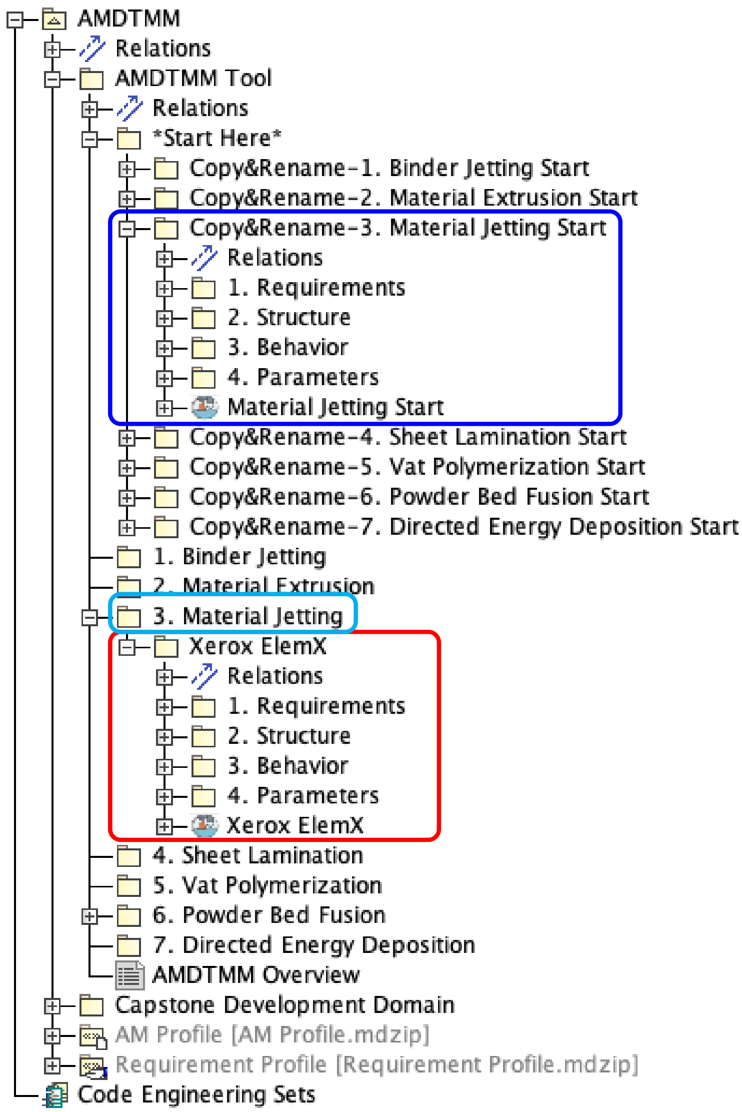

Figure 4.3. Xerox ElemX Instantiation Using the Pre-Developed Template

4.2.1 Requirements (Specification)

The first pillar of the AMDTMM framework is focused on printer specifications and requirements. To build this section out comprehensively, it was essential to gather as much information, as made available, from the printer manufacturer (Xerox) and existing specifications from on-line resources. The requirements section in the framework allows the user to upload documents into the model, providing not only Objective Quality Evidence (OQE), but overall traceability to the specifications that were generated and imported into the Xerox ElemX instantiation within the AMDTMM. The team collaborated with CAMRE to further gather specific documentation on the Xerox ElemX and learned about the printer's behavior and periodic maintainability. The Xerox ElemX system specifications data-sheet served as the primary reference for the requirements generated, with supplemental requirements being generated from the Xerox ElemX Customer Packet. Table A.1 in Appendix A presents the MSOSA SysML requirements table exported from the AMDTMM for the Xerox ElemX. Although Table A.1 only depicts the four columns for *ID, name, text,* and *source*, the SysML requirements table can show other attributes inherited by the *printer requirement* stereotype, as discussed in Section 3.5.1.1: *Requirements Profile*. Traceability from the Xerox ElemX's requirements to the SysML *blocks* using the *satisfy* relationship were also generated and depicted in Figure A.1 in Appendix A.

4.2.2 Structure (Physical)

The second pillar of the AMDTMM framework explored the physical structure of the Xerox ElemX, focusing on the internal subsystems and components that collectively form the printer. In order to construct a comprehensive and accurate representation of these structures, the Xerox ElemX customer packet served as a vital source of information, complemented by collaboration with members of CAMRE. However, due to the proprietary nature of some printer components and the lack of publicly available data, the team had to make engineering assumptions regarding the interactions between various internal subsystems. As part of the physical structure analysis, the team examined aspects such as printer heads, build platforms, material handling systems, and control systems. These components were then represented digitally in the AMDTMM by the use of blocks, with specific properties assigned to each block. Relationships between these blocks were also established, illustrating how the subsystems interact and exchange information with one another through the use of SysML *proxy ports*. Figure B.4 in Appendix A depicts the Xerox ElemX block definition diagram, providing a visual representation of the printer's hierarchy, while Figure A.6 in Appendix A depicts the internal structure of the ElemX to showcase the information flows between subsystems in an internal block definition diagram.

4.2.3 Behavior (Functional)

The third pillar focused on the behavior of the Xerox ElemX, which presented a challenge due to the lack of physical access to the printer. Despite this obstacle, the team utilized the Xerox ElemX customer packet to create a state machine diagram that illustrates the operational state lights of the printer. This comprehensive state machine encompassed every mode of operation the ElemX experiences, offering a clear understanding of the printer's behaviors and transitions across different operational states. Furthermore, the state machine is executable with programmed logic to step through each state using signals to transition to the next. Figure A.8 in Appendix A illustrates the Xerox ElemX state machine diagram. This section is one that can be further refined in future CAMRE work.

4.2.4 Parameters (Performance Data)

The fourth and final pillar of the AMDTMM characterized the performance data of the Xerox ElemX. The team has received test data from CAMRE from ongoing testing on the USS *Boxer*. The test data consisted of the acceleration and temperature of different printer components during use. Description of the objects printed in the test data, such as size and format, was not provided, but valuable data could be inferred from comparing the acceleration of different printer components to the quality of the printed part. If testing was performed underway, nautical impact to the platform could affect the quality and efficacy of each printed component. However, additional performance data showcasing the measured capabilities of the printers are needed to populate this section of the framework to further increase the utility and overall usefulness for CAMRE. The goal is to expand this pillar of the framework inside the AMDTMM so this tool can be leveraged in the future as additional research and experimentation are performed on the ElemX. The additional information would result in further defining this pillar of the AMDTMM framework to help further characterize the capabilities of the printer within the AMDTMM.

4.3 Concept Laser M2 Series-5 Instance

In addition to the Xerox ElemX, the Concept Laser M2 Series-5 printer, developed by General Electric, was selected by the team as the second case study. The team selected this printer after reviewing previous CAMRE research capstone projects as discussed in Chapter 2: *Background and Literature Review*. In the capstone report, "Architecture for a

CBM+ and PHM centric digital twin for warfare systems" [30], the Concept Laser M2 was the subject of the capstone group's research. The Concept M2 was built out in a similar fashion as the Xerox ElemX instantiation within the AMDTMM, with the intent to show how to integrate previously executed CAMRE work. However, only three out of the four pillars of the framework were developed for the Concept M2 Series-5 printer due to missing measured information needed to build out the *parameters* section.

4.4 Conclusion

The AMDTMM was designed with the user experience as a core design philosophy. By utilizing a centralized landing page and a containment tree navigational structure, the AMDTMM facilitates ease of access in an organized fashion. The AMDTMM is structured so that individual types of AM printers are organized into hierarchical packages, categorized by the seven types of printers found in the DOD AM Strategy. Users can add, remove, or edit existing printer entries, tailoring each DT to their needs. The AMDTMM captures both the physical structure and functional behavior of designated printers adhering to the DT framework and serving as a repository. These features, coupled with the built-in User Guide found in Appendix B: *AMDTMM User Guide*, highlight the user experience focus that was at the forefront of the AMDTMM design.

CHAPTER 5:
Recommendations and Conclusions

The objective of the AMDTMM capstone project was to create a DT MM to serve as a centralized repository for CAMRE and the tri-maritime services. The vision for this project was to enable the tri-maritime fleet to model and simulate the AM process using digital representations of 3D printers. In order to achieve this goal, the team utilized an MBSE approach and the MSOSA modeling tool to design the model, as outlined in the CAMRE Broad Area Study. The team successfully developed an architecture for seven different types of printers and, as a proof of concept, created a higher fidelity model of the Xerox ElemX. However, due to limited information on the printer, a partial DT was developed using provided and researched information. Despite this, the current state of the partial DT model presents numerous opportunities for future enhancements.

5.1 Areas for Future Work

The AMDTMM provides a modular framework designed to evolve with the contributions of future CAMRE work. As a centralized repository, its utility will be determined by CAMRE and other researchers among the tri-maritime services by adopting to the organizational structure and framework in the AMDTMM. The AMDTMM can be further expanded by integrating external simulations and models, such as ExtendSim, Matlab, Simulink, etc. Simulink integration could be relatively straightforward due to built-in compatibility with MSOSA. However, the team encountered issues with integration because of an insufficiently developed relevant Simulink model. Another possible expansion of the AMDTMM is to integrate components that facilitate compatibility with the Internet of Things (IoT). The phrase IoT refers to, "scenarios where network connectivity and computing capability extend to objects, sensors, and everyday items not typically considered computers, allowing these devices to generate, exchange, and consume data with minimal human intervention" [41]. In this scenario, IoT will facilitate the transfer of data from the physical model sensors to the digital model and vice versa. Successful integration of IoT into the MM will provide users with the potential capability to predict part failure on the physical model based on the quality of data transferred using IoT. Furthermore, the physical AM component's reliability and availability can be analyzed using a live transfer of data from the physical model to the digital model.

The current state of the partial DT offers numerous avenues for expansion, enabling users to study and understand complex AM system component functionalities. A completed model can offer users the capability to simulate the printing process of an item using seven different types of printers. Such a simulation would provide information on the printing process time, power consumption, heating plate temperature, and final product quality. Ultimately, those heuristics would require additional development within the existing model.

Furthermore, an additional recommendation for future work could be adding information on the time needed to print a part, environmental behavior, and maintainability. The time required to print a part, dependent on its size and form, is crucial for gauging user demand and determining mission-critical, time-sensitive uses. Information on printer behavior resulting from environmental interference, such as sensitivity to vibration and sea motion, is necessary for proper printer usability and the quality of the parts produced/printed. Maintainability information, such as Mean-Time-Between-Failures, periodic replacement of worn components, and time to repair/replace worn/damaged components, will allow users to forecast running costs and downtime. Integrating all of the recommendations mentioned can enhance the AMDTMM's capability and better assist CAMRE or the tri-maritime services in selecting the most suitable printer for specific environment and mission requirements.

5.2 Conclusion

As AM technology gains traction across various industries, its applications within the DOD have expanded from producing small components to creating critical replacement parts for equipment. However, ensuring the quality of produced parts remains a challenge, often leading to waste. Implementing a process that simulates production can significantly improve the likelihood of generating high-quality products. A DT model, the digital counterpart of a physical system or product, has been successfully adopted in several industries to optimize their processes and proven to enhance the user's, or stakeholders, understanding on how actual systems perform.

The CAMRE team at NPS aimed to develop an AMDTMM of a 3D printer using the MSOSA system modeling tool while leveraging DOD's Digital Engineering Strategy processes for MBSE. The project commenced with a research phase centered on AM and DT technologies, supplying the necessary foundation for the design process of the AMDTMM. The developed DT framework consisted of the seven different types of printers, per the DOD's AM Strategy, which provided a versatile, modular, and scalable framework to support the ongoing advancement of AM research and applications in an organized repository. Through the collaboration with CAMRE and industry partners, the AMDTMM has the potential to evolve in scope and utility to better assist the user in the selecting, understanding, and enhancing of each 3D printer instantiation for the desired application.

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APPENDIX A:
Xerox ElemX Instantiation

This Appendix serves as reference information from the AMDTMM for the Xerox ElemX.

Table A.1. Xerox ElemX Requirements. Adapted from [4], [42]

Beginning of Table			
ID	**Name**	**Text**	**Source**
1	ElemX-1 Input power	The ElemX SHALL not exceed 480 volts 3 phase at 50 amps.	XeroxElemx_System Specifications.pdf
2	ElemX-2 Total Weight	The ElemX SHALL not exceed 4730 lbs (2146 kg).	XeroxElemx_System-Specifications.pdf
3	ElemX-3 Print area	The ElemX SHALL have a print volume of 12 in x 12 in x 4.7 in (300 mm x 300 mm x 120 mm).	XeroxElemx_System-Specifications.pdf
4	ElemX-4 Chiller Weight	The ElemX SHALL chiller with maximum weight not exceeding 340 lbs (154 kg).	XeroxElemx_System-Specifications.pdf
5	ElemX-5 Chiller Dimensions	The ElemX SHALL have a chiller volume of 9.3 ft x 4 ft x 7.3 ft (284 cm x 125 cm x 221 cm).	XeroxElemx_System-Specifications.pdf
6	ElemX-6 Required Room Space	The ElemX SHALL require no more than 20.5 ft x 12.4 ft x 10.3 ft (624 cm x 326 cm x 320 cm) of space.	XeroxElemx_System-Specifications.pdf
7	ElemX-7 Chiller power	The ElemX SHALL not exceed 230 volts single phase at 30 amps.	XeroxElemx_System-Specifications.pdf
8	ElemX-8 Build Rate	The ElemX SHALL have a maximum build rate of 0.5 pounds per hour (84 ccc/hour).	XeroxElemx_System-Specifications.pdf

Continuation of Table A.1			
ID	**Name**	**Text**	**Source**
9	ElemX-9 Maximum part weight	The ElemX SHALL not exceed 2 lbs per produced part.	XeroxElemx_System-Specifications.pdf
10	ElemX-10 Accuracy	The ElemX SHALL have a dimensional accuracy in the X and Y direction greater than +/- 0.6 mm and in the Z direction greater than +/- 0.5 mm.	XeroxElemx_System-Specifications.pdf
11	ElemX-11 Layer Thickness	The ElemX SHALL have a minimum layer thickness of 0.24 mm.	XeroxElemx_System-Specifications.pdf
12	ElemX-12 Heat	The ElemX SHALL provide the capability to heat each part as required by the operator.	XeroxElemx_System-Specifications.pdf
13	ElemX-13 Post processing	The ElemX SHALL have the ability to enable post processing.	XeroxElemx_System-Specifications.pdf
14	ElemX-14 Gas	The ElemX SHALL provide argon inert gas only in the print head region.	XeroxElemx_System-Specifications.pdf
15	ElemX-15 Surface finish	The ElemX SHALL provide a sand cast comparable surface finish to all parts produced.	XeroxElemx_System-Specifications.pdf
16	ElemX-16 Part Density	The ElemX SHALL ensure each part produced has a density of greater than 98.5 percent.	XeroxElemx_System-Specifications.pdf
17	ElemX-17 Input material	The ElemX SHALL provide the ability to use 354 (4008) aluminum alloy as a material.	XeroxElemx_System-Specifications.pdf
18	ElemX-18 Input material weight	The ElemX SHALL accept material on a spool at a weight not to exceed 20 lbs (9.1 kg).	XeroxElemx_System-Specifications.pdf

Continuation of Table A.1			
ID	**Name**	**Text**	**Source**
19	ElemX-19 Material diameter	The ElemX SHALL be capable of utilizing 0.062 in (1.6 mm) of wire diameter on a spool.	XeroxElemx_System-Specifications.pdf
20	ElemX-20 PC needed	The ElemX SHALL be Windows 10 compatible.	XeroxElemx_System-Specifications.pdf
21	ElemX-21 Memory	The ElemX SHALL have a minimum of 16 GB of RAM.	XeroxElemx_System-Specifications.pdf
22	ElemX-22 Wire Reel Weight	The ElemX SHALL support a wire reel of 20 lbs (9.07185 kg).	XeroxElemx_System-Specifications.pdf
23	ElemX-23 Chiller water temp	The ElemX SHALL provide 20 degrees Celsius water.	Day1_ElemX_1-1_Customer-Training_11222021.pdf
End of Table			

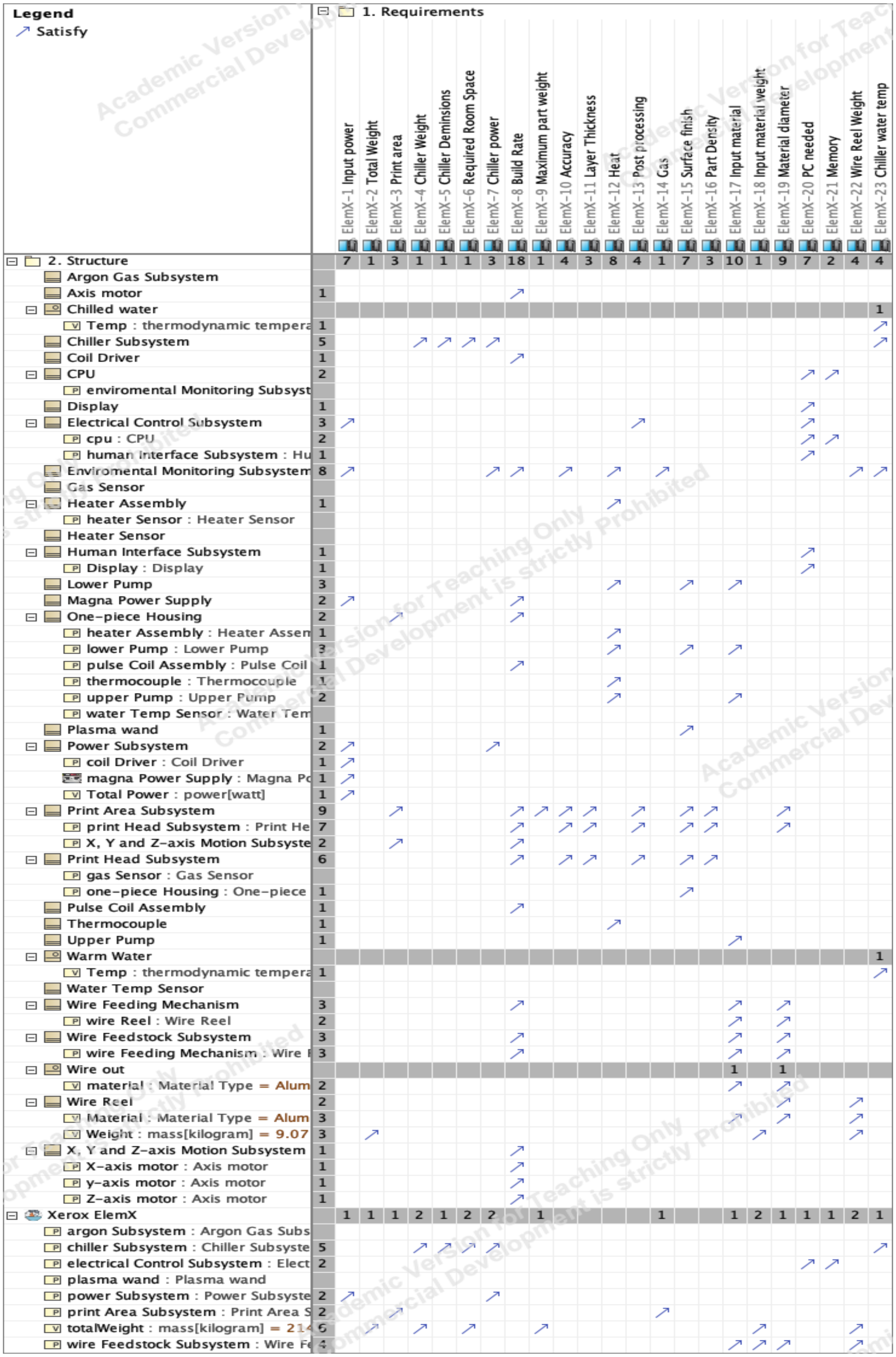

Figure A.1. Xerox ElemX Traceability Matrix

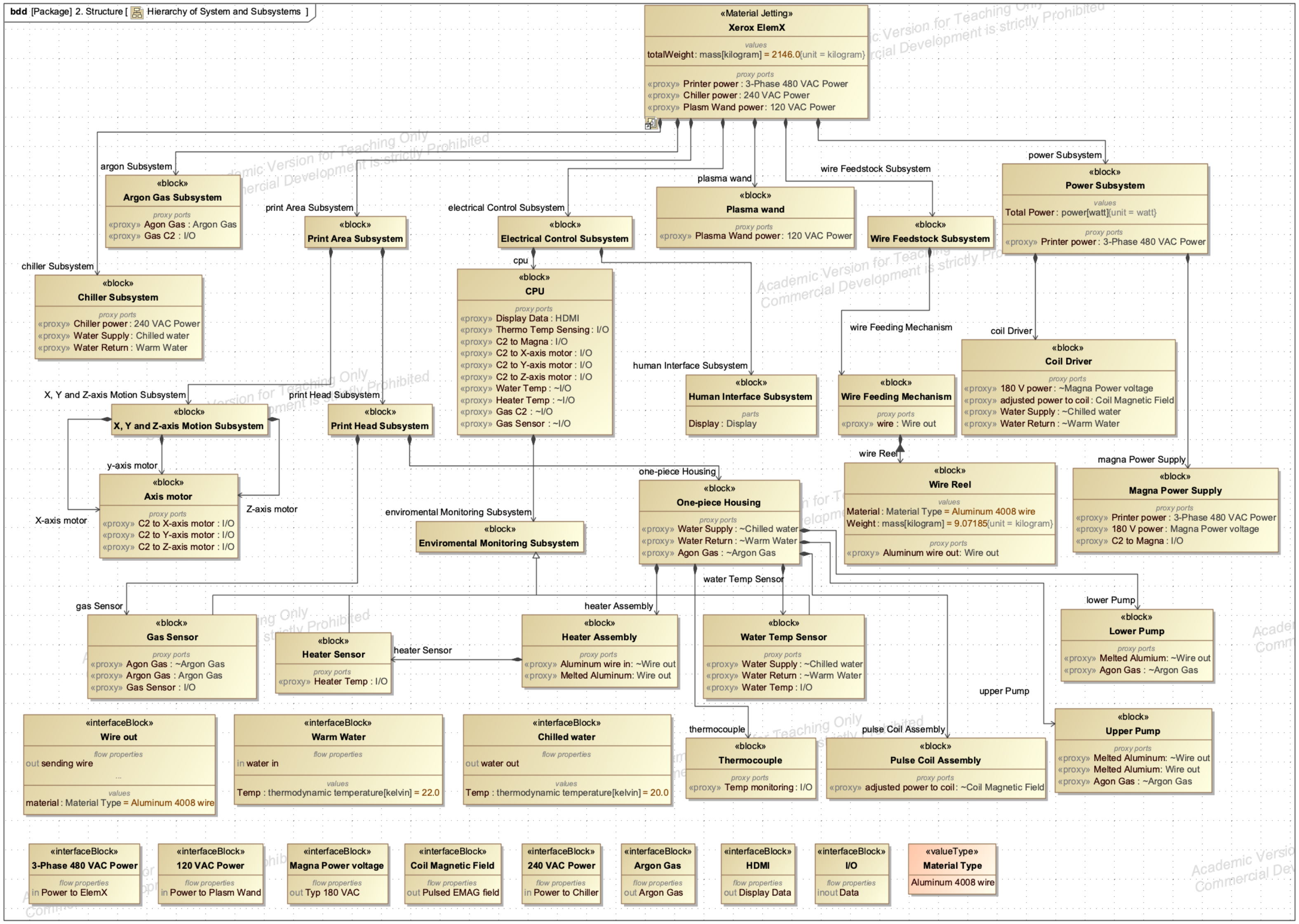

Figure A.2. Xerox ElemX Block Definition Diagram

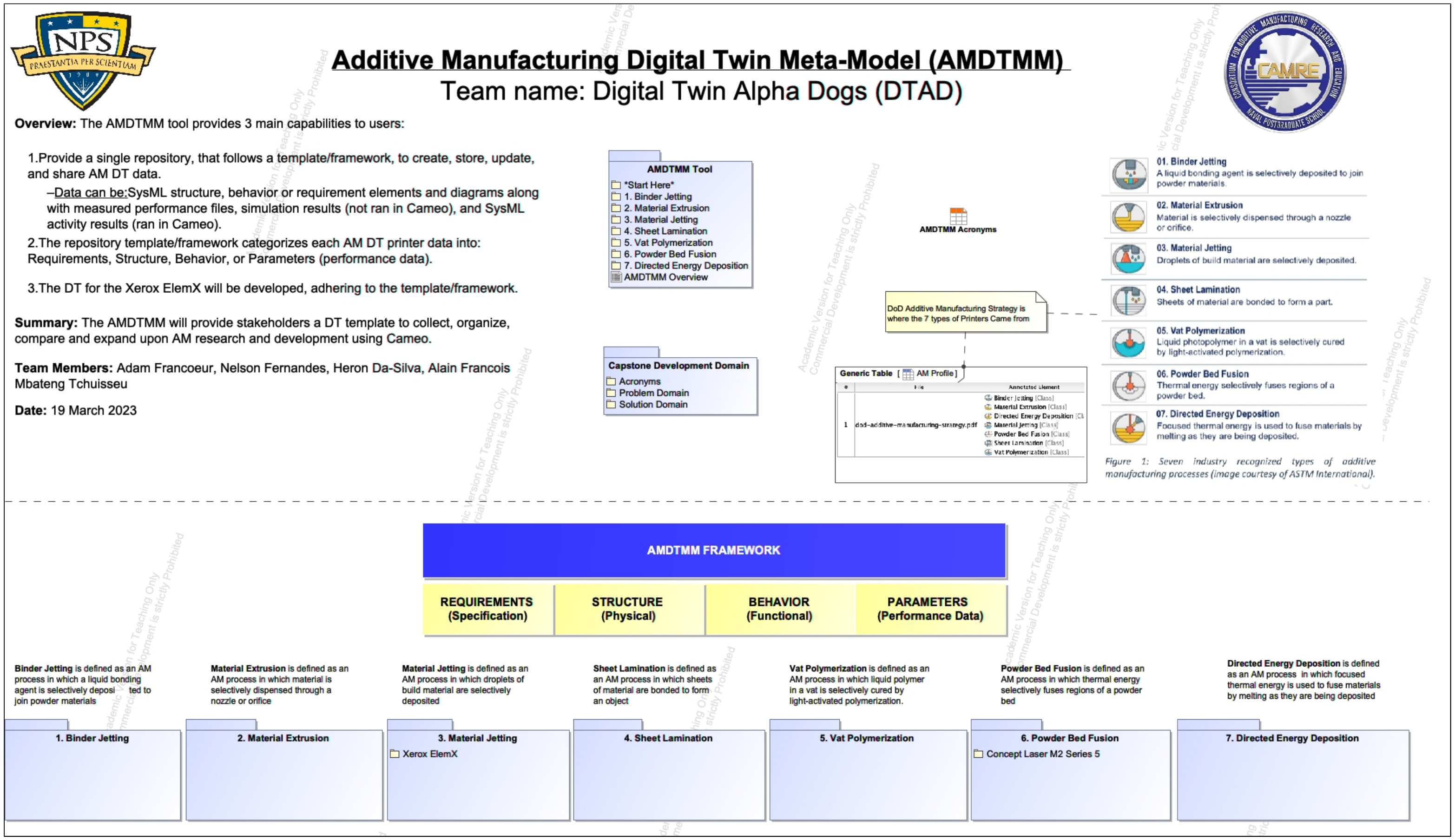

Figure A.3. AMDTMM Landing Page

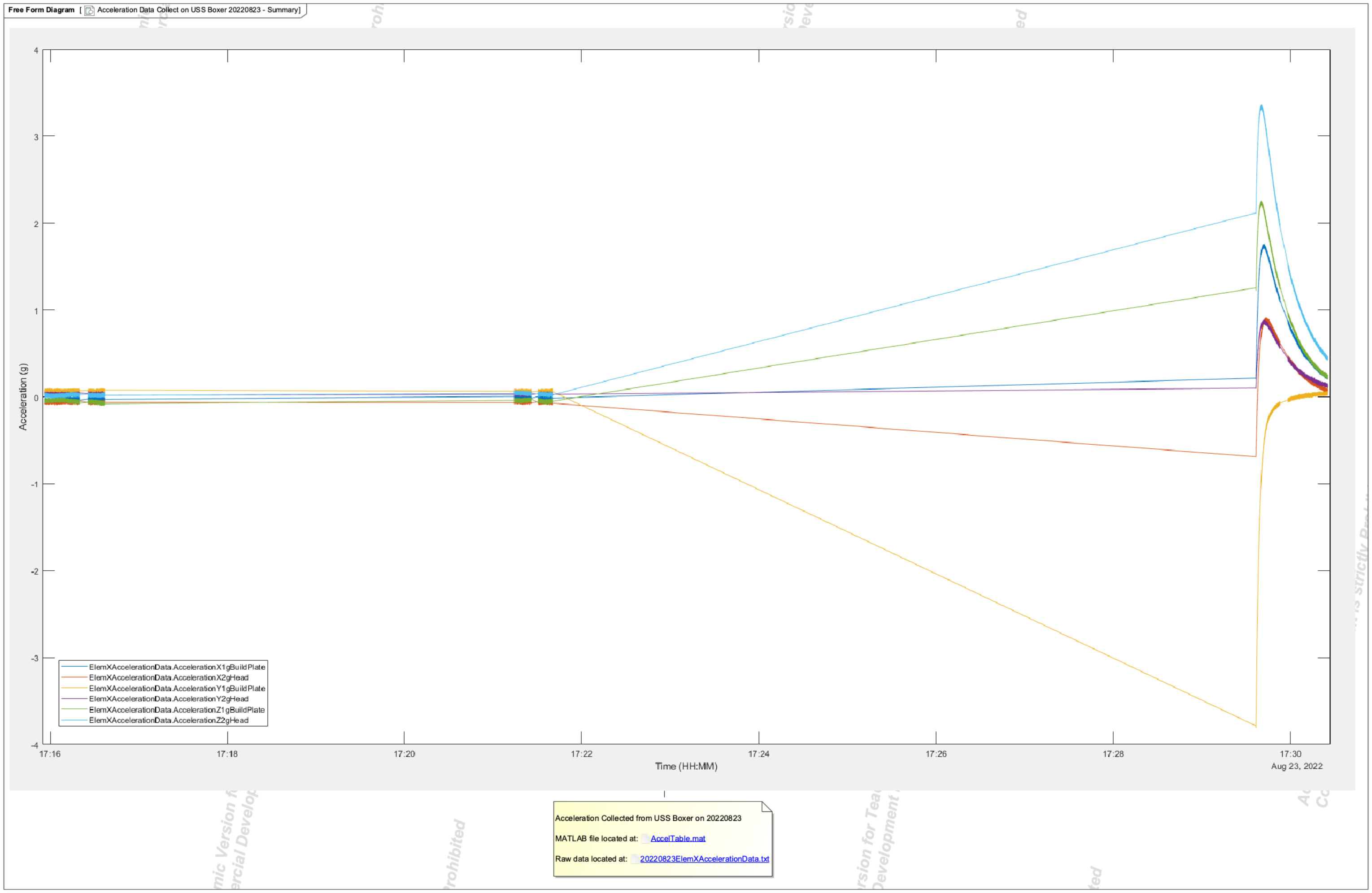

Figure A.4. Xerox ElemX Parameters - Acceleration Data

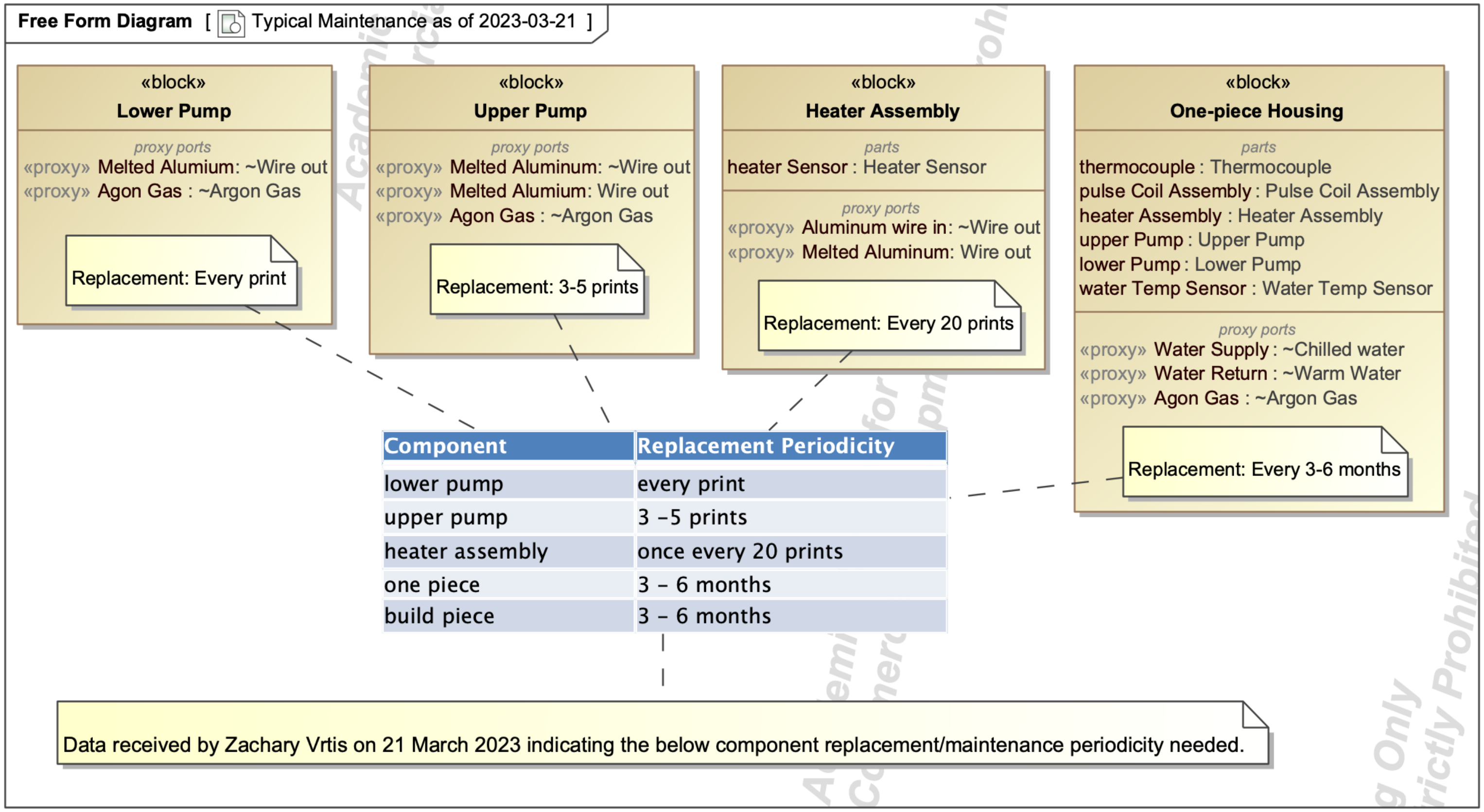

Figure A.5. Xerox ElemX Parameters - Typical Maintenance

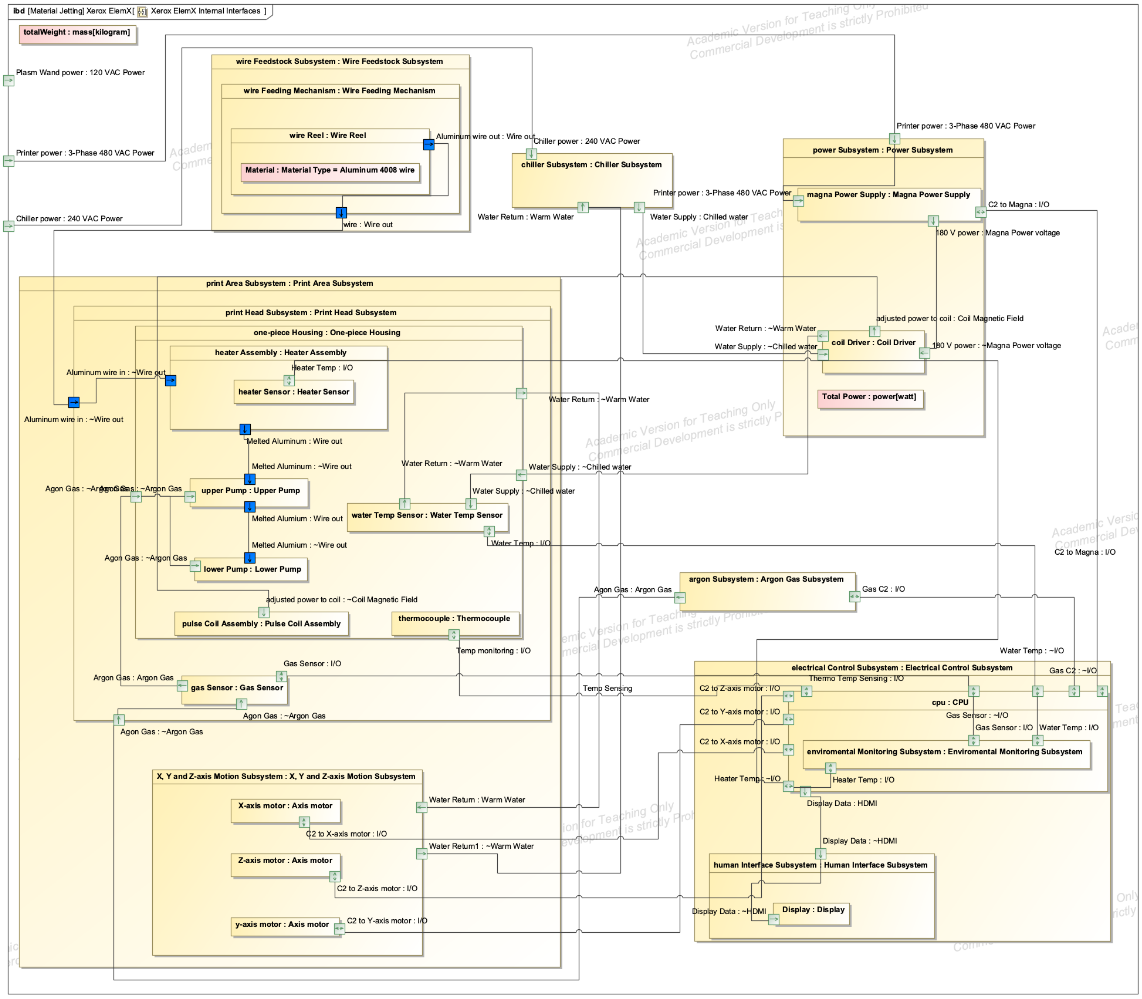

Figure A.6. Xerox ElemX Internal Block Definition Diagram

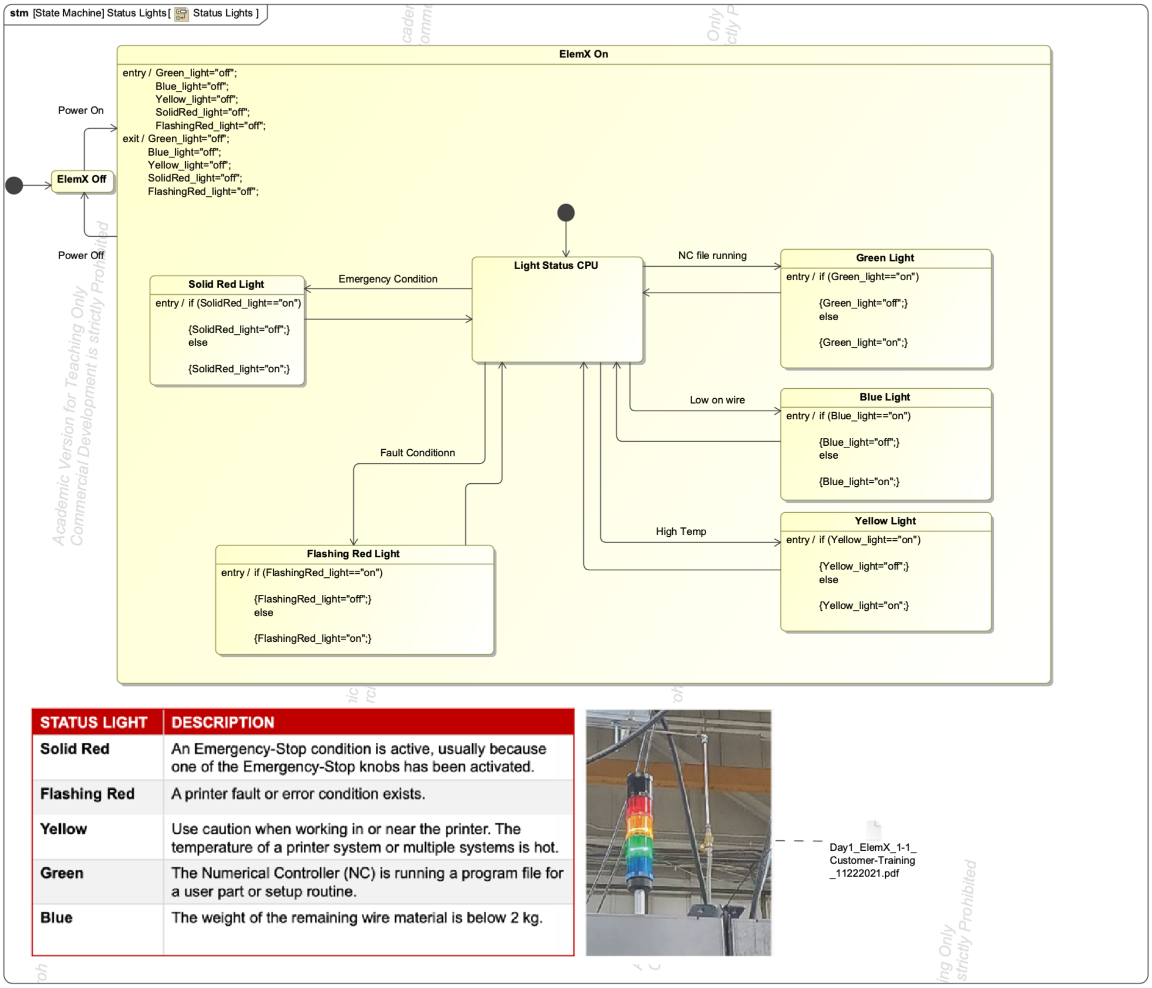

Figure A.7. Xerox ElemX Behavior. Adapted from [42]

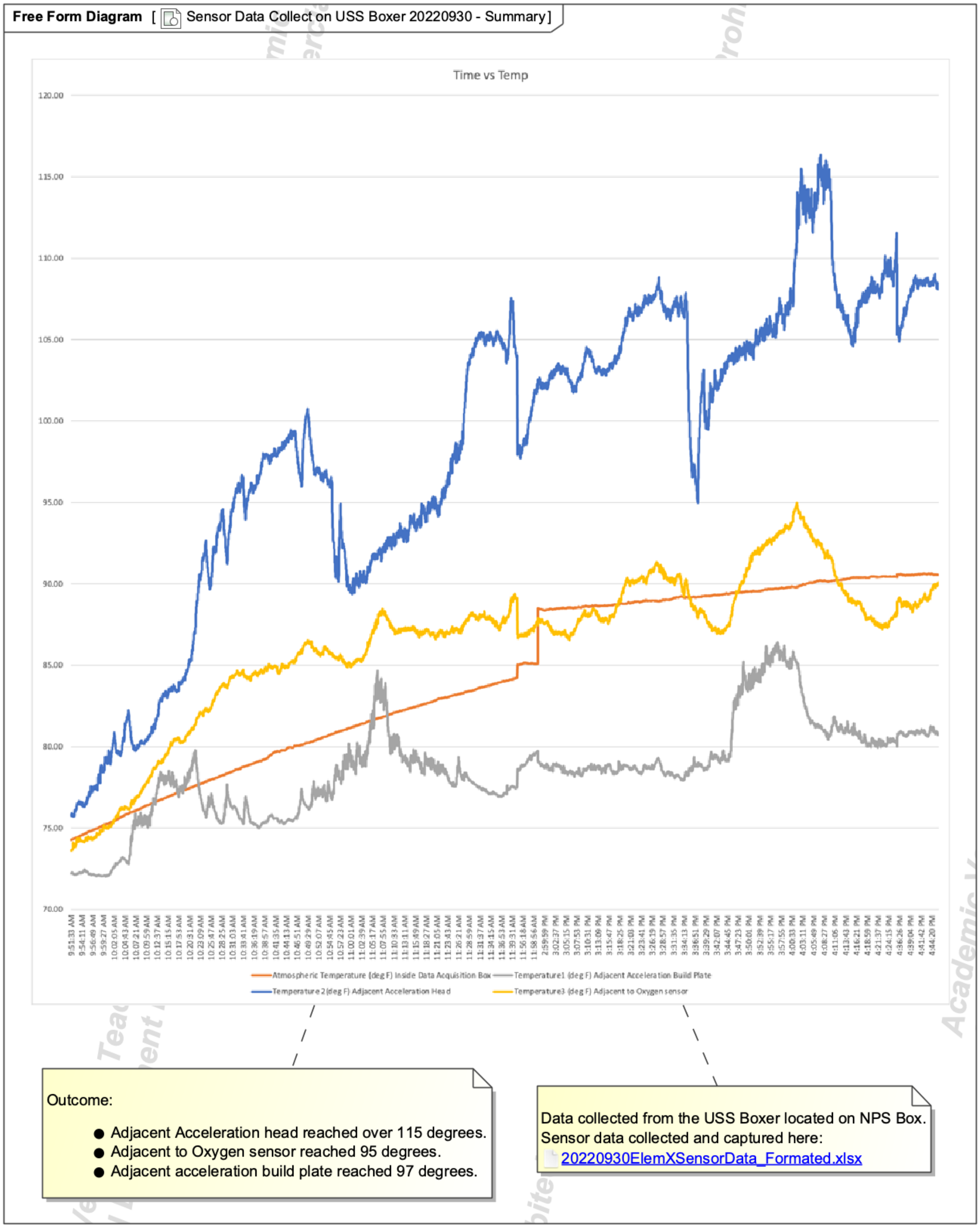

Figure A.8. Xerox ElemX parameters - Sensor Data

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APPENDIX B: AMDTMM User Guide

This Appendix serves as reference information from the AMDTMM User Guide.

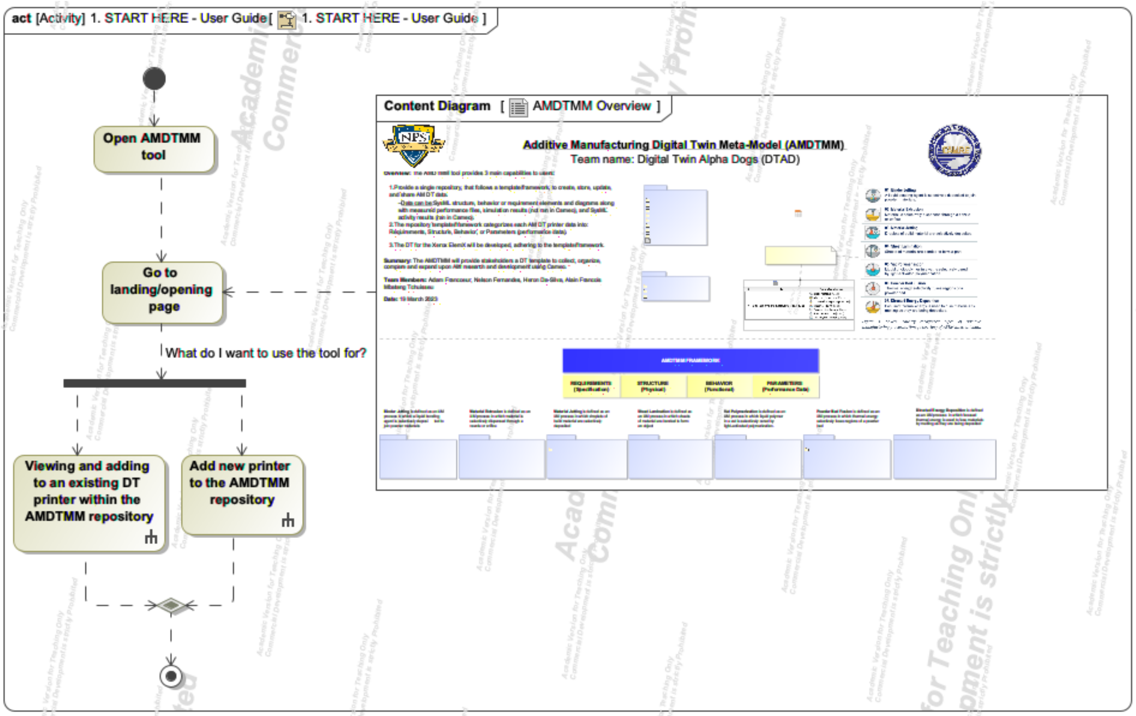

Figure B.1. AMDTMM User Guide - Start Here

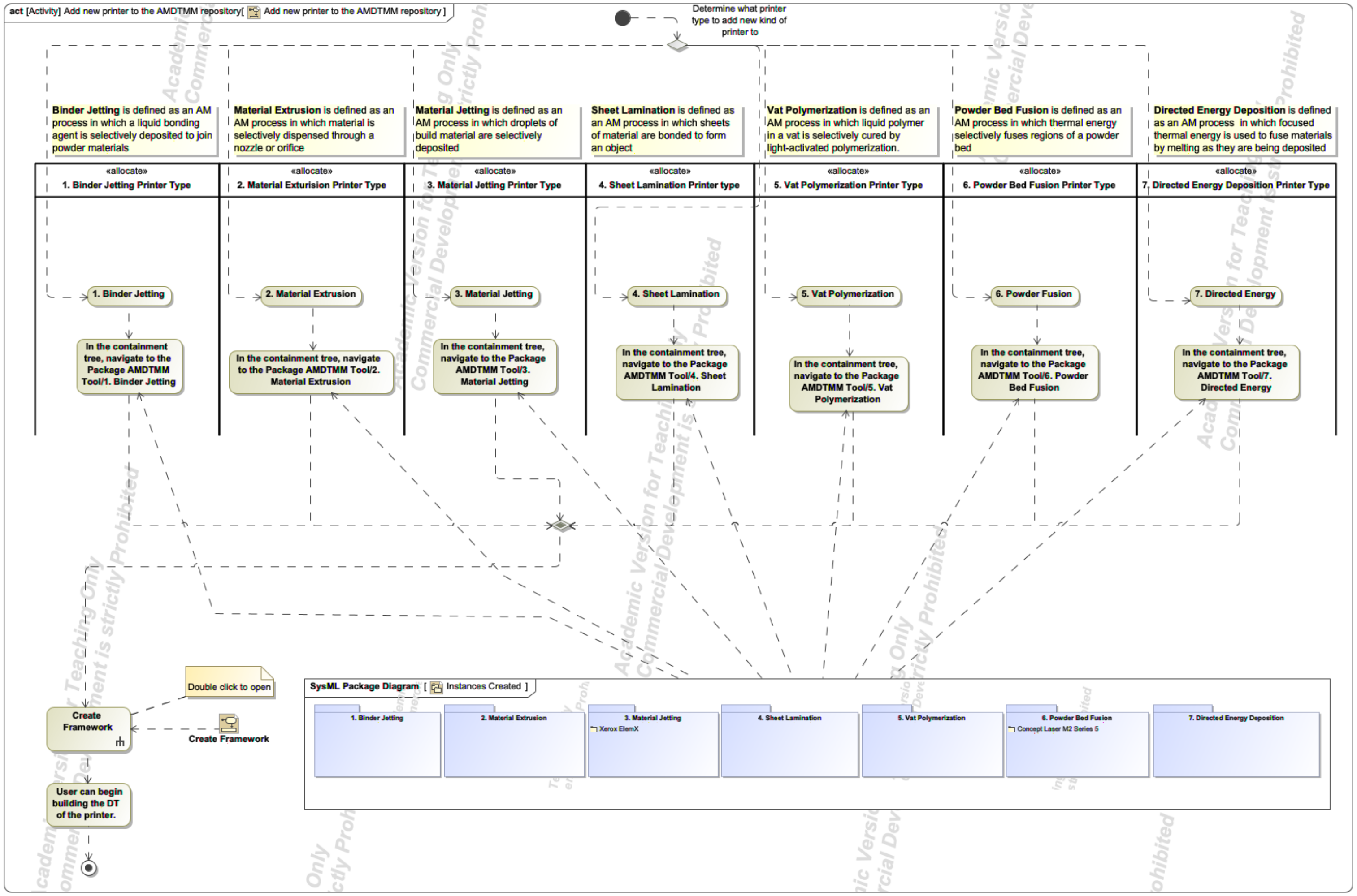

Figure B.2. AMDTMM User Guide - Printer Selection

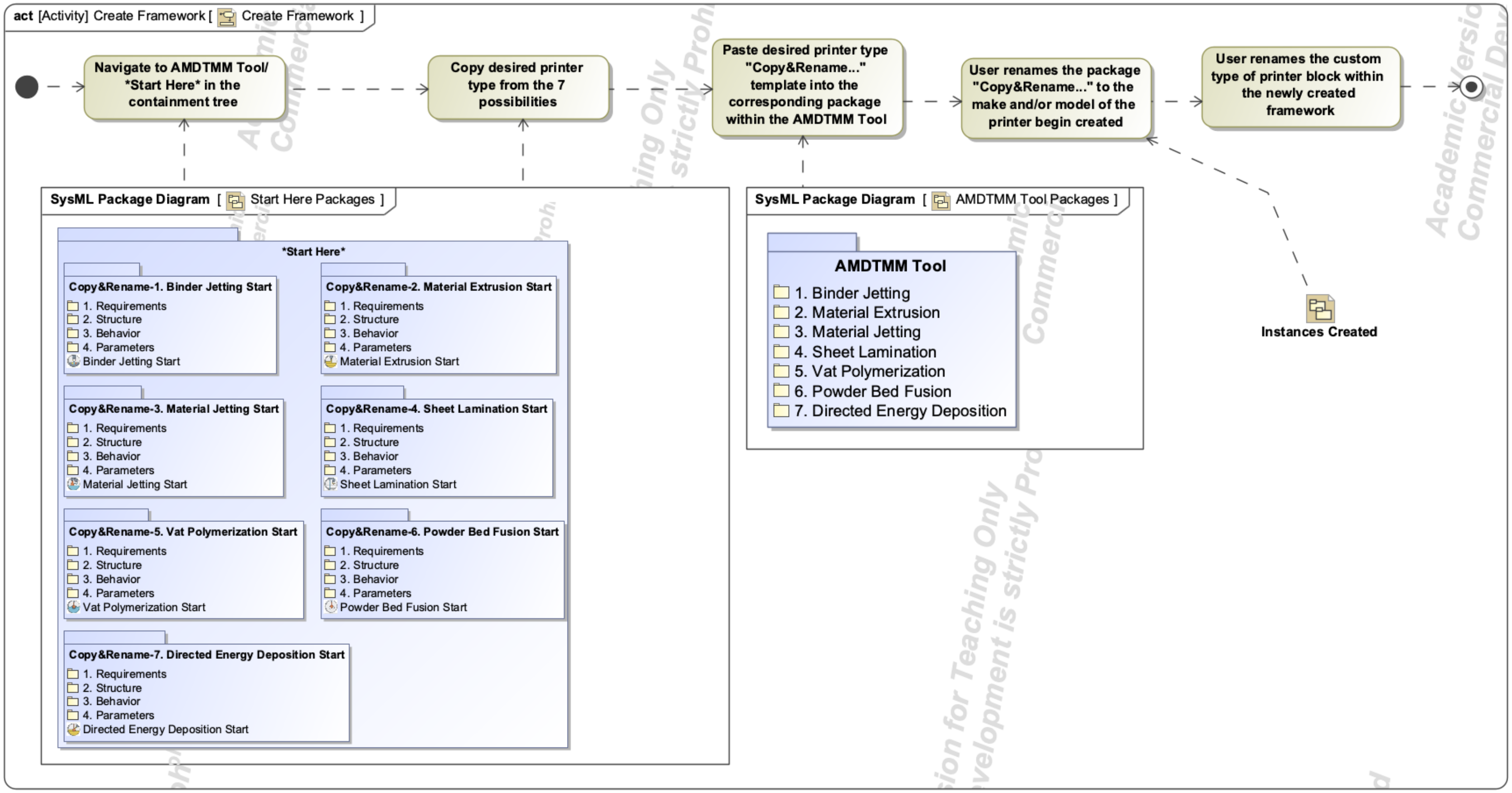

Figure B.3. AMDTMM User Guide - Create Framework

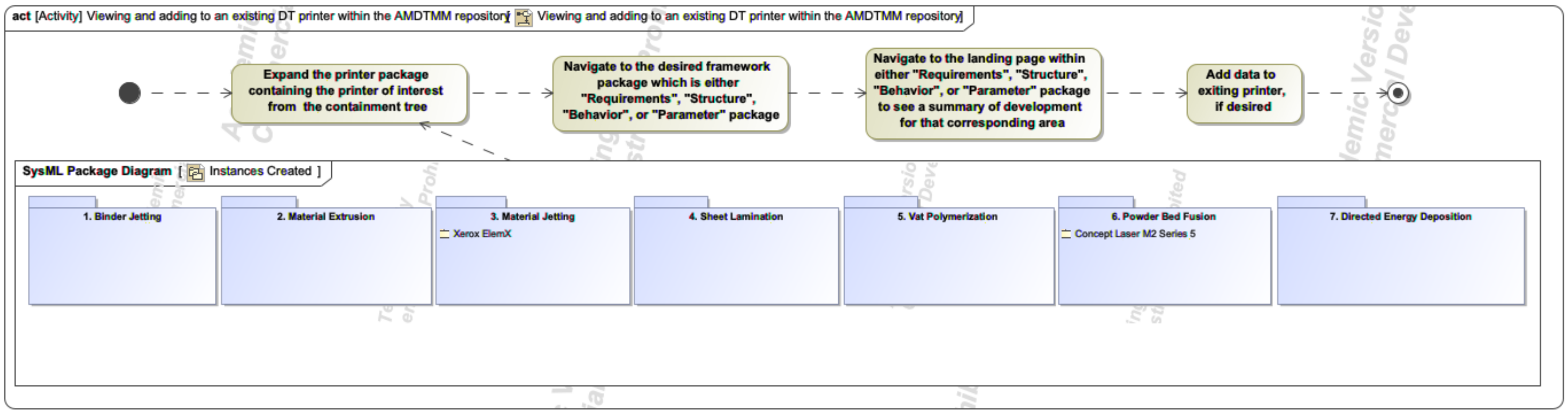

Figure B.4. AMDTMM User Guide - View/Update Existing DT

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