



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

### **DIGITAL TWIN DEVELOPMENT AND ITS EFFECTIVENESS**

by

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September 2023

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**DIGITAL TWIN DEVELOPMENT AND ITS EFFECTIVENESS**

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requirements for the degree of

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## ABSTRACT

The Department of Defense (DOD) underscores the need for real-time system performance feedback, essential for optimizing operational efficiency and informed decision-making in combat scenarios. Key to this endeavor is the digital twin (DT) concept where it can facilitate the shift from traditional time-based maintenance to condition-based maintenance, harnessing advancements in prognostic and health management technologies. This research proposes a notional DT framework for real-time data collection, rooted in the model-based systems engineering (MBSE) approach and integrated with Department of Defense Architecture Framework (DoDAF) 2.0 views. Using the Xerox ElemX 3D printer as a benchmark, the study highlights the DT's potential in enhancing printer optimization and reliability through predictive capabilities. The Technology Readiness Level and the Validation Square methods of validation were merged for comprehensive evaluation to ensure the DT framework's transition from conceptual design to functional deployment occurs. The research concludes with forward-looking recommendations, including AI integration into DTs and advanced security protocols.

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## LIST OF ACRONYMS AND ABBREVIATIONS

|        |                                                          |
|--------|----------------------------------------------------------|
| 3D     | Three-dimensional                                        |
| ADT    | Autonomous Digital Twin                                  |
| AI     | Artificial Intelligence                                  |
| AM     | Additive Manufacturing                                   |
| Ao     | Operational Availability                                 |
| CBM    | Condition-based Maintenance                              |
| CPS    | Cyber-Physical Systems                                   |
| DL     | Deep Learning                                            |
| DOD    | Department of Defense                                    |
| DoDAF  | Department of Defense Architecture Framework             |
| DT     | Digital Twin                                             |
| DTDL   | Digital Twin Deep Learning                               |
| FDM    | Fused Deposition Modeling                                |
| FFT    | Fast Fourier Transform                                   |
| HMI    | Human-Machine Interface                                  |
| IDT    | Informational Digital Twin                               |
| MBSAP  | Model-Based System Architecture Process                  |
| MBSE   | Model-Based System Engineering                           |
| MEDRAF | Multidisciplinary Early Design Risk Assessment Framework |
| ML     | Machine Learning                                         |
| MOEs   | Measures of Effectiveness                                |
| PHM    | Prognostic and Health Management                         |
| RAM    | Reliability, Availability and Maintainability            |
| SDT    | Supporting Digital Twin                                  |
| SMART  | Specific, Measurable, Attainable, Realistic and Timely   |
| T&E    | Test and Evaluation                                      |
| TBM    | Time-based Maintenance                                   |

|     |                             |
|-----|-----------------------------|
| TRL | Technology Readiness Level  |
| USN | U.S. Navy                   |
| V&V | Validation and Verification |

## EXECUTIVE SUMMARY

The Department of Defense (DOD) values consistent and immediate system feedback. Such real-time data not only serves a pivotal role in combat situations but also influences system maintenance decisions (Ashworth et al. 2021). The emergence of Digital Twins (DTs) presents a promising opportunity to collect system feedback data and use that data to make decisions on systems operations and maintenance issues.

The DT, as defined by Song et al. (2023), is a virtual reflection of a physical entity or system. One of its foremost values is in real-time data extraction. Beyond mere extraction, DTs offer an evolved analytics framework versus prior approaches. This potential propels DTs as an effective tool to transition from Time-Based Maintenance (TBM) to Condition-Based Maintenance (CBM) while integrating Prognostic and Health Management (PHM) technologies (E. B. K. Lee, Van Bossuyt, and Bickford 2021).

This research investigates existing DT developmental models, introducing a notional DT framework designed for real-time data capture. A conceptual framework is developed that harmonizes and syncs the Model-Based Systems Engineering (MBSE) approach from the MagicGrid Book of knowledge (Dassault Systèmes 2021) with the six life cycle phases from Bickford et al. (2020). This research further incorporates DoDAF views to assure stakeholder consistency, interoperability, and DT efficiency. The resulting methodological alignment with engineering models, such as the Vee model, guarantees a well-defined system understanding, capturing stakeholder necessities, defining capabilities, and assessing performance (Loaiza, Cloutier, and Lippert 2023).

A Xerox ElemX 3D printer is used as a representative example to demonstrate the proposed framework. The example delves into the utility of DT in CBM and details how data from the 3D printer can be harnessed for PHM. Establishing a DT for a 3D printer allows for the intensive analysis of sensor-acquired data which can unveil patterns and anomalies. This in turn can facilitate modifications in printer settings, components, and methodologies, thereby enhancing output quality and component longevity. Once a foundational baseline is established, a mature DT can carry out this analysis automatically,

employing its predictive power to preemptively address potential complications, conserving resources, and reinforcing printer reliability.

Transitioning from concept to reality requires a robust Verification & Validation (V&V) process and hence this research provides commentary and direction on how to conduct V&V of the proposed DT framework. The V&V approach is two-fold, integrating both Technology Readiness Level (TRL) and the Validation Square (Pedersen et al. 2000). TRL serves as a litmus test for technological maturity intrinsic to the DT framework (Tzinis 2012). It progresses from rudimentary research to matured, field-tested technology. Concurrently, the Validation Square assures a DT's operational precision, validating that the simulated data mirrors the real-world dynamics. This combined approach improves trust in a DT's reliable performance in its operational arena.

The research culminates with forward-looking recommendations. These include the potential of geographically dispersed DTs, integrating Artificial Intelligence and Machine Learning into DTs, bolstering DT security protocols, refining MBSE methodologies for system optimization, enhancing data analytic frameworks, and elevating V&V methodologies to meet future challenges.

As defense operations are at the tip of an analytical revolution, DT could be an effective tool to offer real-time data extraction, analysis, and predictive capabilities to defense operations. By aligning with rigorous V&V methodologies, DT promises not only enhanced operational performance but also a proactive approach to system maintenance and development. Embracing DTs could be the future of defense system optimization.

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# **I. INTRODUCTION**

The Department of Defense (DOD) requires that systems provide accurate and immediate feedback on their performance throughout their lifespan through real-time data collection. If data can be extracted from systems, these data can be used to analyze how the systems are working, make maintenance decision and keep systems operational (Ashworth et al. 2021). Hence, real-time data is essential for making quick decisions during combat, and it can also be used to improve maintenance and future system development.

## **A. BACKGROUND AND PROBLEM STATEMENT**

To optimize the operational availability/readiness of its defense systems, the U.S. Navy (USN) adopts a combination of ongoing and reactive maintenance strategies as part of its maintenance philosophy. As the current mode of maintenance largely focuses on time-based maintenance (TBM), the USN is unable to assess the full system's health condition as systems and equipment is serviced or replaced at scheduled intervals. In other words, TBM does not consider the actual health condition of the system and might over-maintain systems when it is not necessary or under-maintain systems due to changing conditions and varying levels of usage. This can lead to an ineffective maintenance strategy and reduced equipment reliability. However, based on a study by Ashworth et al. (2021), the transition from the TBM to condition-based maintenance (CBM) can improve Ao because CBM reduces system downtime.

A well-designed digital twin (DT) can be a good tool to extract data in real time that can assist with maintenance decisions. A DT is a virtual copy of a physical object or system (Song et al. 2023). On top of data extraction, the emergence of the DT as an analytics framework also offers new possibilities to utilize system models to analyze physical assets once they are in use (E. B. K. Lee, Van Bossuyt, and Bickford 2021a). The development and implementation of DTs will enable the transition from the current TBM to CBM by leveraging existing prognostic and health management (PHM) technologies.

## **B. MOTIVATION FOR THESIS**

Trauer et al. (2020) states that a “DT is a virtual dynamic representation of a physical system, which is connected to it over the entire life cycle for bidirectional data exchange.” The data collected from the DT can be useful to improve equipment reliability with the successful transition from TBM to CBM leveraging on PHM technologies. Recent studies demonstrate that model-based systems engineering (MBSE) processes can be used to operationalize DTs. There are benefits to integrate DTs and system development by leveraging the work done during the conceptual design phase of the system engineering design process (sometimes referred to as system synthesis) so that extra effort is not needed to be invested in the development of a DT after the system has been fielded.

Ashworth et al. (2021)’s findings align with a study conducted by Bickford et al. (2020), which shows that the application of a DT is a promising and effective approach to collect operational system health and performance metrics of fielded systems. Having access to readiness metrics for operational systems will enable data-driven decisions about planning, maintenance, and operations. Bickford et al. show that MBSE processes can operationalize DT and that DT can be developed in parallel with the system development process.

It is, hence, important to review existing DT development models to enable smooth and efficient integration of DT development into the mainstream system development process. On top of this, it is also important to determine the effectiveness of DT in CBM and how these data could be used for PHM.

## **C. RESEARCH OBJECTIVES**

This thesis reviews the existing DT development models and paths and creates a notional DT framework that can be used for real data collection of systems. Next the thesis discusses and analyzes the effectiveness of DT in CBM and discusses how the data can be used for PHM by using a Xerox ElemX 3D printer or similar as an exemplar.

#### **D. REASEARCH METHOD**

This thesis encompasses five phases. In Phase 1, a literature review is conducted on (1) the existing available methods to operationalize DT through MBSE, (2) a concept of operation of DT is developed, and (3) capabilities and limitations of operationalizing a DT are identified. Phase 2 encompasses an in-depth review and evaluation of Bickford et al.'s method (2020) of operationalizing DTs through MBSE. In Phase 3, a notional DT framework is constructed. In Phase 4, a case study DT of a Xerox ElemX 3D printer (or similar) is developed from the DT printer template. Phase 5 analyzes the data and information gathered from the physical 3D printer to determine the effectiveness of DTs in CBM and the integration of PHM in the process. Phase 6 investigates the verification and validation of the notional DT framework to ensure its reliability and potential for practical implementation.

#### **E. EXPECTED BENEFITS OF THESIS RESEARCH**

The application of DTs is a promising and effective approach to collect operational system health and performance metrics of fielded systems, which will enable quantitative data-driven decision making. The integration of DT development within the conceptual design phase of system development enables system designers to leverage the work done for efficiency so that extra effort is not needed to be invested in the development of a DT after the system has been fielded. This concurrent development of DT with the conceptual design phase can also save additional time and money that might be incurred. The DT is believed to be able to provide good quantitative data to enable data-driven decisions upfront during the operationalization of system. The Navy, PEO and DOD are the primary stakeholders who will benefit from this thesis.

The three-dimensional (3D) printer is chosen as the system of interest for this study due to the constraint that the project scope shall not exceed the classification level of Distribution Statement A: Approved for public release. Distribution is unlimited. Using a DT system for a 3D printer on a surface vessel can still offer valuable knowledge about sensitive, high-precision systems in the particular and changing environments that are exclusive to naval operations (Ashworth et al. 2021).

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## **II. BACKGROUND AND LITERATURE REVIEW**

The purpose of this background and literature review is to provide a critical analysis of the existing literature on digital twin development and its effectiveness in industrial applications. Specifically, this review will also focus on the effectiveness of digital twin technology in improving operational efficiency, reducing downtime, and enhancing overall performance in manufacturing industries. Finally, this review aims to identify the research gap such as the absence of a standardized framework or architectures for developing DTs and the lack of demonstrated efficacy of proposed frameworks or architectures in the current literature on this topic.

The first three sections of the review provide a brief overview of digital twin technology, including its definition, classification, and its applications. The fourth section discusses MBSE and its usage to build a DT framework. The fifth and sixth sections focus on available DT architectures as well as the challenges faced for DT applications, highlighting the key findings and limitations of existing studies. The seventh section discusses 3D printing and additive manufacturing. Finally, the conclusion summarizes the main findings of the review, highlights the research gap, and provides recommendations for = research in this area. This review contributes to the development of a comprehensive framework for future research on this topic.

### **A. DIGITAL TWIN**

A DT is a virtual representation of a physical entity. It enables seamless bidirectional integration of data between a physical object and its corresponding digital counter parts (Hickey, Gachon, and Cosgrove 2023). In a perfect scenario, all the information that is available from a physical system that has been developed and deployed can also be obtained from the DT (Hickey, Gachon, and Cosgrove 2023). It is possible for users to concurrently manage both the digital system and the physical system, while also being able to observe the status of the device in real-time (Guan et al. 2023). An effective DT can provide an extremely accurate and detailed representation of the system by visually

displaying information involved in constructing, operating, and maintaining a production process.

In recent years, it was realized that DTs can also provide additional functionalities for the original entity using various techniques. These techniques include simulating the actual behavior of the physical system through data or incremental decision optimization (Song et al. 2023). One example is to apply DTs to fault diagnosis or prognostics. A lot of time must be invested to collect data from actual failures for a good fault prediction as prognostic methods require data from actual failures coupled with data driven models to predict failure (Gregg, Steele, and Bossuyt 2017). However, with the establishment of DTs, fault prediction could be enhanced by generating simulated data instead of collecting scarce data from actual failures (Song et al. 2023). Coupled with the utilization of components such as sensors, actuators, databases, as well as models and machine learning technologies, intelligent decision-making solutions could be generated from the data collected from DTs.

Since a DT is an replica of its physical counterpart, it can also offer users an exceptionally accurate, high-fidelity, and real-time controllable performance (Gallala et al. 2022). These attributes are particularly advantageous in situations where reliable, safe, and timely interactions between the user and the machine are required, as they facilitate instantaneous optimization and decision-making.

In summary, the utilization of DTs enables a smooth two-way incorporation of data between tangible objects and their corresponding digital replicas, delivering a precise and up-to-the-minute depiction of the physical system (Hickey, Gachon, and Cosgrove 2023). The technology can acquire new capabilities and enhance fault prediction through the simulation of physical entity behavior and the utilization of components such as sensors, actuators, databases, models, and machine learning technologies. The exceptional precision and the ability to control real-time performance of DTs render them optimal for situations that demand secure, effective, and swift interactions between the user and the physical system (Gallala et al. 2022).

## B. CLASSIFICATION OF DIGITAL TWINS

DTs can be classified by application. DTs have diverse applications and serve multiple goals, including data management, offering user support, and enabling decision-making through personalized recommendations or autonomous operations. DTs can be classified into three categories based on application: (1) Informational Digital Twin (IDT), (2) Supporting Digital Twin (SDT) and (3) Autonomous Digital Twin (ADT) as shown in Figure 1 (Wilking, Schleich, and Wartzack 2021). These DT classes have different capabilities and levels of integration.

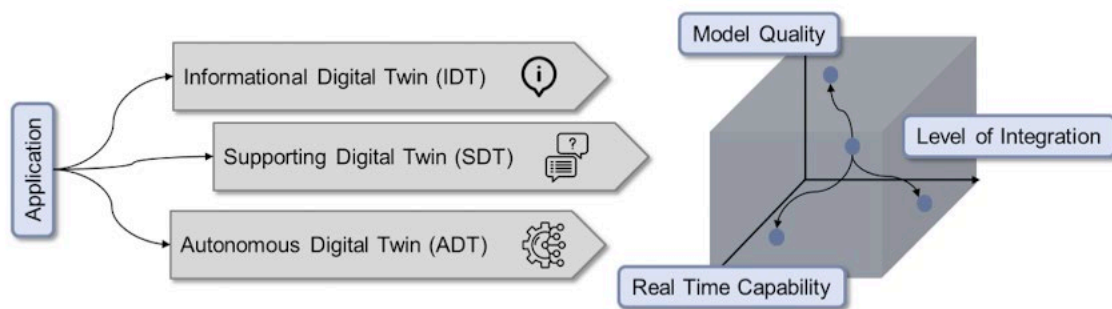


Figure 1. Classification and Dimensions of Digital Twins. Source: Wilking, Schleich, and Wartzack (2021).

Wilking, Schleich, and Wartzack (2021) explain how the three DT classes build off each other. The IDT drives data collection from the physical counterpart. The collected data is processed to provide useful information for the user. An IDT uses models to analyze the required data but does not provide recommendations for further action. This is a basic level of a DT that collects and presents data. One example of IDT is a manufacturing plant model that simulates the production processes. The IDT provides the data, but utilization or analysis of the data has to be conducted by the user to optimize production schedule, minimize downtime, and reduce waste.

The SDT, on the other hand, uses analysis and simulations to process the data obtained from the physical system. In contrast to the IDT, the SDT does more than just present data to the user. The SDT analyzes and processes data to provide users with

information and recommendations to aid in decision making. SDTs are often being utilized in the predictive maintenance field. The SDT not only collects data but is able to analyze the remaining lifetime of components to recommend maintenance and repair operations ensuring reasonable recommendations and support for decision-making.

ADT is the third tier of DTs where on top of SDT, it can use the provided recommendations to influence the behavior of the physical product. Though the user may still receive notifications, the objective of the ADT is to respond promptly to the evolving data of the physical twin, such as changes in a production environment, with the aim of saving valuable time.

DTs can serve various objectives and be classified by application. The three different classes of DTs differ in terms of their model quality, real-time capability, and level of integration. By utilizing DTs, operation processes can be optimized, decision-making can be enhanced, and time and resources invested in collecting scarce data from actual failures could be reduced. DTs can provide users with a precise, high-quality, and controllable real-time performance, making them extremely appealing in situations that require secure, effective, and swift interactions between the user and the machine (Loaiza, Cloutier, and Lippert 2023). For the purpose of this research, the SDT is the most applicable type of DTs to collect operational system health and performance metrics of fielded systems and enable quantitative data-driven decision making.

### **C. APPLICATIONS OF DIGITAL TWIN**

The use of DTs in the military has the potential to gather operational data on system health and performance. However, current development efforts often lack proper problem definition, resulting in models that fail to meet stakeholders' needs (American Institute of Aeronautics and Astronautics Digital Engineering Integration Committee 2023). The lack of standardization in development and implementation of DTs leads to limited interoperability and the need for subject matter experts, highlighting the need for standardized methodologies to fully realize their potential and increase adoption (American Institute of Aeronautics and Astronautics Digital Engineering Integration Committee 2023).

Research was conducted to investigate the utilization of DTs with emphasis on SDT and ADT for predictive maintenance applications. During the course of research, it was noted that Cyber-physical systems (CPS) and DTs are both closely related to the integration of physical and digital systems, but they have distinct concepts and applications. Tao et al. (2019) presented on the correlation of DT and CPS. Cyber-physical systems use sensors and actuators to interact and control the physical system in the cyber space while DTs use models and data to predict and interpret behavior of the physical system. CPS improves the exchange of information between a physical system and DTs to monitor parameters, collect data, analyze data and even remotely control physical systems (J. Lee et al. 2020).

To offer predictive services, a DT-based CPS (DT-CPS) must be able to collect, simulate, and analyze data throughout the product life cycle. Hence a smart DT-CPS structure should consist of five features as show in Figure 2: (1) a smart connection, (2) data to information conversion, (3) big data analytics, (4) virtual systems, and (5) service layer (J. Lee et al. 2020). J. Lee et al. (2020) also provided an outline for the DTDL-CPS architecture explaining the five features shown in Figure 2.

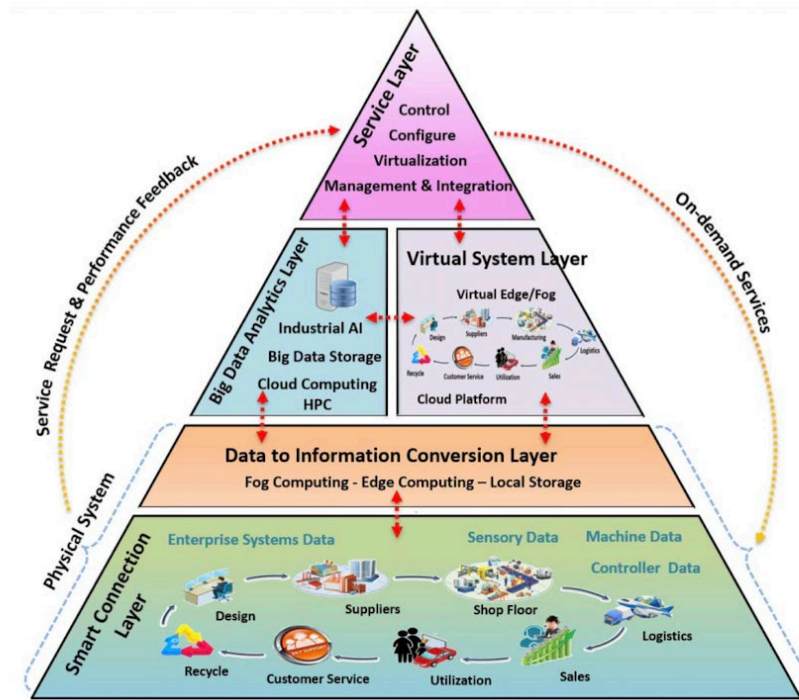


Figure 2. DTDL-CPS Architecture for Smart Manufacturing Systems.  
Source: J. Lee et al. (2020).

The “smart connection” refers to the data connection obtained from sensors, actuators, controllers, or enterprise systems. In the “data to information conversion” layer, computational resources may be employed to decrease communication delays, preprocess data, manage interactions among smart objects, and execute control commands. The “data analytics” layer functions as a hub for data storage and advanced analytics, providing data to the “virtual system” layer. The “virtual system” layer comprises digital models that replicate the physical systems. The “service” layer enables the implementation of DT Deep Learning (DTDL) CPS, resulting in a highly synchronized and intelligent CPS that offers services such as intelligence, control, visualization, optimization, PHM for use in the physical system. It is also explained that Deep learning (DL) is a subset of machine learning (ML) techniques that can handle raw data and generate the necessary representations for a variety of applications, including classification, regression, clustering, and pattern recognition. Hence, by combining DL with DT, it is possible to achieve self-maintenance,

self-configuration, and predictive services, resulting in the ability to offer autonomous functionalities.

Within this DTDL-CPS system, prediction data that are generated will be transmitted to the virtual system where all collected historical data will be integrated with DT models to identify predictive maintenance strategies (J. Lee et al. 2020). The optimized strategy would then be transmitted back to the physical system for implementation. This is an iterative process which occurs constantly in a closed-loop framework for predictive maintenance.

For newly deployed or fielded systems, there are often challenges to acquire substantial amount of measured data and fault data to enable reliable DL-based predictive services. In this case, DT can also be used to generate data by simulating the actual working conditions. Song et al. (2023) proposed the development of a DT-assisted fault diagnosis system to overcome the issue with lack of failure data. DT can be used to generate simulated data and, hence, be able to enhance fault prediction by supplementing the actual failure data that may be lacking. It should be noted that the accuracy of the simulated fault diagnosis is proportional to the amount of simulated data that the DT can generate. The results obtained from Song et al. (2023) DT-assisted fault diagnosis system showed that the simulated data can provide 98.86% accuracy of fault diagnosis.

Another area of application of DT is in the PHM environment. PHM was initially used to evaluate a system's health by analyzing previous failure data along with current monitoring data. Today, PHM has demonstrated its ability to forecast system health metrics and thus anticipate impending failures. When combined with CBM, PHM can reduce downtime and enhance operational capabilities (Bickford et al. 2020). Ashworth et al. (2021) developed a DT model for a 3D printer onboard a Naval Ship with a focus on identifying sensors that would be most effective for comparing the Ao outcomes of TBM and CBM approaches. Results from implementing the DT system on the 3D printer showed that transitioning to CBM led to a decrease in system downtime and an improvement in the Navy's maintenance methodology (Ashworth et al. 2021). Through the use of a DT system, transitioning from TBM to CBM resulted in a change of maintenance philosophy from being proactive to reactive. This is due to the increased knowledge gained about the

system's conditions and performance, leading to a more efficient and effective approach to maintenance.

A DT can be utilized to replicate the behavior of a system and, hence, be able to simulate the performance of a system. In the study conducted by H. Zhang et al. (2023), a DT model was developed to design high-performance lithium-ion batteries with LiFePO<sub>4</sub> and graphite materials. The researchers used the DT model to perform a virtual simulation to examine how variations in the electrode structure affect the battery's electrochemical performance and to identify optimal parameter settings for an ultrahigh-power lithium-ion battery. Based on the optimal parameters determined, the LiFePO<sub>4</sub>/graphite battery will be manufactured and tested to evaluate its performance and hence validate the DT model in the process. The validated model will be subsequently employed to enhance the LiFePO<sub>4</sub>/graphite battery's performance when subjected to exceedingly high-rate constant current and pulse discharging scenarios. The study determined that the DT model accurately predicted the battery's performance and helped determine the optimal parameters needed to achieve an ultrahigh power capability.

To further aid users in their decision-making process, DT can be developed to provide route selection capability with mission engineering focus. A route optimization module that is built in the DT will be able to recommend the optimal route to enhance the user's decision making process (E. B. K. Lee, Van Bossuyt, and Bickford 2021b).

Alternatively, a DT can also be a source of information or a useful tool for project managers. DTs can be used to investigate aspects of risk and resource management (Hickey, Gachon, and Cosgrove 2023). The use of a DT is being considered as a way to create a digital technical file containing referencing information. The advantage of this approach is that the DT would serve as a centralized source of information that can be accessed in a more efficient manner. In addition, during the development of a system, program managers can use a DT to manage risk by mitigating unpredictable behavior rising from the physical systems.

The integration of DT technology with CPS has shown potential in offering autonomous functionalities and predictive services. A smart DT-CPS structure should

consist of five features, namely a smart connection, data to information conversion, big data analytics, virtual systems, and service layers. The use of DL in combination with DT can result in self-maintenance, self-configuration, and predictive services. DT can also be utilized to generate simulated data to supplement actual data for fault diagnosis. Additionally, DT technology has applications in the design of high-performance batteries, PHM environment, and in identifying the most effective sensors for CBM. The use of DT technology can enhance the operational capabilities of CPS and can also be a useful tool for project managers. Overall, the integration of DT with CPS has shown immense potential in revolutionizing various industries and enhancing their efficiency and effectiveness.

#### **D. MODEL-BASED SYSTEM ENGINEERING (MBSE)**

DT is a virtual representation of a physical entity and hence developing a DT could be as complex as developing the physical system. This is because creating an accurate and realistic virtual representation of a physical system requires a deep understanding of the underlying processes, systems, and interdependencies involved. In addition, developing a DT often requires the use of advanced technologies and tools, such as machine learning algorithms, simulation software, and data analytics tools. However, MBSE processes can operationalize DTs as MBSE is a branch of systems engineering that concentrates on performing the standard process of requirements development, system design, implementation, testing, and operations in a model-based setting (Bickford et al. 2020).

MBSE is typically characterized as a technique utilized by system architects to assist them in generating and validating requirements, synthesizing systems, and verifying them. The MBSE is an approach that uses computer models represent the different aspects of a system such as system properties, specification and behavior which will help to enhance the design and development of complex systems (Loaiza, Cloutier, and Lippert 2023). Ultimately, MBSE can help to reduce design errors, enhance system performance, shorten development cycles, and improve overall system quality by ensuring consistency and traceability throughout the life cycle of the system (Loaiza, Cloutier, and Lippert 2023).

As MBSE relies on computer modeling, the system models developed via MBSE are highly interconnected, share a standard language and information base, and are very adaptable to changes (Ashworth et al. 2021). It is common to constantly change and update requirements in the design phases of system development and these requirement changes affect the entire system model. MBSE is a good approach to be able to keep track of these changes and update the system automatically (Loaiza, Cloutier, and Lippert 2023). This approach automates the process of examining and updating the models and documents that were affected by the changes. This can save time and effort, and it can also help to ensure that the changes are made correctly and consistently.

MBSE is also a good approach to complement the application of “Vee” model for project development (Loaiza, Cloutier, and Lippert 2023) as it is an effective method for creating a DT and evaluating the performance, reliability, appropriateness, lifespan, and other aspects of a live system that stakeholders deem important, using data gathered from the DT (Bickford et al. 2020).

MagicGrid serves as a connection between theory and practice in MBSE, bringing together three critical components – method, language, and modeling tool (Dassault Systèmes 2021). MagicGrid can help to develop and manage complex systems. Hence, the MagicGrid technique can be used to assist with the MBSE process of guiding DT architecture development. The utilization of the MagicGrid technique to execute and integrate life cycle process activities will enable the traceability of each activity across the entire system as it provides a framework for the modeling process, which encompasses the problem, solution, and implementation domains for the system model (Ashworth et al. 2021).

It is important to determine the relationship among the system development life cycle phase, the system engineering process, and the MBSE efforts. Bickford et al. (2020) presented a table (refer to Table 1) to define the relevant life cycle phase in relation to the systems engineering process and MBSE efforts. This table helps to frame the system development stages, which make it feasible to decompose data elements that can drive the implementation of the DT.

Table 1. Systems Engineering and MBSE Efforts. Adapted from Bickford et al. (2020).

| Life cycle phase           | Systems Engineering Processes       | MBSE Efforts                                                                                             |
|----------------------------|-------------------------------------|----------------------------------------------------------------------------------------------------------|
| Concept exploration        | Concept Exploration                 | Capability Views                                                                                         |
|                            | CONOPS Development                  | Operational Views                                                                                        |
|                            | System-level Requirements (Reqs)    | System Services Models                                                                                   |
| Preliminary Design         | Subsystem-level requirements        | Activity Diagrams                                                                                        |
|                            | High-level Design                   | System Views                                                                                             |
|                            |                                     | Interface Diagrams                                                                                       |
| Detailed Design            | Component-level Requirements        | System Models                                                                                            |
|                            | Detailed Design                     | Performance Models                                                                                       |
|                            |                                     | CAD Models                                                                                               |
|                            |                                     | Logistics Models                                                                                         |
| Implementation (Assembly)  | Hardware and Software Development   | CAD Model Iterations                                                                                     |
|                            | System Assembly                     | Performance Model Iterations                                                                             |
|                            |                                     | Product Support Model Iterations                                                                         |
| Test and Evaluation        | Component Requirements Verification | Use of System Models Performance and Product Support Models to verify system operability and performance |
|                            | Subsystem Req Verification          |                                                                                                          |
|                            | System Verification                 |                                                                                                          |
|                            | Performance Testing                 |                                                                                                          |
|                            | Suitability Testing                 |                                                                                                          |
| Operations and Maintenance | Life cycle Sustainment              | Use of various models to maximize reliability, availability, and performance                             |
|                            | Reliability Analysis                |                                                                                                          |
|                            | Performance Analysis                |                                                                                                          |
|                            | Modernization                       |                                                                                                          |

In summary, the implementation of MBSE provides significant benefits to the system development process. Through computer modeling, MBSE facilitates the crafting and evolution of intricate systems, ensuring accuracy, uniformity, traceability, and cohesion across the system’s full lifespan. MBSE produces flexible system designs that can readily accommodate changes in specifications allowing for highly interconnected and adaptable system models that can be easily updated with changes in requirements. To add on, MBSE also supports the use of the systems engineering “Vee” model. This aids in the creation of a DT and in evaluating the performance, reliability, appropriateness, remaining

operational lifespan, and other elements of a live system that stakeholders deem necessary. The MagicGrid technique can be used to guide DT architecture development in the MBSE process, providing a framework for the modeling process and enabling the traceability of each activity across the entire system (Dassault Systèmes 2021). Finally, Table 1 presented by Bickford et al. (2020) defines the relevant life cycle phase in relation to the systems engineering process and MBSE efforts, which helps to decompose data elements that can drive the implementation of the DT. Overall, the implementation of MBSE with the support of the MagicGrid technique can significantly enhance the system development process by enabling more efficient and effective design and testing of complex systems.

## **E. DT ARCHITECTURE FRAMEWORKS**

The application of DTs is a promising and effective approach to gather data on the health and performance of deployed systems. Bickford et al. (2020) stated that the availability of the readiness and availability metrics of fielded systems will enable making informed data-driven decisions across planning, maintenance, and operational stages. It was also shown that in Bickford et al. (2020) that there are benefits to integrating DTs and early system development by leveraging the conceptual design phase to avoid investing in the development of a DT after the system has been fielded. A DT can be developed in parallel with the system, and the DT's development can be managed as its own system development process.

AIAA Digital Engineering Integration Committee (2023) also stated that in order to create a good DT, it is essential to identify and consider the targeted stakeholders and users of the DT, their viewpoints and interests, the matters to be investigated, the inquiries to be resolved as well as the judgments to be aided by the DT (i.e., the purpose of the DT). The type of analysis to be conducted either by the DT or from the data generated should be identified upfront to guide the requirements for data and modelling capabilities of the DT. It should be noted that an MBSE approach coupled with the system engineering “Vee” model concept could be useful to an operationalized DT as MBSE allows for good traceability of information, requirements, decisions and even verification activities throughout the entire system and process while the “Vee” model provides a structured and

systematic approach to the development of a complex system (Loaiza, Cloutier, and Lippert 2023).

Loaiza, Cloutier, and Lippert (2023) suggested a small-scale DT implementation framework for manufacturing systems. The authors utilized concepts from the “Vee” model of systems engineering and an MBSE approach. The DT framework was developed by integrating life cycle processes on the left side of the “Vee” model as seen in Figure 3, such as concept of operations, system requirements, high-level design, and detailed design, using the MBSE approach.

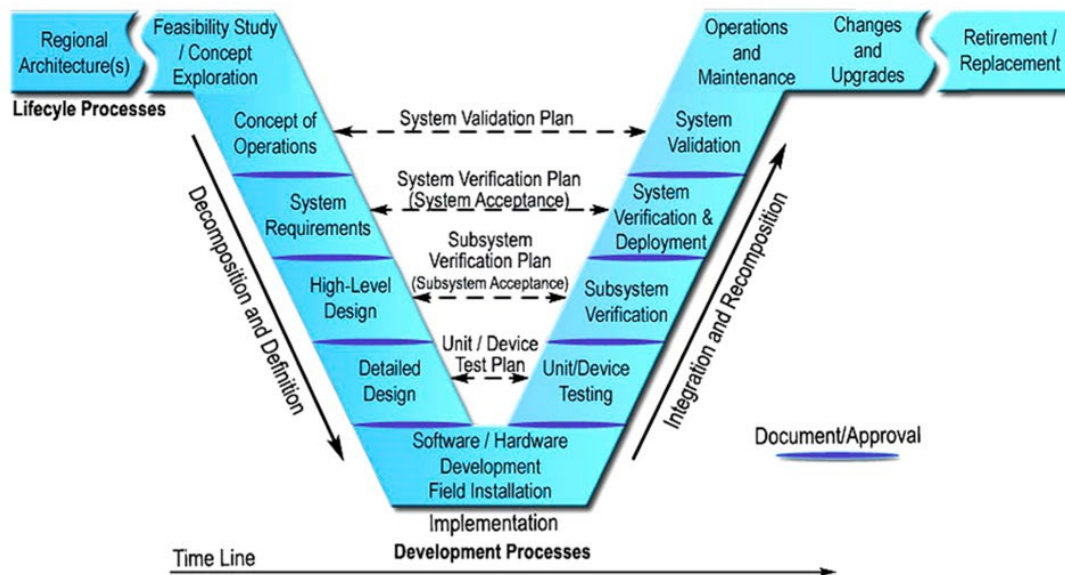


Figure 3. “Vee” model of the System Engineering Process. Source: Loaiza, Cloutier, and Lippert (2023).

Loaiza, Cloutier, and Lippert (2023) introduced a DT implementation framework for small-scale manufacturing systems that consists of three primary areas: physical, virtual, and information illustrated in Figure 4. This framework facilitates constant data exchange among the three areas.

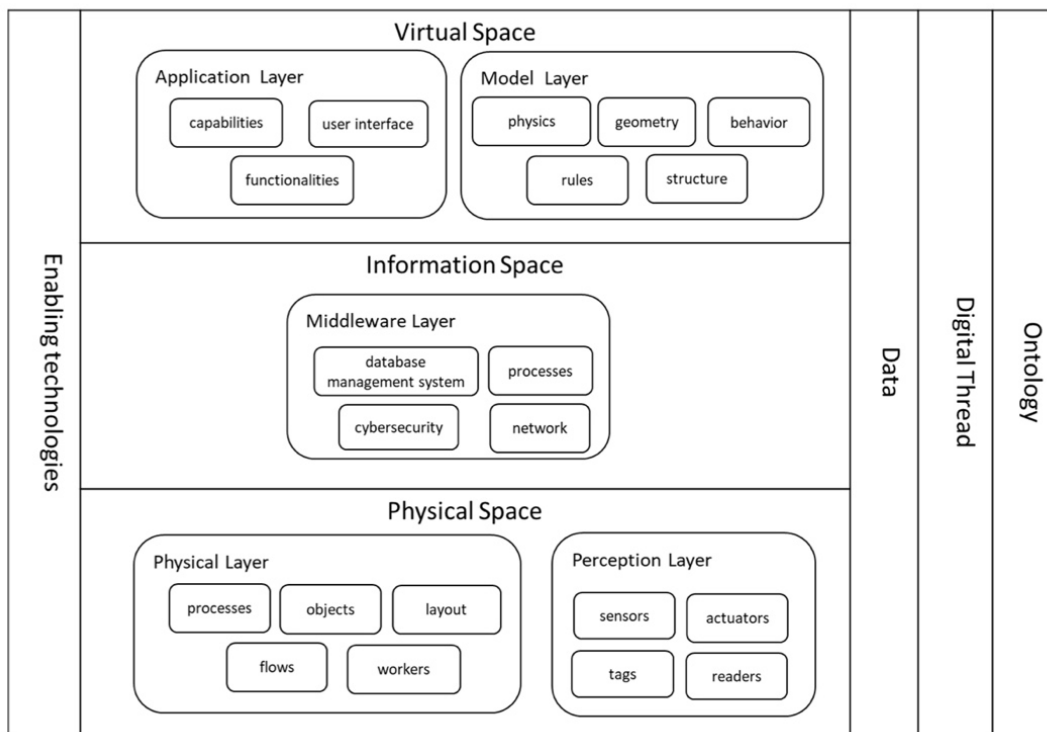


Figure 4. Small-scale DT Implementation Framework. Source: Loaiza, Cloutier, and Lippert (2023).

Loaiza, Cloutier, and Lippert (2023) explained that “the physical space provides real-time data for digital twin capabilities such as simulation, control, and monitoring.” DT technology can automate processes and allow physical objects to control themselves with sensors and actuators that are installed on the physical systems. The study showed that it is hence important to ensure that the right sensors and actuators were installed on the physical systems. The authors further explained that the virtual space is a complete replica of the physical space with identical attributes, structure, behavior, and information. The information space is the middleware layer that maintains a constant connection and communication between the physical and virtual spaces. This connection and communication includes both internal and external communication as well as the system’s network and internet connection. A digital thread is used by the DT to generate data traceability and keep operators informed, which facilitates data exchange between the physical and virtual space. The DT implementation framework developed by Loaiza,

Cloutier, and Lippert (2023) uses the left-side of the “Vee” model to guide the development of the desired DT and it focuses on mainly on small-scale manufacturing systems, so the framework may not be applicable or suitable for larger or more complex systems or when used in different manufacturing environments. This article also does not provide a case study or empirical evidence to demonstrate the effectiveness or efficiency of the proposed framework in practice.

On the other hand, X. Zhang et al. (2021) experimented with the idea of applying a model-based system architecture process (MBSAP) to develop and operationalize DTs. The authors explained that MBSAP is a method for incremental MBSE that achieves solutions through successive rounds of design, development, and testing. The approach discussed by X. Zhang et al. (2021) is illustrated in Figure 5, and it involves analyzing requirements based on provided files such as CONOPS and white papers, using operational viewpoints (OV) and transforming them into “logical/functional viewpoints (LV/FV)” and mapping the LV to “physical viewpoints (PV)” to build the architecture. As discussed by the authors, the development of the DT system architecture could take reference from a MBSAP process but adjusted to align with the functional traits of the DT system. The primary steps involved in the MBSAP process includes the designing of the conceptual system-level as well as subsystem and component architecture to build a virtual model and implement the final product. The architecture analysis show that X. Zhang et al. (2021)’s framework perform well in terms of showing variability and functionality but it falls short in terms of safety, reliability and performance due to insufficient focus on these aspects.

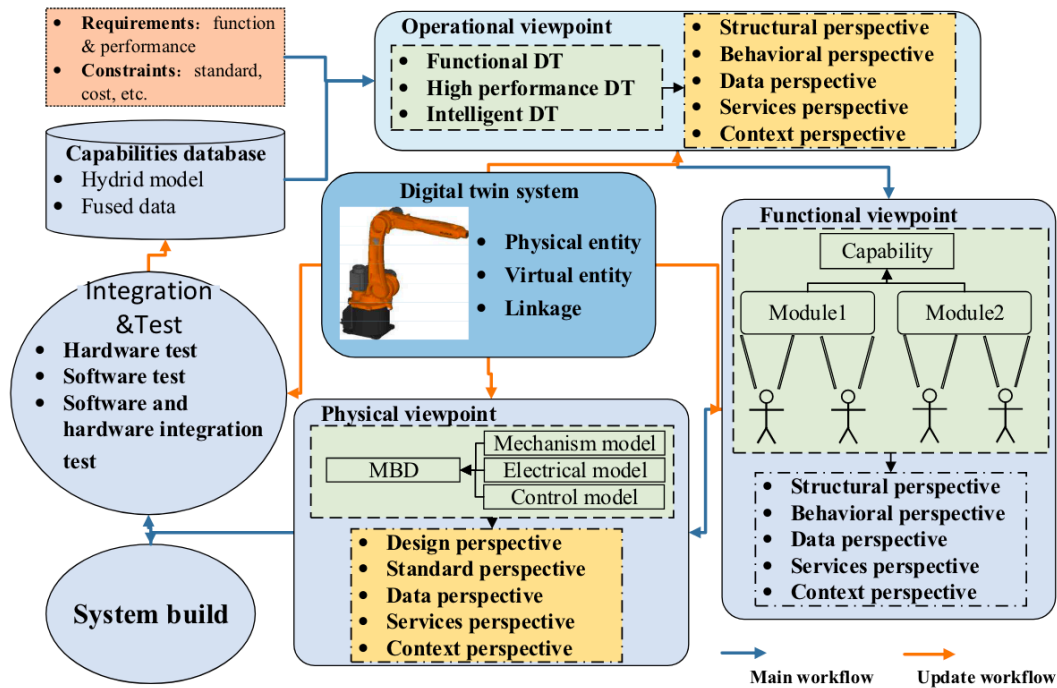


Figure 5. Model-Based Digital Twin System Architecture Process. Source: X. Zhang et al. (2021).

Bickford et al. (2020) describes the decision-making process involved in designing the DT using conventional MBSE process. The approach adopted by Bickford et al. (2020) illustrates the steps involved in defining, designing, constructing, testing, and deploying a physical system and how it can be mapped to the development of a DT shown in Figure 6. The six phases are elaborated below:

1. During the concept exploration phase, stakeholders enable the development of the system concept of operations as well as the extraction of requirements. This phase is crucial in understanding the intended applications and mission pathways of the system. Moreover, it offers a deep understanding of what stakeholders expect from the DT. Thus, it's the perfect moment to pinpoint the primary goal of the DT.
2. In the preliminary design stage, essential system functions are developed from primary requirements, mission pathways, and concept of operations. During this phase, the DT's architecture and its concept of operations can

be crafted utilizing the MBSE approach to assess impacts that degrade the mission. The individual developing the DT should determine the required data elements that align with the DT's goals and objectives with the appropriate data sources and components. Once the DT architecture and data components are set, the digital thread can be initiated and utilized to assist in analyzing various options. To conclude, the DT structure should be finalized by identifying sensors, determining the application programming interface, and detailing the prerequisites for data gathering and storage. Subsequently, the DT specifications should be incorporated into the physical design.

3. In the detailed design phase, sensors and component data must be mapped to the DT's functions to develop algorithms for performance analysis and PHM. The DT software models must be developed in this phase. DT designers should have adequate information by the end of the detailed design phase to finalize the preliminary design, test algorithms, and validate recommendations using artificial/dummy data.
4. In the implementation stage, various elements such as sensors, hardware, and software come together to form the DT. This allows DT designers to tap into sensors, hardware components, and software that produce the data the DT will analyze. The DT can offer feedback on system performance, which can be used to enhance its design. By this point, the goals, structure, and design of the DT should be firmly established, and the sensor specifications for the DT, identified earlier, should be integrated into the physical system.
5. During the test and evaluation (T&E) phase of the program, DT developers can utilize the DT to collect test data and refine DT algorithms. Moreover, there are potential to employ the DT and algorithms to assist in testing and verifying components, subsystems, and the entire system.

The Bickford et al. (2020) approach also takes into account the need for continuous improvement and refinement of DTs over time. As discussed by Bickford et al. (2020), this approach provides System Engineers with a straightforward and instinctive structure to implement PHM-focused DTs for their systems, leading to decreased deployment costs and enhanced operational readiness. The DT discussed in the article by Bickford et al. (2020) offers an architecture to capture, store, and analyze component performance and reliability data which can resolve reliability and performance issues. However, it did not address the performance or risk-based analysis decision making based on the data collected and generated by the DT.

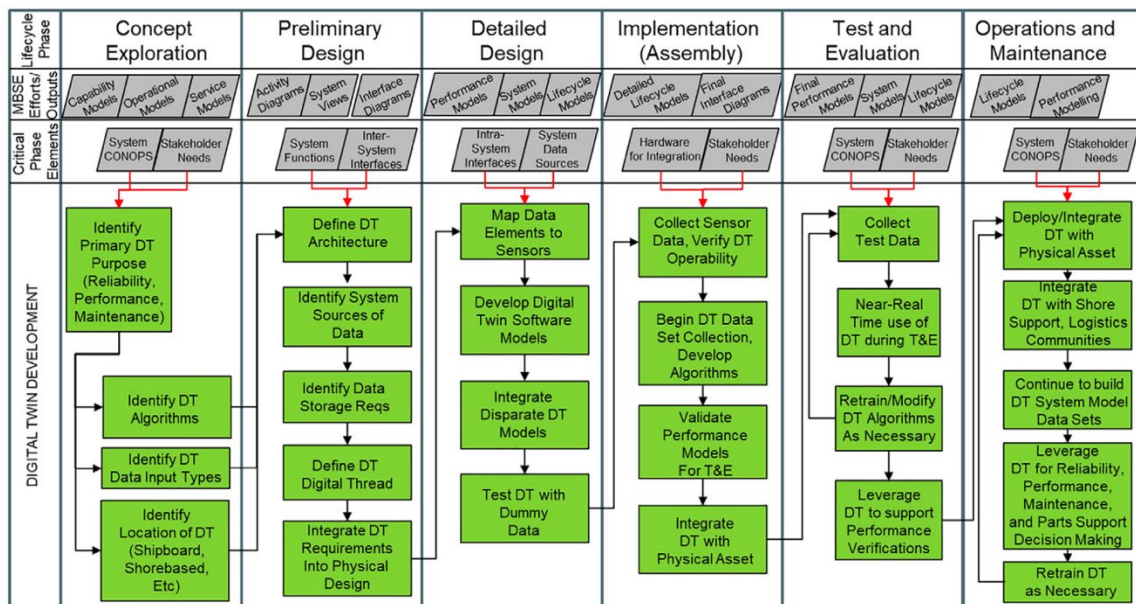


Figure 6. DT Development through MBSE Process. Source: Bickford et al. (2020).

In conclusion, DT technology offers numerous benefits for various sectors, including the ability to collect real-time operational data, enable data-driven decision-making, and enhance system performance. The development of a successful DT requires clear identification of stakeholders and users, their needs, and the purpose of the DT. The integration of the DT development process with the traditional MBSE process and “Vee” model concept can ensure a structured and systematic approach to the development of

complex systems. Furthermore, the use of MBSAP in the development of DT architecture can ensure a more incremental approach to MBSE and a better fit to the functional characteristics of the DT system. MBSE processes that drive the physical system development also similarly drive the development of the DT. Hence, there are benefits to integrating DTs and early system development by leveraging on the work done during the conceptual design phase so that extra effort is not needed to be invested in the development of a DT after the system has been fielded. However, it is also crucial to understand that although a DT is created in conjunction with a physical asset, its creation can occur before the physical system is developed. Moreover, under suitable conditions, a DT can facilitate the development of the physical system by offering a platform for modeling and simulation. By following these approaches, stakeholders can achieve a better understanding of their systems, optimize system performance, and ultimately achieve greater success in their operations.

#### **F. ADDITIVE MANUFACTURING AND 3D PRINTING**

The 3D printer is chosen as the system of interest for this study due to the constraint that the project scope shall not exceed the classification level of Distribution Statement A: Approved for public release. Using a DT system for a 3D printer on a surface vessel can offer similar valuable knowledge about sensitive, high-precision systems in the particular and changing environments that are exclusive to naval operations (Ashworth et al. 2021). A 3D printer is a subset of additive manufacturing (AM) as it is one of the possible techniques that could create 3D objects by adding material layer by layer. AM is a process of creating 3D objects from digital models by adding successive layers of material until the desired shape is achieved (Joint Defense Manufacturing Council 2021). Other AM techniques include laser sintering, fused deposition modeling, and stereolithography.

AM has the potential to decrease the amount of time equipment is out of service, enhance the effectiveness of maintenance, and lessen the expenses of logistics by allowing parts to be produced nearer to the time and location where they are required (Ashworth et al. 2021). Additionally, AM technology can be used to aid older systems by improving their state of readiness in cases where replacement parts are unavailable. 3D printers were

used in the Navy as one of the AM technologies to print spares and legacy parts. This use of AM indicates that the 3D printer design technology produces high-quality, reliable components if replacements are solely developed from AM.

Fused Deposition Modeling (FDM) is a prevalent additive manufacturing technique that utilizes a heated nozzle to melt a thermoplastic filament and deposit it layer by layer to form a 3D object (Steuben, Van Bossuyt, and Turner 2016). FDM printers offer a cost-effective solution for fabricating objects and can accommodate a diverse range of thermoplastic materials. However, when it comes to producing metal components onboard ships, the traditional approach involves using metal powders in most 3D printers. Metal powders are generally not the most favorable material for 3D printing in naval applications due to their porous characteristics, which can result in reduced strength and low density in the printed components. Additionally, the flammable, explosive, and hazardous nature of metal powders poses a significant safety risk during the printing process. Currently, Xerox has created a new method for printing metal parts without depending on metal powders. Their latest invention, the ElemX liquid metal printer, employs inexpensive metal that is readily available to print metal parts swiftly, safely, and cost-effectively on demand (Schehl 2021). The ElemX operates in a manner akin to an inkjet printer found in offices, where a metal wire is melted, and tiny droplets of molten metal are dispensed by layer to fabricate metal objects.

Farooqi (2021) describes the working mechanics of the Xerox ElemX 3D printer. The initial step involves gradually introducing a coil of aluminum wire into a heated reservoir (see Figure 7) that can attain temperatures as high as 815 degrees Celsius (1500 degrees Fahrenheit). The aluminum wire rapidly melts due to its low melting point of 660 degrees Celsius (1220 degrees Fahrenheit). The molten aluminum is then gathered in an ejection chamber that is made of a specialized ceramic material. This chamber is positioned inside an electromagnetic coil, which generates a magnetic field strong enough to compress the liquid aluminum within the chamber (see Figure 8). With every activation of the magnetic field, a droplet of molten aluminum is squeezed out of the ejection chamber and collected on a tray below. These droplets gradually accumulate into the desired shape. It takes roughly five minutes for the molten aluminum to cool and another fifteen minutes for

it to solidify. The ejection tube can discharge up to 1,000 drops per second, and the production rate can be precisely calibrated based on the requirements of the job. It should also be noted that the Xerox ElemX 3D printer is capable of printing with a variety of metals, not limited to aluminum. It can print with stainless steel, titanium, Inconel, and other metal alloys as well. The printer's advanced technology and materials handling system allow for precise printing of complex metal parts with high accuracy and repeatability.

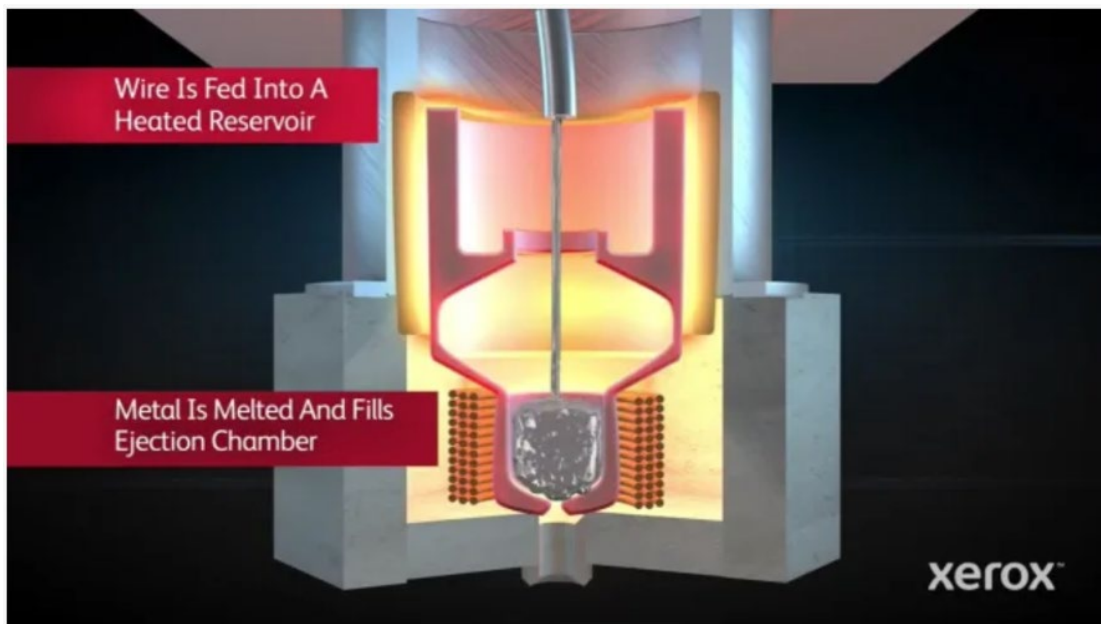


Figure 7. Xerox 3DP—Wire Melts in the Heated Reservoir and Collects in the Ejection Chamber. Source: Farooqi (2021).

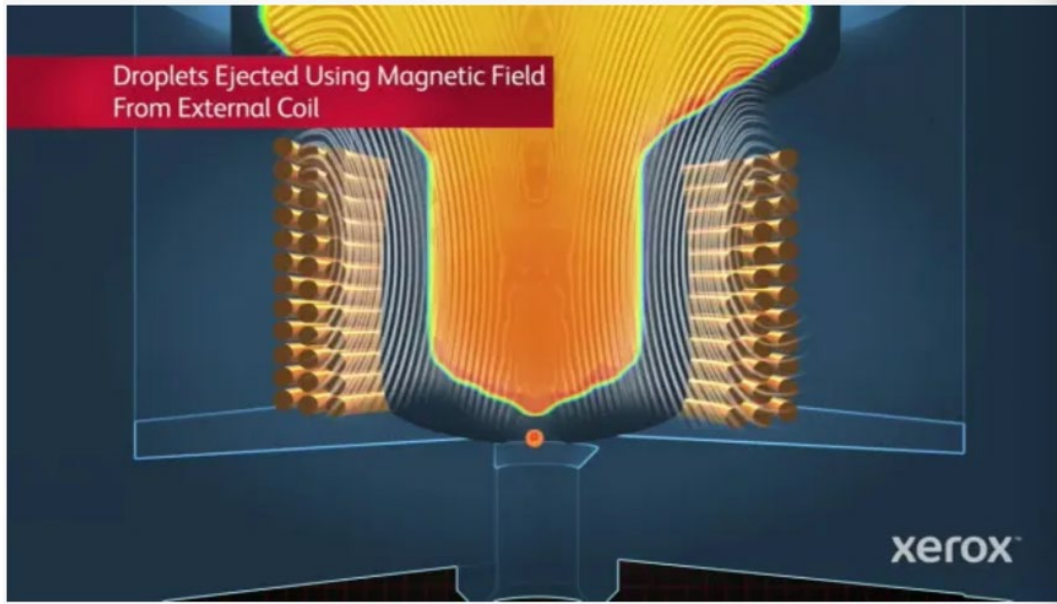


Figure 8. Xerox 3DP—Magnetic Field Squeezes out the Liquefied Metal One Drop at a Time. Source: Farooqi (2021).

## G. CONCLUSION

DT technology offers many advantages for various sectors, including the ability to collect real-time operational data, enable data-driven decision-making, and enhance system performance. Employing DT hence shows potential as a successful method for gathering operational data on the health and performance metrics of deployed systems. Based on the literature review, it can be concluded that MBSE coupled with the system engineering “Vee” model concept could be useful to operationalized DT. The development of a successful DT requires clear identification of stakeholders and users, their needs, and the purpose of the DT. The integration of the DT development process with MBSE processes and “Vee” model concept can ensure a structured and systematic approach to the development of complex systems.

From the research conducted, it can be noted that DT frameworks or architectures that were discussed by the authors were good baseline as a starting point to build a generic DT framework however there were some challenges and shortcomings that were required to be resolved. The articles were unable to demonstrate the efficiency of the proposed

framework or architecture and they were unable to address the performance or risk-based analysis decision making based on the data collected and generated by the DTs.

In conclusion, DT technology has the potential to revolutionize the way we gather and analyze operational data for various sectors. However, the lack of standardization in the development and implementation of DT has led to limited interoperability and difficulty in addressing the right issues for stakeholders. To fully realize the potential of DT and increase their adoption, standardized methodologies need to be developed. Several approaches have been proposed in the literature gathered and as DTs continue to evolve, it will be important to refine and improve these methodologies to ensure they are effective and efficient in meeting the needs of stakeholders. In order to advance the understanding and implementation of DT technology in the context of AM, a more detailed DT model will be developed with 3DP as the primary case study. This model will enable the collection and analysis of real-time data on the health and performance metrics of AM systems, allowing for data-driven decision-making and enhanced system performance. To add on, an important consideration in the development of DTs is the structure of the model, which includes factors such as the location of the model, the storage of data, and the user intervention points. Determining the optimal structure for a DT is crucial for its successful implementation and integration with existing systems. By examining these factors in the context of AM, this study aims to identify best practices and develop a framework for the design and implementation of DTs in other domains as well.

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### III. NOTIONAL DT FRAMEWORK

This chapter aims to develop a notional framework for a DT. In order to construct a resilient and efficient DT framework, leveraging the Department of Defense Architecture Framework (DoDAF) offers distinct advantages (Piaszczyk 2011). The DoDAF views provide a methodical approach to capturing and defining the diverse components, functionalities, and interactions within the DT framework.

The notional DT framework developed herein serves as a conceptual model, outlining the framework's specific components and functionalities. It serves as a fundamental basis for subsequent development and research efforts. Additionally, this framework will visually portray the interrelationships and interactions among different components.

Valuable insights from the work of Bickford et al. (2020) regarding DT development through MBSE processes were drawn. The conceptual development of the notional framework in this study aligns with the MBSE process from the MagicGrid Book of Knowledge (Dassault Systèmes 2021), harmonizes with the six life cycle phases adopted from Bickford et al. (2020) methodology, and incorporates the DoDAF views in the process. By incorporating the DoDAF views into the creation of the notional DT framework, stakeholders can attain consistency, interoperability, and effectiveness in the design and implementation of DTs. It is worth noting that this process generally adheres to the systematic approach of traditional system engineering models like the Vee model described by Loaiza, Cloutier, and Lippert (2023). These models facilitate a thorough comprehension of the system context, capture stakeholder requirements, define capabilities, and measure effectiveness. Such a methodical approach enhances decision-making processes and augments the overall performance of the DT system.

Figure 9 outlines the architectural process of designing the DT, providing a visual representation of the phases involved.

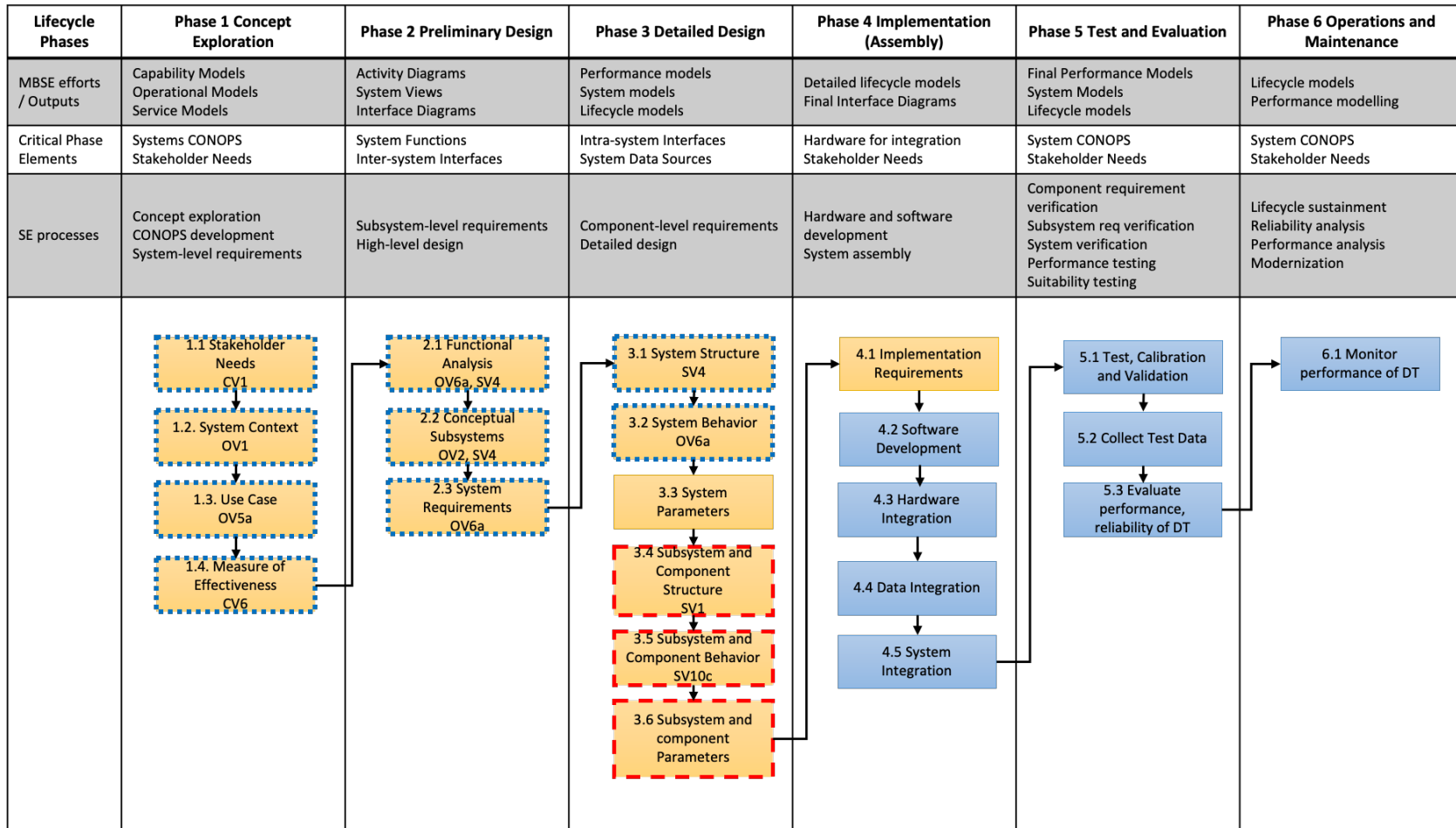


Figure 9. Architectural Process of Designing the DT

In Figure 9, the processes highlighted in yellow boxes represent the key components that are strongly recommended to be developed using MSOSA. Steps 3.4, 3.5, and 3.6, highlighted with red dots, are considered optional but are particularly recommended for designs involving complex subsystems, components, structures, and behavior. Additionally, the processes highlighted in blue are part of the life cycle phases in the standard systems engineering process, encompassing implementation, test and evaluation, as well as operations and maintenance. However, it is important to note that they are not directly related to DT development. The following sections of this chapter detail the steps necessary to successfully complete the method.

## **A. PHASE 1: CONCEPT EXPLORATION**

In this phase, the high-level concept and feasibility of the DT are explored. It involves identifying the goals, objectives as well as expected outcomes of the DT implementation. During this phase, stakeholders' needs are analyzed, requirements are elicited, and a conceptual design for the DT will be developed. Concept exploration is important as it establishes a clear problem statement, assesses feasibility, elicits requirements, explores solution options, facilitates stakeholder alignment as well as mitigates risks. It sets the foundation for the subsequent phases of DT development, ensuring that the DT is designed and implemented with a clear understanding of its purpose, objectives, and potential benefits.

The concept exploration phase involves understanding and defining stakeholder needs, establishing the system context, developing use cases, and defining measures of effectiveness. Throughout the concept exploration phase, there is iterative and collaborative engagement with stakeholders. Their feedback and input are considered to refine and validate the stakeholder needs, system context, use cases, and measures of effectiveness. This iterative process ensures that the design and development of the DT align with the stakeholders' requirements and expectations.

By following this process of stakeholder needs, system context, use case development, and measures of effectiveness, the concept exploration phase lays the groundwork for the subsequent phases of the DT development life cycle. It provides a clear

understanding of the desired functionalities, system boundaries, and evaluation criteria, which serve as a basis for the preliminary design and detailed design phases.

## **1. Step 1.1: Stakeholder Needs**

The first step in the concept exploration phase is to identify and understand the needs of the stakeholders. Stakeholders can include users, customers, domain experts, and other individuals or organizations affected by or involved in the DT system. Through interviews, surveys, and discussions, the requirements, expectations, and desired functionalities of the DT are gathered. This information serves as the foundation for the subsequent steps in the concept exploration phase.

The Capability Viewpoint Vision model (CV-1) can be used to effectively capture and understand stakeholder needs. The CV-1 model aids in defining stakeholder needs by offering a high-level comprehension of the envisioned future state or end-state for the digital twin system. Although the CV-1 model may not explicitly capture specific stakeholder needs, it serves as a guiding framework that influences and shapes the subsequent analysis and documentation of these needs. By taking into account the vision and objectives delineated in the CV-1 model, one can ensure that stakeholder needs harmonize with the overarching direction and purpose of the DT system.

## **2. Step 1.2: System Context**

Once the stakeholder needs are understood, the next step is to establish the system context. This involves identifying the boundaries and interfaces of the DT system and understanding its relationships with other systems, processes, or entities. The system context provides a high-level view of how the DT fits within the larger ecosystem, considering factors such as data sources, communication networks, and dependencies. It helps in identifying the relevant inputs, outputs, and interactions that need to be considered in the design and development of the DT.

The High-Level Operational Concept Graphic (OV-1) model within the DoDAF framework can also serve as an artifact for capturing the operational concept and context of the system. The OV-1 model illustrates the overarching operational activities, roles, and

external entities involved in the system's operation. It aids stakeholders in visualizing how the system fits within the broader operational environment, enhancing their understanding of the system's purpose and functionality.

The OV-1 model and the system context model to be developed in MSOSA can often serve the same purpose of capturing the context and relationships of the system. Depending on the specific requirements and preferences of the project, they can be represented as a separate model or combined into a single comprehensive depiction.

### **3. Step 1.3: Use Case**

Use cases are developed to capture the specific scenarios, tasks, or interactions that the DT needs to support or function. Use cases are further defined using activity or sequence models that describe the sequence of actions, inputs, and outputs that occur between the stakeholders and the DT system. They provide a detailed understanding of the functionalities and capabilities required to meet the stakeholder needs. Use cases help in defining the scope of the DT system and guide the subsequent design and development activities.

Within the DoDAF framework, the Operational Activity Decomposition Tree (OV-5a) model facilitates the decomposition of operational activities into lower-level activities and tasks, enabling a comprehensive understanding of the operational processes. By leveraging the OV-5a model, stakeholders can identify and document specific use cases within these processes. The hierarchical structure provided by the OV-5a model captures the relationships between activities and tasks, aiding in the identification, organization, and categorization of use cases. This systematic approach ensures that all pertinent use cases are thoroughly documented, addressing the diverse functionalities and requirements of the DT system.

### **4. Step 1.4: Measure of Effectiveness**

Measures of effectiveness (MOEs) are established to assess the performance and success of the DT system. MOEs are quantitative or qualitative metrics that evaluate how well the DT meets the stakeholder needs and achieves the desired objectives. These metrics

can include factors such as accuracy, reliability, response time, scalability, usability, cost-effectiveness, or environmental impact. MOEs provide a means to evaluate the performance of the DT during its development and operation, enabling objective assessments of its effectiveness.

The DoDAF model that aids in capturing MOEs is the Capability to Operational Activities Mapping (CV-6) model. The CV-6 model establishes a clear mapping between the system's capabilities and the operational activities they support. By leveraging this model, stakeholders can establish a direct link between specific capabilities and the corresponding measures of effectiveness. This mapping facilitates the assessment of the system's effectiveness based on its underlying capabilities.

## **B. PHASE 2: PRELIMINARY DESIGN**

In the preliminary design phase, the overall functional architecture of the DT is established. This includes defining the system boundaries, identifying the main components and subsystems, and specifying their interactions and interfaces. The preliminary design phase also involves selecting the appropriate technologies, tools, and platforms to support the implementation of the DT. This phase is important as it enhances system understanding, defines the DT's architecture, validates requirements, facilitates trade-off analysis, identifies risks, promotes collaboration, establishes a foundation for detailed design, and supports effective communication and documentation. It plays a crucial role in shaping the direction of the DT development and ensuring that the subsequent design and implementation activities align with the desired goals and requirements.

In the preliminary design phase of the DT development, several key activities take place to define the system requirements getting ready to develop the structure, behavior, and parameters in the detailed design phase. Throughout the preliminary phase, there is a continuous refinement and iteration of the functional analysis, conceptual subsystems, measurement of effectiveness and system requirements. Stakeholder engagement and feedback play a vital role in ensuring that the DT system design meets the desired objectives and specifications. By following this process, the preliminary design phase

establishes a solid foundation for the subsequent detailed design phase, where the DT system is further developed and refined based on the defined requirements.

## **1. Step 2.1: Functional Analysis**

The functional analysis involves decomposing the overall DT system into its constituent functions. It identifies the specific tasks, activities, or operations that the DT needs to perform to meet the stakeholder needs and use cases identified in the concept exploration phase. The functional analysis helps in understanding the required capabilities and functionalities of the DT system.

The Operational State Transition Description model (OV-6b) is a DoDAF model that effectively supports functional analysis. It provides a structured representation of operational states and transitions within a system. The OV-6b model enables stakeholders to understand how the system behaves over time, including its states, modes, conditions, and triggers for transitions. By visualizing and documenting the sequence of events and interactions, the model helps identify functional requirements, dependencies, and potential operational scenarios and this ensure that the DT system adheres to the prescribed operational state transition in a systematic manner.

By combining the strengths of both the OV-6b model and activity diagrams, stakeholders can gain a holistic view of the DT system's functional analysis, ensuring a more efficient and effective development process. This integrated approach fosters better decision-making, streamlined development, and ultimately results in a high-performing and reliable digital twin.

Another valuable DoDAF model for capturing functional analysis is the Systems Functionality Description (SV-4). The SV-4 model provides a structured representation of the system's functionalities and their interrelationships. It offers a detailed account of the functions performed by individual system components and illustrates how these functions collectively contribute to achieving the desired system capabilities. By utilizing the SV-4 model, stakeholders can effectively capture the functional decomposition and allocate system functions to specific components or subsystems. This model serves as a visual aid in organizing and understanding the intricate interplay between different system

functionalities, thereby facilitating a comprehensive understanding of the DT system's capabilities and contributing to the overall system design.

## **2. Step 2.2: Conceptual Subsystem**

Based on the functional analysis, the DT system is further divided into conceptual subsystems. These subsystems represent logical groupings of functions that work together to accomplish specific tasks or provide specific capabilities. The conceptual subsystems help in organizing and structuring the DT system, providing a high-level view of its architecture and components.

Within the DoDAF framework, the Operational Resource Flow Description (OV-2) model assumes significance in capturing the operational resource flows present within the DT system. By meticulously analyzing these resource flows, encompassing inputs, outputs, and transformations, stakeholders can identify logical groupings of resources and their interactions. This analysis, facilitated by the OV-2 model, assists in the identification and delineation of conceptual subsystems, offering insights into how various subsystems contribute to the overall functioning of the DT system.

Another essential model within the DoDAF framework is the Systems Functionality Description (SV-4) model, which not only captures the system's functionalities but also proves instrumental in defining and describing conceptual subsystems. Through the SV-4 model, stakeholders engage in decomposing system functionalities into lower-level functions, which are subsequently assigned to specific subsystems. This process culminates in the establishment of a hierarchical structure that effectively represents the conceptual subsystems housed within the DT system.

The OV-2 and SV-4 models, employed in tandem, enable stakeholders to effectively define, analyze, and document the conceptual subsystems critical to the DT system. By leveraging the insights gained from resource flows and functional decomposition, stakeholders can gain a comprehensive understanding of the relationships and dependencies between subsystems. This comprehensive understanding fosters informed decision-making, collaboration, and the development of a well-structured DT system architecture.

### **3. Step 2.3: System Requirements**

System requirements are derived from the functional analysis and the stakeholder needs identified in the concept exploration phase. The requirements specify the desired behaviors, capabilities, performance, and constraints of the DT system. They outline what the system must achieve to meet the stakeholder expectations and use cases. System requirements serve as a foundation for the subsequent design and development activities.

System requirements are derived from a systematic approach that involves conducting a functional analysis and carefully identifying stakeholder needs during the concept exploration phase. It is recommended to adopt the SMART (Specific, Measurable, Attainable, Realistic and Timely) method (Doran 1981) to develop the requirements. SMART requirements go beyond mere descriptions and provide precise specifications for the desired behaviors, capabilities, performance, and constraints of the DT system.

The Operational Rules Model (OV-6a) is a DoDAF model that focuses on capturing the operational rules and constraints that govern the behavior and functionality of the system. It helps in defining the conditions, triggers, and responses associated with specific operational activities. By utilizing the OV-6a model, stakeholders can document and analyze the functional requirements and constraints that need to be considered in the design and development of the DT system. This model ensures that system requirements align with the operational rules and constraints identified during the analysis.

## **C. PHASE 3: DETAILED DESIGN**

In the detailed design phase, the architectural details of the DT are further refined. The systems, subsystems and components identified in the preliminary design phase are further decomposed, and their structures, behaviors and parameters are defined. This phase involves developing detailed models, specifying data flows, and designing algorithms and control mechanisms for the DT. It also includes considering factors such as performance, scalability, security, and maintainability. The detailed design phase is important as it ensures clarity of functionality, data modeling and integration, algorithm design and implementation, user interface design, performance optimization, scalability, and flexibility. It establishes the foundation for the successful implementation and operation of

the DT, supporting accurate representation of the physical system and enabling effective analysis, simulation, and decision-making based on the captured data.

By following this process, the detailed design phase establishes the specific configurations, structures, behaviors, and parameters of each subsystem and component within the DT system. This detailed specification serves as a blueprint for the subsequent implementation and development activities, guiding the construction of the DT system.

### **1. Step 3.1: System Structure**

The system structure defines the organization and arrangement of the subsystems and their interconnections within the DT system. It represents the architecture and components of the DT system, including hardware, software, data flows, and interfaces. The system structure helps in visualizing the overall system design, facilitating communication and coordination during the development process.

The SV-4 model provides a structured representation of the system's functionalities and their interrelationships. It describes the functions performed by the system components and how they contribute to achieving the desired system capabilities. The SV-4 model aids in capturing the functional decomposition and allocation of system functions to specific components or subsystems. It helps stakeholders visualize and document the system structure by illustrating the relationships between functions and components within the DT system.

### **2. Step 3.2: System Behavior**

The system behavior describes how the DT system should behave in response to different inputs, events, or stimuli. It captures the dynamic aspects of the system, including its responses, interactions, and transformations. The system behavior can be described through various means, such as state diagrams, activity diagrams, or behavior models. Understanding the system behavior is crucial for ensuring that the DT system accurately emulates the behavior of the physical system it represents.

The OV-6a model focuses on capturing the operational rules and constraints that govern the behavior and functionality of the system. It helps in defining the conditions,

triggers, and responses associated with specific operational activities. By utilizing the OV-6a model, stakeholders can document and analyze the behavioral requirements and constraints that need to be considered in the design and development of the DT system. The OV-6a model provides a structured representation of the system behavior, facilitating a clear understanding of the rules and conditions that guide the system's operation.

### **3. Step 3.3: System Parameters**

System parameters define the variables, settings, or configurations that influence the behavior and performance of the DT system. These parameters should include thresholds, limits, algorithms, and model parameters. Defining the system parameters allows for customization, optimization, and adaptation of the DT system to specific contexts or requirements.

### **4. Step 3.4: Subsystem and Component Structure**

The subsystem structure represents the organization and arrangement of components within a subsystem. It defines the relationships, dependencies, and interactions between the components. The subsystem structure specifies how the components within the subsystem collaborate to achieve the desired functionalities and behaviors. It helps in visualizing and understanding the internal architecture of each subsystem.

On the other hand, the component structure defines the internal organization and arrangement of elements within a component. It describes how the elements within the component are connected, grouped, or organized to perform specific functions or tasks. The component structure provides a detailed view of the composition and interactions of elements within the component, helping to ensure efficient and effective operations.

The Systems Interface Description (SV-1) is a DODAF model that is useful in capturing system interfaces and their relationships with external entities, presenting a visual representation of the overall system structure. This includes interactions with other systems, users, and stakeholders. By leveraging the SV-1 model, stakeholders can effectively document and analyze the subsystem structure within the broader system architecture, fostering seamless communication and coordination between different

components while highlighting crucial connections and dependencies between subsystems. Moreover, the SV-1 model enables precise definition and description of the system's components, encompassing hardware, software, and other relevant elements. It provides valuable insights into how these components are interconnected and exchange vital information and resources, offering a comprehensive and holistic view of the system's intricate component structure.

## **5. Step 3.5: Subsystem and Component Behavior**

Subsystem behavior and component behavior are both important for understanding how a system works. The subsystem behavior describes the dynamic operation and response of a subsystem to inputs and stimuli. It defines the sequence of actions, algorithms, and processes that the subsystem follows to produce the desired outputs. Subsystem behavior captures how the subsystem processes data, applies models, performs simulations, or interacts with other subsystems. Understanding the subsystem behavior is crucial for ensuring the accurate emulation of the physical system and achieving the intended functionalities.

On the other hand, the component behavior focuses on the dynamic functionality and operation of individual components. It describes how each component processes inputs, performs computations, and generates outputs. Component behavior captures the specific algorithms, models, or simulations used by the component to fulfill its designated purpose. Understanding the component behavior is essential for ensuring accurate and reliable representations of the physical system within each component.

The DoDAF Systems Event-Trace Description (SV-10c) model can be used to help determine the subsystem and component behavior. The SV-10c model focuses on capturing the behavior and interactions of subsystems within the overall system architecture. It provides a structured representation of the subsystems' behavior, including the sequence of actions, activities, and operations they perform to achieve their specific functions. By utilizing the SV-10c model, stakeholders can document and analyze the behavioral aspects of each subsystem. The SV-10c model allows stakeholders to define and describe the inputs, outputs, and interfaces associated with each subsystem, as well as the interactions

and dependencies between subsystems. It helps in understanding how subsystems contribute to the overall system behavior and how they interact with each other to achieve system-level objectives.

## **6. Step 3.6: Subsystem and Component Parameters**

Similar to system parameters, subsystem and components parameters define the specific variables, settings, or configurations that influence the behavior and performance of individual components within a subsystem. These parameters can include parameters specific to algorithms, models, or simulation techniques employed by the subsystem. Defining subsystem parameters at a component level allows for further customization and optimization within each subsystem.

## **D. PHASE 4: IMPLEMENTATION (ASSEMBLY)**

In the implementation phase, the physical and digital components of the DT are built and assembled. This involves procuring or manufacturing the necessary hardware components, integrating sensors, actuators, and other physical elements of the 3D printer. Simultaneously, the software components of the DT are developed and integrated, including data acquisition, analytics, visualization, and control algorithms. The implementation (assembly) phase is important as it involves integrating the physical and digital components of the DT, developing and integrating software functionalities and interfacing with the physical system. This phase transforms the design into a functioning DT and ensures that it accurately represents the physical system while providing the desired functionalities and capabilities. In the implementation (assembly) phase of developing a DT, the focus is on translating the design specifications into a functioning system that can be integrated with the physical system. Throughout the implementation (assembly) phase, close collaboration between software developers, hardware engineers, data specialists, and domain experts is crucial.

### **1. Step 4.1 Implementation Requirements**

In this step, the design specifications and system requirements from the previous phases are translated into implementation requirements. These requirements define the

technical aspects, functionalities, and performance characteristics that need to be implemented in the DT system. They guide the development process by specifying the necessary software, hardware, interfaces, and data integration methods.

## **2. Step 4.2: Software Development**

The implementation phase involves the development of the software components and modules required for the DT system. This includes writing code, implementing algorithms, creating interfaces, and integrating necessary libraries or frameworks. The software development process adheres to best practices, coding standards, and quality assurance measures to ensure reliable and efficient performance.

## **3. Step 4.3: Hardware Development**

If the DT system involves physical components or sensors, the implementation phase includes the integration of hardware elements. This may involve connecting sensors, actuators, controllers, or other physical devices to the DT system. Hardware integration ensures that the DT can interact with the physical system, collect real-time data, and provide control or feedback signals.

## **4. Step 4.4: Data Integration**

Data integration is a crucial step in the implementation phase. It involves establishing data connections and interfaces between the DT system and various data sources, such as sensors, databases, or external systems. Data integration ensures that the DT can access relevant and real-time data from the physical system, enabling accurate emulation, monitoring, and analysis.

## **5. Step 4.5: System Integration**

Once the individual software components, hardware elements, and data connections are implemented, the system integration phase begins. This involves bringing all the components together and ensuring they work seamlessly as a cohesive system. System integration includes testing the DT system for functionality, performance, and interoperability.

## **E. PHASE 5: TEST AND EVALUATION**

The test and evaluation phase focuses on verifying and validating the DT's performance and functionality. Various testing methods and techniques are employed to ensure that the DT meets the defined requirements. This includes functional testing, performance testing, integration testing, and validation against real-world scenarios. The test results are used to identify and address any issues or gaps in the DT implementation. The test and evaluation phase were important as it verifies the functionality and performance of the DT, validates compliance with requirements, identifies and resolves issues, assesses the user experience, tests integration and interoperability, evaluates performance under stress, and obtains user acceptance. This phase ensures the reliability, effectiveness, and quality of the DT, leading to its successful deployment and utilization in supporting analysis, simulation, and decision-making processes. By following this process, the test and evaluation phase provides valuable insights into the DT system's performance, reliability, and accuracy. It helps validate the system against the defined requirements, identify areas for improvement, and ensure that the DT system can effectively support decision-making, analysis, and simulation processes.

### **1. Step 5.1: Test Calibration and Verification**

The first step is to calibrate and verify the DT system. Calibration involves aligning the DT system's parameters, models, and algorithms with the physical system to ensure accurate emulation. Verification involves confirming that the DT system behaves as intended and produces results consistent with the expected behavior. This step may include comparing the DT outputs with known or measured values from the physical system, conducting simulation experiments, or analyzing specific test cases.

### **2. Step 5.2: Test Data Collection**

Test data collection involves gathering data from the DT system during various testing scenarios or operational conditions. This data can come from simulated environments, real-world measurements, or a combination of both. The collected data serves as input for evaluating the performance, reliability, and accuracy of the DT system.

It may include sensor readings, control inputs, system responses, and other relevant variables.

### **3. Step 5.3: Evaluate Performance and Reliability of DT**

Performance evaluation focuses on assessing how well the DT system meets the defined performance criteria and requirements. It involves analyzing the collected test data to evaluate the accuracy, precision, responsiveness, and robustness of the DT system. Performance evaluation may include comparing the DT outputs with expected values, assessing the deviation from the physical system's behavior, and identifying any discrepancies or anomalies. Reliability evaluation aims to determine the DT system's ability to consistently perform as expected over time and under different conditions. It involves assessing the system's reliability, availability, and fault tolerance. Reliability evaluation may include analyzing the system's failure modes, conducting stress tests, assessing error propagation, and evaluating the system's ability to handle uncertainties and disturbances. It helps identify potential weaknesses, vulnerabilities, or limitations of the DT system.

## **F. PHASE 6: OPERATIONS AND MAINTENANCE**

Once the DT is successfully tested and evaluated, it enters the operation and maintenance phase. This phase involves deploying the DT in a production environment, monitoring its performance, and providing ongoing maintenance and support. It includes regular updates, troubleshooting, and addressing any operational issues that may arise. Continuous monitoring and maintenance of the DT ensure its reliability, accuracy, and effectiveness throughout its operational life cycle. The operation and maintenance phase is important as it enables continuous monitoring of the DT's performance, facilitates updates and upgrades, ensures data validation and calibration, optimizes performance, detects faults, performs maintenance and repairs, provides user support and training, and promotes documentation and knowledge management. This phase ensures the long-term reliability, effectiveness, and sustainability of the DT, enabling it to provide ongoing value and support for analysis, simulation, and decision-making processes.

## **G. CONCLUSION**

In conclusion, the Notional DT framework offers a comprehensive and structured approach to designing, developing, and implementing DT solutions. Throughout this chapter, we have explored the key components of the framework through the six life cycle phases. The framework's flexibility and adaptability make it applicable across various industries and use cases enabling businesses and organizations to capitalize on the power of data-driven insights. In the next chapter, the various artifacts and DODAF models will be applied to the Xerox 3D printer case study and will be discussed in detail.

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## **IV. CASE STUDY: XEROX ELEM3D PRINTER DT**

In this chapter, a case study is presented that develops a Xerox Elemx 3D printer DT which exemplifies and showcases the application of the hypothetical DT framework discussed in Chapter III. It is important to note that the presented case study does not encompass a comprehensive analysis of a particular system. Instead, it serves as an illustrative example to demonstrate how the methodology can be applied in a simplified manner, emphasizing the advantages and benefits of the approach.

### **A. XEROX ELEM3D PRINTER DT MISSION CONTEXT**

By employing advanced technologies such as sensors, data analytics, and artificial intelligence, the 3D printer DT can continuously monitor its operational parameters and capture real-time data on the health and condition of its components. Through predictive maintenance techniques, the DT system can identify potential issues and forecast maintenance requirements before they result in unplanned downtime or equipment failure. Condition-based maintenance allows for the optimization of maintenance activities by leveraging data-driven insights to determine the precise timing for maintenance interventions based on the actual condition of the printer. PHM takes this a step further by employing sophisticated algorithms to analyze data patterns, identify early signs of degradation or impending failures, and provide actionable insights for proactive maintenance actions (Bickford et al. 2020). By embracing these approaches, the 3D printer DT enhances operational efficiency, minimizes costly repairs, maximizes system availability, and extends the overall lifespan of the printer, ultimately delivering significant cost savings and improved productivity.

### **B. CASE STUDY: THE SYSTEMS ENGINEERING PROCESS**

In this case study, we employ the conceptual framework introduced in Chapter 3 as the cornerstone for constructing the 3D printer DT. The methodological process of developing the 3D printer DT using MBSE processes via MSOSA, encompassing Steps 1.1 to 4.1 (excluding 3.4 to 3.6), is systematically described in the subsequent sections. It

is important to clarify that Steps 4.2 to 6.1 hold no direct relevance to DT development and, as such, are not addressed within the case study.

Figure 10 serves as a visual representation of the DT template established within MSOSA, strategically designed to enable a seamless navigation experience throughout the methodology aimed at shaping the 3D printer DT. This step-by-step guide encompasses the journey from Steps 1.1 to 4.1, aligning with the visualization presented in Figure 9.

MagicGrid Project: [DT Template]

| Phase 1: Concept Exploration                                                                                                                                                                                                                                                                                                                                                                                      | Phase 2: Preliminary Design                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Phase 3: Detailed Design                                                                                                                                                                                                                                                                                | Phase 4: Implementation (Assembly)                                                                                                                                                   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| System CONOPS<br>Stakeholder needs                                                                                                                                                                                                                                                                                                                                                                                | Intra-system Interfaces<br>System Data Sources                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | System Functions<br>Inter-system Interfaces                                                                                                                                                                                                                                                             | Hardware for Integration                                                                                                                                                             |
| <div>1.1 Stakeholder Needs</div> <div>Content of Package 1.1 Stakeholder Needs</div> <div>Requirement Tables</div> <div>1.1.1 Stakeholder Needs</div> <div>SysML Block Definition Diagrams</div> <div>1.1.1 CV-1 Vision</div> <div>Requirement Diagrams</div> <div>Implementation Requirements Specification</div> <div>System Requirements</div> <div>System Requirements1</div> <div>System Requirements2</div> | <div>2.1 Functional Analysis</div> <div>Content of Package 2.1 Functional Analysis</div> <div>Activity Decomposition Maps</div> <div>2.1 SV-4 Perform DT Functions</div> <div>Activity Diagrams</div> <div>Analyze Data</div> <div>Collect and store data</div> <div>Perform DT Functions</div> <div>Receive Data from physical 3D printer</div>                                                                                                                                                                                                              | <div>3.1 System Structure</div> <div>Content of Package 3.1 System Structure</div> <div>SysML Block Definition Diagrams</div> <div>3.1.1 Exchange Items</div> <div>3.1.1 Logical Architecture of 3DP DT</div> <div>SysML Package Diagrams</div> <div>Scope for Auto-completion and Type Selection</div> | <div>4.1 Implementation Requirement</div> <div>Content of Package 4.1 Implementation Requirements</div> <div>Requirement Diagrams</div> <div>4.1.1 Implementation Requirements</div> |
| <div>1.2 System Context</div> <div>Content of Package 1.2 System Context</div> <div>SysML Block Definition Diagrams</div> <div>1.2 System Context MR</div> <div>SysML Internal Block Diagrams</div> <div>1.2.2 External Context Diagram (CV-1)</div>                                                                                                                                                              | <div>2.2 Conceptual Subsystems</div> <div>Content of Package 2.2 Conceptual Subsystems</div> <div>Blackbox ICD Tables</div> <div>DT of 3DP Blackbox ICD</div> <div>SysML Block Definition Diagrams</div> <div>2.2.2 3DP DT Interfaces</div> <div>2.2.2 Data Collection Interface</div> <div>2.2.2 Data Storage Interface</div> <div>SysML Internal Block Diagrams</div> <div>DT of 3DP</div> <div>Whitebox ICD Tables</div> <div>DT of 3DP Whitebox ICD</div> <div>SysML Internal Block Diagrams</div> <div>OV-SA Operational Resource Flow Description</div> | <div>3.2 System Behavior</div> <div>Content of Package 3.2 System Behavior</div>                                                                                                                                                                                                                        |                                                                                                                                                                                      |
| <div>1.3 Use Case</div> <div>Content of Package 1.3 Use Cases</div> <div>SysML Block Definition Diagrams</div> <div>1.3 CV-5a Operational Activity Decomposition Tree</div> <div>Use Case Diagrams</div> <div>1.3 Use Cases of DT</div>                                                                                                                                                                           | <div>2.3 System Requirements</div> <div>Content of Package 2.3 System Requirements</div> <div>Requirement Derivation Maps</div> <div>2.3 System Requirements</div> <div>Requirement Diagrams</div> <div>2.3 System Requirements</div> <div>SysML Block Definition Diagrams</div> <div>2.3 CV-5b Event Trace Description</div> <div>Generic Tables</div> <div>2.3 CV-5a Operational Rules Model</div>                                                                                                                                                          | <div>3.3 System Parameters</div> <div>Content of Package 3.3 System Parameters</div> <div>SysML Block Definition Diagrams</div> <div>3.3 System Parameters of 3DP DT</div>                                                                                                                              |                                                                                                                                                                                      |
| <div>1.4 Measure of Effectiveness</div> <div>Content of Package 1.4 MoEs</div> <div>SysML Block Definition Diagrams</div> <div>1.4 Measures of Effectiveness</div> <div>SysML Block Definition Diagrams</div> <div>1.4 CV-6 Capability to Operational Activities Mapping</div>                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                      |

Figure 10. DT Template Developed in MSOSA

## **1. Concept Exploration**

In the concept exploration phase of the case study on the development of a 3D printer DT, the high-level concept and feasibility of the DT are being explored. The goals, objectives, and expected outcomes of implementing the 3D printer DT are identified. During this phase, stakeholders' needs are carefully analyzed to understand their requirements and expectations. The exploration phase involves eliciting requirements and developing a conceptual design for the 3D printer DT. This stage is crucial as it establishes a clear problem statement, assesses the feasibility of the DT, explores various solution options, and mitigates risks associated with its implementation. Additionally, stakeholder alignment is facilitated through iterative and collaborative engagement, incorporating their feedback and input to refine and validate the stakeholder needs, system context, use cases, and measures of effectiveness.

### ***a. Stakeholder Needs***

The Capability Viewpoint mission model (CV-1) was developed within the MSOSA program to facilitate the systematic derivation of stakeholder needs and it can be illustrated in Figure 11. The overarching vision entails the Navy's imperative to leverage a DT for a seamless transition from time-based maintenance to condition-based maintenance, while effectively implementing prognostic and health management capabilities for the 3D printer system. In the CV-1 model, meticulous attention was given to defining high-level stakeholder needs, which include objectives such as optimizing operational availability of the physical host, minimizing life cycle costs associated with the physical host, streamlining logistical processes to reduce delays, augmenting additive manufacturing production capacity for on-site part manufacturing during deployments, and establishing a predictive maintenance schedule for the physical host.

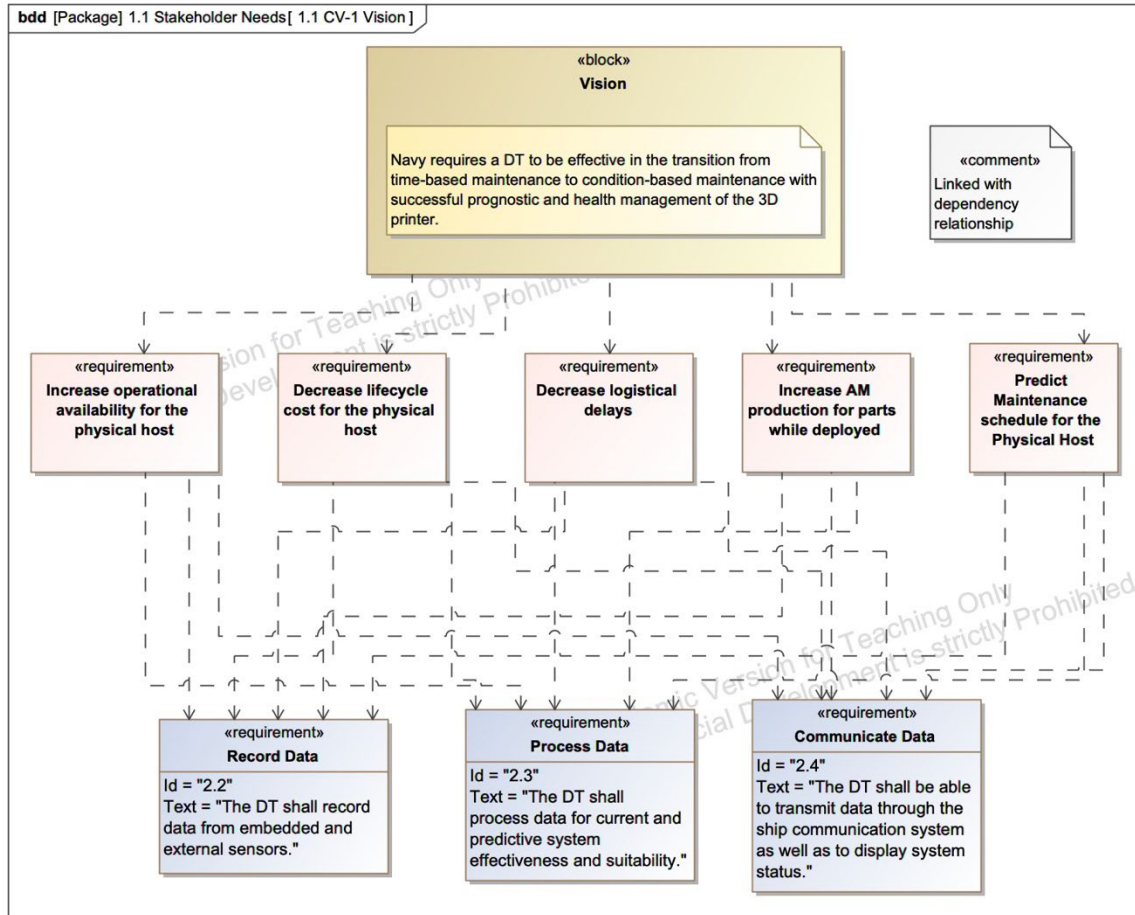


Figure 11. Capability Vision Diagram of 3D Printer DT (CV-1)

To add on, as part of the MSOSA approach, a comprehensive stakeholder needs table was constructed (see Figure 12). This systematic analysis and documentation enable a thorough understanding of the stakeholder needs and guide the subsequent phases of the DT development process.

| #  | △ Name                                                          | Text                                                                                                                                                                      |
|----|-----------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1  | ☐ R 1 High Level Stakeholder needs                              |                                                                                                                                                                           |
| 2  | ☐ R 1.1 Increase operational availability for the physical host |                                                                                                                                                                           |
| 3  | ☐ R 1.2 Decrease lifecycle cost for the physical host           |                                                                                                                                                                           |
| 4  | ☐ R 1.3 Decrease logistical delays                              |                                                                                                                                                                           |
| 5  | ☐ R 1.4 Increase AM production for parts while deployed         |                                                                                                                                                                           |
| 6  | ☐ R 1.5 Predict Maintenance schedule for the Physical Host      |                                                                                                                                                                           |
| 7  | ☐ R 2 Functional Requirements of DT                             | Functional Requirements of the DT.                                                                                                                                        |
| 8  | ☐ R 2.1 Collect Ship Sensor Data                                | The DT shall receive data from ship sensors external to the 3D printer physical asset.                                                                                    |
| 9  | ☐ R 2.2 Record Data                                             | The DT shall record data from embedded and external sensors.                                                                                                              |
| 10 | ☐ R 2.3 Process Data                                            | The DT shall process data for current and predictive system effectiveness and suitability.                                                                                |
| 11 | ☐ R 2.4 Communicate Data                                        | The DT shall be able to transmit data through the ship communication system as well as to display system status.                                                          |
| 12 | ☐ R 2.5 Control Physical 3DP                                    | The DT shall be able to control the physical 3DP.                                                                                                                         |
| 13 | ☐ R 3 External Interface Requirements                           |                                                                                                                                                                           |
| 14 | ☐ R 3.1 Graphical user interface                                | The software shall contain a user interface web portal providing access through a web browser application available to the shore support community of maintenance laptop. |
| 15 | ☐ R 3.2 Hardware interface                                      | The system shall be able to physically connect to external systems.                                                                                                       |
| 16 | ☐ R 3.3 Software interface                                      | The system shall be able to send compatible strings of code and decode messages with the external systems.                                                                |
| 17 | ☐ R 3.4 Communications interface                                | The system shall contain a working interface with the physical host and ship's communications system for transmitting and receiving data.                                 |

Figure 12. Stakeholder Needs Table of 3D Printer DT

### b. System Context

In this case study, the OV-1 model and the context diagram was developed in MSOSA and combined into a single comprehensive diagram (see Figure 13). The context diagram model provides a visual representation of the interconnections between these components, emphasizing the integration of the DT, physical 3D printer, ship-based deployment, and the support crew. It serves as a foundation for understanding the system's boundaries, dependencies, and the overarching framework within which the 3D printer DT operates.

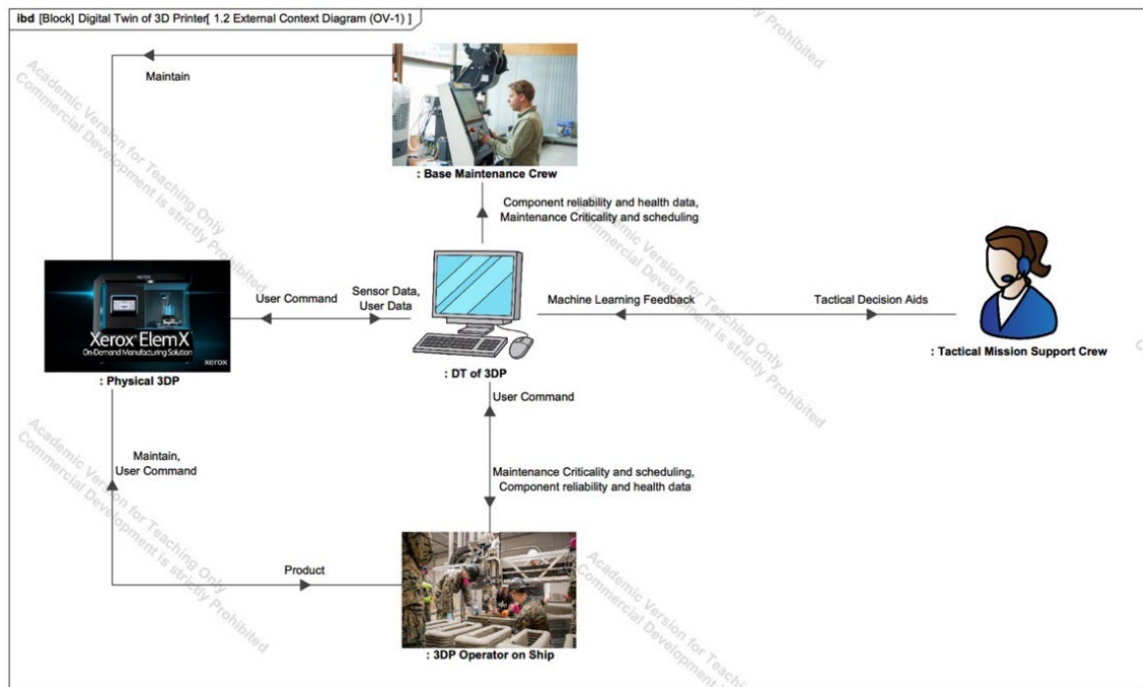


Figure 13. System Context Diagram of 3D Printer DT

In this system, the physical 3D printer transmits sensor data and usage information to the 3D printer DT, facilitating data exchange between the physical and virtual representations. Conversely, the DT can provide user commands to control the operations of the physical 3D printer, enabling seamless interaction between the two entities.

The 3D printer operator, situated on the ship, possesses the capability to control the physical 3D printer directly using the physical system interface, while also having the

option to control it through the 3D printer DT. This dual control mechanism empowers the operator with flexible control options based on their operational requirements. Furthermore, the 3D printer DT supplies the operator with critical information such as maintenance schedules, component reliability, and health data, enabling informed decision-making and ensuring efficient utilization of the 3D printer.

The base maintenance crew plays a vital role in the system, receiving crucial data from the 3D printer DT, including component reliability, health information, maintenance criticality, and scheduling. They are responsible for conducting maintenance activities on the physical 3D printer, leveraging the insights provided by the DT to execute timely and effective maintenance tasks.

Finally, the tactical mission support crew serves as recipients of tactical decision aid derived from the 3D printer DT. They utilize this information to make informed decisions and provide valuable feedback, contributing to the continuous improvement and optimization of the 3D printer DT's performance.

### *c. Use Case*

The development and refinement of the use case scenario for the 3D Printer DT were supported by the implementation of the OV-5a diagram (see Figure 14). OV-5a served as a crucial tool in decomposing complex operational activities into lower-level activities and tasks, facilitating a detailed understanding of the system's functional requirements. OV-5a can be developed in the MSOSA program where the functional operational activities were decomposed into lower-level activities.

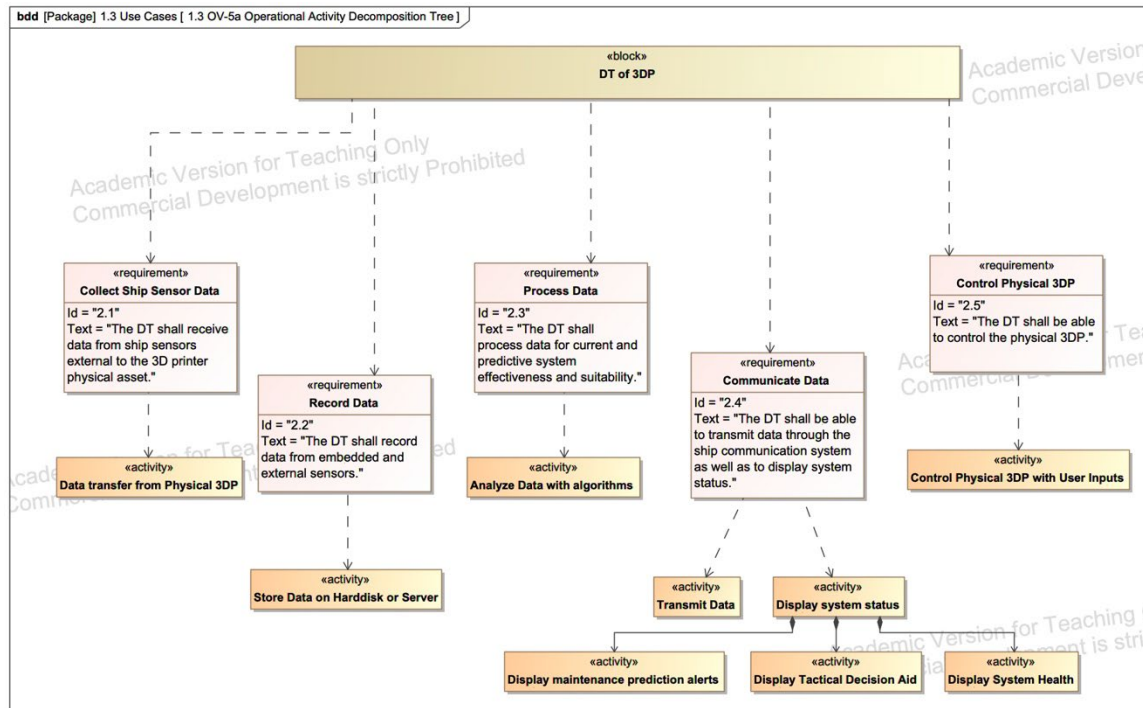


Figure 14. Operational Activity Decomposition Tree of 3D Printer DT (OV-5a)

Next, with the application of the MSOSA modeling framework, a comprehensive use case scenario was crafted, capturing the sequence of actions, inputs, and outputs that characterize the operational workflow of the 3D Printer DT system (see Figure 15 and 16). This use case scenario serves as a blueprint for effectively demonstrating the system’s functionalities and operational capabilities.

The scenario begins with the activation of the 3D printer, followed by a series of system checks to ensure proper functionality. Subsequently, the 3D printing process is initiated, utilizing the physical 3D printer to materialize the desired objects. Throughout this process, sensor data generated by the physical 3D printer is seamlessly transmitted to the 3D printer DT for further analysis and utilization.

The 3D printer DT efficiently collects, stores, and analyzes the transmitted sensor data, employing advanced algorithms and techniques to derive valuable insights and assess the health status of the system. This analysis enables the DT to predict maintenance

requirements and provide a comprehensive display of the system's health and predictive maintenance status.

At this juncture, the base maintenance crew has the capability to request and access the analyzed data directly from the 3D printer DT. This data equips them with crucial information regarding system health, enabling them to plan and execute necessary maintenance activities effectively.

Simultaneously, the tactical mission support crew can leverage the capabilities of the 3D printer DT to request and obtain tactical decision aid. This aid facilitates informed decision-making, aligning the operations of the 3D printer with the broader mission objectives and strategic considerations.

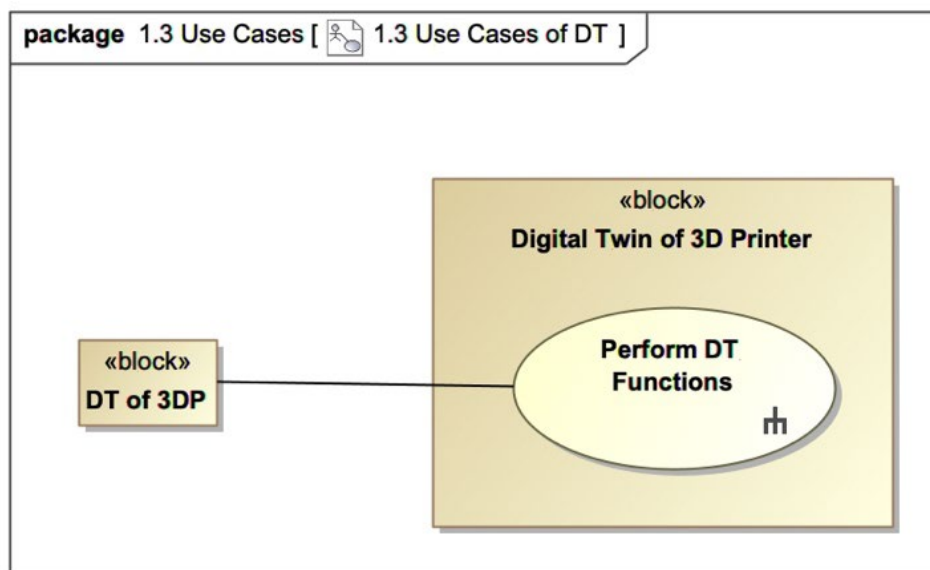


Figure 15. Use Case of 3D Printer DT

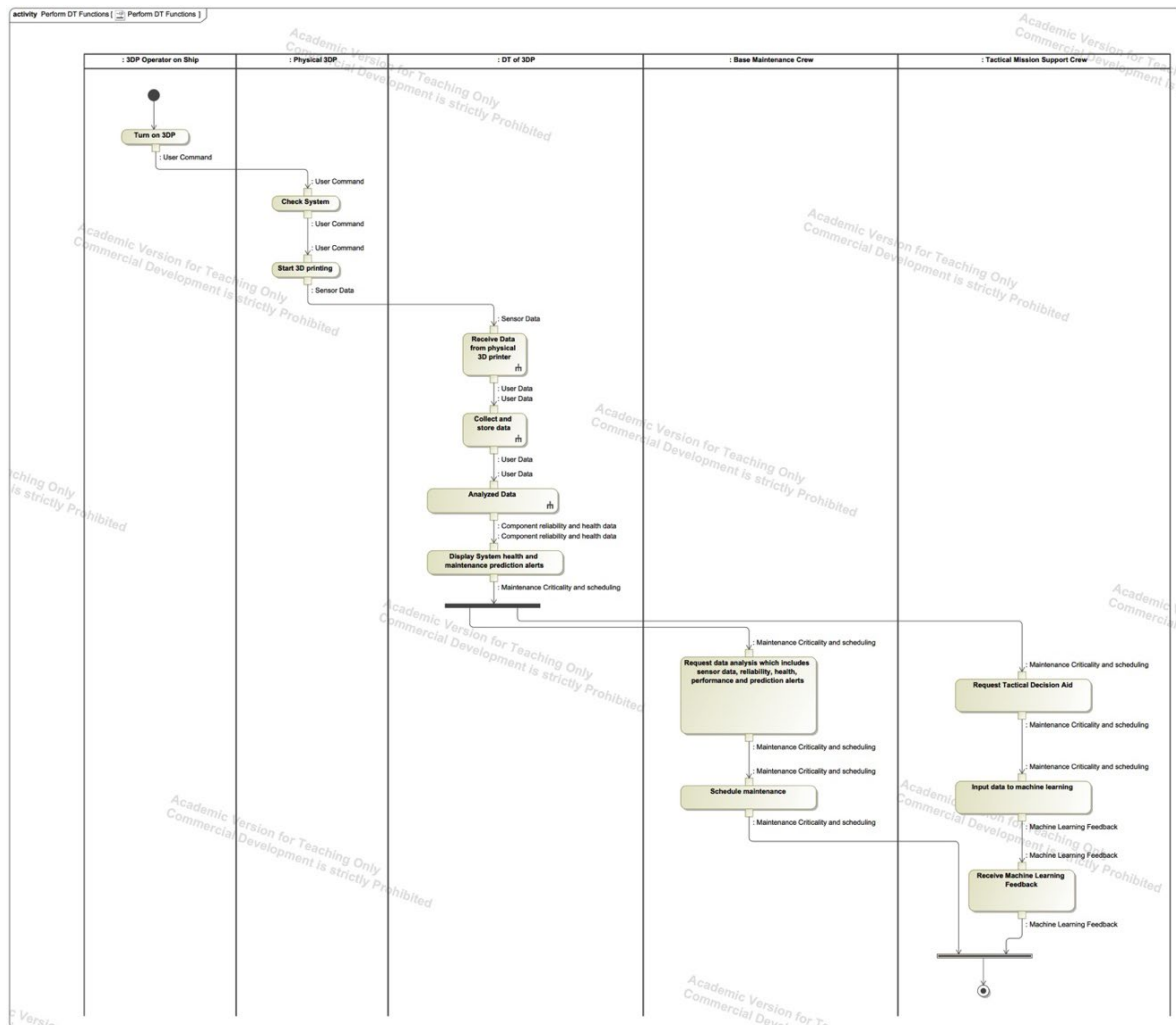


Figure 16. Activity Diagram (Perform DT functions) of 3D Printer DT

#### d. Measure of Effectiveness (MOEs)

MOEs are established as quantitative or qualitative metrics to evaluate how well the DT and meet the desired objectives. As previously defined, MOEs are developed based on the five high level stakeholder needs requirements. To facilitate the process of defining MOEs, the DODAF CV-6 model, which maps capabilities to operational activities and MOEs, can be utilized as illustrated in Figure 17.

In the context of the DT, two primary capabilities that are paramount are the command and control of the physical 3DP and the ability to monitor the status of the physical 3DP. The purpose for these capabilities is to enhance logistic supportability and

the overall success rate of printed parts as well as to improve the maintainability of the 3D printer itself.

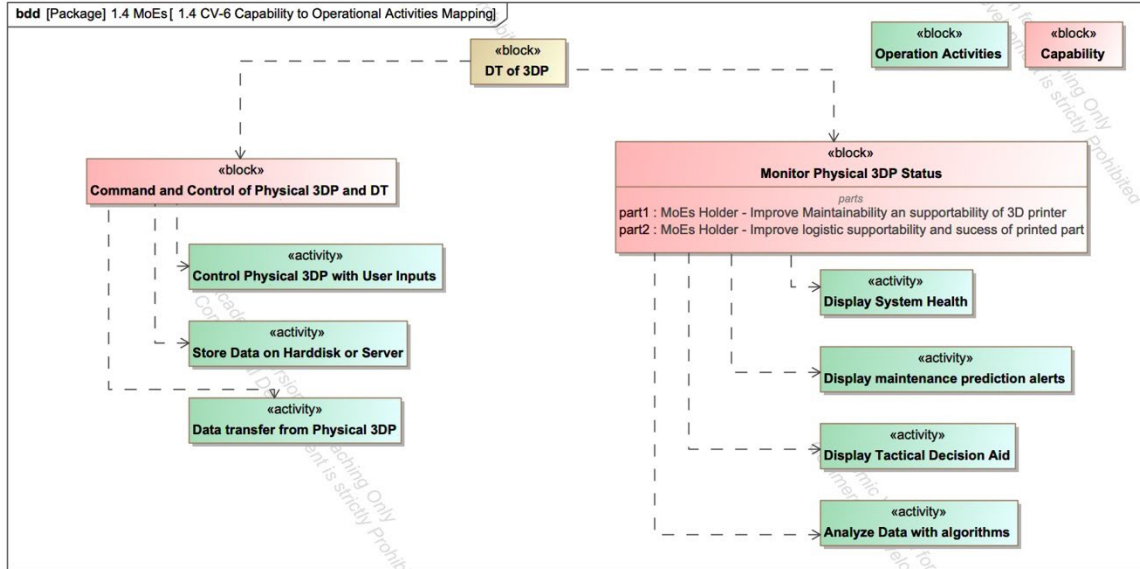


Figure 17. Capability to Operational Activities Mapping of 3D Printer DT (CV-6)

MOEs are developed in MSOSA (see Figure 18) based on the need to enhance logistic supportability and the overall success rate of printed parts as well as to improve the maintainability of the 3D printer.

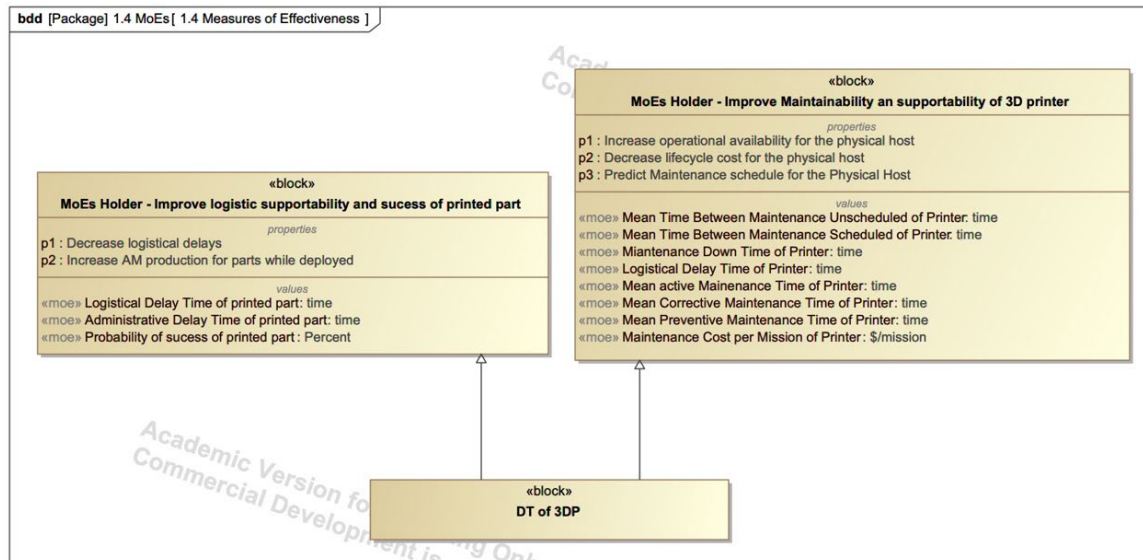


Figure 18. Measures of Effectiveness of 3D Printer DT

## 2. Preliminary Design

The preliminary design phase of the case study on the development of a 3D printer DT includes functional analysis, conceptual subsystems, and system requirements. These activities focus on understanding the desired functions, subsystems, and architecture, forming a good foundation for the detailed design development.

### a. Functional Analysis

In the MBSE process from the MagicGrid Book of knowledge (Dassault Systèmes 2021), functional analysis requires the creation of an activity diagram to decompose the system's functions. For each function decomposition, the activity diagram should encompass input and output components, ensuring that the activity parameter nodes align seamlessly with the respective inputs and outputs. In the context of this case study, three distinct activity diagrams have been created, namely: (1) "Receive Data from Physical 3D Printer" (see Figure 19), (2) "Collect and Store Data" (see Figure 20), and (3) "Analyze Data" (see Figure 21).

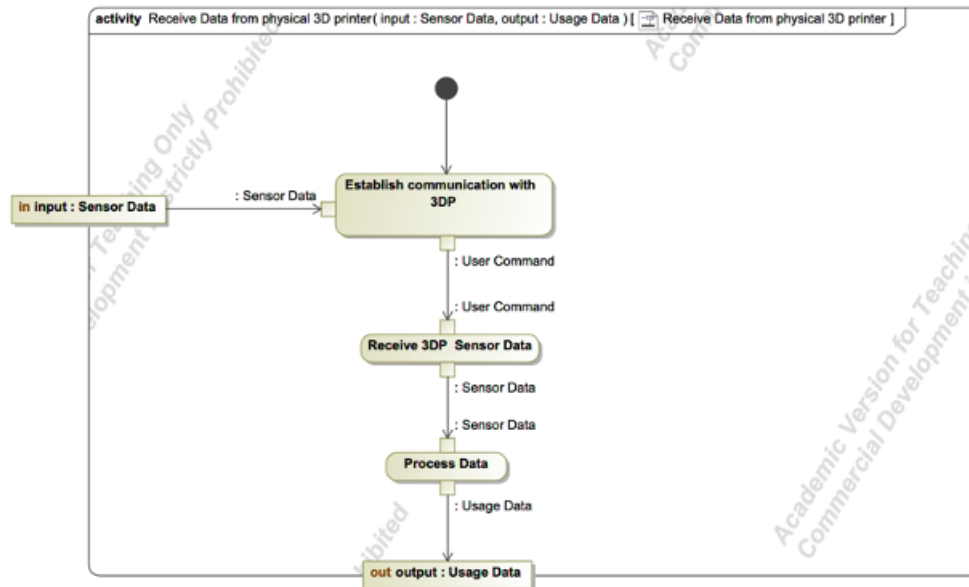


Figure 19. Functional Analysis of “Receive Data from Physical 3D Printer” for 3D Printer DT

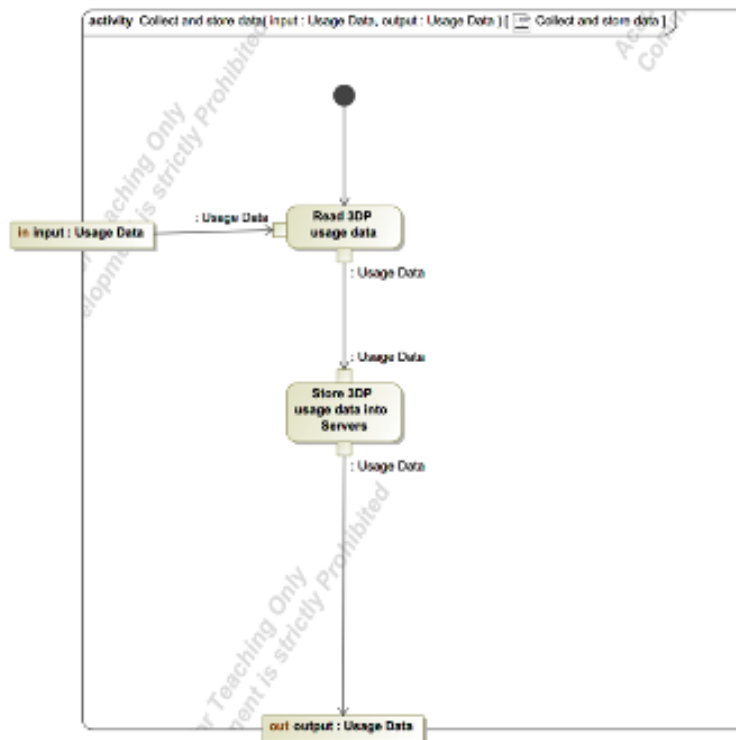


Figure 20. Functional Analysis of “Collect and Store Data” for 3D Printer DT

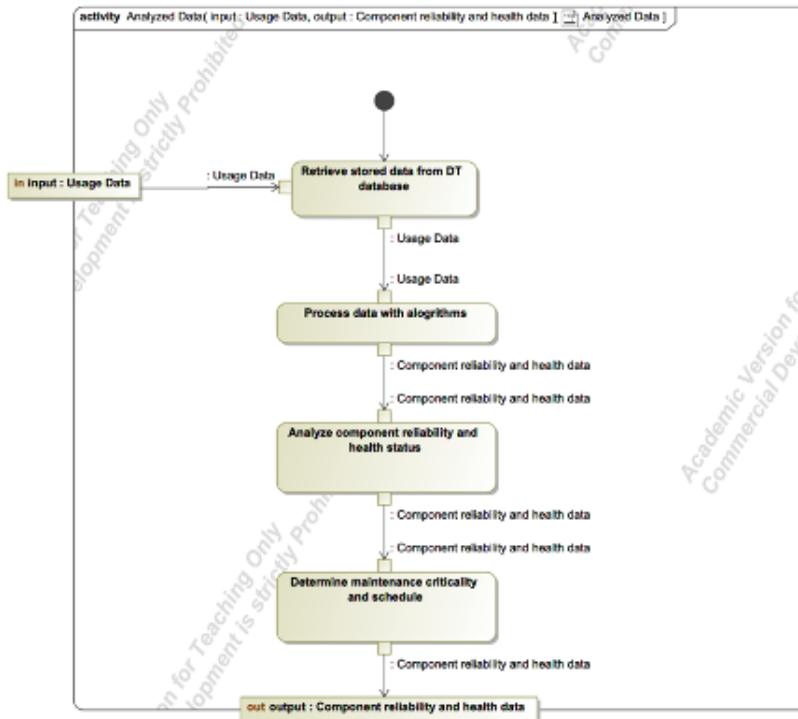


Figure 21. Functional Analysis of “Analyzed Data” for 3D Printer DT

The SV-4 diagram illustrated in Figure 22 provides a comprehensive and precise representation of the discrete functions performed by each system component, explaining their integral role in achieving the desired system capabilities. The development of the SV-4 model entails the creation of an activity decomposition map derived from the meticulously crafted functional analysis activity diagram within the MSOSA framework.

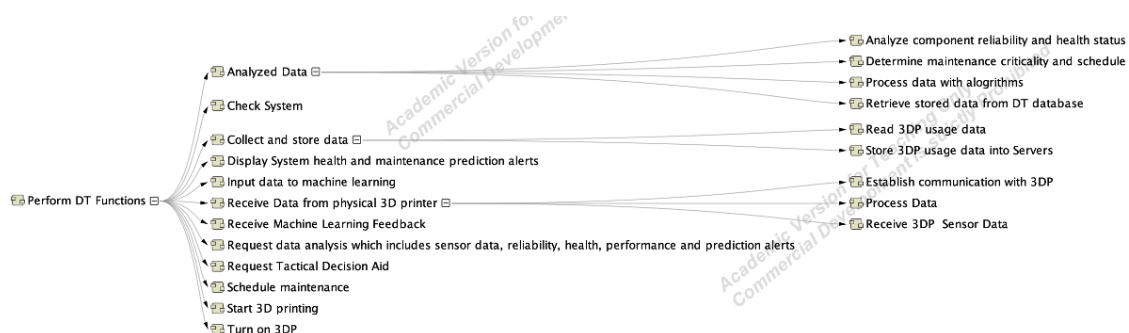


Figure 22. Systems Functionality Description of 3D Printer DT (SV-4)

**b. Conceptual Subsystem**

The OV-2 model serves as a comprehensive depiction of the operational resource flows within the DT, enabling a thorough understanding of the interactions between resources and providing valuable insights into their dynamics. The model illustrated in Figure 23 offers a visual representation of these operational resource flows, facilitating the identification of critical points, bottlenecks, and potential areas of improvement within the DT. It allows for a deep understanding of how resources interact and impact each other, enabling informed decision-making regarding resource allocation, optimization, and system design. By leveraging the OV-2 model, organizations can effectively analyze and optimize their DT operations, ensuring the smooth flow of resources and enhancing overall system performance. It serves as a valuable tool for capturing and visualizing the complex dynamics of resource interactions within the DT, enabling stakeholders to make informed decisions and drive improvements in operational efficiency and effectiveness.

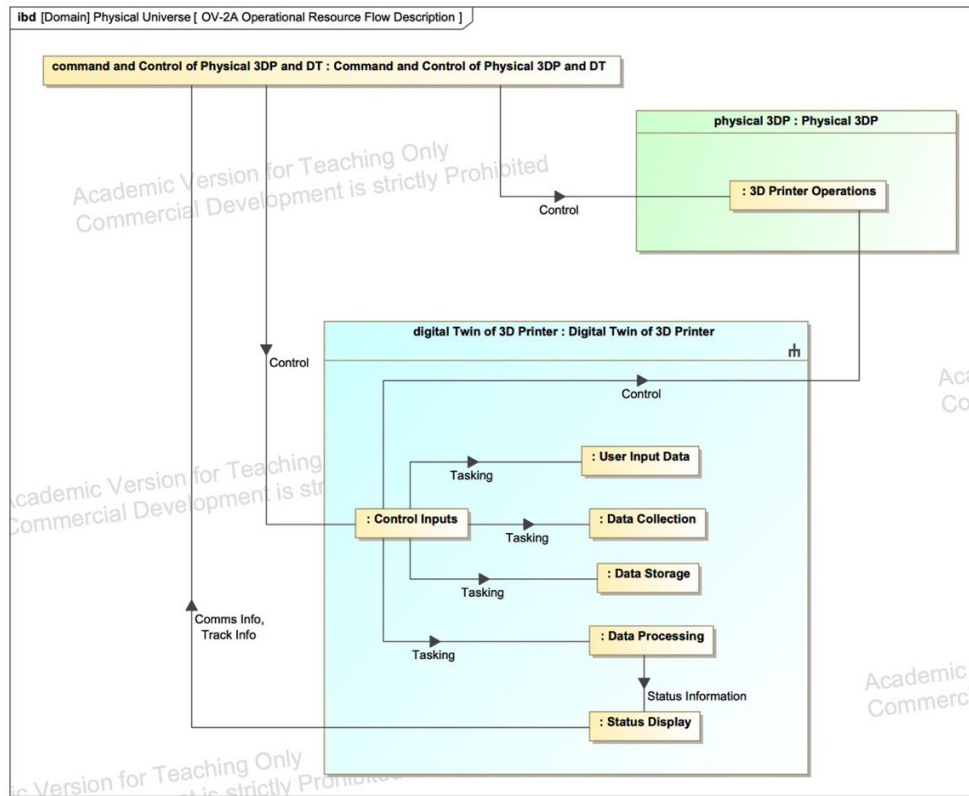


Figure 23. OV-2 Operational Resource Flow Description

The SV-4 model that has been developed previously can be used to define and capture the conceptual subsystem. By leveraging both the OV-2 and SV-4 model, the conceptual interfaces could be developed in the MSOSA program illustrated in Figure 24.

Within the context of this case study, four principal conceptual interfaces have been identified for the DT of 3D printers. These interfaces include manual control, sensor data transfer, sensor data analysis, and output information. Each of these interfaces plays a distinct role in facilitating effective communication, interaction, and coordination between the various components and stakeholders involved in the DT ecosystem.

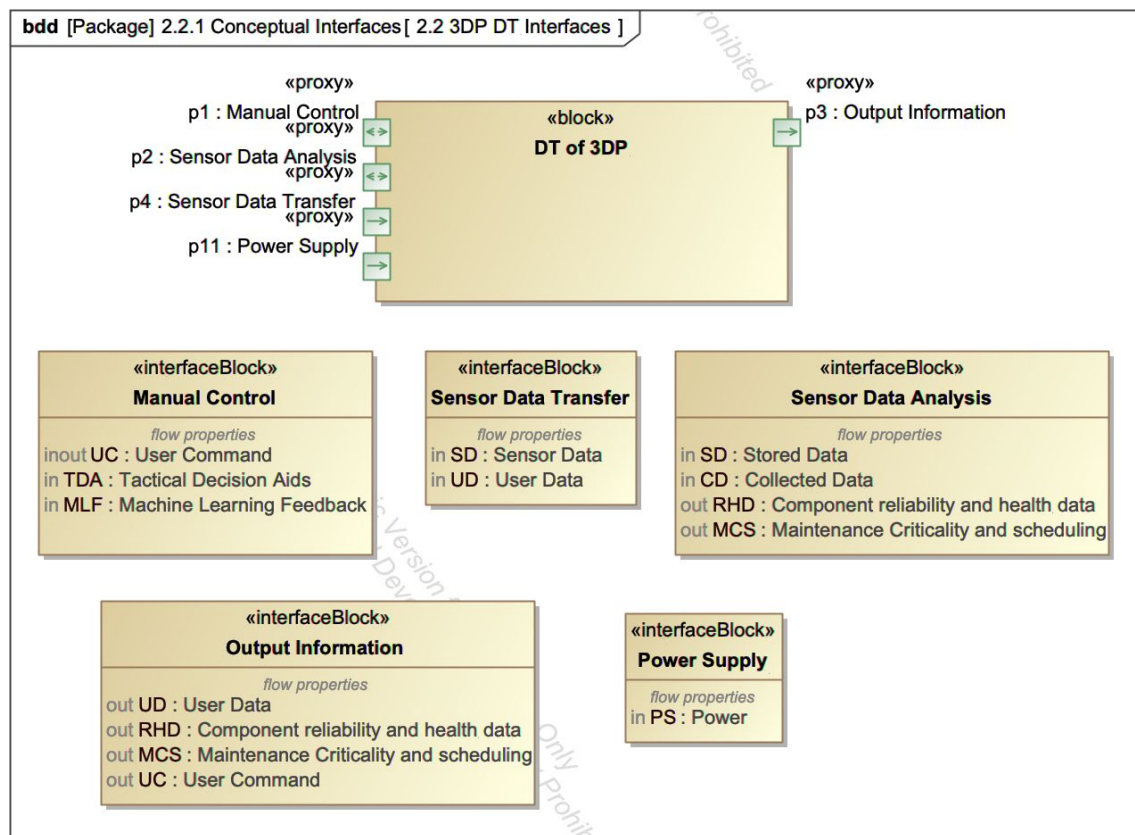


Figure 24. 3D Printer Interfaces

The internal block diagram illustrated in Figure 25 serves as a tool to define the conceptual subsystems and their interactions. Connectors, equipped with one or more item flows, establish the interplay between the relevant conceptual subsystems. Connectors with

item flows connecting part properties to the diagram frame illustrate interactions among the conceptual subsystems.

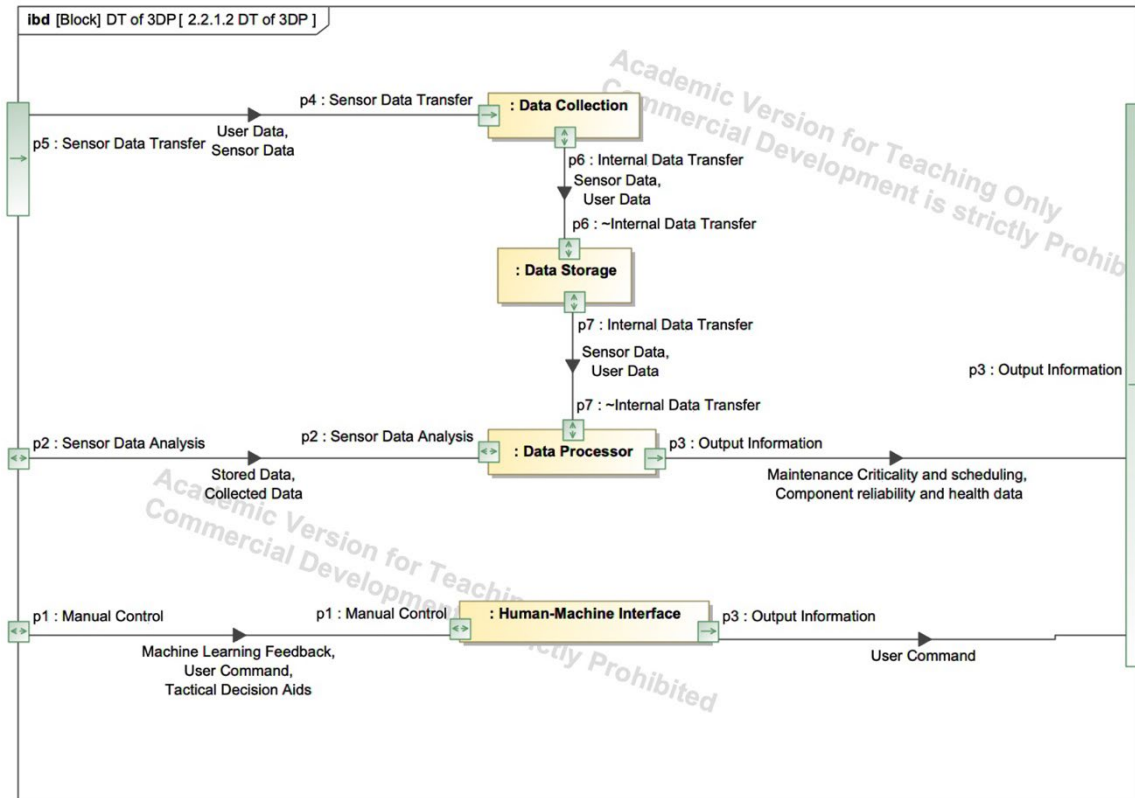


Figure 25. The Internal Block Diagram of 3D printer conceptual subsystems

### c. System Requirements

The OV-6a model illustrated in Figure 26 serves as a comprehensive representation of the operational rules governing the behavior of the DT system. Users are presented with two distinct options upon initiating the 3D printer and DT system. They can either exercise direct physical control over the 3D printer or opt to operate the DT through its user interface. The DT interface empowers users with control over the printer, real-time data gathering, and input capabilities. The DT effectively stores data from the physical printer and user inputs, generating crucial insights on component reliability, health status, and maintenance scheduling.

| #  | Name                                           | Rule Specification                                                                                                     | Rule Kind   |
|----|------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|-------------|
| 1  | User Control on DT                             | { } Users provide control commands via the DT.                                                                         | Constraints |
| 2  | User Control on 3DP                            | { } Users provide control commands on the physical 3D ...                                                              | Constraints |
| 3  | Control 3DP via DT                             | { } Users control physical 3D printer via the DT.                                                                      | Constraints |
| 4  | Data Stored in DT                              | { } User input data will be stored in the DT with time...<br>{ } Real time data collected will be stored in the DT ... | Constraints |
| 5  | 3DP and DT started                             | { } User have the option to provide control commands v...<br>{ } Both the physical and 3D printer have to be powere... | Constraints |
| 6  | Output: Maintenance Criticality and Scheduling | { } Maintenance Criticality and scheduling of the 3D p...                                                              | Constraints |
| 7  | DT collect Real time data                      | { } DT collect real time data generated by sensors tha...                                                              | Constraints |
| 8  | Data processed in DT                           | { } Data stored in the DT will be analyzed collectivel...                                                              | Constraints |
| 9  | Data collected on 3DP is transmitted to DT     | { } Data generated has to be transmitted to the DT for...<br>{ } Data is generated via sensors installed on the phy... | Constraints |
| 10 | Data input in DT by user                       | { } Data can be input by user physically. Data input s...                                                              | Constraints |
| 11 | Output: Component reliability and health data  | { } Component reliability and health data will be prov...                                                              | Constraints |

Figure 26. OV-6a Operational Rules Model

The 3D printer DT must offer a highly realistic and accurate simulation of the physical 3D printer's behavior and functionalities. This requires a high-fidelity model that closely resembles the actual 3D printer, incorporating its design, components, and capabilities. The system should possess sufficient computational performance to handle complex simulation algorithms and real-time updates, ensuring seamless synchronization with the physical 3D printer's status and operational data. Users should be provided with intuitive visualization and interactivity, allowing them to control and manipulate the virtual 3D printer, make parameter adjustments, and observe the simulated printing process. Compatibility with the specific make and model of the physical 3D printer is crucial to ensure precise representation and correlation between the digital twin and its real-world counterpart. Ultimately, the DT should serve as a powerful tool for performance analysis, predictive maintenance insights, and experimentation, enabling users to enhance 3D printing processes and optimize overall efficiency.

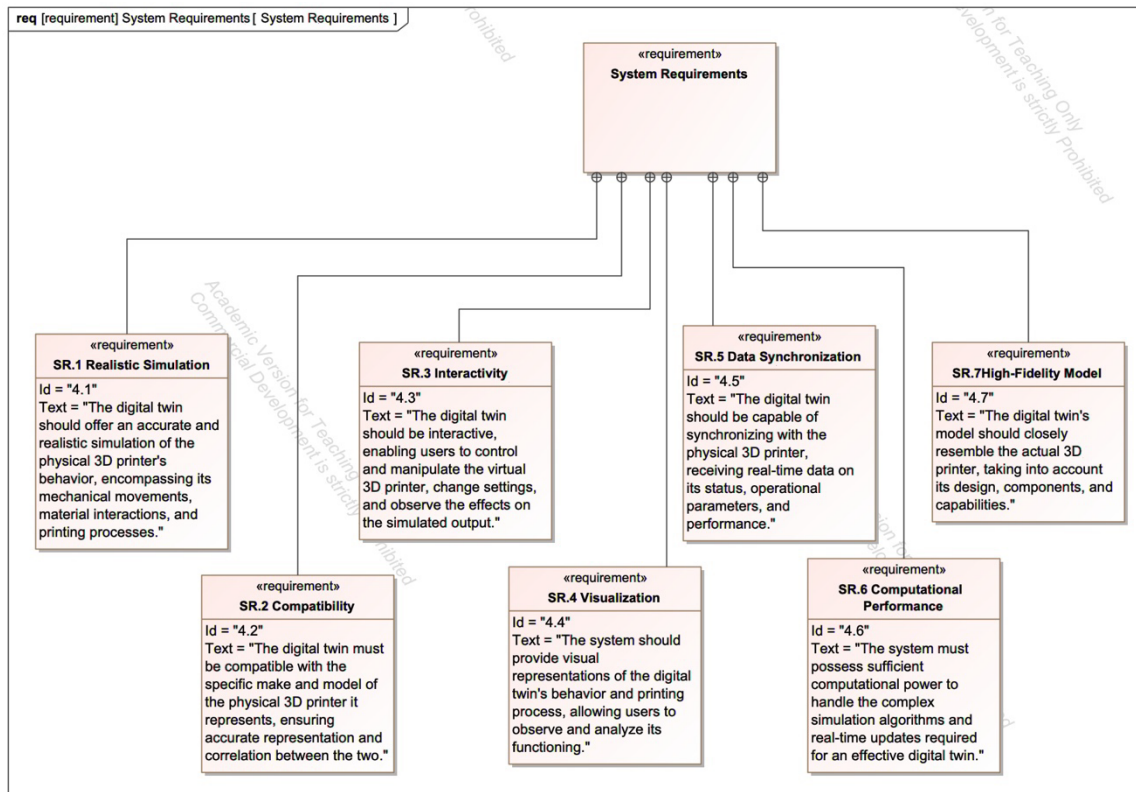


Figure 27. System Requirements

### 3. Detailed Design

During the detailed design phase of the case study on developing a 3D printer DT, the emphasis lies in the refinement and specification of the DT. This phase encompasses three essential elements: system structure, system behavior, and system parameters, each of which plays a significant role in shaping the virtual representation of the physical 3D printer. To ensure a comprehensive understanding of the DT's design, its subsystems and component breakdowns should be addressed, but the focus remains on the core aspects: system structure, system behavior, and system parameters. While more complex DT designs may require further definition of subsystems and components, this case study concentrates on providing in-depth descriptions of the system structure, system behavior, and system parameters. By focusing on these critical elements, the case study will effectively demonstrate the process of crafting a 3D printer DT.

### a. System Structure

The SV-4 model constructed earlier can be used to visualize the system structure by showing the relationships between the functions and components in the DT system. Building upon this foundation, the logical architecture of the 3D printer DT was developed, providing a comprehensive view of how subsystems are arranged and interconnected within the DT system (see Figure 28). Notably, this case study identifies four main subsystems that play crucial roles in the DT's functioning: the Data Collection System responsible for gathering real-time data from the physical 3D printer, the Human-Machine Interface (HMI) System facilitating user interaction and control, the Data Processing System analyzing the collected data to generate valuable insights, and the Data Storage Systems securely storing the accumulated data. By identifying and delineating these key subsystems, the case study lays a foundation for understanding the 3D printer DT's logical architecture, enabling effective coordination and optimization of its functionalities.

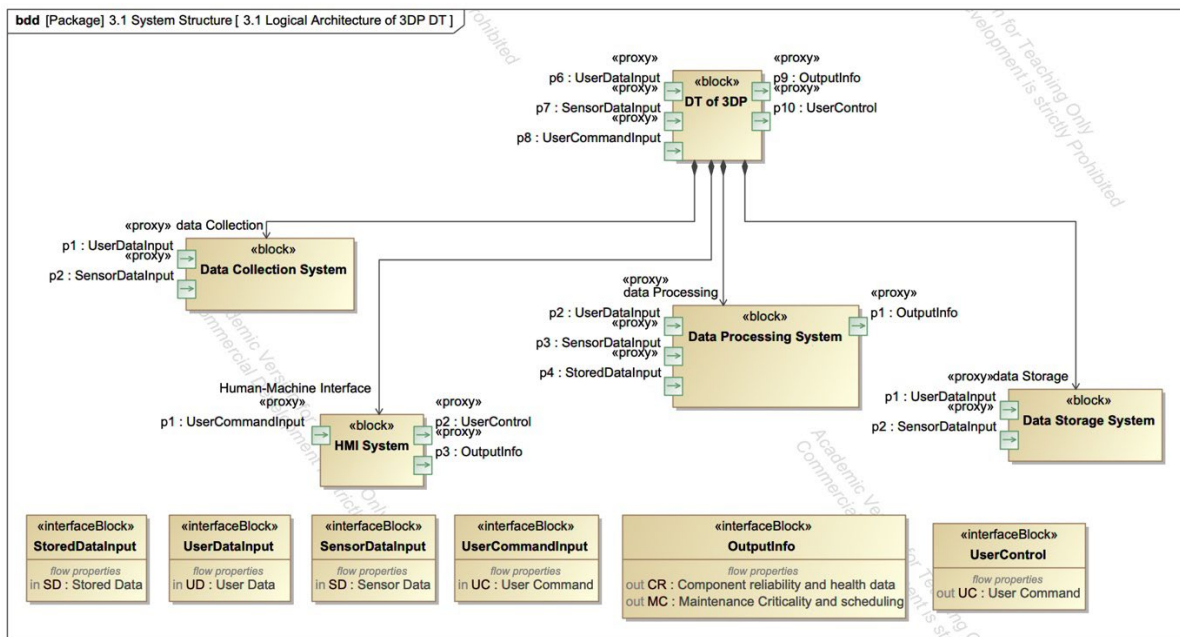


Figure 28. Logical Architecture of 3D Printer

***b. System Behavior***

Using the OV-6a model built in the earlier section, the system behavior was defined. The Ov-6a model can capture the responses, interactions, and transformation of the systems. As described earlier, the users are presented with two distinct options upon initiating the 3D printer and DT system. They can either exercise direct physical control over the 3D printer or opt to operate the DT through its user interface. When utilizing the DT interface, users are empowered with a range of functionalities. They can exercise control over the 3D printer, allowing them to operate or fine-tune its operation. Additionally, the DT interface facilitates real-time data gathering on the 3D printer's performance, enabling users to monitor its efficiency closely. Furthermore, users can also input relevant information through the interface, contributing to the system's overall data pool. The DT system will be able to effectively store the collected data from both the physical 3D printer and the user inputs. Subsequently, the stored information will be processed within the DT, culminating in the generation of crucial insights encompassing vital aspects such as component reliability and health status, as well as essential maintenance criticality and scheduling information.

***c. System Parameters***

System parameters are essential elements in a DT system, influencing its behavior and performance. They include thresholds, limits, algorithms, and model parameters. In this case study the mean time between unscheduled maintenance of the printer was selected to be modelled as an example in Figure 29 as this is vital for effective preventive maintenance planning, minimizing downtime, optimizing costs, implementing predictive maintenance, ensuring quality and safety, and prolonging the printer's lifespan.

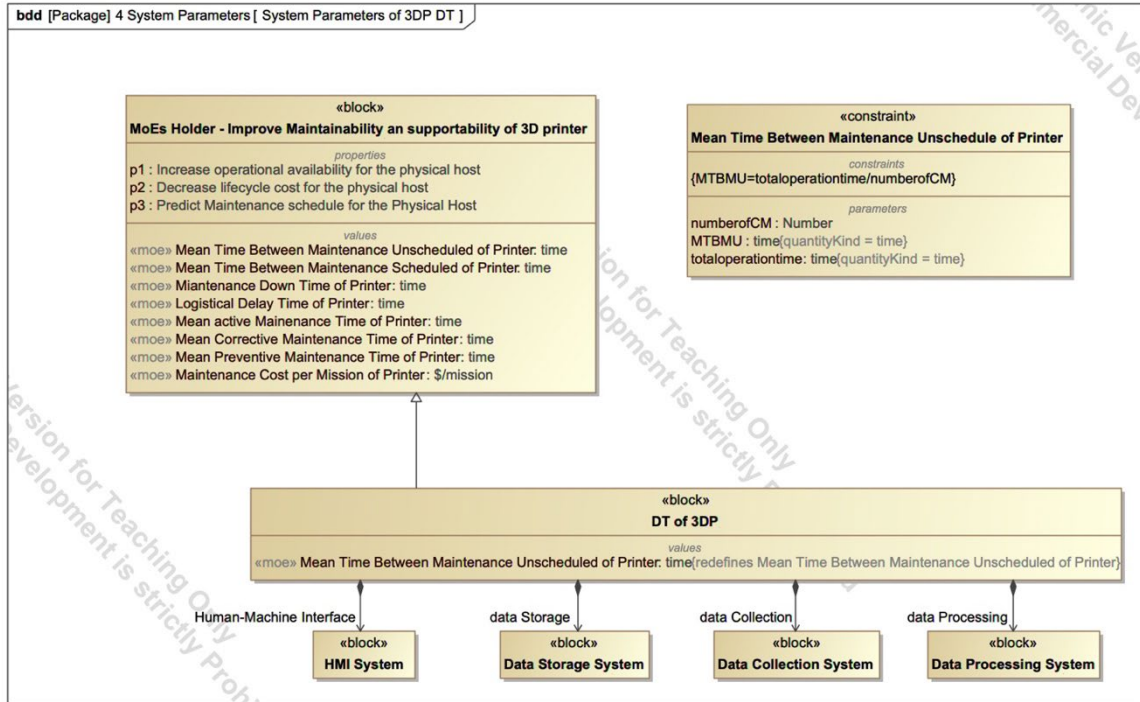


Figure 29. System Parameters of 3D Printer DT

#### 4. Implementation

The implementation phase of the DT is when the physical and digital components of the DT are built and assembled. This stage entails the procurement or manufacturing of essential hardware components, as well as the integration of sensors, actuators, and other physical elements within the DT. Concurrently, the software components are developed and integrated, encompassing data acquisition, analytics, visualization, and control algorithms.

While there are further steps involved in the implementation phase, it is essential to focus solely on the implementation requirement step for the purposes of this chapter, as the remaining steps do not directly impact the DT's development.

##### a. Implementation Requirements

Implementation requirements are the specific details that need to be considered when implementing a system or process. They define what and how of the implementation, and they help to ensure that the implementation is successful.

In this case study, these requirements comprise a comprehensive set of elements illustrated in Figure 30. Firstly, hardware components such as the display, computer, and power supply form the foundation of the system. Secondly, the inclusion of crucial sensors like proximity sensors and temperature sensors, along with actuators, enables accurate data acquisition and system responsiveness. Thirdly, the software, encompassing both the user interface and firmware, acts as the backbone, determining the system's functionality and user experience. Fourthly, seamless data exchange is facilitated by connectivity and communication options like Wi-Fi/Ethernet and USB. Lastly, efficient energy consumption is ensured through power management features, including sleep mode functionality and reliable power backup solutions.

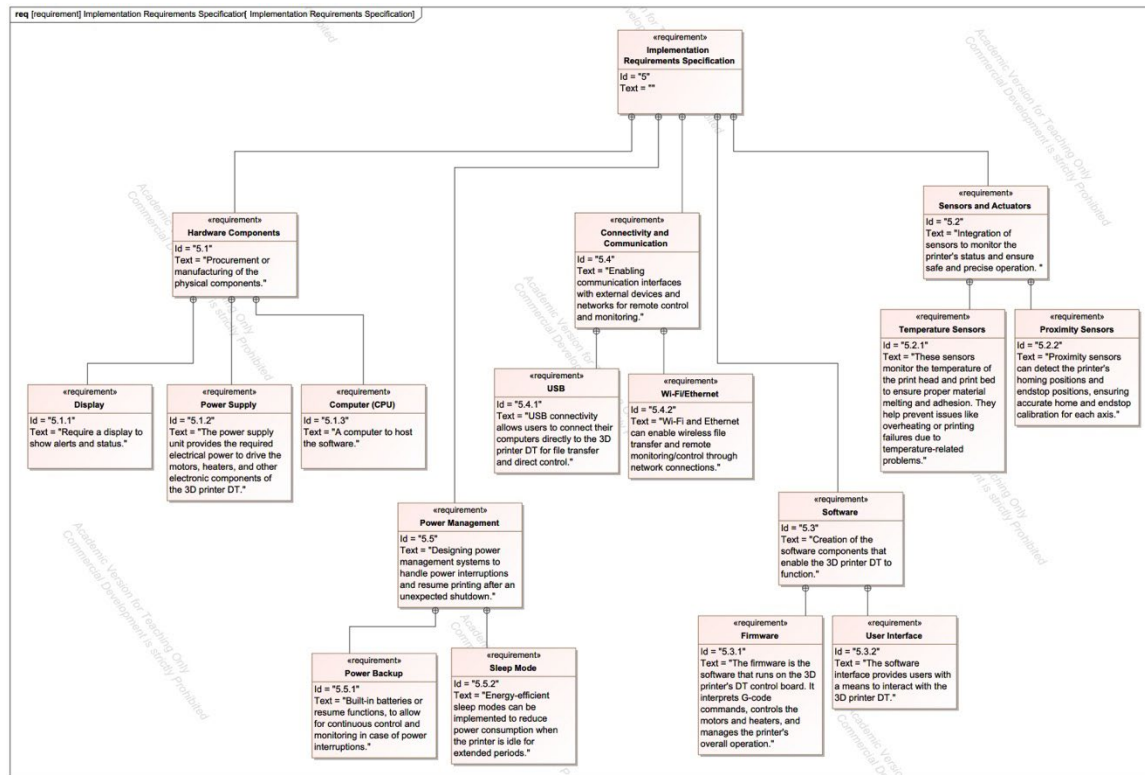


Figure 30. Implementation Requirements of 3D Printer DT

### ***b. Software Development***

The implementation phase of software development for the DT system entails crafting software components and modules. This encompasses coding, algorithm execution, interface design, and library integration.

To enable smooth implementation of the software development, it is important to conduct good data collection and baseline establishment. Data were collected from existing sensors that are currently installed on Xerox ElemX 3D printers located at or under the control of the Naval Postgraduate School. These sensors play a crucial role in capturing real-time data encompassing variables like temperature, pressure, acceleration, and material flow during the printing process. By assessing the data gathered from these sensors, the interplay between variables during printing can be understood. This understanding helps to establish a fundamental baseline for the creation of the algorithms that could be used in the DT. This baseline can also serve as a benchmark against which deviations, anomalies, and potential issues are detected during the 3D printing process. However, it is important to recognize that the data employed for this illustrative purpose is not universally applicable to all printers. Specific evaluations need to be undertaken to determine the most suitable sensors for different printers and the data patterns indicating potential printer or part failures. Further, it should be noted that the sensors were installed on the 3D printers for a different purpose not related to DT development, and the sensors and resulting data are used here for illustrative purposes in the case study only.

#### **(1) Data Collection Methodology**

The acquisition of the data from the sensors installed on the Xerox ElemX 3D printer is triggered when the 'High Voltage' button is turned on, signifying that the printer is ready to initiate the jetting process. Two distinct data files are generated for each jetting duration, with one file containing sensor readings (atmospheric pressure, relative humidity, oxygen concentration, machine inclinometer for pitch and roll, atmospheric temperature, temperature of build plate, head, and oxygen sensor) at a lower speed of 1 Hz, while the other records accelerations of build plate and head at a much higher frequency of 2 kHz.

The key focus of the analysis centers around the acceleration data in the XYZ axis, which has been intentionally collected to facilitate Power Spectrum analysis (normalized) of both the Build plate and the Head components. Understanding the power spectral characteristics of these components is essential for gaining insights into their dynamic behavior and potential sources of variation during the 3D printing process.

## (2) Data Analysis and Interpretation

The collected acceleration data from the 3D printer were analyzed using Matlab by importing the .txt file and using a Fast Fourier Transform (FFT) to conduct a power spectrum analysis. FFT is a method that converts a signal, which is a function of time, into a representation that shows the different frequency components present in that signal (see Figure 31). It provides insights into the frequency content of a signal and helps identify the strength or intensity of various frequencies present within it (Hanly n.d.). In this case, the power spectrum analysis can be used to examine and interpret the vibrations in the 3D printer. The vibration analysis aims to understand the dynamic behavior of systems, detect potential faults or irregularities, and ensure optimal performance and reliability.

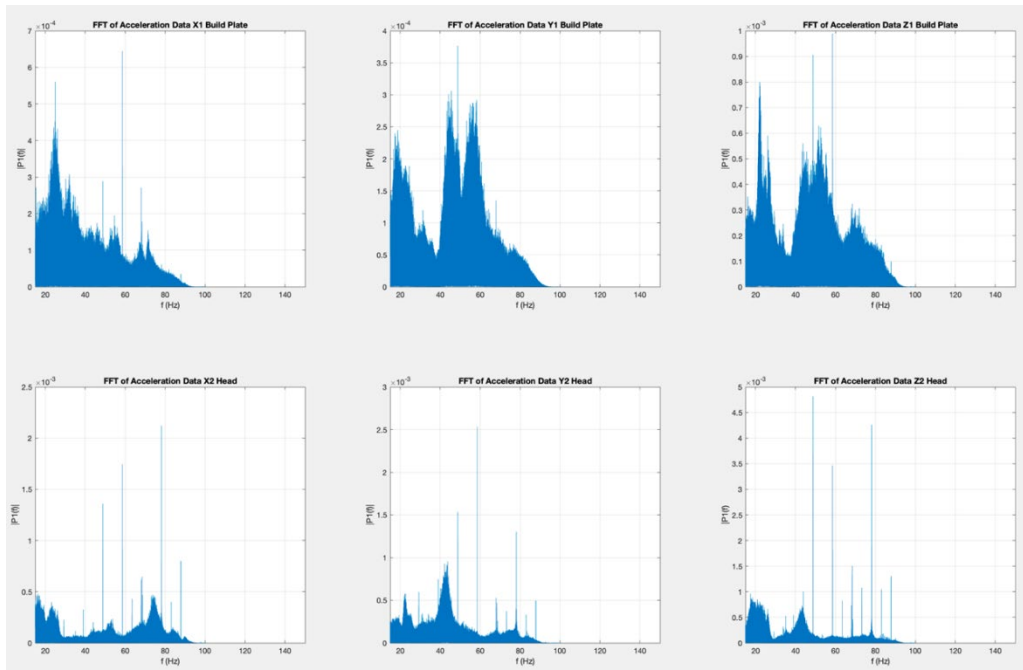


Figure 31. FFT of Acceleration Data Collected

It can be observed from the power spectrum analysis that there are more vibrations collected on the build plate as compared to the jetting head. The observation of greater vibrations collected on the build plate in comparison to the jetting head, as revealed by power spectrum analysis, carries several implications. This discrepancy suggests the presence of potential mechanical imbalances within the 3D printer system which might impact print quality. Additionally, the heightened vibrations on the build plate could be indicative of variations in the structural integrity of the printer, necessitating a closer examination of its design and construction. The potential impact on print quality should also be considered, as excessive vibrations may lead to inaccuracies and compromised output.

Nevertheless, it is important to acknowledge that the current dataset available for analysis is limited in both quantity and accompanying information. Consequently, conducting an all-encompassing analysis to arrive at definitive conclusions regarding the potential avenues for maintenance, calibration, and operational optimization presents challenges. The emergence of opportunities aimed at enhancing efficiency, print quality, and the overall performance of the printer hinges on a more robust dataset. In order to facilitate a more conclusive analysis, it becomes imperative to not only collect data but also to capture the physical quality of the printed components in tandem with the dataset. This holistic approach allows for the establishment of a robust baseline, thereby facilitating the development of algorithms tailored for the 3D printer DT.

This data-driven analysis can serve as a cornerstone for informed decision-making and iterative enhancements. The comprehensive assessment of the sensor-derived data enables us to pinpoint patterns, anomalies, or trends that could signify the need for adjustments in printer settings, hardware components, or even the printing methodology itself. As a result, the overall quality of the printed output can be refined, and the longevity of the printer's components can be optimized.

After the successful baseline establishment, the analysis can be conducted by a fully developed DT. One of the key advantages of entrusting this analysis to a fully developed DT lies in its capacity to simulate and predict potential outcomes. As the DT encompasses a digital representation of the 3D printer's behavior based on real-world data, it offers a

virtual environment for testing various scenarios without the need for physical interventions. This predictive capability empowers us to proactively address issues before they manifest, thereby minimizing downtime, reducing material wastage, and enhancing the printer's reliability.

## **5. Conclusion**

In conclusion, this chapter has provided a tangible case study centered around the creation of a Xerox Elemx 3D printer DT in MSOSA by exemplifying the practical implementation of the theoretical DT framework described in Chapter 3. While it's crucial to recognize that the case study does not delve into an exhaustive analysis of a specific system (not explored in depth), its purpose is to serve as an illustrative instance. This instance has been simplified to showcase the application of the methodology offering a hands-on illustration and hence showing the viability and potential of the methodology within the realm of DT development.

## **V. VALIDATION OF THE DT NOTIONAL FRAMEWORK**

Validation and verification (V&V) play a pivotal role in upholding the accuracy and dependability of the DT notional framework. V&V involves assessing whether the system or component requirements are comprehensive and accurate, and whether the outputs of each development phase meet these requirements. Within the context of the DT notional framework, V&V serves to ensure that the framework represents the physical system it models. This encompasses confirming the precision of its data, the correctness of its models, and the reliability of its simulations. The following sections of this chapter will discuss the V&V methodology used in the V&V of the DT notional framework.

### **A. METHODOLOGY**

It is important to note that the methodology of V&V in this study is focused on the V&V of the DT notional framework as the implementation of the DT notional framework is a crucial step in the development, as it involves transforming the conceptual design into a tangible and functional system.

The methodology of V&V in this case incorporates both the Technology Readiness Level (TRL) and the Validation Square (Pedersen et al. 2000). The TRL serves as a benchmark to evaluate the maturity of the specific technologies underpinning the DT framework (Tzinis 2012). By progressing through the levels, one can gauge how close a technology is to deployment, with early TRLs focusing on basic research and the highest levels indicating a fully matured, field-tested technology. Meanwhile, the Validation Square provides a structured approach to ensure the DT operates as intended and that the simulated data truly represents its real-world counterpart. By combining TRLs and the Validation Square, one can establish a dual-pronged methodology: while TRLs gauge technology maturity and readiness, the Validation Square ensures the accurate and reliable performance of the DT in its intended operational environment.

## B. DISCUSSION

As seen in Figure 32, the methodology unfolds in a streamlined three-phase process. Initially, the TRL is assessed to gauge the foundational maturity of the DT product. This step is pivotal in comprehending the technology's current standing and charting a path towards its full-scale deployment. Subsequently, the Validation Square is used to verify the DT product's accuracy and authenticity. By combining the TRL and Validation Square in the integrated approach, a comprehensive evaluation framework is established that not only considers the technological readiness but also ensures the precision and credibility of the resultant DT product. This synergy equips stakeholders with a holistic understanding, fostering confident decision-making and promoting successful adoption and implementation.

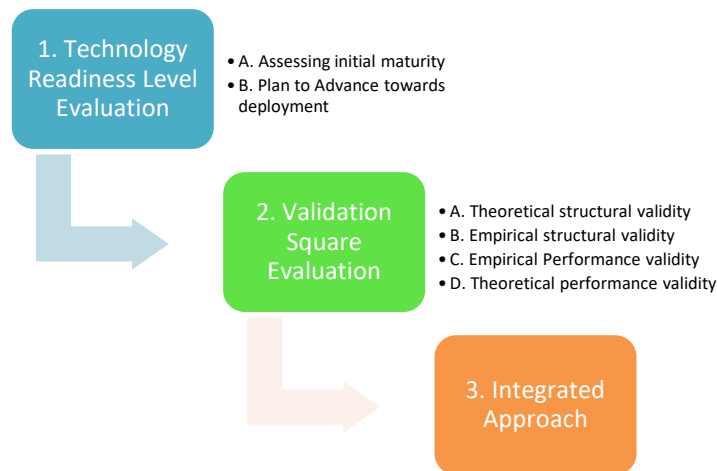


Figure 32. Verification and Validation Methodology

### 1. Technology Readiness Level (TRL) Evaluation

The TRL is a scale that represents the maturity level of a technology and in the context of a DT notional framework, TRL can help stakeholders understand how mature and ready a DT system is for deployment in real-world scenarios (Tzinis 2012). A brief outline of the TRL tailored to the DT concept is created in Table 2.

Table 2. The TRL Scale Tailored to the DT Concept. Adapted from Tzini (2012).

| TRL Scale | Description                                                                                                                                                                                             |
|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1         | Basic principles observed and reported. This level concerns the fundamental understanding of the DT concept, with no practical application yet.                                                         |
| 2         | Concept and application formulated. Initial ideas for a DT framework are developed, but it is still largely theoretical.                                                                                |
| 3         | Analytical and experimental proof of concept. Preliminary models or prototypes of the DT are created, demonstrating the feasibility of the idea.                                                        |
| 4         | Component and/or system validation in a laboratory environment. The DT framework is tested in a controlled environment, ensuring its components function as intended.                                   |
| 5         | Component and/or system validation in a relevant environment. The DT is tested in conditions that mimic its eventual operational setting but is still largely in a controlled or simulated environment. |
| 6         | System/subsystem model demonstrated in a relevant environment. The DT system is further refined and tested in more realistic scenarios, perhaps integrated with some real-world data or systems.        |
| 7         | System prototype demonstrated in an operational environment. A prototype DT system is deployed in the real world, testing its capabilities in actual operational settings.                              |
| 8         | Actual system completed and qualified through tests and demonstrations. The DT system is nearly ready for full deployment, having passed rigorous testing and validation.                               |
| 9         | Actual system proven and accepted in operational conditions. The DT system is fully operational and integrated, functioning seamlessly in its intended environment.                                     |

It is imperative to first assess the initial technology maturity of the DT notional framework with respect to the TRL scale indicated in Table 1. By gauging and understanding the initial readiness of the DT notional framework, the stakeholder will be able to then plan and identify areas that require further development and testing to advance the system development towards TRL 9.

## 2. Validation Square Evaluation

The Validation Square is a tool used to evaluate how well a model, such as a DT notional framework, represents reality (Pedersen et al. 2000). The Validation Square

typically examines the following four aspects listed in Table 3. In the table, some recommended evaluation methods are also provided to aid in the Validation Square evaluation.

Table 3. Evaluation Methods for the Validation Square. Adapted from Pedersen et al. (2000).

| Aspects of Validation Square    | Purpose                                                                                                                                                                                                                                  | Suggested Evaluation Methods                                                                                                                                                                                                                                                                                                                                                          |
|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Theoretical Structural Validity | This involves ensuring that the foundational theories and principles that underpin the DT notional framework are well-established and logically consistent.                                                                              | <ul style="list-style-type: none"> <li>• Evaluate literature review critically.</li> <li>• Examine the logic and rationale behind the design and structure of the DT to ensure consistency of the proposed design.</li> <li>• Review the theoretical constructs on which the DT framework is built. Are they based on well-established principles or models?</li> </ul>               |
| Empirical Structural Validity   | This necessitates the collection of empirical evidence to verify that the structure and components of the DT notional framework align with real-world design scenarios and challenges and verifies the performance of the design method. | <ul style="list-style-type: none"> <li>• Collect real-world data related to the entities or systems that the DT aims to simulate.</li> <li>• Compare the DT's structure and its inherent relationships with observed example problems, data patterns, and structures.</li> <li>• Adjust and calibrate the DT's structural components to better reflect empirical findings.</li> </ul> |
| Empirical Performance Validity  | This aspect entails conducting practical tests and experiments to demonstrate the actual performance and practicality of the DT notional framework when applied to real design problems.                                                 | <ul style="list-style-type: none"> <li>• Test the DT's simulations or predictions against actual real-world results to measure its accuracy.</li> <li>• Consider different scenarios, stress-testing the DT to evaluate its robustness and reliability.</li> <li>• Analyze error margins, discrepancies, and outliers to refine the DT's performance parameters.</li> </ul>           |

| Aspects of Validation Square     | Purpose                                                                                                                                          | Suggested Evaluation Methods                                                                                                                                                                                                                                                                                                                                                                 |
|----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Theoretical Performance Validity | This evaluates whether the outcomes produced by the framework align with the theoretical expectations and objectives set for the design process. | <ul style="list-style-type: none"> <li>Compare the outcomes of the DT simulations with theoretical predictions or benchmarks.</li> <li>Assess if the DT adheres to established theoretical models or principles when generating outcomes.</li> <li>Engage theoreticians or experts in the domain to validate the alignment between the DT's outputs and theoretical expectations.</li> </ul> |

### 3. Integrated Approach

In this approach, the TRL is aligned to the insights from the Validation Square and the alignment can be seen in Table 4.

Table 4. TRL and Validation Square Integrated Approach

| TRL | Validation Square Aspect         | Description                                                                                                                                                                                                                                                 |
|-----|----------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Theoretical Structural Validity  | <ul style="list-style-type: none"> <li>At these stages, technologies are typically based on theoretical constructs and principles.</li> <li>Ensure that the foundational concepts of the DT framework are sound and validated.</li> </ul>                   |
| 2   |                                  |                                                                                                                                                                                                                                                             |
| 3   |                                  |                                                                                                                                                                                                                                                             |
| 4   | Empirical Structural Validity    | <ul style="list-style-type: none"> <li>As the technology enters the demonstration phase in laboratory environments, its structural coherence and theoretical performance need validation against empirical evidence and theoretical predictions.</li> </ul> |
| 5   |                                  |                                                                                                                                                                                                                                                             |
| 6   | Theoretical Performance Validity |                                                                                                                                                                                                                                                             |
| 7   | Empirical Performance Validity   | <ul style="list-style-type: none"> <li>At these stages, the DT is tested and refined in actual operational settings, demanding stringent empirical validation of its performance.</li> </ul>                                                                |
| 8   |                                  |                                                                                                                                                                                                                                                             |
| 9   |                                  |                                                                                                                                                                                                                                                             |

## C. ASSESSMENT

Assessing the initial TRL of the DT notional framework, it is noticed that it is currently standing at TRL 4. This level indicates that the framework is undergoing examination and testing within the structured and controlled confines of the MSOSA environment. At this stage, the focus is on ensuring that each component of the DT framework functions as intended and that it seamlessly integrates with the broader system. While it is a substantial step forward, it is crucial to note that TRL 4 is predominantly about validation in a simulated setting, setting the stage for more advanced, real-world testing in subsequent readiness levels. The feedback and insights gleaned from this phase will be invaluable in refining and advancing the framework's capabilities.

On the other hand, it should be noted that DT notional framework is theoretical structural validated as the design of the DT notional framework is based on the evaluation of the literature review conducted. The conceptual development of the notional DT framework in this study is based on well-established models and principles such as the MBSE process from MagicGrid, harmonized with Bickford's six life cycle phases (Bickford et al. 2020), and incorporating the DoDAF model in the process. For the empirical structural validity of the DT notional framework, the study uses the 3D printer case study to verify the performance of the design method. In the empirical performance validity, data are collected from the 3D printer to evaluate health data of the 3D printer.

The DT notional framework is fortified by theoretical structural validity through extensive literature review done in Chapter 2. Delving into the architecture of this framework it should be noted that the framework is an integration of established models and foundational principles. A prime example is its adoption of the MBSE process drawn from MagicGrid. Additionally, the framework showcases an alignment with the six life cycle phases which ensures a holistic approach to its development and application. Also, the incorporation of the DoDAF model stands as a testament to the framework's commitment to adhering to recognized standards and best practices. Transitioning from the theoretical to the empirical structural validity, the research draws parallels with a tangible 3D printer case study to show the framework's validity. This case study serves as a practical touchstone, juxtaposing the envisioned design method of the DT framework with real-

world performance outcomes. Venturing into empirical performance validity, the research does not stop at theoretical comparisons. It delves deeper, extracting and analyzing data from the 3D printer. This empirical data acts as a cornerstone, allowing for a meticulous assessment of the health and operational metrics of the 3D printer, ensuring that the framework's principles are not just theoretically sound but also empirically validated. Thus, it can be concluded that the framework is currently at TRL 4.

Advancing the DT notional framework from its current TRL 4 to TRL 9 requires a strategic, phased approach. To move towards TRL 5, a comprehensive review of the outcomes from the testing within the MSOSA environment, pinpointing vulnerabilities and optimization areas should be conducted. With these insights, the framework will undergo refinements, progressively being tested in environments that simulate real-world conditions, ensuring scalability and robustness. To transit into TRL 6, the focus will be on deploying a complete system model in a realistic setting, with an emphasis on its interactions and data fidelity. Following this, a full-scale prototype will be developed moving towards TRL 7, where it will be rigorously tested in its actual operational environment focusing on empirical performance validity. After rectifying any identified issues, the transition to TRL 8 will see the DT framework subjected to definitive validation tests. This journey culminates in TRL 9, marking the framework's full-scale deployment and industry-wide endorsement.

#### **D. LIMITATION AND CHALLENGES**

When leveraging the prescribed V&V techniques, there are several challenges and constraints that should be noted. Foremost, the TRL approach has a pronounced concentration on technological advancement and maturation. While this focus ensures thorough technical evaluation, it often overshadows other parts of a product's life cycle. Key aspects such as user-friendliness, adaptability to market fluctuations, and seamless integration with external systems might get marginalized.

To add on, it is also crucial to recognize the inherent subjectivity within both the TRL and Validation Square methodologies. This subjectivity usually occurs during the interpretive phases. When results are being dissected or when consequential decisions are

on the line, the influence of personal biases or individual stakeholder perspectives can sway the evaluation. This can potentially lead to discrepancies in judgments and may introduce variances in the V&V process.

## **E. RECOMMENDATIONS/FUTURE WORK**

To address the predominant emphasis of the TRL on technological maturity, it is recommended to broaden its criteria. This can be achieved by incorporating comprehensive metrics that encompass aspects beyond mere technical progression, such as usability testing results, market analysis feedback, and successful integration trials with existing systems. In tandem, the TRL framework should be regularly updated, ensuring it remains adaptive to technological evolutions and industry nuances. Moreover, the inherent subjectivity found in both the TRL and Validation Square methodologies can be curtailed by adopting structured decision-making processes, wherein predefined criteria guide evaluations, significantly reducing individual biases. Enlisting independent third-party experts for periodic reviews can also offer an unbiased lens, ensuring evaluations remain objective. Furthermore, the assembly of diverse evaluation teams, drawn from varied backgrounds and expertise, can ensure a multitude of perspectives, reducing the influence of individual biases and facilitating a more balanced and holistic assessment.

## **VI. CONCLUSION**

This study has navigated the intricate landscape of DT implementation by presenting a comprehensive approach encapsulated within the Notional DT framework. The Notional DT framework is a good approach that guides the design, development, and implementation of DT solutions.

The practical implementation of the theoretical DT framework has been showcased in the tangible case study involving the creation of a Xerox ElemX 3D printer DT within MSOSA showing that this methodology is practical and usable. While the case study's scope is not exhaustive, its purpose is to provide a tangible example, simplifying the methodology's application to highlight its potential within DT development.

The study also illustrates the need to establish a successful data baseline in the development of the DT and its analytical functions. Following the establishment of a successful baseline, a fully developed DT can conduct analysis to offer predictive capabilities to proactively address issues, reduce downtime, material wastage, and enhance reliability.

Finally, the study also highlights the importance of the role of V&V of the DT notional framework and the DT itself. V&V ensures the alignment of the framework with the physical system it represents, encompasses data accuracy, model correctness, and simulation reliability. This rigorous process underscores the framework's trustworthiness and robustness, reinforcing its practical viability.

### **A. RECOMMENDATIONS FOR FUTURE WORK**

Within this section, the recommendations listed may help with the progression of research beyond the boundaries of the current study. These recommendations encompass the exploration of multi-location DT, the fusion of Artificial Intelligence (AI) and ML into the DT landscape, fortify the security architecture surrounding DTs, refine MBSE methodologies for system optimization, augment data analysis paradigms, and elevate of Validation and Verification methodologies to new heights.

## **1. Multi-Location DT**

An exciting avenue for future exploration involves extending the capabilities of DTs to operate across different physical locations. Enabling the connection of multiple DTs to a single physical system, even when dispersed, could usher in new possibilities for remote monitoring, collaborative problem-solving, and harmonized decision-making. Investigating the intricacies of maintaining synchronization and accuracy across these distributed DTs would be a significant stride in broadening their utility.

## **2. AL and ML Integration**

Integrating AI and ML into the analysis and processing phases presents an enticing horizon. By harnessing AI's predictive capabilities and ML's pattern recognition, the potential to uncover intricate insights within the data grows significantly. These technologies could empower the DT to autonomously detect anomalies, predict failures, and optimize performance, thereby advancing the DT's capacity to facilitate smarter decision-making and proactive actions.

## **3. Enhancing DT Security**

Security remains a paramount concern in the digital realm. As the significance of DT increases, ensuring their immunity against cyber threats becomes imperative. Future research should delve into fortified mechanisms for securing DTs, including encryption protocols, anomaly detection algorithms, and stringent access controls, mitigating the risks of hacking and unauthorized access. The Multidisciplinary Early Design Risk Assessment Framework (MEDRAF) methodology as described by Papakonstantinou et al. (2021), is one method to determine the security risk of the DT so that a good DT security system can be developed. However, much more work is needed in this area to adequately secure DTs.

## **4. MSOSA Integration and Process Completion with the Integration of Reliability, Availability, and Maintainability**

While MSOSA is a powerful platform, future work could focus on refining its compatibility with the entire process flow. This includes addressing any potential gaps or challenges that might impede seamless integration, ensuring that all stages of the DT's life

cycle are effectively executed within the MSOSA environment. Additionally, an avenue for optimization lies in the integration of Reliability, Availability, and Maintainability (RAM) considerations into the MSOSA environment, particularly during the design stage. This expansion builds upon the work of Diatte, O'Halloran, and Van Bossuyt (2022), offering the potential to enhance the framework's capabilities further. By incorporating RAM factors, the DT's design could be developed with resilience as a consideration, thus ensuring that reliability, availability, and ease of maintenance are integral to the process. This amalgamation not only enhances the DT's effectiveness but also contributes to a more robust approach to system design and operation.

## **5. Augmenting Data Analysis**

The importance of robust data for analysis cannot be overstated. Future endeavors should focus on augmenting the quality, quantity, and comprehensiveness of the dataset. This might involve capturing physical attributes alongside data, enabling a more comprehensive analysis, and enabling the development of tailored algorithms for 3D printer DT optimization.

## **6. Advancing V&V**

To enhance the efficacy of the V&V process, it is recommended to broaden the criteria beyond technical progression. Incorporating metrics like usability testing results and market feedback can provide a more holistic evaluation. Regular updates to the TRL framework should be considered, keeping it aligned with evolving technologies and industry nuances. Employing structured decision-making processes, third-party reviews, and diverse evaluation teams can collectively mitigate subjectivity and enhance the objectivity of assessments.

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