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A METHODOLOGY FOR DIGITAL TWINS OF PRODUCT LIFECYCLE SUPPORTED BY DIGITAL THREAD

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ABSTRACT

The technological advancement has led to the transition of manufacturing industries to Smart Manufacturing and Industry 4.0. Promising concepts such as Digital Twin and Digital Thread could help speed up the transition. One of the benefits of using digital twins is to allow the continuity of lifecycle information. However, currently, most of the digital twin implementations focuses on modeling a particular lifecycle stage of a physical element in "silos". It is challenging when incorporating diverse data streams from different lifecycle stages. Digital thread has been used to represent the information flow along the product lifecycle. Using information across Product Lifecycle stages will facilitate the interoperability and reusability of digital twins. Because data from each lifecycle stage could be accessed and managed systematically, this will ensure the value and the credibility of the digital twin. A lot of confusion still remains in industry about what are digital twin and digital thread as well as their relationships. In addition, using the lifecycle data from a digital thread for digital twin implementation is complex because of the heterogeneity of standards and technologies involved. In this paper, we provide definitions of digital twin and digital thread. We highlight the benefit of using them for interoperability and reusability of a digital twin for product lifecycle management and analysis. We propose a methodology for implementing digital twins using lifecycle data supported by a digital thread. Finally, we showcase the proposed methodology by providing an example of integrating digital twins with digital thread.

Keywords: Digital Twin, Digital Thread, Product Lifecycle, Manufacturing standards, Interoperability

1. INTRODUCTION

The advancement of new technologies including Internet of Things (IoT), Artificial Intelligent (AI), and Cloud Computing has enabled the development of digital twins. Shao highlighted the growing interest of manufacturing industry to digitized their processes and equipment making the Digital Twin "the center of the digital transformation" [1].

Digital twin is a digital representation of a physical element, enabled by real time and historical data collected from the physical element. One of the benefits of a digital twin is to ensure the information continuity throughout the lifecycle of its physical counterpart. Currently, most of the digital twin implementations are focusing on modeling a specific lifecycle stage of a physical element in "silos" [2]. This "silo-effect" makes it challenging when incorporating diverse data streams from different lifecycle stages to analyze or compare features across various lifecycle stages features.

Digital thread has been introduced to answer the industry needs to relate the different type of information available in the Product Lifecycle. It is has been mainly used to unify and orchestrate data across the lifecycle of a product, from design, to engineering, manufacturing, operation, and service. Integrating digital twins and digital thread would allow the best use of the product lifecycle information and facilitate the creation, integration, validation, and reuse of digital twins.

In the manufacturing industry, there still remains confusion about what is the difference between digital twin and digital thread and what kind of relationships they have. In this paper, we provide definitions of both concepts and describe the benefit of interoperability by combining digital twins and digital thread for Product Lifecycle management and analysis. We also propose a methodology to guide the implementation of digital twins supported by a digital thread. Finally, we showcase the proposed methodology by applying it to an example case study.

The remainder of this paper is organized as follows. Section 2 describes the product lifecycle stages and discusses the concepts and definitions of digital twin and digital thread. Section 3 introduces the methodology for implementing digital twins at the product lifecycle stages supported by the digital thread. Section 4 presents an example use case to further explain and showcase the methodology. Section 5 provides the conclusion.

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2. DIGITAL TWIN AND DIGITAL THREAD IN MANUFACTURING

This section first discusses the product lifecycle stages and then provides formal definitions of Digital Twin and Digital Thread in manufacturing.

2.1 Product Lifecycle stages

Terzi et al. [3] separated the product lifecycle into three different group following the product evolution through time: Beginning Of Life, Middle Of Life, and End Of Life. Each category groups different stages of the product lifecycle and define a specific aspect of the product through its conception to its dismissal. Hedberg et al. [4] defined the product lifecycle information and data into different categories, i.e., design, analysis, manufacturing, quality assurance, and customer and product support. This definition aims to encapsulate the different type of data that encompass the product lifecycle. For this paper, we chose to follow the simplified definition of manufacturing product lifecycle defined by Bernstein et al. [5]. The simplified product lifecycle allows us to focus the scope of our study to better analyze and understand the digital thread applications and the characteristics of the design, manufacturing, and inspection of a part in the product lifecycle.

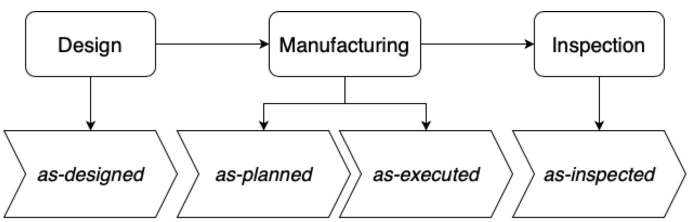

FIGURE 1: Schema representing the Manufacturing Product Lifecycle.

Figure 1 shows the simplified product lifecycle stages that focus on the design, manufacturing, and inspection of a product. The first stage represents the product "as-designed" before its production. Design related information such as Geometric Dimensioning and Tolerancing (GD&T) specifications, manufacturing and assembly considerations, are defined in order to ensure the production. The manufacturing stage consists of two aspects that respectively represent the process planning and the actual process execution. Data for the inspection stage describes plans, processes, and measurements that allow for the correct representation of the final product "as-inspected".

Each product lifecycle stage has been developed in "silos" to address a specific industry need [2]. Thus, standardized efforts have focused on describing and representing information to acknowledge precise processes in each particular product lifecycle stage. With the rapid development of new technologies and digitization in Smart Manufacturing, more and more data associated with each stage are created. However, due to those heterogeneous data standards and formats, effectively use and interoperate the data across the product life cycle stages is challenging. Digital twins that incorporate the data supported by digital thread will enable the systematic use of the data, ensure information continuity, support interoperability and reusability of the models and data.

2.2 Digital Twin

The Digital Twin Consortium defines the digital twin as “a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity" [6]. ISO defines “digital twin in manufacturing” as “a fit-for-purpose digital representation of an observable manufacturing element (OME) with synchronization between the OME and its digital representation" [7]. OMEs include personnel, equipment, materials, manufacturing processes, facilities, environment, products in a manufacturing environment. The synchronization between a digital twin and its physical elements is realized through real-time data collected by using IoT devices and smart sensors.

In the manufacturing domain, from product design to production optimization and quality control, there exist various applications that could benefit from implementing digital twins. For example, a real-time control application can monitor manufacturing elements through their digital twins and makes necessary changes to a manufacturing process near real-time; a predictive maintenance digital twin can monitor state changes of a physical system, identify anomalies, and schedule necessary maintenance activities with minimal interruption of the production; an engineering design application can use product digital twins to learn about previously manufactured products to optimize new and existing product designs.

2.3 Digital Thread

Reports have shown that a “need exists for information standards that derive requirements to facilitate up-stream and downstream flows in the product lifecycle, [and] data-format standards are not enough” [8]. Thus, realizing a digital thread across the product lifecycle stages is recognized to be challenging for the manufacturing industry [9]. In order to address and better understand this challenge, the link between existing data standards and formats needs to be identified and ultimately related to one another. However, due to the "silo" development of the product lifecycle stages standards, data are lost through the translation and transfer of information processes.

Thus, the Digital Thread concept has first emerged as a “metaphor” to represent the flow of information between the different standards defined to represent the data through the product lifecycle [10]. The NIST MBE Summit confirmed the industry actors’ interest in digital manufacturing and defined the Digital Thread as “the digital integration of design and production throughout the entire product lifecycle” [11]. Hedberg et al. [12] described the digital thread as "an integrated information flow that connects all of the phases of the product lifecycle using an accepted authoritative data source [and] provides the infrastructure needed to link heterogeneous systems to support decision making, knowledge generation, and control".

The digital thread concept is now considered a key enabler to Smart Manufacturing and Industry 4.0 and is crucial to advance manufacturing processes.

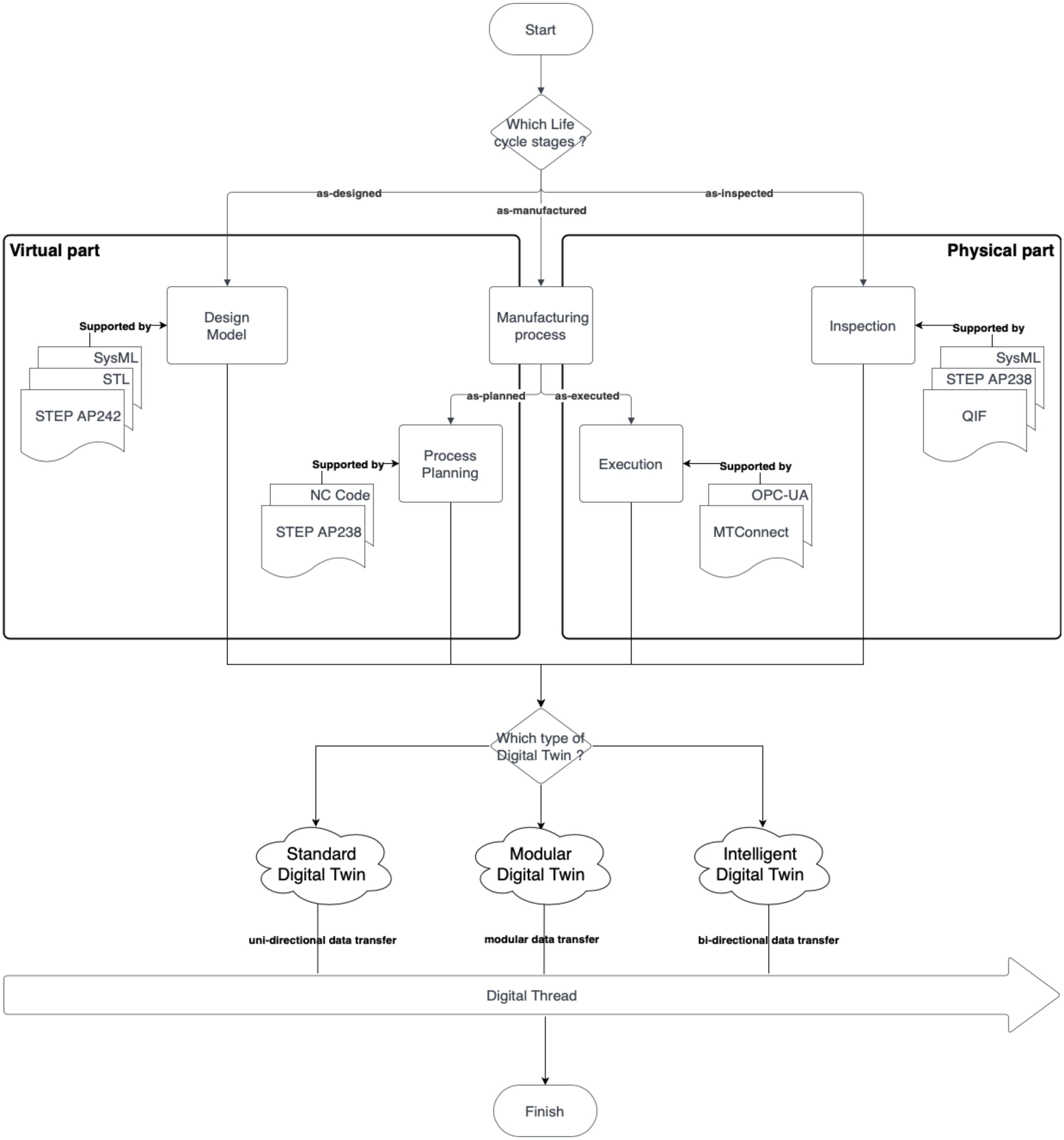

FIGURE 2: A methodology flowchart to design Digital Twin for Product Lifecycle supported by Digital Thread.

3. METHODOLOGY

To enable manufacturers better accessing product lifecycle data and building digital twins with a dynamic and systematic view, we propose a methodology to guide users to start their digital twin implementations. This methodology will provide a step-by-step procedure for manufacturers to follow when implementing digital twins at each lifecycle stage, where possible data types and formats, applicable candidate standards and technologies will be identified, and the types of digital twin implementations decide how data will be transferred from the digital thread to the digital twin.

3.1 Description of the methodology

Figure 2 depicts a flowchart of the proposed methodology to guide manufacturers to design a digital twin supported by a digital thread using the product lifecycle information. The digital thread represents the information about a specific part throughout its manufacturing lifecycle. The digital thread allows to retrieve and link the data corresponding to the processes executed in each stages to effectively produce the part. We assume that the preprocessing of the data in order to realize the digital thread have been done separately with the systems deployed in the manufacturing environment.

The digital thread allows manufacturers to access all the information related to a specific manufactured part. The digital twin is receiving a feed of data from the digital thread with standard formats. Thus, the resulting digital twin use the product lifecycle data to monitor status, diagnose faults, predict future operations, and optimize performance indicators. Most importantly, the digital twin can relate data from different life cycle stages to derive actionable recommendations.

The first step of the methodology is to identify the PL stages for which the digital twin will be created. Each lifecycle stage focuses on a specific aspect of the part at a specific point of time. Thus, each stage encompasses different information of the part throughout its manufacturing lifecycle. For example, the design stage contains GD&T information, the manufacturing stage contains process planning and execution information and the inspection stage contains quality related information of the part. At each stages, examples of data standards used have also been listed.

The data from each stage is linked through the digital thread that enables users to relate the specific information of the part at each lifecycle stage. This cross-linked dataset can then be used to feed the Digital Twin and represent the part being designed, manufactured and inspected at different point of time. The digital twin can then be designed and realized to answer the application needs. Note that, depending on the purpose of the digital twin application, the digital twin may only need data from one stage of the product lifecycle, e.g., a digital twin of the manufacturing process may only need data for the process executed.

The second step of the methodology help understand the interoperability between the digital twin and digital thread by deciding the type of digital twins and the data exchange requirements. The goal is to identify the type of Digital Twin needed in order to facilitate the transfer of information between digital twin and digital thread. We have defined three different types of digital twin implementations : the Standard, Modular, and Intelligent Digital Twins.

- **Standard Digital Twin** is a commonly used type of Digital Twin that aims to create a unique twin for a specific application. This digital twin allows for multiple analysis on its physical counterpart but doesn't support reusability or evolution of the application.

- **Modular Digital Twin** is a more advance type of Digital Twin that contains a core Digital Twin on which application specific module can be integrated. This type is adaptive and can be reuse for multiple application based on the same system. This digital twin allows to accommodate evolution of its physical counterpart and additional data types and formats.

- **Intelligent Digital Twin** is an autonomous Digital Twin that uses advanced technologies to systematically adapt itself based on new data flows or application requirements. This digital twin allows ensure the validity and accuracy of the twin by continuously updating itself based on evolution of its digital counterpart.

Figure 3 represents the standards implementation of a digital twin supported by a digital thread. Based on the specific digital twin application needs, data is pulled from the digital thread toward the digital twin. A new digital twin is developed for each application and each type of information is retrieve independently from the digital thread. The transfer of information is uni-directional from the digital thread to the digital twin.

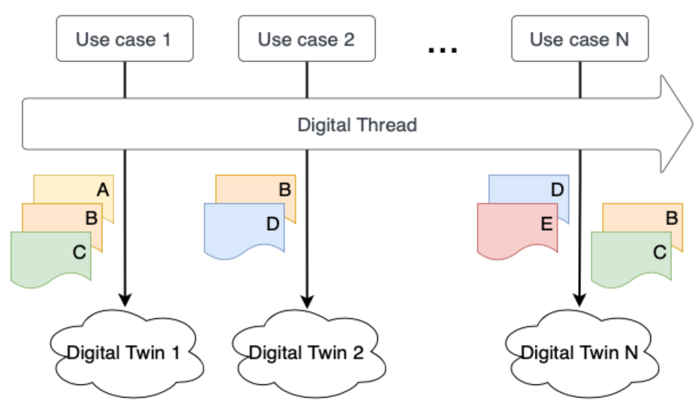

FIGURE 3: Schema representing the Standard Digital Twin implementation supported by the Digital Thread.

Figure 4 represents a modular implementation of a digital twin supported by a digital thread. A core digital twin will systematically retrieve a certain type of data from the digital thread. Modules will be added on top of the core digital twin to integrate additional information from the digital thread and address new application needs. The advantage of such solution is that there is less redundancy when integrating some data type and information in a specific digital twin application.

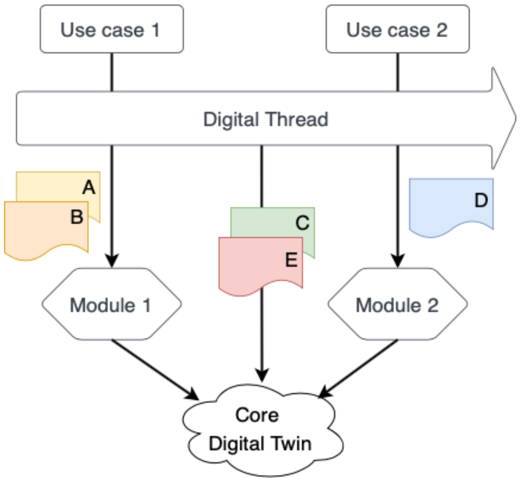

FIGURE 4: Schema representing the Modular Digital Twin implementation supported by the Digital Thread.

Figure 5 represents an intelligent digital twin supported by a digital thread. An autonomous digital twin is able to retrieve application specific information from the digital thread and is also able to adapt based on the evolution needs. The bi-directional exchange of data between the digital twin and digital thread allows users for an easier development of broader system applications.

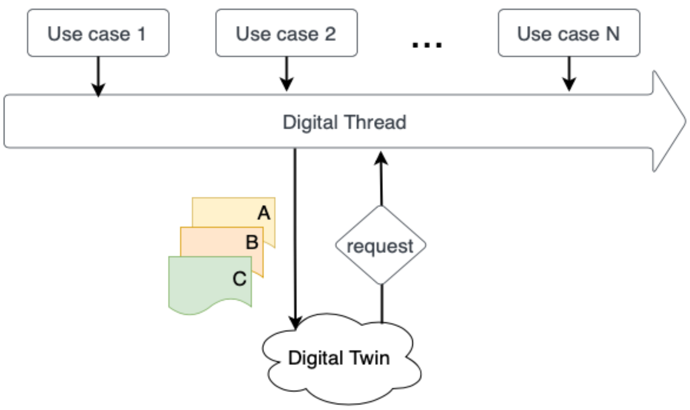

FIGURE 5: Schema representing the Intelligent Digital Twin implementation supported by the Digital Thread.

The scope of the methodology is to help manufacturers decide what standards to use, what data types are relevant at each life cycle stage and how to communicate with the digital thread for the types of digital twins they are building. The methodology does not specify detail building blocks for the digital twin implementations. Please refer to ISO 23247, Digital Twin Framework for Manufacturing, for guidelines of developing digital twins in manufacturing [1].

3.2 Manufacturing Data Standards

Table 1 presents an overview of the different data standards that are commonly used in the manufacturing industry for each product lifecycle stages. Sobel et al. [13] have categorized the standards commonly used in the manufacturing industry such as : Process, Semantic Models, Transport Syntax, Communication, Security. The presented overview focuses on Process, Semantic Models, and Transport Syntax manufacturing standards, related standards have been listed based on their types. The "X" signifies that the corresponding standards is used in the specified stages. However, a standard might be used to represent a specific information of a stage and not necessarily all the data used and produced in that stage. We will focus on describing one standard from each stages to give an example of how the information is managed in each stage.

	Standards	Design	Manufacturing		Inspection
		as-designed	as-planned	as-executed	as-inspected
Process	ISO 9000	X	-	-	X
	ISO/IEC 27001	-	X	X	-
	ISO 50001	-	-	X	-
	CMMI	-	X	X	-
	STEP-NC	-	X	-	X
	NC Code	-	X	-	-
Semantic Models	ISA 95	X	X	-	-
	STEP AP242	X	-	-	X
	QIF	X	X	-	X
	STL	X	-	-	-
	SysML	X	-	-	-
Transport Syntax	OPC/UA	-	-	X	-
	MQTT	-	-	X	-
	AMQP	-	-	X	-
	MTConnect	-	-	X	-

TABLE 1: Standards used in the Manufacturing Product Lifecycle categorized by data representation.

In the design stage, design information can be represented using STEP AP242. ISO 10303, also referred as STandard for the Exchange of Product Data (STEP), follows the EXPRESS schema representation and group together different Application Protocols (AP) that aims to standardize the product lifecycle. STEP AP 242 [14] have been developed to represent geometric features and design information so that different Computer Aided Design (CAD) tools can export and exchange designs in the same format.

The manufacturing stage is composed of two phases that produce different type of data. The "as-planned" phase may use standard such as STEP AP238 or STEP-NC [15] and Numerical Control (NC) Code [16] to characterize the machining operation. MTConnect [17] and OPC/UA [18] aims to standardized the communication protocols from the machine controller in order to capture the data "as-executed" throughout the machining process.

In the inspection stage, the Quality Information Framework (QIF) [19] can be used to plan, represent, store and exchange inspection data from processes to measurements.

4. EXAMPLE USE CASE

To demonstrate our methodology, we apply it on a test part dataset from the Smart Manufacturing Systems (SMS) Test Bed repository at NIST. Shaw et al. developed a case study on a heat sink part for power electronics components in an aerospacebased application [20]. Figure 6 represents the design and model of the heat sink part. The end goal of the study was "to reflect on real manufacturing (as-executed) data to suggest changes with the planning procedure of a design".

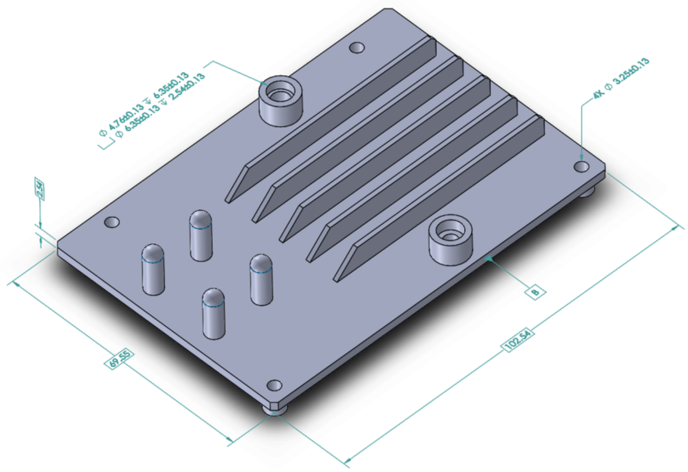

FIGURE 6: Solid model of the heat sink part used in the case study. Adopted from Feng et al. [20].

4.1 Use case description

Our use case digital twin focuses on informing the design to help decision making and improve the manufacturing process. Figure 7 shows the difference between simulated planned execution data and the actual measured machine data. Discrepancies between the estimated planned time of execution and the actual machine operation duration are highlighted in red. For the designed part, there are discrepancies from the design to the actual final part and from the planned machining execution and actual executed operation.

From the conceptual design to the inspected part there is several different standards. In this example, the total data package of the part includes the full set-up sheets, Computer Aided Manufacturing (CAM) programs, machine instructions in NC code (ISO 6983 [21]), design data as an STEP AP242 file [22], operation data collected via MTConnect [17] and simulated QIF [19] data generated from the native CAD file. Feng et al. developed a data driven digital thread to link the different data types and standards throughout the product lifecycle of the part.

Thus, in order to reconcile the planned execution and the actual machine operation, a digital twin of the part design and a digital twin of the machining process will help analyze machine operation to optimize design choice and process planning.

4.2 Apply the methodology

The first step of our methodology is to analyze the digital twin needs and identify the lifecycle stages involved for the digital twin to answer application needs. The digital thread have already been implemented to relate the data standards used for each lifecycle stages [20]. The data as-designed, as-planned, as-executed and as-inspected have been linked in order to follow the manufacturing lifecycle of the heat sink part.

The first data type in the digital twin implementation is the design model from the STEP AP242 part design and specifications. The design model of the part describes its geometry, which is the baseline for comparing with the manufactured part (shown in Figure 7 as the design feature highlighted). Since we are focusing on comparing the expected and actual machine operations in this case, we don't need the tolerancing and design specific manufacturing requirements that focuses on the physical part geometry.

The second data type in the digital twin implementation is the process planning of the machine operation from G-Code. We need to use the G-Code data to simulate the planned machine operation (shown in Figure 7 as the *Simulated* tool position) and have an expected timeline of the machining process.

The third data type in the digital twin implementation is the actual machining operation execution retrieved using MTConnect from the machine controller. We need the executed machining operation to realize the actual operation timeline of the machining process (shown in Figure 7 as the *Measured* tool position).

The inspection data of the physical heat sink part that have been manufactured is not needed in this digital twin example. We are focusing on improving the designed part and the manufacturing efficiency by analyzing the machining process planned and executed operations. Thus the data from the inspection of the physical part is not needed.

The second step of our methodology is to identify the type of digital twins for the use case to enable a comprehensive interoperability with the digital thread.

Since the standards and types of data are known and we do not anticipate additional data formats to be included in the digital twins. The Intelligent Digital Twin type is not relevant because we don't need the digital twin to automatically analyze and adjust the required information for this use case. Thus, a bi-directional data transfer between the digital twin and the digital thread is not be necessary for this use case.

The Standard Digital Twin could be used to develop digital twins for representing the design model, and the planned and executed machining operation, which means data transfer will be a single uni-directional link from the digital thread. This digital twin will help optimize the heat sink part design based on the machining operation discrepancies.

However, we decided to select the Modular Digital Twin type in order to allow for a potential broadening of the scope of the digital twin. Indeed, the machining operations are not the only factor that could affect the efficiency of the manufacturing process. The inspection information from the QIF data might be relevant in optimizing the design. The design tolerances and specifications might also affect the operation timeline and efficiency. Thus, we choose the modular digital twin with a core digital twin that would receive design model information from the digital thread and a first module receiving planned and executed machining operation. This way, we will have the opportunity later to add additional modules that could manage other relevant data standards such as QIF data, for example.

Finally, to exchange information with the digital thread, the first digital twin module will manage the simulated planned machine operation from the G-Code simulation and compare the

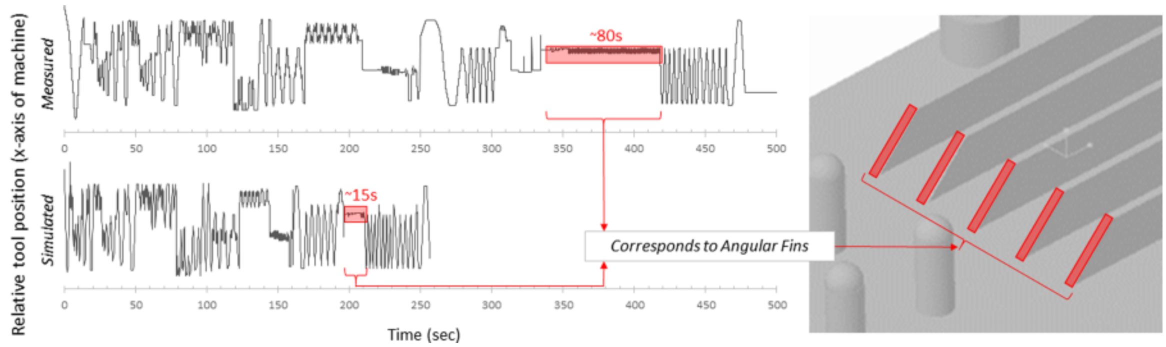

FIGURE 7: Comparison of simulated data for planned part build compared to actual machine data. Adopted from Feng et al. [20].

actual machining operation provided by MTConnect from the machine controller data. The core digital twin supported by the digital thread will manage the model design from the STEP AP242 model and incorporate the machining process planned and executed machining operation from the first module. Then, analysis on the digital twin representation of the heat sink design and operation product lifecycle stages will allow to identify specific design features that affect the machining process efficiency, such as Angular Fins, in this use case.

4.3 Analyze the methodology

Our systematic methodology aims to guide the implementation of digital twins across the product lifecycle supported by a digital thread to leverage the relevant information from different lifecycle stages. In this use case example, we showcase that this methodology allows manufacturers to systematically utilize and analyze the manufacturing lifecycle information and empowers digital twin with information continuity, in turn to enable better model and data reusability and interoperability. We also highlighted the importance of using the digital thread to support the digital twin development for cross product lifecycle stages and the interoperability between digital twin and digital thread.

However, in this paper, we only focus on the manufacturing process from the design to the inspection of the product. We didn't include the Middle of Life of the product, i.e., the distribution, the use and the support stages, nor the End of life, i.e., the retiring, recycling and dismissing, of the product. We anticipate that this methodology could be extended to include the corresponding product lifecycle stages by identifying and analyzing relevant data types, standards, and technologies . This will be our future work for the next step.

5. CONCLUSION

Digital twin and digital thread concepts are key enabler to Smart Manufacturing and industry 4.0. However, the interoperability between the two is still under research and a lack of common understanding remains about what they are and how they are related. In this paper, we attempted to provide formal definitions of the digital twin and digital thread concepts and highlighted their relationships throughout the product lifecycle. We also proposed a methodology to help implement digital twins supported by a digital thread throughout a simplified product lifecycle stages. We finally showcased the proposed methodology using a use case from the NIST SMS Testbed and focused on demonstrating the interoperability between digital twin and digital thread.

The goal of our methodology is to provide a systematic approach to implement a digital twin that could encompass information from multiple lifecycle stages and use a digital thread to link the different type of information to the digital twin applications.

DISCLAIMER

REFERENCES

[1] Shao, Guodong et al. "Use Case Scenarios for Digital Twin Implementation Based on ISO 23247." *National Institute of Standards: Gaithersburg, MD, USA* .

[2] Helu, Moneer, Joseph, Alex and Hedberg Jr, Thomas. "A standards-based approach for linking as-planned to as-fabricated product data." *CIRP Annals* Vol. 67 No. 1 (2018): pp. 487–490.

[3] Terzi, Sergio, Bouras, Abdelaziz, Dutta, Debashi, Garetti, Marco and Kiritsis, Dimitris. "Product lifecycle management–from its history to its new role." *International Journal of Product Lifecycle Management* Vol. 4 No. 4 (2010): pp. 360–389.

[4] Hedberg, Thomas, Feeney, Allison Barnard, Helu, Moneer and Camelio, Jaime A. "Toward a lifecycle information framework and technology in manufacturing." *Journal of computing and information science in engineering* Vol. 17 No. 2.

[5] Bernstein, William Z, Hedberg Jr, Thomas D, Helu, Moneer and Feeney, Allison Barnard. "Contextualising manufacturing data for lifecycle decision-making." *International journal of product lifecycle management* Vol. 10 No. 4 (2017): pp. 326–347.

[6] Digital Twin Consortium. "The definition of Digital Twin." (2020). URL https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin.htm.

[7] ISO 23247-1. *ISO 23247-1: Automation Systems and Integration - Digital Twin Framework for Manufacturing - Part 1: Overview and general principles*. International Organization for Standardization, Geneva, Switzerland (2021).

[8] Hedberg Jr, Thomas D., Hartman, Nathan W., Rosche, Phil and Fischer, Kevin. "Identified research directions for using manufacturing knowledge earlier in the product life cycle." *International Journal of Production Research* Vol. 55 No. 3 (2017): pp. 819–827. DOI 10.1080/00207543.2016.1213453.

[9] Helu, Moneer and Hedberg Jr, Thomas. "Enabling Smart Manufacturing Research and Development using a Product Lifecycle Test Bed." *Procedia Manufacturing* Vol. 1 (2015): pp. 86–97.

[10] Feeney, Allison Barnard, Frechette, Simon P. and Srinivasan, Vijay. "A Portrait of an ISO STEP Tolerancing Standard as an Enabler of Smart Manufacturing Systems." *Journal of Computing and Information Science in Engineering* Vol. 15 No. 2. DOI 10.1115/1.4029050. Accessed 2022-04-05, URL https://doi.org/10.1115/1.4029050.

[11] Lubell, Joshua, Frechette, Simon P, Lipman, Robert R, Proctor, Frederick M, Horst, John A, Carlisle, Mark and Huang, Paul J. "Model-Based enterprise summit report." Technical report no. Army Research Lab Abderdeen Proving Ground MD Weapons and Materials Research ... 2014.

[12] Hedberg, Thomas, Helu, Moneer and Sprock, Timothy. "A Standards and Technology Roadmap for Scalable Distributed Manufacturing Systems.": p. V003T02A019. 2018. DOI 10.1115/MSEC2018-6550.

[13] Sobel, Will. "AVM Task 3: Standards Development and Promulgation." Technical report no. National Institute of Standards and Technology. 2016.

[14] ISO 10303-42. *Industrial automation systems and integration – Product data presentation and exchange – Part 42: Integrated generic resource: Geometric and topological representation*. International Organization for Standardization, Geneva, Switzerland (2003).

[15] Hardwick, Martin and Loffredo, David. "Lessons learned implementing STEP-NC AP-238." *International Journal of Computer Integrated Manufacturing* Vol. 19 No. 6 (2006): pp. 523–532.

[16] Association, Electronic Industries et al. *Interchangeable Variable Block Data Format for Positioning, Contouring, and Contouring/Positioning Numerically Controlled Machines*. Electronic Industries Association (1980).

[17] MTConnect Institute. "MTConnect Standard." (2014). URL http://www.mtconnect.org/. Accessed on 03.31.2017.

[18] Leitner, Stefan-Helmut and Mahnke, Wolfgang. "OPC UA–service-oriented architecture for industrial applications." *ABB Corporate Research Center* Vol. 48 No. 61-66 (2006): p. 22.

[19] Dimensional Metrology Standards Consortium. "Part 1: Overview and Fundamental Principles in Quality Information Framework (QIF) - An Integrated Model for Manufacturing Quality Information." (2014). URL http://qifstandards.org/. Accessed on 03.31.2017.

[20] Feng, Shaw C, Bernstein, William Z, Hedberg, Thomas and Barnard Feeney, Allison. "Toward knowledge management for smart manufacturing." *Journal of computing and information science in engineering* Vol. 17 No. 3.

[21] ISO 6983-1. *Automation systems and integration – Numerical control of machines – Program format and definitions of address words – Part 1: Data format for positioning, line motion and contouring control systems*. International Organization for Standardization, Geneva, Switzerland (2009).

[22] ISO 10303-242. *Industrial automation systems and integration – Product data presentation and exchange – Part 242: Application protocol: Managed model based 3d engineering*. International Organization for Standardization, Geneva, Switzerland (2014).