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Leveraging Digital Transformation to Build the Technology Of Tomorrow Using Yesterday's Equipment

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LEVERAGING DIGITAL TRANSFORMATION TO BUILD THE TECHNOLOGY OF TOMORROW USING YESTERDAY'S EQUIPMENT

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ABSTRACT

Today's industry sectors are filled with machines developed years ago. Healthcare, manufacturing, sustainment operations, and many others have equipment that may be reliable, but lacks certain capabilities that the newest technology delivers. The digital environment is becoming a necessity for users who want greater insights into how to improve their processes. A solution to this problem would be to purchase the newest equipment that contains robust measures to generate, collect, and analyze data. However, this solution may not be financially feasible for some and for others may sacrifice machine downtime and reliability. To combat these issues, this research focuses on applying a digital transformation approach to legacy equipment. Collected and analyzed data is used to develop advanced digital tools such as augmented reality, virtual reality, artificial intelligence, and digital dashboards. A use case of Automated Fiber Placement (AFP) is used to showcase the benefits of the digital transformation approach compared to typical controls retrofit. While both approaches result in similar benefits, the owner of the equipment must decide which approach will ensure that the most optimized process. In addition, a use case of military maintenance programs is discussed to provide a logical way ahead for a larger scale implementation of digital transformation. Both use cases show the benefits of the digital transformation approach and help to crystallize what the future of product life cycle management will look like.

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LIST OF ABBREVIATIONS

AFP .... Automated Fiber Placement

AH .... Attack Helicopter

AI .... Artificial Intelligence

AR .... Augmented Reality

CH .... Cargo Helicopter

CPM .... Center for Predictive Maintenance

HTC .... High Tech Computer Corporation

MSG .... Maintenance Steering Groups

NCU .... Numerical Control Unit

OEM .... Original Equipment Manufacturer

OSI .... Open Systems Interconnection

PCU .... Personal Computer Unit

PLC .... Programmable Logic Controller

SQL .... Structured Query Language

U.S. .... United States

UH .... Utility Helicopter

UofSC .... University of South Carolina

VR .... Virtual Reality

CHAPTER 1

INTRODUCION TO DIGITAL TRANSFORMATION

In the current era of technology Digital Transformation is a blanket term typically used to cover the digitization of physical data into a virtualized form. A simple web search will bring up thousands of results ranging from stories of large retail chains saving their business by using digital transformation to companies who say they are experts on the subject and can help for the right price. Even social media giants such as Instagram and Facebook have utilized digital transformation not only in their applications and interfaces, but they have also found a way to digitize an end user and sell parts of their digital identity to the highest bidder for advertising[1]. Because of the vast use of the term, digital transformation needs to be deciphered. Once the roots of digital transformation are known applying a digital framework to disparate use cases becomes a simpler task.

1.1 Deciphering Digital Transformation

A vast amount of research has been done by academia and industry to define digital transformation. Extensive literature reviews have examined thousands of journal articles and sources to collect and analyze definitions[2,3]. This section will not attempt to repeat the work done by other scholars but instead aim to collect the definitions from their reviews and identify the foundations of digital transformation to serve as supporting material for the next section. This approach attempts to eliminate two things. First, most of these reviews are concerned with creating their own definition from the collection of definitions they critique or do not agree with. This inherently causes more confusion

because the product of such literature review is another definition that can then be subject to the same cycle. Second, terms such as Industry 4.0, Internet of Things, and Digital twin are usually packaged with definitions of digital transformation and add another layer of complexity because each term has thousands of conflicting definitions. To mitigate these problems this section will not include definitions of digital transformation that include the above terms. Table 1.1 gives definitions of digital transformation from various academia and corporate sources.

Table 1.1 Definitions of Digital Transformation and their Sources

Definition	**Source**
a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies	2
Digital transformation encompasses both process digitization with a focus on efficiency, and digital innovation with a focus on enhancing existing physical products with digital capabilities.	4
Digital transformation refers to the adoption of data and digital solutions for business activities and processes. It engages people with digital workflows to promote the full advantage of technology investments across an organization	Siemens
Digital transformation is the process of using digital technologies to create new — or modify existing — business processes, culture, and customer experiences to meet changing business and market requirements.	SalesForce
The use of new digital technologies, in order to enable major business improvements in operations and markets such as enhancing customer experience, streamlining operations or creating new business models.	5

By no means are definitions above an adequate representation of all the definitions of digital transformation that exist in the world today. However, the definitions created from the literature reviews involves examining large quantities of other definitions. The review papers cited above use methodologies, such as tools from

grounded theory[6], in their literature review to maintain balance and ensure a robust definition is created from the collected information[2]. The two companies listed in the table above are thought to be pioneers in digital transformation for both business and manufacturing and therefore serve as candidates from the industrial point of view.

From the definitions above three key words can be either explicitly or implicitly identified as parameters of digital transformation; those three words are data, digital technologies, and processes. In all the definitions there is a common outcome of process improvement regardless of industry sector. Based on this information a digital transformation framework should include the three key parameters and conclude at the improvement of a process. The inherent nature of a framework means that it should serve as a starting point and the be customized according to a use case. Not everything will fit into a digital transformation framework, nor does everything need to. Instead, steps should be taken to analyze a process, identify the problems, and then decide whether digital transformation can be used as a vehicle to come to a solution. For the remainder of this work the focus will turn towards use cases in the engineering world. It is worthy to note that the developed framework is intended to fit numerous industry sectors but to prove the framework's usefulness several unique use cases will be dissected. From this point forward it is up to the reader to translate the framework to another industry.

1.2 CPM at UofSC's Digital Transformation Framework

For 20+ years the Center for Predictive Maintenance at the University of South Carolina has been a pioneer in the digital age. Work at the center began in 1998 when the U.S Army partnered with researchers to examine the health of military rotorcraft. This partnership gave rise to cost benefit analysis studies[7], component testing[8], predictive

maintenance[9], natural language processing[10], and digital transformation[23-25]. Each of the above topics was applied to, but not limited to, Apache AH-64, Blackhawk UH-60, Chinook CH-47, and Osprey V-22 military rotorcraft. Additionally, CPM is the only facility in the world to have a full scale and full power AH-64 drivetrain test stand where over 5500 hours of component testing have taken place (Figure 1.1).

Most studies performed on the AH-64 drivetrain focused on condition-based maintenance. This process focuses on installing examining the condition of a system, sub-system or component instead of using a traditional preventative maintenance

Figure 1.1: The AH-64 Drivetrain located at CPM with corresponding airframe locations.

approach. One of the key areas of condition-based maintenance is installing sensors onto systems to analyze the health and usage of the components in real-time[11]. From this sensor data, one can infer the relations between collected metrics and physical phenomena to produce what are called condition indicators. These condition indicators can then be packaged and visualized so that operators, engineering, maintenance

technicians, and others are aware of the health of components and whether actions need to be taken to ensure the reliability of the system.

After testing on the rotorcraft components concluded, the center began to shift its focus towards predictive maintenance. A vast amount of failure data was generated from testing and served as a foundation for work focused on predicting failures. This led to new technologies such as IoT and smart systems that could apply the same methodology to different use cases. These use cases included fault diagnosis on an intermediate gearbox of an AH-64 Apache, valve control of a chemical factory simulation and monitoring of premature infants in the neonatal intensive care unit. Each of these use cases focused on collecting, analyzing, and visualizing sensor data to make predictions. The large-scale collection and analysis of this data from various use cases led to the center developing a digital transformation framework.

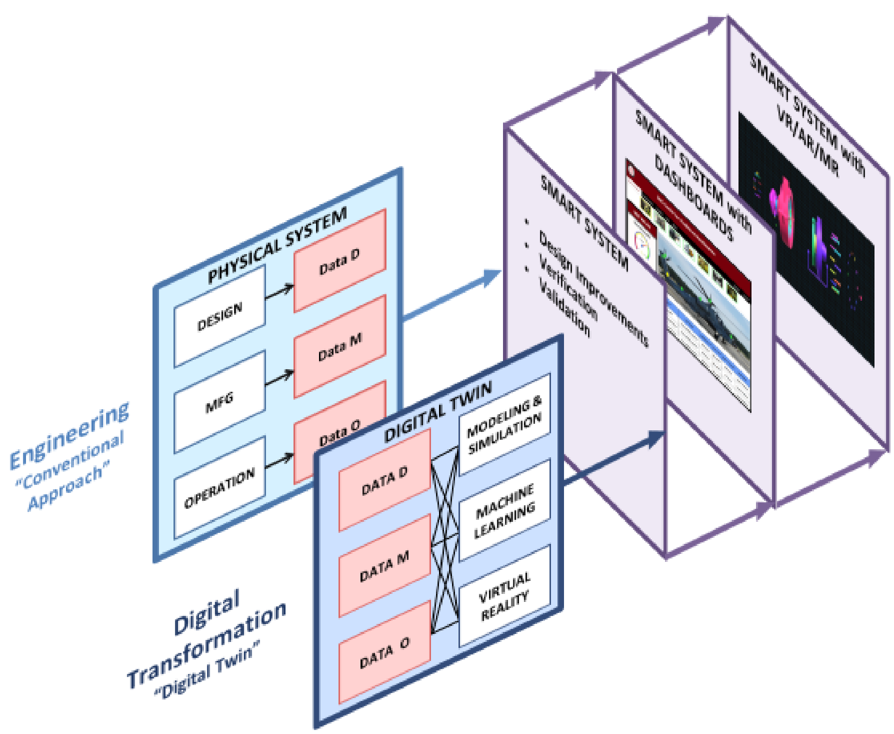

Figure 1.2: A digital transformation framework encompassing both physical and digital aspects of a system.

In the research programs dedicated to AH-64 testing, the team at CPM realized how a legacy system can be digitally brought to life through data collection and analysis. The AH-64 system has existed since the late 1970's and while it has received major block updates throughout the years it still lacked an element that provides users an end to end understanding of how maintenance can be improved through sensor data analysis and operator training. From these programs focusing on the AH-64's tail rotor drive train and other components, CPM developed the foundations of a framework that help to assist in conceptualizing the application of digital transformation to a legacy machine (Figure 1.2). In a general sense, a framework contains components that fit together in a logical sense to end up at a final product. A fully developed framework is generic enough to be applied to numerous different use cases and leaves some freedom to an end user to implement and tweak some of the elements to fit specific operator needs. For digital transformation this means that the previously mentioned three areas, data, models, and deployable tools, need to fit together in a logical sense to result in process improvement. In Figure 1.2 the digital transformation framework starts with data. Both sides, physical and digital, are examined to extract any necessary data from the process. Design, manufacturing, and operation are given as examples for a typical engineering approach to a product's life cycle, however, these words are interchangeable based on the system begin evaluated with a digital transformation framework. Data is a necessary aspect to evaluate a candidate system for digital transformation. Analyzing the available data gives a user a strong understanding of what steps need to be taken to ensure that the right data is being collected. The amount, frequency, and quality of the data add nothing to a digital transformation framework unless it is a data point that can improve a product through

analysis and presentation. Once the right data is being collected an end user can focus on modeling that data to extract key insights into the product and potential problem areas that require additional analysis. Additionally, models can be in the form of 3D or 2D drawings that may need to be made if a product was not subjected to it at the initial design phase. Obtaining these digital drawings allows for both computational analyses using techniques such as finite element analysis and visualization of a system to an end user. Having a digital representation of the product is also a necessary part of data visualization to assist in operator understanding and physics-based modeling. Figure 1.3 gives an example of the tail rotor drive train of an AH-64 fully recreated in virtual reality. Finally, the last component of a digital transformation framework focuses on deployable tools. After data has been collected and analyzed it is necessary to present findings and insights to an end user. Presentation has been done through digital dashboards but new

Figure 1.3: A Virtual Reality Demonstration of an AH-64 tail rotor drive train complete with major components and interactable mechanics.

and emerging technologies such as augmented and virtual reality provide new mechanisms in which to present information to users. Deployable tools can also encompass machine learning and artificial intelligence areas to help provide additional data points and solve problems autonomously for further product improvement. Each of the three areas discussed above provide a product an opportunity for management, improvement, continued sustainment of a product. Combined, the three areas result in a digital transformation framework that can collect, analyze and present data to end users that they can leverage. Some newer products will have a head start in this framework and digital aspects and data are already built in through sensors. However, legacy products do not have the same opportunity and therefore the approach to digital transformation must be treated differently to account for the problems posed by the absence of potentially valuable data and information. Figure 1.4 shows how this thesis plans to address these issues through three main sections. Chapter 2 will focus on defining digital transformation and the tools it uses. Chapter 3 will show digital transformation applied to several use cases in different industry sectors. Chapter 4 will analyze the benefits of the applications and draw conclusions on what is next for the digital transformation framework.

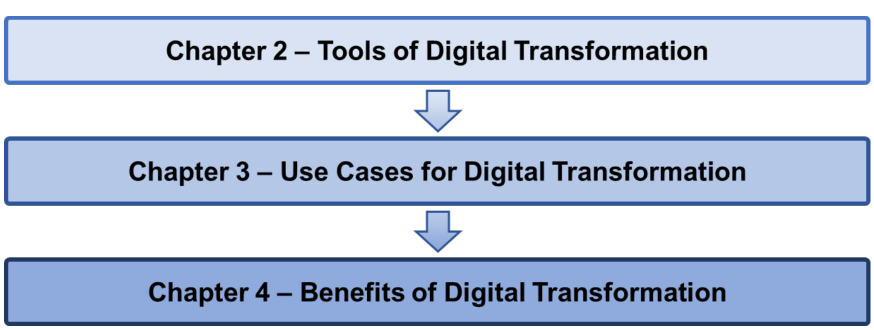

Figure 1.4: A structure of this thesis divided into three main sections.

CHAPTER 2

TOOLS OF DIGITAL TRANSFORMATION

2.1 Digitalization Tools

To create a digital infrastructure an individual must focus on what they are trying to represent. The represented items may be physical, digital, or a combination of both. For example, historical artifacts are a physical system that can be scanned and recreated digitally in three dimensions[12]. These three-dimensional models can be used to validate other historical artifacts and provide a record of the item if the original ever gets destroyed or lost. Alternatively, a video game player could have a library of digital games. Each individual video game is a digital element that can be categorized, stored, and played on demand. By using advanced machine learning techniques, a company can extract the data from the user's library on playtime, genre, production company, and other areas to advertise games that the user may not have but enjoy playing. In either scenario digitalization tools are used to generate, collect, and store data for additional purposes. Figure 2.1 gives examples of digitalization tools and their general purpose. These digitalization tools all serve to enhance the digital aspects of a system or systems. For the purposes of this research virtual and augmented reality, artificial intelligence, and digital twins are discussed to demonstrate the individual and collective effectiveness of these tools. Defining each of these terms poses a similar problem to that of digital transformation discussed earlier. With the growing interest in these areas, it is difficult to create a cohesive definition for each of these technologies. The next few

sections will give simple definitions for a few of these technologies to provide the reader a priori knowledge for the application section discussed later in the paper.

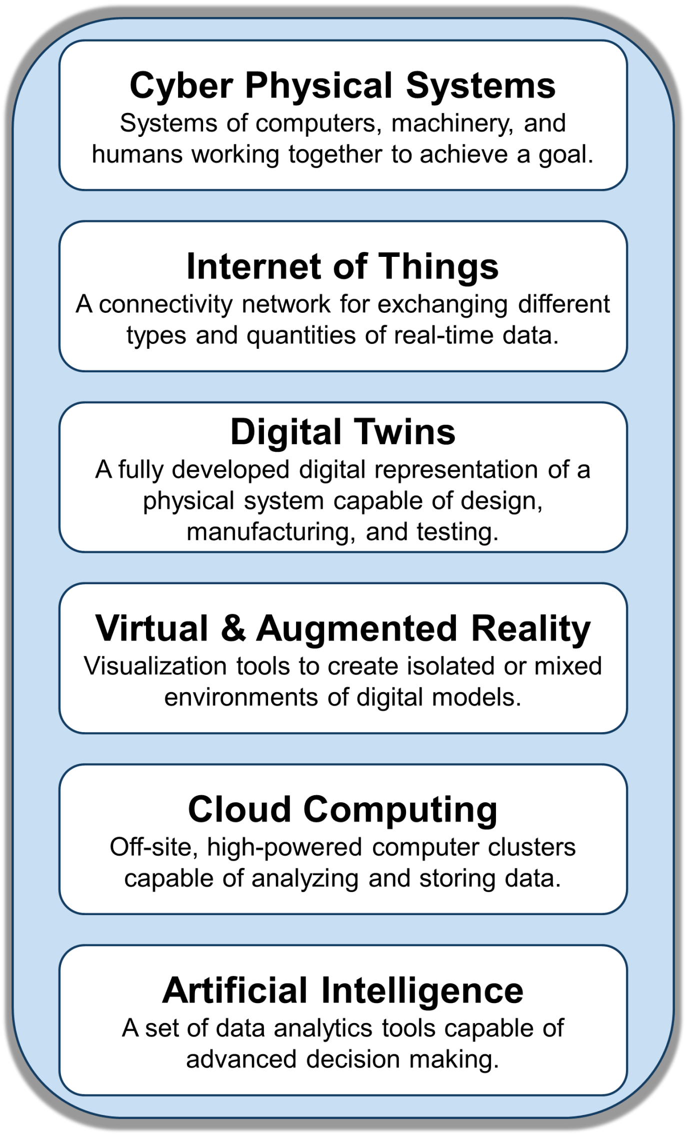

Figure 2.1: A list of digitalization tools for data collection, analysis, and visualization.

2.2 Augmented and Virtual Reality

In the past two decades augmented and virtual reality have skyrocketed in popularity. Virtual reality headsets have flooded the commercial market and large companies like Facebook, Google, and HTC have either invested in the virtual reality

world. Research follows this trend with the number of publications hitting close to 60,000 in 2017, compared to 10,000 at the start of the millennium. Augmented Reality shows a similar trend peaking at close to 30,000 in 2017. Figure 2.2 shows these trends in addition to key milestones in the virtual and augmented reality world.

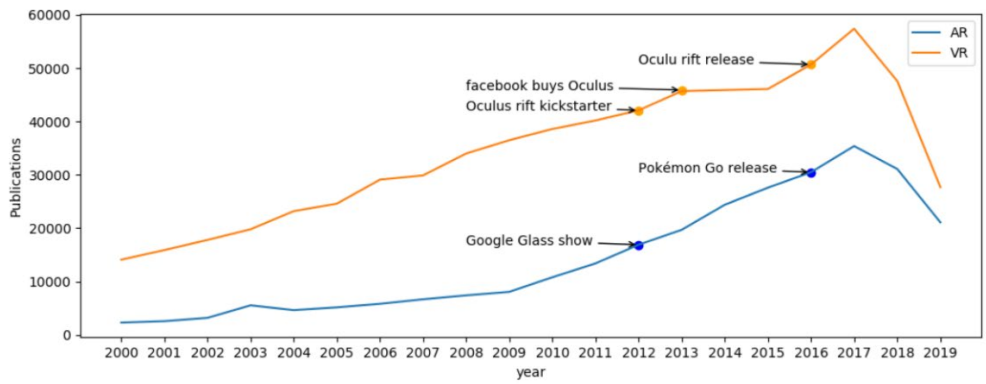

Figure 2.2: Number of publications on Augmented and Virtual reality since 2000[13].

A typical explanation for augmented and virtual reality uses the world's current reality as a contrasting factor. In virtual reality the user is made to feel separated from their current reality through the obstruction of senses such as vision and hearing. The user is still entirely in the current reality and is subject to its laws of physics, but their experience in the virtual reality can be designed to mimic any sort of variability. If virtual reality is designed to make the user forget about their current reality, augmented reality aims to enhance the user's current reality without separating them from it. In terms of senses augmented reality focuses on keeping the user entirely engaged in the current reality through vision, hearing, and touch but introduce additional elements that the user can interact with. Introducing specific technology with these definitions limits them and therefore items such as headsets, classes, and motion trackers are left out. The application of the applied framework later in the paper will use some of these specific hardware

technologies but not forgo the foundational definitions they serve to support.

2.3 Digital Twins

Perhaps the single most popular buzzword of the last decade is digital twin. Nearly every industry sector has some concept for what functions a digital twin should have. This array of use cases results in the same problem posed by defining digital transformation where many definitions create chaos. To remedy this problem the digital twin can be defined by two components: a dynamically updateable computational model and a growing data set[14]. Both components are related to their physical counterpart and serve to simulate, visualize, and predict. Connecting digital transformation to digital twins through their respective definitions is a necessary step to connect between the physical and digital world. As discussed previously digital transformation focuses on transforming physical systems into data sources, deployable tools, and computational models. Knowing that a digital twin must contain a computational model and a data source to supply that model, it is a logical conclusion that digital transformation is a vehicle to take a physical system into a digital space with a digital twin being one of many destinations. Defining digital twin and connecting it to digital transformation is only half of the battle. Applying this definition can also cause confusion due to where and what it is applied to. Manufacturing equipment is an example of where a digital twin can either be for the equipment itself or for the part that the equipment is manufacturing. In either case it is up to the creator to specifically detail what the digital twin is for and how it utilizes the generated data. Two examples are given later in the paper detailing work done for both manufactured equipment and manufactured products.

2.4 Companion Artificial Intelligence

Artificial intelligence refers to intelligent computational systems that can dynamically learn based on a data set. Subsets of artificial intelligence include topics such as machine learning and neural networks. These tools can be integrated with robots, cameras, and other technology to create a system capable of performing a task like a human. Although artificially intelligent systems have the capability of performing complex tasks, users in a manufacturing setting are typically reluctant to delegate a critical task to a computer. A study conducted in the automotive industry interviewed 39 engineers from different automotive companies and institutes. The researchers then created a list of use cases involving artificial intelligence and asked the automotive experts to rank them according to their business value and feasibility. The use cases included items such as predictive maintenance, factory energy monitoring, staff assignment, collaborative robots, and visual quality control. Figure 3.3 shows a scatter plot of these results. The researchers noted that artificial intelligence solutions with large complex data sets that needed to be integrated together were typically ranked last while solutions focused on a single data point or system were ranked highest[15]. Another data point to extract from Figure 2.3 is that solutions involving the artificial intelligence working alongside a human were ranked highly. The six solutions in the top right portion of the chart focus on the artificial intelligence solution analyzing a data set and presenting information to a human to make a decision. For example, predictive maintenance monitors sensors and time intervals on components to produce a snapshot of component health. The sensor data is analyzed and integrated by the artificial intelligence, but the decision to swap the component out based on real life circumstances is left up to the

maintenance manager. Therefore, artificial intelligence solutions should be focused on collaborative efforts between humans and computers. Having the artificial intelligence provide insights and suggestions to humans for the final decision will be both feasible and impactful from a business value perspective.

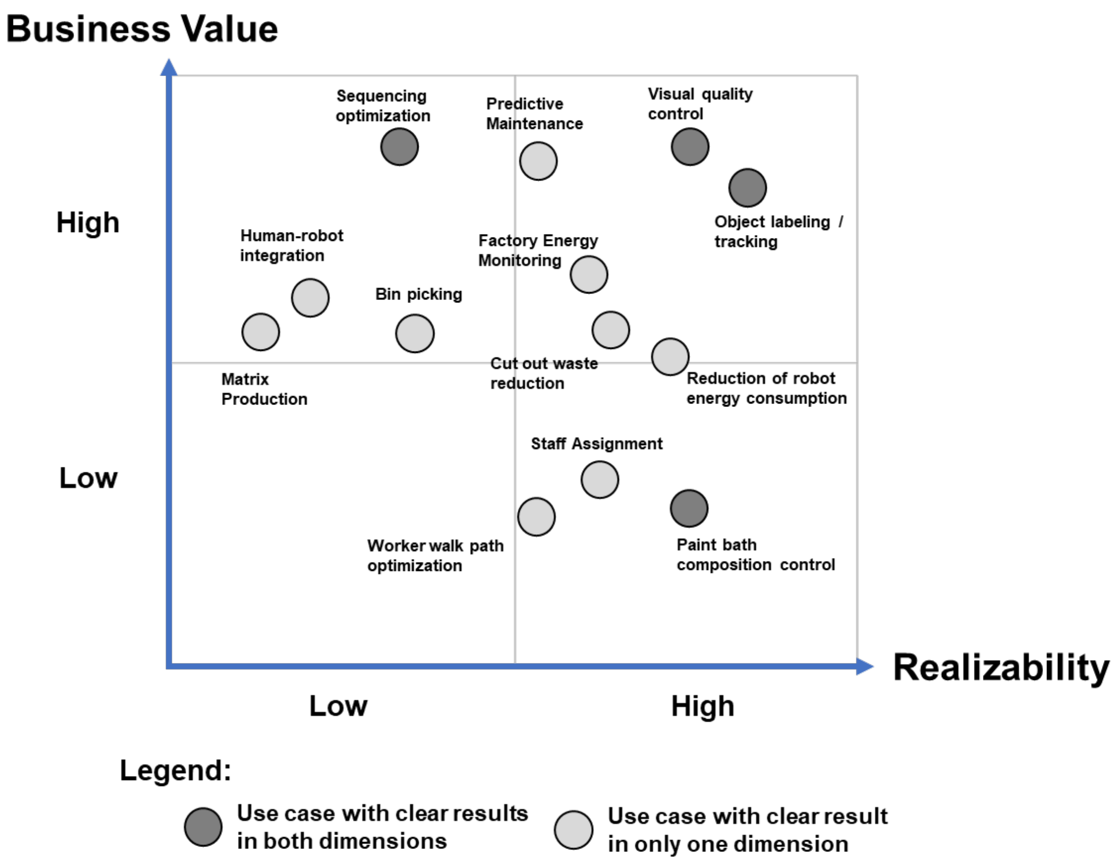

Figure 2.3: Scatter plot results of different artificial intelligence solutions ranked by business value and realizability[15].

CHAPTER 3

USE CASES FOR DIGITAL TRANSFORMATION

This section will focus on various use cases for the digital transformation. Initially, two industry scale use cases are introduced to show the research conducted for this thesis. Following the industry use cases, two small use cases from CPM are introduced to show additional applications of the framework.

3.1 Automated Fiber Placement

Automated Fiber Placement (AFP) is a manufacturing process where pre impregnated strips of fiber, typically carbon or glass, are placed onto a tool surface using some form of heat and compaction. The individual strips of fiber are called tows and have sizes such as 0.125 and 0.25 inches. A fiber placement head adds and cuts tows to form a desired two- or three-dimensional geometry[16]. A layer of tows constitutes a ply and multiple plies constitute a laminate. Laminates can have variability in shape, size, thickness, orientation of the fiber, and material type. Carbon fiber materials are typically divided into two types, thermoset and thermoplastic. Thermoset materials are pre-impregnated with a resin that makes the tows easier to work with. However, once this resin is cured the resin cannot be recovered and only the fiber can be used again. Thermoplastic materials are similar, but a thermoplastic matrix takes the place of the resin that is used in thermosets. This makes thermoplastics much easier to recycle, but harder to work because of the higher processing temperatures[17].

3.1.1 Legacy Control Systems

The Ingersoll Lynx Automated Fiber Placement Machine in the McNair center has manufactured composites for nearly 10 years (Figure 3.1). However, the Siemens 840D Powerline control was originally manufactured in the early 1990's and was not designed to be used with modern day digitalization tools.

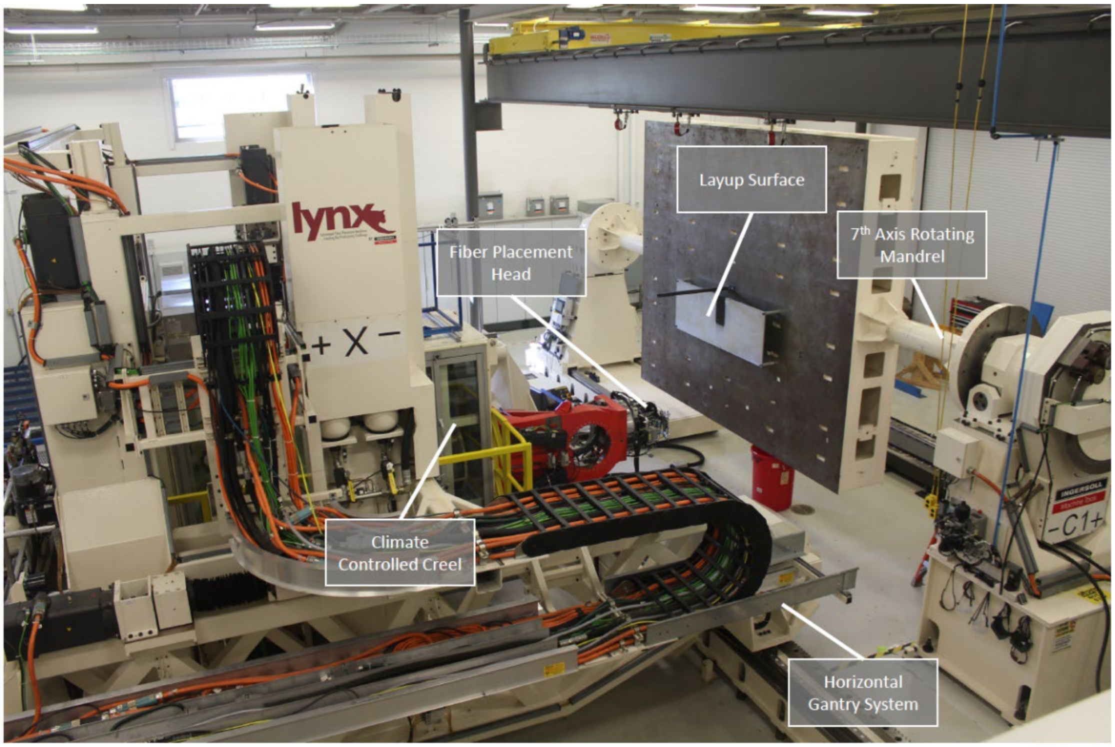

Figure 3.1 Ingersoll Lynx Automated Fiber Placement Machine at the McNair Center.

From 1970-2010 both manufacturing tools and products began to embrace three major concepts that helped advance the technology of the time. Those three areas are computers, sensors, and networks. As previously stated, computers allowed designers, programmers, and operators to translate the process between steps. Computer Aided Design, CAD, provided a designer the ability to create two-dimensional models of the part. Those models were then transformed by a computer and given to a programmer who could use Computer Aided Manufacturing, CAM, to generate the machine tool paths

necessary to create a part. Post processors built on computer code then translated the CAM data to a format such as G-Code that could be taken and run on the machine by an operator. Additionally, some products contained computers, such as aerospace vehicles, that an operator interact with and extract health and usage data after the manufacturing phase of the product life cycle.

The introduction of the programmable logic controller (PLC) in the 1970's gave machine tool designers an increase in control over their machines and introduced the ability to generate diagnostics[18]. Process data such as temperature, vibration, force, torque, pressure, and many other variables provided designers, programmers, and operators the ability to gain knowledge of control limits of components. These control limits combined with human knowledge ensured they produced quality parts with minimum damage and wear to the manufacturing equipment. This combination of knowledge was shared throughout the manufacturing and operating phases of a product and provided a network of communication that provided process improvement. It was not until the early 90's that the internet provided a way for machines to exchange data independent from human interaction.

Communication protocols for industrial PLC's originally started as proprietary interfaces that exchanged information between a single supplier's hardware. These interfaces performed incredibly well if a machine designer or end user was going to solely use a single electronics hardware supplier. However, if there was a need to set up communication between multiple hardware suppliers things became chaotic quickly. The need for standardized protocols started to become clear. The Open Systems Interconnection (OSI) model served as a templated to create standardized communication

protocols for PLC and automation equipment manufacturers. Key parameters are defined within each layer of this model to encompass all aspects of an electronic communication platform. Starting from the connector and cable type and moving all the way to how information is sent by bits over the connection, the OSI model serves as an industrial standard for creating these platforms. As the demand for network connectivity grew, the need for a standard protocol emerged. Automation and controls engineers aligned with network engineers and began to develop everything around ethernet networks. Ethernet is a set of four twisted pair cables that are terminated with a RJ-45 jack. Ethernet offered a significant advantage to other standards because it had the ability to carry multiple protocols on the same physical layer. This allowed for communication between many devices at the same time without sacrificing speed[19]. Large automation equipment manufacturers have transitioned to ethernet based communication systems. Profinet, EtherCAT, ControlNet, DeviceNet, and Modbus TCP are all examples of ethernet based protocols that are used for industrial control systems today. However, before ethernet based communication became an industry standard, control equipment exchanged information over protocols based on bus systems. Profibus and Modbus are two examples of bus systems that predate their ethernet based successors, Profinet and Modbus TCP, respectively. The main two advantages of ethernet based system are communication speeds and an unlimited address space. While Profinet is the clear path for the future of automation and controls engineering, 56.1 million Profibus nodes existed in 2016[20]. These older bus-based systems are continuing to grow outdated each year, but machine owners and operators want advanced technology for the rapidly developing industry sector. Previous generation manufacturing and operational equipment has its

disadvantages. Outdated computational and controls equipment, increased maintenance, and lack of spare parts all contribute to problems for aging equipment. Computational equipment lacks the speed and bandwidth that modern solutions require and increased maintenance results in higher demand for spare parts that have sometimes been deprecated or discontinued. There are solutions to these problems such as retrofits and third-party parts, but these typically have an associated cost and provide little improvement to the overall equipment's functionality in a modern manufacturing setting. Ultimately it is up to the operator and owner's discretion to decide the future of the equipment. They can either invest more money into a new machine with state-of-the-art equipment, with large up-front cost, or continue to operate their aging equipment, with smaller maintenance related costs. Typically, machine operators opt for the proven and aged manufacturing equipment. The equipment has garnered trust from the operator and if it does the job well there is no need for a large upgrade. This large upgrade can bring advanced technology, such as augmented and virtual reality, machine learning, and digital dashboards, but comes with machine downtime due to install and new operator training for the new equipment. Therefore, if the outdated equipment could be improved with the addition of advanced technology, the impacts such as cost, machine downtime, and new operator training could be mitigated. However, solutions for computational speed, process improvement, and increased maintenance need to be developed to provide owners and operators with a proven piece of manufacturing equipment, prepared for the digital age.

3.1.2 Advancing Automated Fiber Placement

To apply the digital transformation framework to the Lynx AFP machine in the McNair Center, data was identified and extracted from the machine. The AFP machine is equipped with a Siemens numerical control unit (NCU) that serves as the brain of the machine. Data is extracted from the NCU using a built in OPC DA server at over an isolated local network. The OPC DA sever contains all variables contained in the PLC

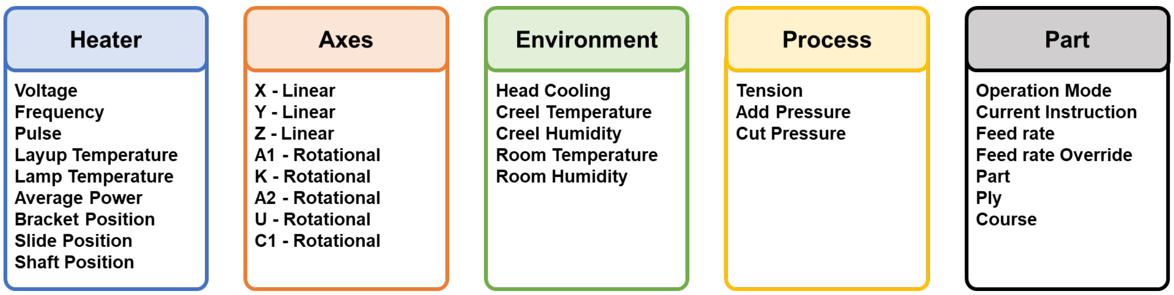

Figure 3.2: SQL Database tables with the data points collected from the AFP.

and NCU. To assist with collection speed, a gigabit network card was installed in the machine's main computer. A server on the same isolated local network uses a C# API to connect and add items to the OPC DA server on the machine. These items are then sampled at approximately 10-20 Hertz. The data is stored in a SQL database in various tables constructed based on the type of parameters. Each data point is connected through the timestamp at which it was collected and the part, ply, and course for each data point is collected to provide additional connection key. Figure 3.2 shows the current collected data from the NCU that is stored in the SQL database.

Connecting the collected data back to the AFP process is the next step to achieve process improvements. In a typical manufacturing analysis humans analyze the process and or collected data to support changing specific parameters such as heater settings or federate. The most common problem in the AFP process is defects induced in the

manufactured part. These are typically caused by the AFP machine and alter the deposited fiber in a certain way. Examples of defects in an AFP manufactured part are missing tows, twisted tows, wrinkled tows, overlapped tows, and gaps between tows. These defects must be corrected in each ply and are typically require fine motor control

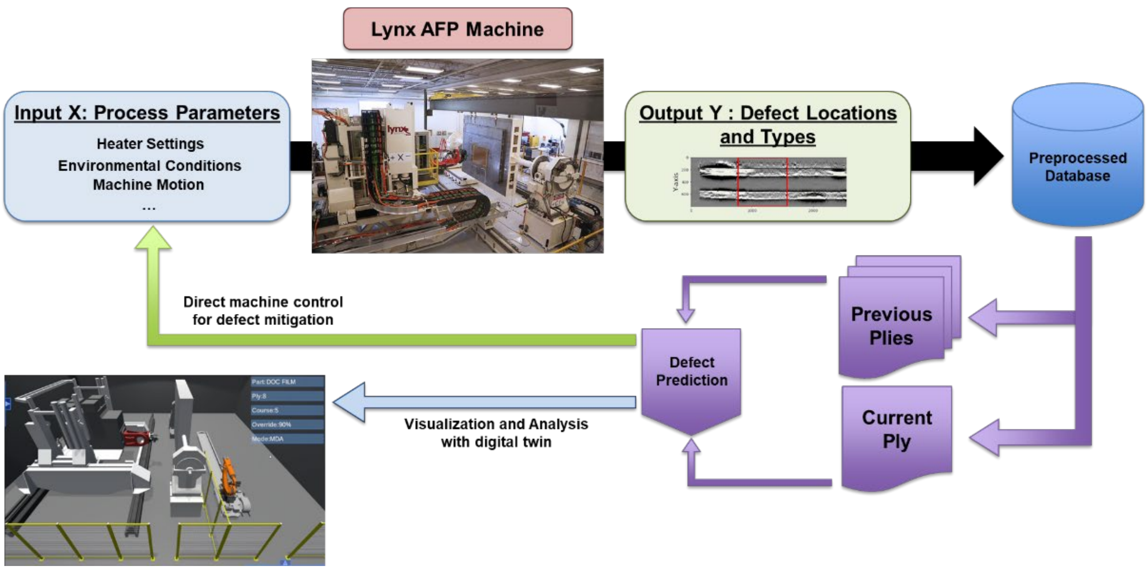

Figure 3.3: A deep learning defect correlation network for the AFP process.

from an AFP operator. Detecting and fixing defects consumes valuable manufacturing time and operator effort. A good AFP operator may be able to recognize what specific process parameters are connected to factors that they can control such as federate, heater settings, and machine motions. However, they may not be able to determine every correlation between defects and parameters. To avoid this problem a defect correlation model was developed that takes in machine parameter data and uses it to predict where and when defects can occur in manufactured AFP parts. Figure 3.3 gives an overview of this process in which the data from processes such as the AFP heater, environmental conditions, and machine motions are integrated and fused with images or logs of defects.

To develop and test the deep learning network an experiment was designed to manufacture five panels with thermoplastic material. The panels had a two-dimensional geometry of 12 inches by 12 inches and were quasi-isotropic with 8 plies. To produce variability in the quality of manufactured panels, each ply was run with different parameters and the AFP operator did not intervene to avoid defects. This approach created a variance in the defects and all the defects were logged using an excel spreadsheet. The collected data from the AFP machine was preprocessed and the defects were connected to the corresponding course where the defect occurred.

This data set serves as a training tool to develop a deep learning model that can use historical data to learn and predict defects in a manufactured part. The model was developed using TensorFlow, Keras, and python. Figure 3.4 shows the layers and

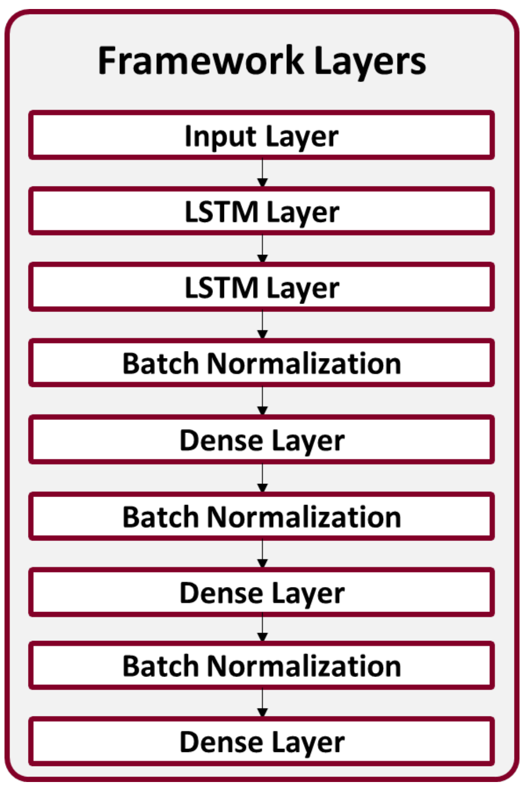

Figure 3.4: Layers of the deep learning model.

construct of the model. 31 process parameters are used as an input to detect one of three outputs. Due to time constraints on the project the team decided to detect failed adhesion of the tows as the main defects. The other two possible outputs of the model are no defect or the presence of another defect that has not been categorized yet. The data points and defects from the five panels were segmented into 95% training data and 5% testing/validation data. This split was due to the limited data generated from the constrained time. The model was tested on unseen validation data and had an accuracy of 96%. While this accuracy is high, the amount of data used the training model was low in comparison of those used in typical deep learning applications. Nonetheless, the developed model's accuracy will increase as data is continually added and additional defects can be detected as the number of occurrences increases. These defects and problematic process parameters can be communicated back to the operator that will be discussed later. This AI approach is based on the companion AI approach discussed earlier where humans and machines interact to make the best possible decisions based on the collected and analyzed data. In addition, The OPC DA server on the machine supports both reading and writing process parameters and therefore the defect learning model can change the process parameters without the need for human intervention. While this system is possible the project team did not complete this as it was not in the project scope.

In addition to the detecting and mitigating defects, the defects and their reasons need to be communicated back the AFP operator. Augmented and virtual reality systems provide avenues for the information to be presented in a clear and concise manner. The team focused on developing an augmented reality demonstration to communicate this

information. Figure 3.5 shows an augmented reality dashboard developed on a pair of Epson BT350 glasses that presents real time process parameters while the AFP operator is manufacturing a part. The augmented reality glasses are equipped with a camera and the AFP operator can use them to take pictures of defects and upload to the local server.

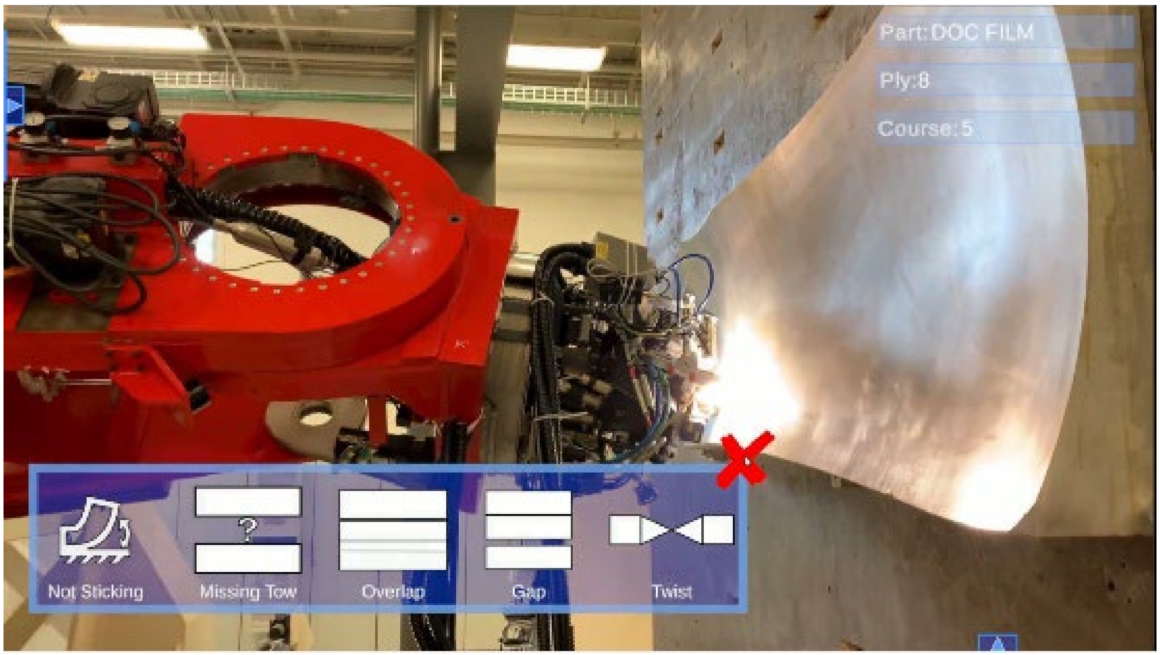

Figure 3.5: An augmented reality dashboard for an AFP operator.

The operator can also log a defect using a menu if a picture is not needed. The glasses communicate with the machine through the local server that hosts a MQTT broker to send and receive information. The pictures and logged defects are also stored on the local database. The augmented reality dashboard can also be deployed to a mobile device such as a phone or tablet that has a camera. If a detected defect requires specific actions from the operator, then virtual reality can be used as a tool to train operators.

As an example, defects such as wrinkled or missing tows can be induced in a manufactured part due to buildup not allowing a tow to pass through in the fiber placement head. Cleaning the fiber placement head is an intricate task that requires

removing hardware, using tools, and cleaning with a q-tip. Virtual reality is a mechanism where an operator can learn how to take apart and clean the fiber placement head in a forgiving environment. Figure 3.6 shows the physical and virtual representations of the head cleaning process. The virtual reality demo was developed on the HTC Vive and uses fine motor control skills with the two controllers. A user is guided using text-based instructions and highlighted components. In addition, a user can pick up a small 3D penguin, named “El Penguino”, just for fun.

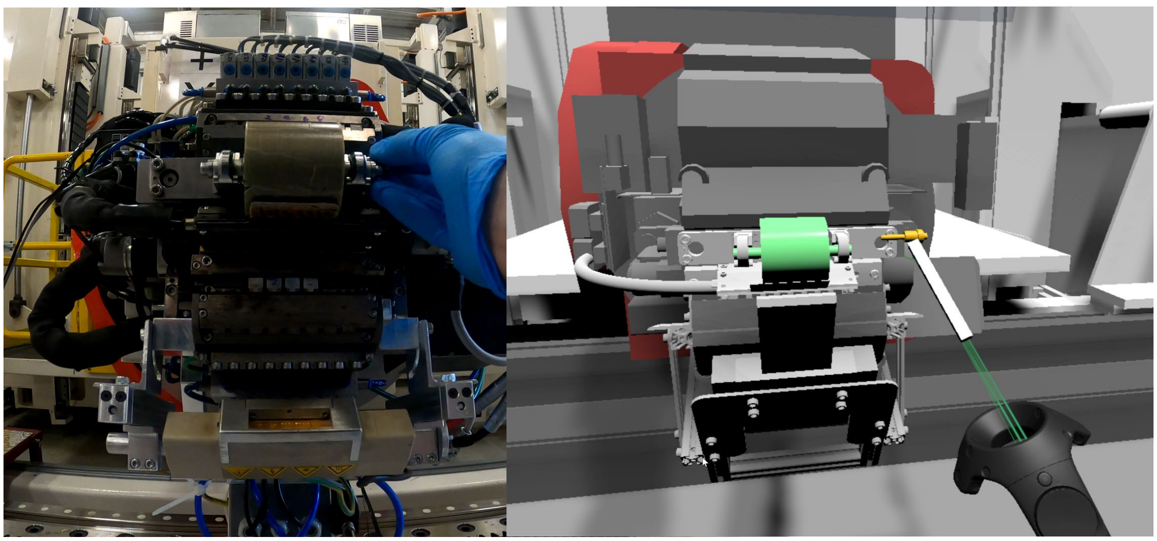

Figure 3.6: A virtual reality head cleaning demonstration for the Lynx AFP.

All the above models show different ways in which digitalization tools can be applied to the automated fiber placement process. Integrating these tools together can result in a digital twin as seen in Figure 3.7. The digital twin is a 3D representation of the AFP machine and inspection robot that moves and reacts in realtime. The defect model runs in the background and presents detected defects to the end user. The process parameters are shown in real time and a user can write process parameters, such as an emergency stop, if they see abnormal behavior in the digital twin.

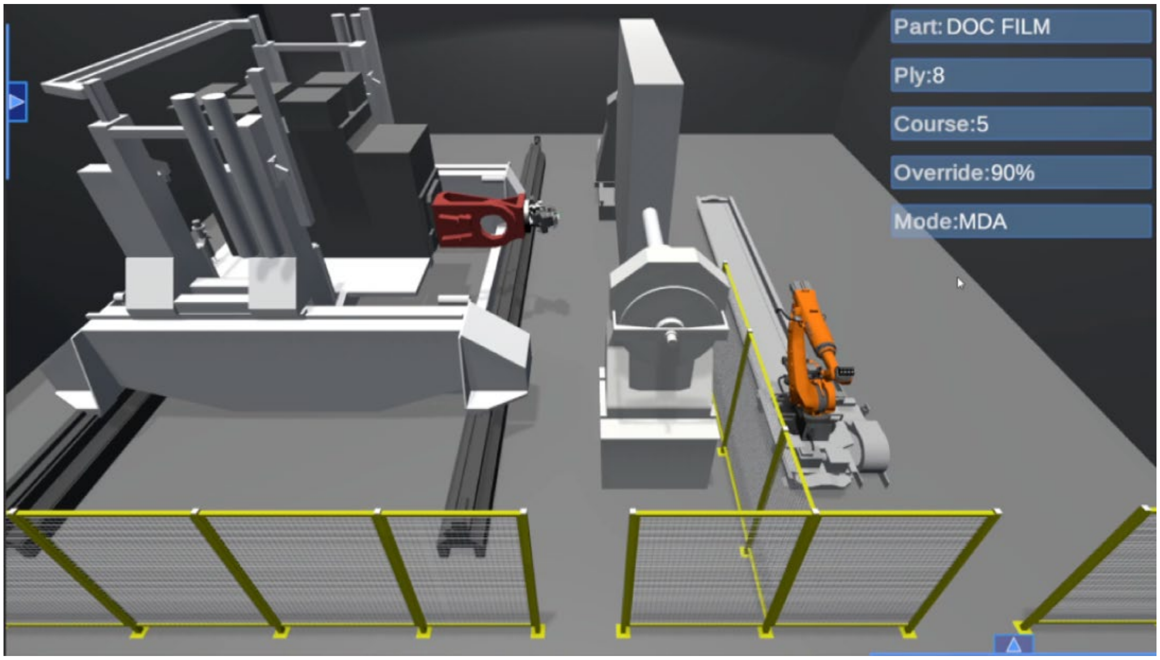

Figure 3.7 A digital twin of the Lynx Automated Fiber Placement Machine.

The developed models show how digitalization tools can be applied to legacy manufacturing equipment. These tools can provide benefits such as cost savings, reduced effort, and decreased down time that will be discussed later. However, in the realm of a product, the manufacturing process is only one stage. Expanding the digital transformation framework to other parts of the product life cycle can develop a consistent and repeatable process where data is exchanged to constantly improve a product.

3.2 Maintenance Steering Groups

Maintenance Steering Groups (MSG) have been the industry standard maintenance development program for the past 60 years. Figure 3.8 shows that MSG-1 was created in 1960 to assist with maintenance on the Boeing 747 engines. MSG-2 shortly followed in 1970 and introduced new concepts such as on condition monitoring. Through the following years it evolved into a top-down approach to maintenance where the aircraft or rotorcraft is divided into zones. Then working groups, review boards and

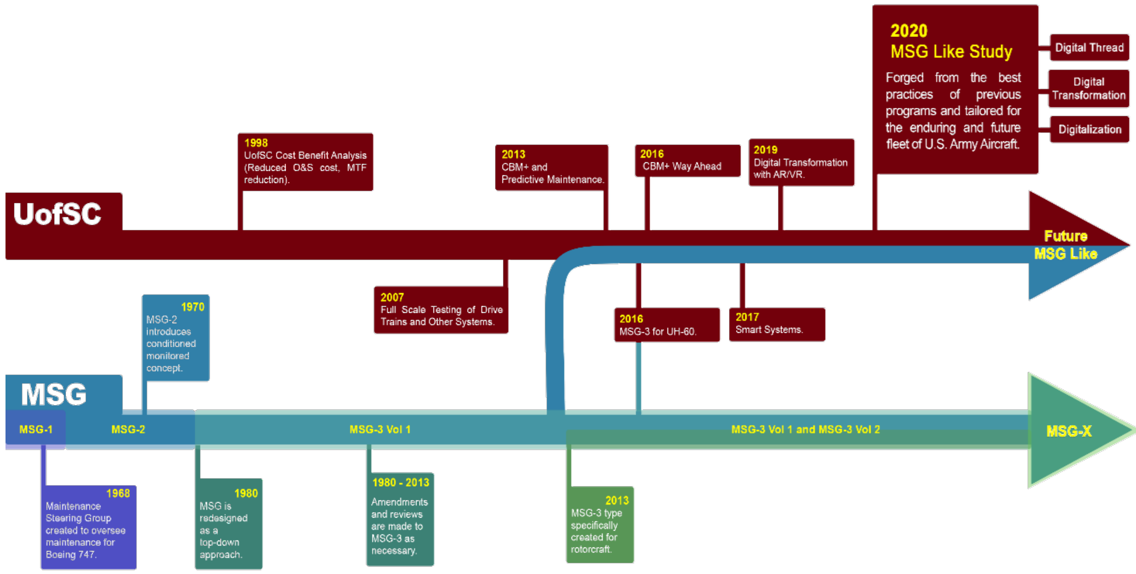

Figure 3.8: A timeline of MSG development and CPM activities.

regulatory authorities develop the initial scheduled maintenance plan for aircraft or rotorcraft components and systems. The current iteration is MSG-3 and has a volume for both fixed wing and rotorcraft. MSG-3 is used as an industry standard for commercial aviation partners today to provide the most uptime while retaining safety and reliability. However, MSG-3 was released in 1980 and though it has received updates through the years, there are many lessons learned from commercial operators and other maintenance cultures that have not found their way into the revised MSG-3 volumes 1 and 2.

Figure 3.8 shows that parallel to MSG development, CPM has been involved in both military and commercial maintenance activities relating to on board sensing, cost benefit analysis, component testing, condition based maintenance (CBM), reliability centered maintenance (RCM), and other areas. In 1998 CPM was part of a team that included Goodrich Aerospace and the Smith Corporation. This team investigated what would be the first generation of onboard sensing known as the Vibration Management

Enhancement Program (VMEP) and Health and Usage Monitoring System (HUMS). CPM was tasked with performing cost benefit analysis of the onboard sensing and showed the U.S. Army the benefits of what would come to be known as CBM. CPM also has experience with MSG and has team members that currently sit on MSG advisory boards. In 2016 CPM was tasked with developing an implementation for the U.S. Army's Blackhawk helicopter program. The project was approved for funding by the Army but was not approved at the federal level. These maintenance activities can be thought of as tools, like the digitalization tools discussed earlier. Maintenance advisors, program managers, and reliability engineers can choose CBM/CBM+, RCM, MSG, or predictive maintenance based on what best fits the need.

The U.S. Army has struggled with maintenance and sustainment costs on their fleets of rotorcraft throughout the years[21]. Future Vertical Lift (FVL) is a program where the U.S. Army is developing two new rotorcrafts to meet its need for future operational requirements. The Future Long Range Assault Aircraft (FLRAA) and Future Attack and Reconnaissance Aircraft (FARA) are the two new programs. As with any new aircraft, a maintenance plan needs to be developed to ensure that the aircraft life and operational capability are sustained for as long as possible. It is for this reason the U.S. Army is examining the application of MSG into its maintenance culture to assist with the current shortcomings of CBM/CBM+ and RCM. CPM is assisting the U.S. Army to develop a program that is "Like" the commercial aviation MSG approach but tailored specifically to the Army's needs. This MSG Like program is built for the future and therefore must be designed with digitalization in mind.

3.2.1 Developing an MSG Like Digital Thread

To create a new MSG Like maintenance culture for the U.S. Army, the CPM team has initiated a team of teams approach seen as a Venn diagram in Figure 3.9 that brings together U.S. Army Aviation Stakeholders, UofSC with their knowledge and experience of maintenance practices, and commercial aviation partners. The areas of overlap in the Venn diagram show key sustainment activities that are common between the two parties'

Figure 3.9: The team of teams responsible for creating the MSG Like Framework.

objectives. At the heart of these three stakeholders and their areas of overlap is the MSG Like Program that brings together the lessons learned, best practices, and collective knowledge of all the stakeholders.

Once the stakeholders in the program were established, CPM developed the outcomes and deliverables for the program. At a high level, an MSG Like Framework is

the final deliverable of the program. This MSG Like Framework organizes new and existing U.S. Army stakeholders into a governance structure that oversees all items

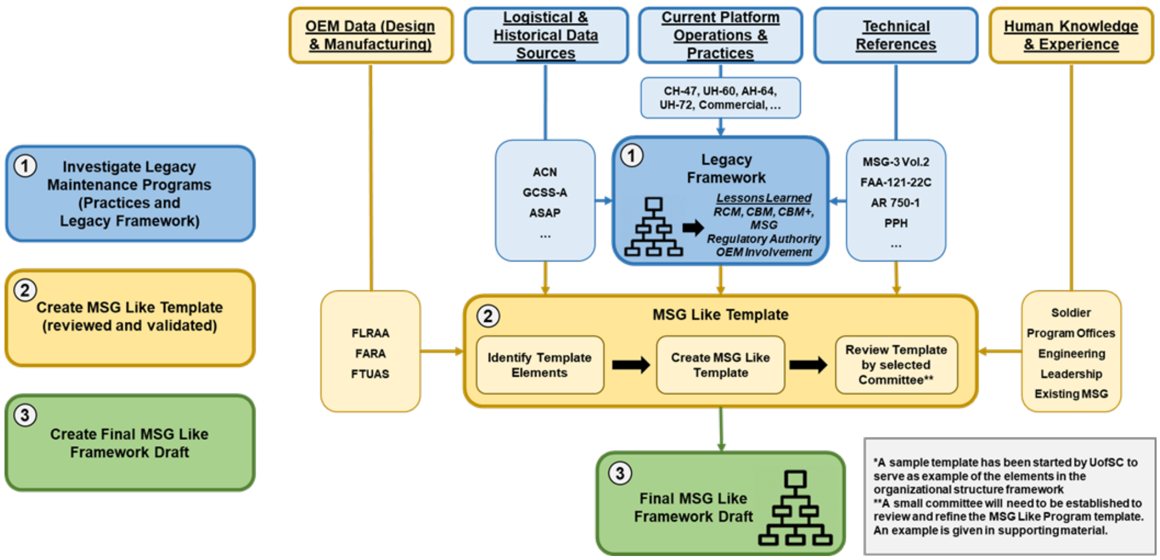

Figure 3.10: A detailed process for creating the MSG Like Framework.

related to U.S. Army maintenance. These items include things such as optimized scheduled maintenance plans, airworthiness approval, redesigns, block upgrades, maintenance task development, and program modernization. CPM identified five sources of data to analyze when developing the Framework. These five data categories are seen in Figure 3.10 and are current platform operations and practices, technical references, logistical and historical data sources, human knowledge and experience, and OEM Future Platform design and manufacturing data.

During Phase 1 of the program, the team analyzed four of these sources of data in multiple different ways. Technical references were read, current platform operations and practices were received through briefings from stakeholders, human knowledge and experience was collected through surveys, and logistical and historical data sources were

identified from briefings. At the time of writing OEM future platform data was not included due to lack of communication with OEMs.

The team analyzed all the collected information and developed an initial MSG Like Framework that is designed to be validated with current U.S. Army stakeholders. The MSG Like Framework cannot be shown in this paper due to confidentiality restrictions. However, the team performed additional analysis to examine how the MSG Like Framework would be the next step in maintenance program development. While maintenance tools such as CBM and RCM leverage digital and analog on board sensing, that is only in one phase of the product life cycle. Digital tools and software are being used in every stage of the product life cycle but there is rarely connection between the digital tools and data they contain. The commonality between each of these product life cycle stages is maintenance. Maintenance programs use every possible point of data from the early design stages to the testing and teardown analysis of failed components. If maintenance is leveraging data from all stages of the product life cycle, then it makes sense to let it serve as the connecting thread.

Similar to digital transformation, a digital thread contains physical and digital representations of a system or component. In addition to connecting a physical asset to the corresponding digital representation, the digital thread weaves different stages of the physical and digital systems together to provide additional benefits. Figure 3.11 shows a proposed digital thread that compliments the MSG Like Framework. The top layer represents the product development life cycle for a physical system. Each hexagon is not meant to represent an equivalent amount of time or effort, but instead to represent a specific process that takes place. The bottom layer represents different digitalization tools

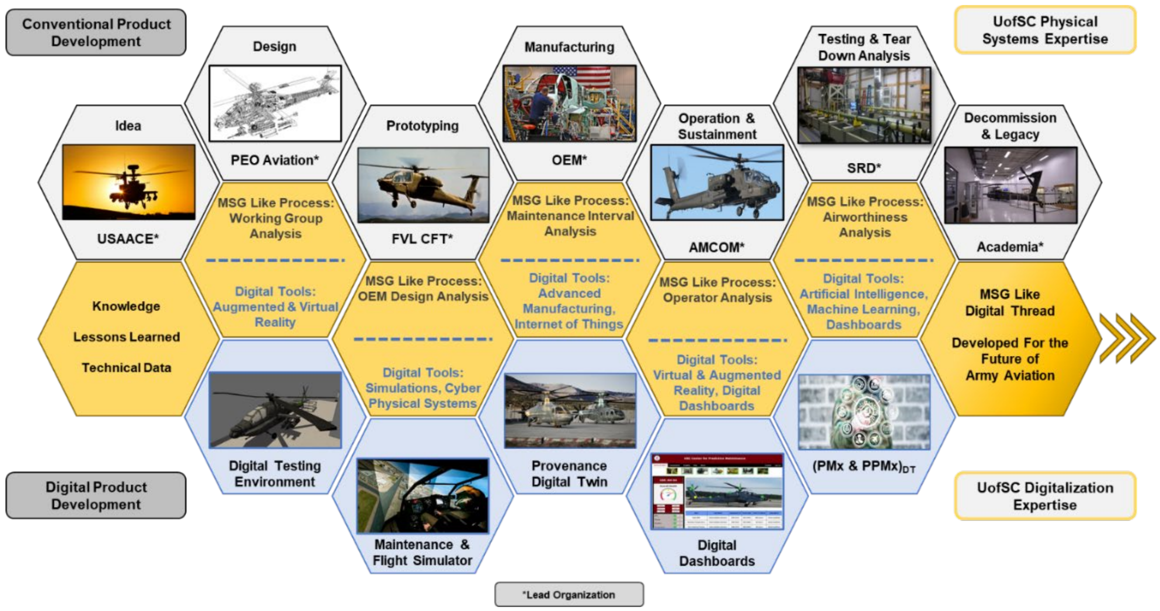

Figure 3.11: A digital thread for MSG Like with proposed digitalization tools.

that are used at each stage of the product life cycle. For example, the manufacturing stage uses digital twins as discussed in section 3.1.2 and the operation and sustainment phase use digital dashboards like the ones discussed in section 3.3.1. At the center, a digital thread exists to stitch together the stages of the product development life cycle and the digital tools. This approach allows data to be seamlessly exchanged from one stage of the product life cycle to another. For example, data that is collected from the sustainment operations can be used to redesign or change manufacturing tolerances for a specific component to better suit the operational needs. The amount of data within the digital thread for enterprise assets, such as military rotorcraft, will be overwhelming for end users. Figure 3.12 shows a digital dashboard designed for an end user analyzing the impact of MSG Like. Features include showcasing what data and how much of it are being leveraged to make decisions. Key performance indicators are presented to showcase the success and trends over the past few months. All the data can be filtered by

rotorcraft platform to provide specific insights. Appendix A shows additional dashboards can be created based on user need, but all are fed from the same data set and interconnected to provide real time feedback when making changes.

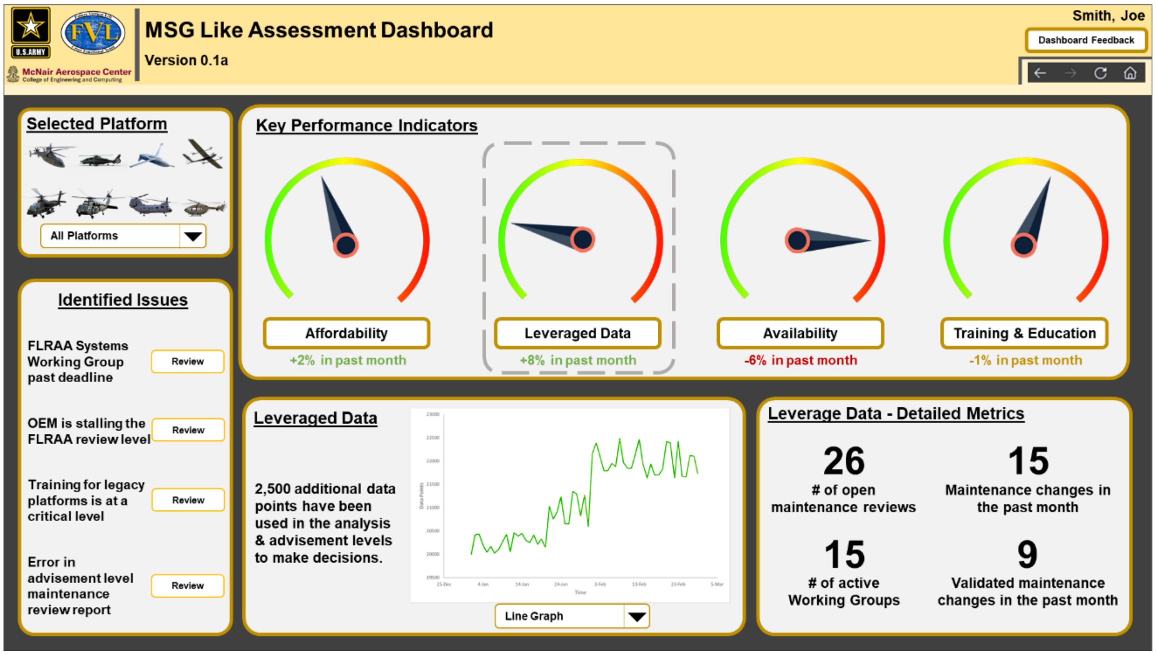

Figure 3.12: A dashboard for analyzing the effectiveness and impacts of MSG Like.

The digital thread is an expansion of the work shown in section 3.1.2. Work done in composite manufacturing is just one stage of the product life cycle. A digital thread for MSG Like will encompass numerous manufacturing types for the various components on a rotorcraft. While the application is different from section 3.1, the foundational concept is still the same. Utilizing different digitalization tools can provide end users with benefits that may result in cost savings, time reduction, and increased part quality.

3.3 Test Beds

This section will discuss two small scale demonstrations that provide an environment where new technologies can be tested and validated. These systems are not

connected to their respective industry standard data sources. This provides a safe space to test technology without the fear or damaging or causing issues based on the data that is collected or analyzed. Each use case showcases a basic system using the Internet of Things and digital dashboards to visualize data collected from a physical system. The data collected and analyzed from each use case is different and therefore shows its versatility and adaptability.

3.3.1 AH-64 Mini Intermediate Gearbox

As previously mentioned, CPM has been involved with commercial and U.S. Army Aviation practices such as test stands, CBM/CBM+, RCM, MSG, and predictive maintenance for the past 20+ years. The group has encountered vast amounts of data from testing and other programs and sought to showcase how the same data can be utilized for presentation to multiple users across a platform. To do so, an intermediate gearbox was extracted from an AH-64 rotorcraft. Figure 3.13 shows the gearbox has a small motor to turn a driveshaft in addition to all the sensors that a normal intermediate

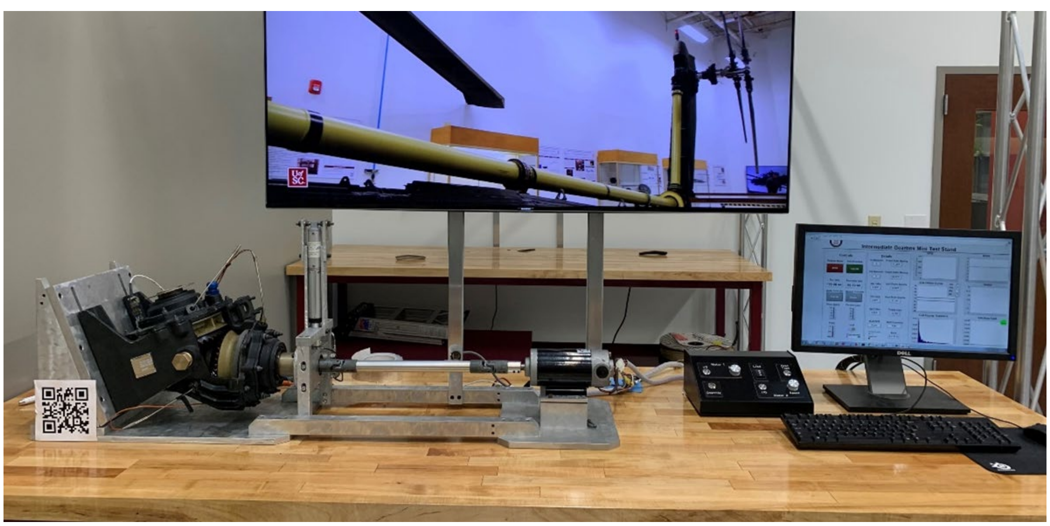

Figure 3.13: Mini Intermediate Gearbox test stand at the McNair Center's Digital Transformation Lab.

gearbox on an actual AH-64 would. Small apparatuses such as heat tape, vibration motor, and a linear actuator can induce simulated faults into the system. The system collects sensor data and analyzes it to detect the induced faults. The intermediate gearbox uses an internet of things approach to stream the data over a network for presentation in dashboards. These dashboards use the same streamed data however they present it in different ways so that a user can understand and interpret the data in a way that makes sense to them. Figure 3.14 shows four dashboards for a program manager and engineer that are analyzing a rotorcraft with a non-mission capable maintenance issue. The mini intermediate gearbox test stand is an excellent foundation for showcasing how two digitalization tools, Internet of Things and Dashboards, can be used to enhance a system for added benefits.

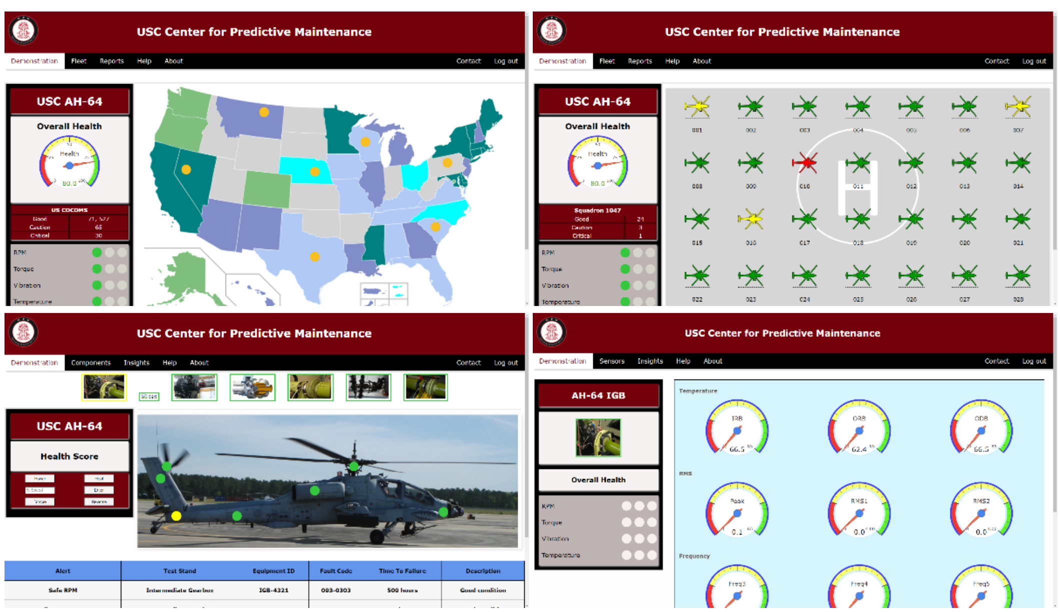

Figure 3.14: Dashboards for an executive (top left), program manager (top right), engineer (bottom left), and maintainer (bottom left).

3.3.2 Premature Infant Monitoring

In 2018, CPM partnered with the University of South Carolina's College of Nursing to investigate the development of a premature infant monitoring device. The College of Nursing's work focused on investigating a correlation between core and peripheral temperature of premature infants in the neonatal intensive care unit[22]. CPM focused on how data can be collected from an infant, processed, and presented to nurses,

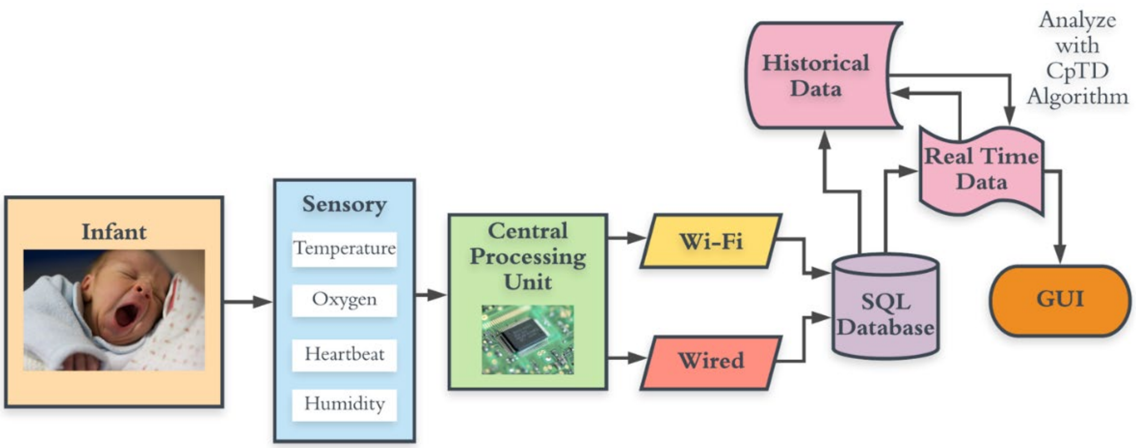

Figure 3.15: A flowchart for collecting, processing, and analyzing data from an infant.

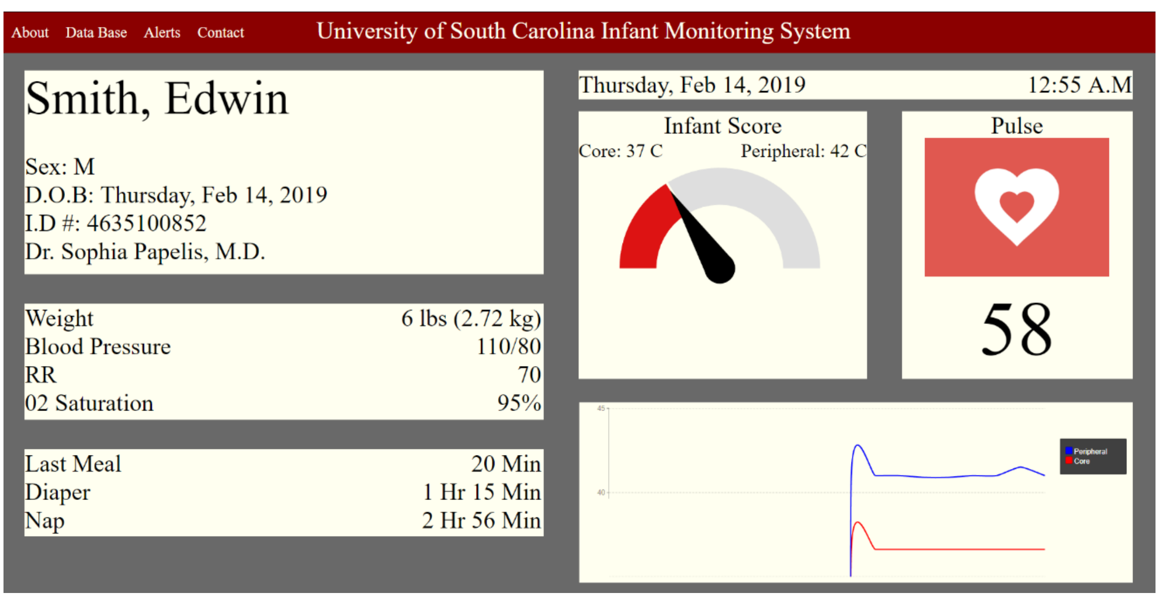

Figure 3.16: A digital dashboard showing infant monitoring data.

doctors, and parents. Figure 3.15 shows an approach to integrate the College of Nursing's algorithm with a manufactured device. Similar to the mini intermediate gearbox, sensor data such as temperature, pulse, and humidity is collected from an infant incubator. This collected data is analyzed and presented using a digital dashboard approach that can be seen in Figure 3.16.

CHAPTER 4

BENEFITS OF DIGITAL TRANSFORMATION AND CONCLUSIONS

It was previously mentioned that digital transformation can result in benefits related to cost, time, and human effort. These are broad categories, and the specific benefits will vary from use case to use case. It is also worth noting that purchasing a new machine or retrofitting an older machine can result in these benefits, however sacrifices may need to be made regarding implementation costs and time. The following sections discusses a comparison of using the digital transformation framework against retrofitting a legacy machine.

4.1 Comparison of Cost, Time, and Effort

The approach developed and presented here must show advantages over a generational upgrade or retrofit. For this example, the Lynx Automated Fiber placement machine will be used as an example to show the impact of cost, time, and effort between the digital transformation approach and a retrofit. To achieve the desired data collection, digital tools, and process planning capabilities for the AFP machine, Siemens recommends an upgrade to their Sinumerik 840D Solution Line control unit which was released in 2011. The Siemens 840D Powerline control unit in the Lynx AFP was released in 1996. To achieve the same feature sets that were developed in this research the Sinumerik ONE control unit would be necessary to use off the shelf products from Siemens such as virtual and augmented reality. However, the Sinumerik ONE was recently released and there is little information regarding the prices of components and

compatibility with older hardware. For this reason, the comparison will be made to the 840D Solution Line control unit.

The cost of retrofitting the Lynx AFP to the Solution Line controller is distributed between hardware, software, and labor costs. The digital transformation approach emphasizes a minimalistic approach when it comes to installing new hardware and therefore the associated labor costs are low. The retrofit approach will come with a higher labor cost due to the need to redesign control cabinets, run new wires, remove old equipment, etc. The digital transformation approach clearly has an upper hand when it comes to the cost of labor. In terms of hardware, the digital transformation approach installed some additional sensors on the machine including tow add control valves, tow cut control valves, creel temperature and humidity, room temperature and humidity, and an infrared temperature sensor. Table 4.1 shows a cost breakdown of these components.

Table 4.1: Hardware cost of the digital transformation approach.

Description	**Quantity**	**Cost**	**Total**
Omega Temperature and Humidity Sensor	2	$524.32	$1,048.64
Infrared Temperature Sensor	1	$170	$170.00
Control Valves	2	$500	$1,000.00
Total			**$2,218.64**

The prices for these components were taken at the time of writing from various industry supply websites. The retrofit approach relies on overhauling the entire control system of the AFP machine. This process is extensive and requires numerous compatibility checks of both hardware and software. Websites, such as PLCHardware, have the components for a retrofit but it relies entirely on the end user to determine what will fit their specific use case. Because a detailed bill of materials for a retrofit would take extensive time, upgrades for the more expensive components were researched and compiled to provide a

minimum estimate of what the hardware costs of the retrofit approach would be. Table 4.2 shows these estimates with the current Lynx AFP and retrofit Siemens parts listed beside each other.

Table 6.2: Minimum hardware costs for a Siemens 840D Solution Line Control retrofit.

Description	Current Siemens Part No	Upgraded Siemens Part No	Cost	QTY	Total
NCU	6FC5357-0BB25-0AA0	6FC5372-0AA30-0AA1	$10,000	1	$10,000
PCU 50.3	6FC5210-0DF31-2AB0	6FC5210-0DF52-3AA0	$7,651	1	$7,651
Operator Panel	6FC5203-0AF05-0AB0	6FC5303-0AF13-0AA0	$7,500	1	$7,500
Drive Control	6SN1118-0DJ23-0AA2	6SL3040-1NC00-0AA0	$1,332	10	$13,320
Field IO Controller (Cabinet)	6ES7153-1AA03-0XB0	6ES7155-5AA00-0AC0	$919	3	$2,757
Field IO Controller (External)	6ES7194-4AD00-0AA0	6ES7154-4AB10-0AB0	$445	2	$890
Field IO 8 DI	6ES7141-4BF00-0AA0	6ES7141-4BF00-0AA0	$210	3	$630
Field IO 4 DO	6ES7142-4BD00-0AA0	6ES7142-4BD00-0AA0	$103	3	$309
Field IO 4 AI	6ES7144-4GF01-0AB0	6ES7144-4GF01-0AB0	$512	3	$1,536
Field IO 16 DI	6ES7321-1BH02-0AA0	6ES7521-7EH00-0AB0	$740	1	$740
Field IO 32 DI	6ES7321-1BL00-0AA0	6ES7521-1BL00-0AB0	$465	6	$2,790
Field IO 16 DO	6ES7322-1HH01-0AA0	6ES7522-1BH01-0AB0	$315	7	$2,205
Field IO 8 AI	6ES7331-7KF02-0AB0	6ES7531-7KF00-0AB0	$890	2	$1,780
Field IO 4 AI	6ES7332-5HD01-0AB0	6ES7532-5HD00-0AB0	$765	2	$1,530
Line Module	6SN1145-1BB00-0FA1	6SL3330-7TE32-1AA0	$13,041	4	$52,164
Line Module	6SN1145-1BB00-0FA1	6SL3330-7TE32-6AA0	$16,075	1	$16,075
Line Filter	6SN1111-0AA00-1DV0	6SL3000-0BE25-5DA0	$485	1	$485
Line Filter	6SN1111-0AA00-1EV0	6SL3000-0BE31-2DA0	$1,310	1	$1,310
Line Filter	6SN1111-0AA00-1FV0	6SL3000-0BE31-2DA0	$1,310	2	$2,620
		Total			**$126,292**

It is worth noting that table 4.2 leaves out some components that are optional in a retrofit. Upgraded motors and encoders are left out because the old ones should be compatible with the new drives. The main components that are necessary to upgrade are the Numerical Control Unit (NCU), Personal Computer Unit (PCU), motor drives, and field IO. These components are the backbone that control the machine and its components. Software costs for Siemens products are not listed publicly on their website at the time of writing. The software used for the digital transformation approach is a 3D engine called Unity and has an annual subscription cost of approximately $1800. It is expected that this is far less than all the programming software needed for the retrofit approach, however it cannot be verified at this time. Comparing the costs of the two approaches, the digital transformation approach costs significantly less. This is an

expected result as the cost of additional sensors are minimal compared to control components meant for precision motion control. However, the digital transformation approach shows that advanced digital tools can be applied to the older Sinumerik 840D Powerline solution. If the legacy system at hand only needs advanced digital tools, then keeping the old hardware and saving some money may be the best approach. However, if replacement components for the legacy are becoming scarce, it may be worth upgrading the controls so that part failure does not cause unnecessary machine downtime.

In terms of effort the focus will be the labor for both approaches. The technical knowledge needed for both approaches is on the same level and will be a combination of controls engineering, mechanical engineering, computer science, and electrical engineering. For the digital transformation approach this was achieved by a team of researchers at UofSC, Clemson, and Fraunhofer USA. The team had a yearlong research grant worth $250,000 to develop the proof-of-concept technology discussed in section 3.1. In comparison, the retrofit approach will rely heavily on the OEMs of the equipment. Ingersoll Machine Tools and Siemens are the main OEMs for the Lynx AFP. A quote was received from Ingersoll which detailed their typical retrofit timeline and cost. For the Lynx AFP the expected timeline would be roughly 10 months for the engineering teams to analyze, rebuild, and install the necessary components for a retrofit. $750,000 was given as a rough quote for the necessary labor to retrofit the machine. In combination with the above hardware costs, a retrofit would be expected to be over $1,000,000. For a machine the size of the Lynx AFP this cost would be expected regardless of the OEMs. Comparing the labor for the two approaches, the timelines are similar however the associated costs drastically differ. Again, this is expected as the

controls retrofit requires much more labor to redesign and install large components while the digital transformation approach focuses on small incremental changes.

4.2 Benefits

From the information presented above, comparisons can be drawn about the differences in the two approaches. To summarize, the digital transformation approach costs less, takes less time, and requires significantly less effort than a typical retrofit approach. However, the two approaches do not result in the same end product and the benefits of each are discussed in the following sections.

The digital transformation approach results in small incremental changes to the hardware of the system. This may be in the form of additional sensors or control components that can collect or modify process parameters. These collected parameters can then be leveraged to predict and make changes to the process that result in increased part quality and decreased production time. For the Lynx AFP this was shown by the prediction of defects that minimizes the operators need to manually inspect or use the Ingersoll ACSIS system. In addition, faster onboarding time was shown through the virtual reality demonstration that taught operators how to clean the head. The digital transformation approach also allows for constant process improvement through the collected process data. As the predictive models use more data, correlations can be seen to allow engineers to make decisions on how to improve the machine or process. However, there are some limitations to using the digital transformation approach. First, the existing hardware is left in place which could result in low speed or performance from aging components. Discontinued parts can be hard to find and therefore the machine may have unnecessary downtime due to supply issues.

The retrofit approach results in an entirely new controls system that can provide upgraded functionality to the system. In the case of the Lynx AFP this will result in more control over the machine and its systems. The newer Siemens control units are designed with data collection in mind and come with numerous ways to extract data such as OPC UA, Modbus TCP, and other interfaces. The upgraded control may provide some additional data points to collect, but the main benefit is the increased collection speed. This is mainly due to the upgrade from Profibus to Profinet that was discussed in section 2.2. Siemens also provides an array of digital twin tools such as Create My Virtual Machine where the data from the NCU can be downloaded and converted into a 3D simulation. This allows for precise simulations and collision avoidance because it is using the validated positional data that is stored in the NCU. Like the digital transformation approach, the virtual machine can be used to train new operators in a virtual environment where crashes and mistakes do not have an impact on part production. In addition, a new control means spare parts and troubleshooting are streamlined. The older control units have been discontinued by Siemens and therefore spare parts are only available through third party sellers. Direct support from the OEMs can provide a decrease in downtime.

Both approaches have features that connect to benefits for the end user. Figure 4.1 represents the features of the two approaches and how they are connected to generalized benefits. The benefits used are manufacturing key performance indicators such as production rates, scrap rates, machine downtime, and part quality. Both approaches will result in benefits for the process, however the differences in how those benefits are reached will help decide which approach to take. If the system or machine is reliable in production and only needs new features, the digital transformation approach may be

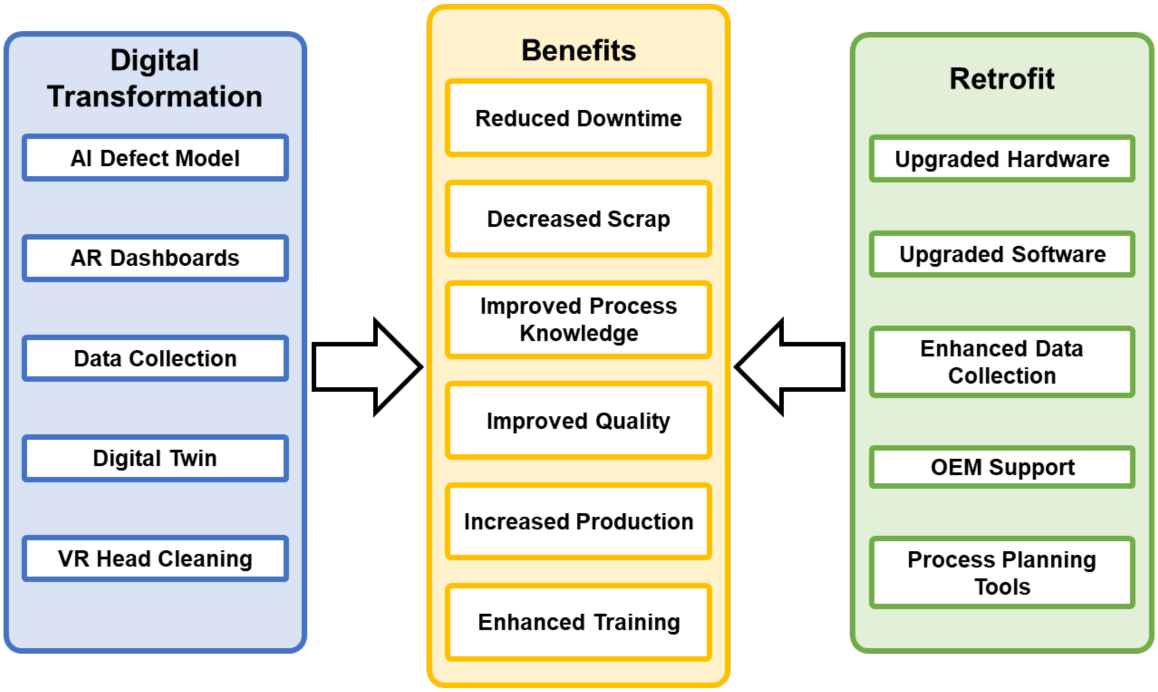

Figure 4.1: The features and common benefits of both approaches.

chosen due to the lower cost and effort to obtain those features. However, if the machine is unreliable or incapable of producing quality parts, it may cost less in the long run to retrofit the machine to ensure reliability is maintained. Therefore, the analysis of current control equipment is important. Analyzing the current state and understanding what impacts it is having on key performance indicators is a vital prerequisite before either approach is chosen.

In addition to benefits of the digital transformation framework, the digital thread can provide supplemental benefits. Examining the MSG Like use case shows that the MSG Like Framework can provide benefits to the end user such as reduced operating and sustainment costs. The digital thread and its digital tools provide additional benefits to both the U.S. Army and OEM. Figure 4.2 begins with the U.S. Army Aviation objectives and shows how the MSG Like Framework and Digital Thread can provide benefits to the

U.S. Army and OEM. The benefits have yet to be shown for the digital thread, but based upon the initial results from the AFP use case inferences can be made about the scalability of the benefits to other stages of the product life cycle.

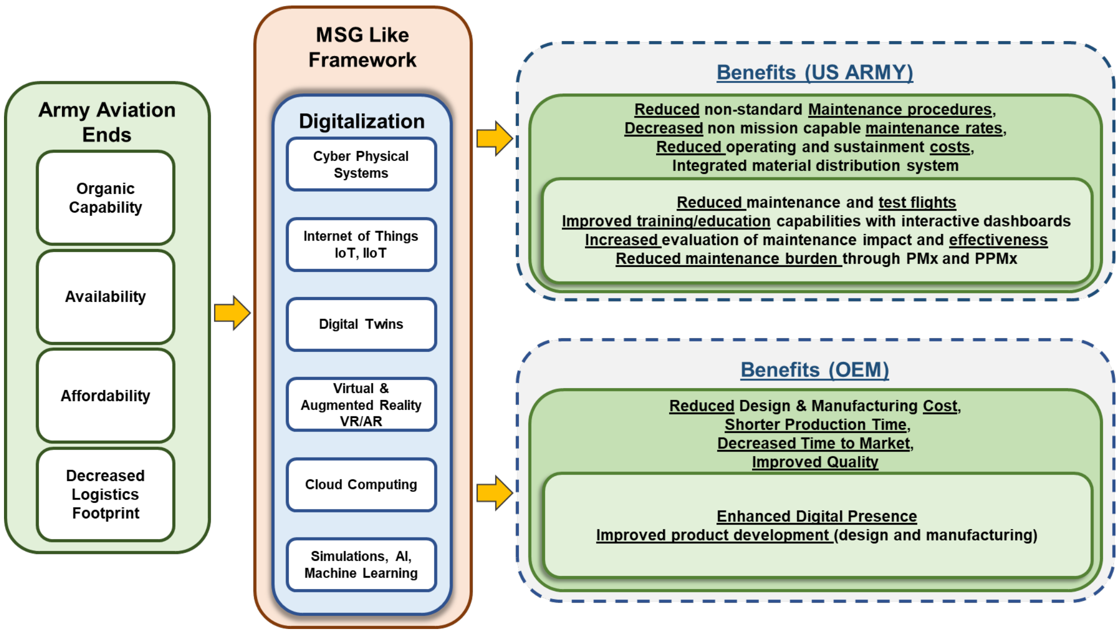

Figure 4.2: The benefits of the MSG Like Digital Thread.

4.3 Conclusions and Future Work

The research presented in this thesis has shown the capabilities of a digital transformation framework applied to legacy machines. The application of such a framework can produce digitalization tools that can result in positive impacts to manufacturing benefits. While the application in this work was composite manufacturing and rotorcraft maintenance, the framework and developed tools are versatile and applicable to many other manufacturing and industry sectors. A contrasting approach for manufacturing was presented in the form of a controls retrofit and the benefits were similar to the digital transformation approach. The downsides of not upgrading existing hardware, such as machine downtime and lack of spare parts, were presented to show potential shortcomings of the digital transformation framework. Choosing the digital

transformation framework is best when the machine is reliable and only needs the addition of emerging digitalization tools. A retrofit might be necessary if the machine is constantly experiencing downtime and spare parts are difficult to source.

The digital transformation framework for legacy manufacturing equipment can be expanded upon to address some of the shortcomings in this research. First, the collected data can be used in predictive maintenance algorithms to give realtime health conditions of components. This approach would help personnel pinpoint some of the bottlenecks when it comes to machine downtime and other negative factors. The predictive maintenance algorithms could work as part of a digital thread approach presented in section 3.2.1. The health status of components could be used to automatically order parts from the supply chain and alert operators. Digital tools developed as part of this digital transformation framework could be expanded to include other training procedures or enhanced digital twin capabilities. These digital tools are programmed agnostically so that the form of data or types of models coming in should not matter. They can be easily altered and remade to ensure maximum compatibility with a variety of manufacturers and use cases. With the vast array of legacy machine tools in the global manufacturing setting today, the decision to upgrade or enhance old equipment will start becoming a normal decision across the industry sectors. The work presented here proposes potential solutions to help those who need to make that decision.

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APPENDIX A

ADDITIONAL DASHBOARDS FOR MSG LIKE USERS

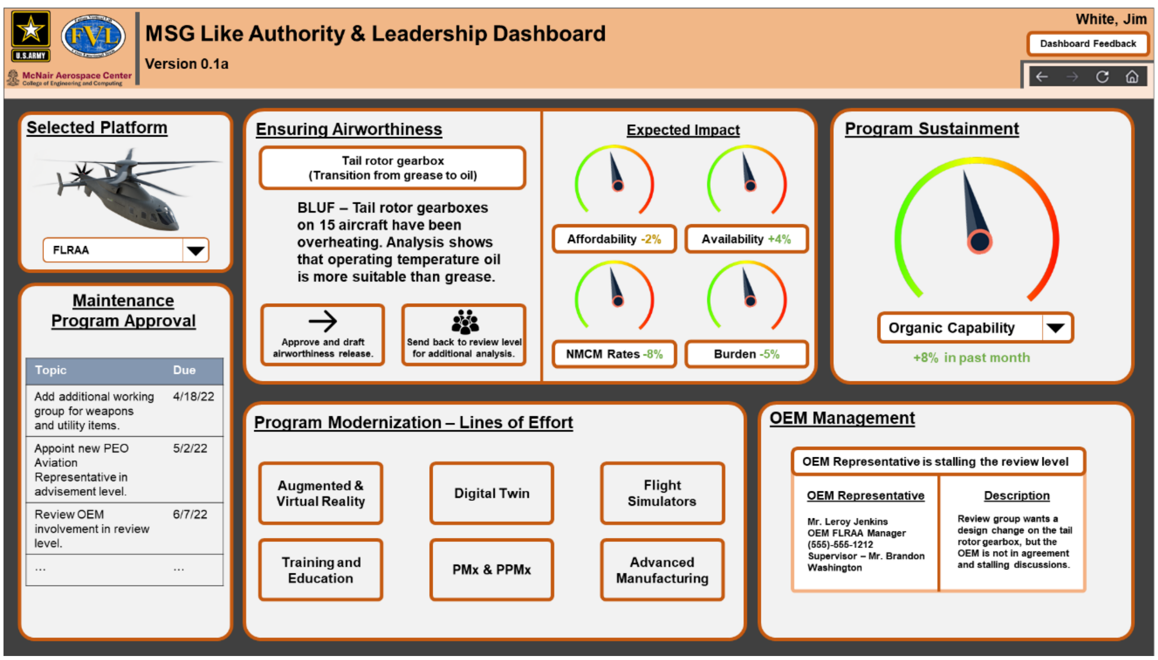

Figure A.1: A dashboard for authority and leadership using MSG Like.

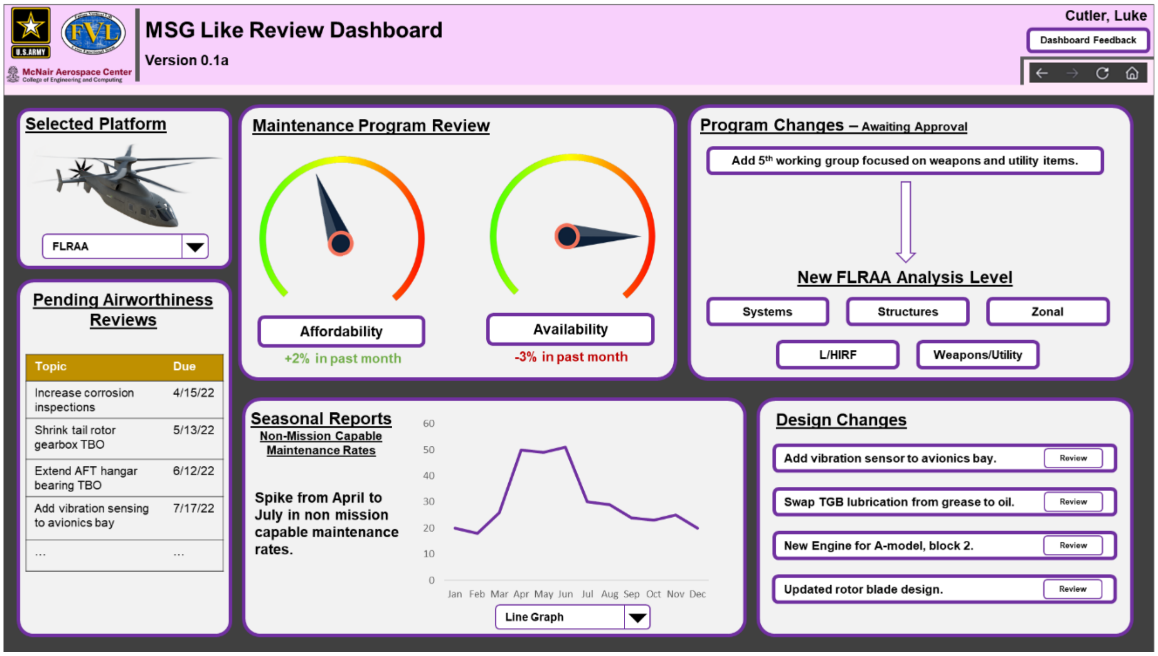

Figure A.2: A dashboard for a review member using MSG Like.

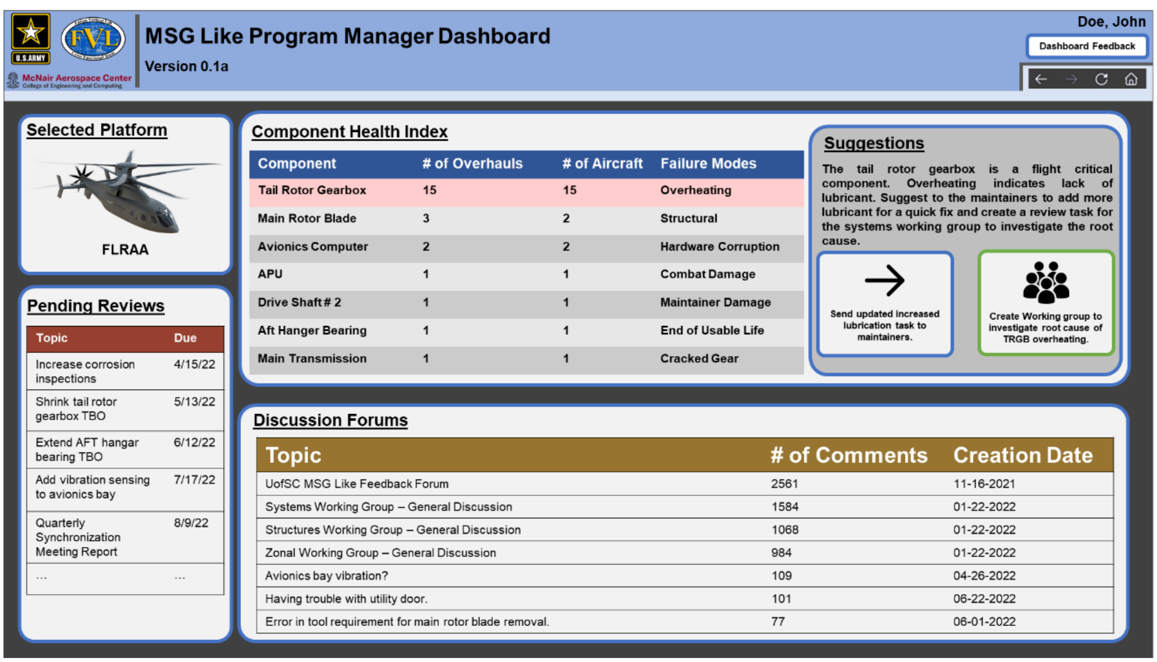

Figure A.3: A dashboard for a program manager using MSG Like.

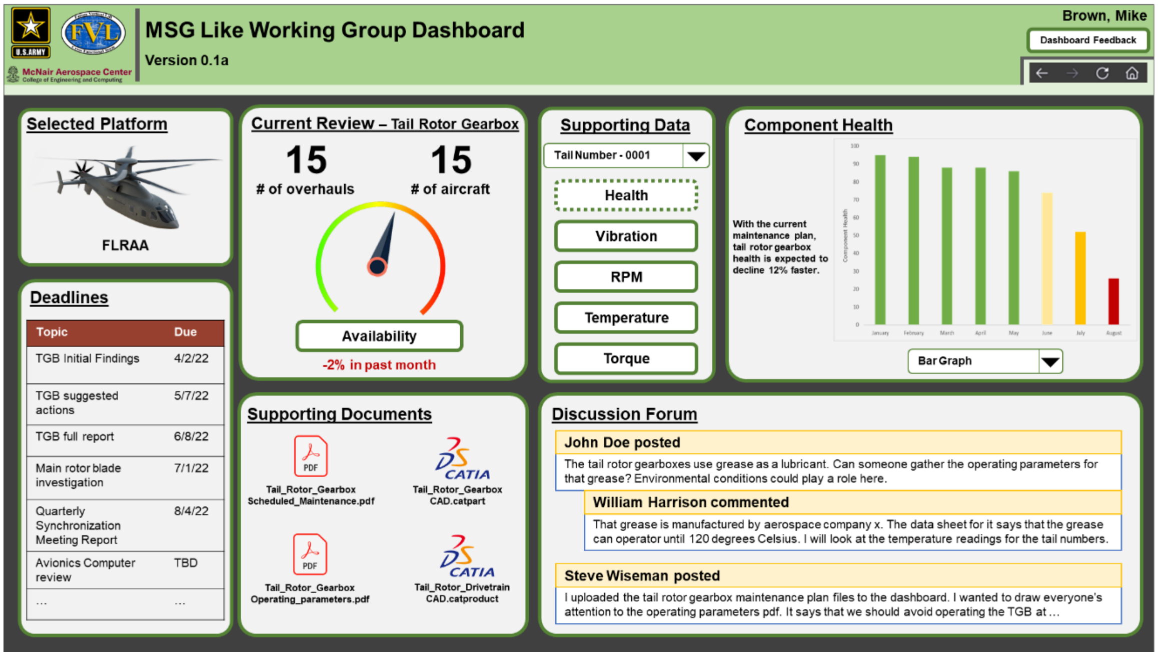

Figure A.4: A dashboard for a working group member using MSG Like.

APPENDIX B

AFP DEFECT PREDICTION MODEL

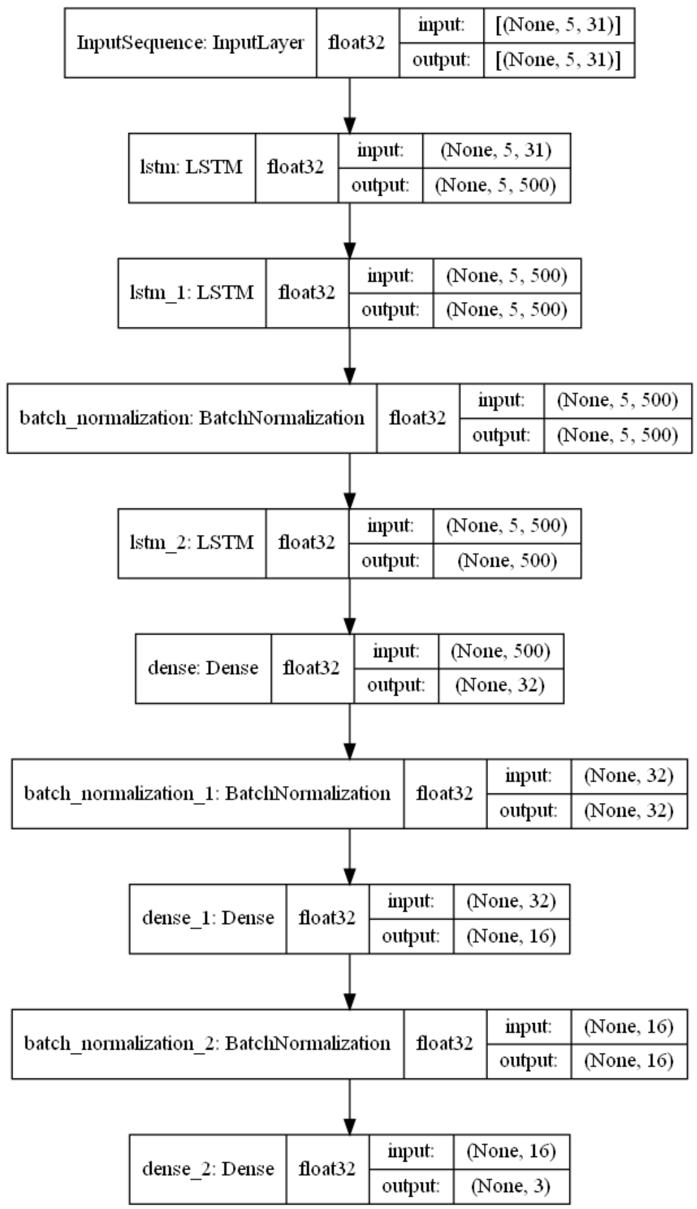

Figure B.1: The Layers of the AFP Defect Deep learning framework.