Digital Twins for Part Acceptance in Advanced Manufacturing Applications with Regulatory Considerations

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Prepared for the 46th MPA Seminar
October 12-13, 2021
Stuttgart, Germany

Introduction

Regulated industries such as the nuclear industry have long been risk averse when certifying new parts and designs, a necessity given the possible implications and consequences of a part failure. These industries often default to a legacy approach, with established parts and known quantities. This legacy approach applies to how parts are manufactured as well. Subsequently, parts developed with unproven or still maturing manufacturing technologies face significant hurdles when vying for acceptance.

Today' advanced manufacturing processes have fundamentally changed how parts can be designed and fabricated. Advancements in manufacturing technologies, sensor technologies, and inspection technologies, accompanied by advancements in digital technologies, have resulted in new paradigms in how parts are developed, procured, and accepted. Additive manufacturing processes personify these advancements. AM processes have created a disruption in how manufactured parts are evaluated, as the uncertainties of these processes have created general trepidation about their acceptance. As digital manufacturing processes, however, AM processes generate substantial amounts of data at each stage of their design to product transformation. This data can be used to create a digital twin of the manufactured part and thus address challenges associated with legacy requirements by leveraging a new paradigm in part acceptance.

In this work, we review basic acceptance criteria for parts. We then characterize these criteria in the context of a part's functional requirements and its manufacturing process signatures. Observations from these characterizations are then related back to the AM design-to-product transformations, identifying correlations between legacy data sets and AM data sets. Finally, understanding digital twins provide a virtual status of a physical counterpart, we posit that a digital manufacturing process such as additive manufacturing should theoretically be a more risk averse option than traditionally manufactured parts, as the digital twin should be able to provide almost "on-demand" insight into the state of the part at any given point along its production process. A case study is presented to demonstrate how a digital twin may be used to provide better insight in an advanced manufacturing process than what is achievable with more traditional manufacturing processes.

Introduction

The acceptance of a new part or process by an organization is almost always predicated on the process or part first being qualified. The concept of "qualification" is widely understood as a demonstration of the ability to meet a required standard [1]. However, the specifics for something to become qualified depend greatly on context and established criteria. When used in the context of a process or a part, qualification can refer to the ability of that process or part to satisfy pre-established standards or performance requirements. In process qualification, these requirements are often related to the demonstration of repeatability and reliability. In part qualification, these standards are often related to the geometry, behavior, and reliability of the part. Part and process qualifications are often linked and there is an expectation of process reliability and repeatability for the consistent fabrication of qualified parts.

"Advanced Manufacturing" is a somewhat fluid term, since the term "advanced" implies that "less-advanced" (though often more mature) alternatives exist. Today's advanced manufacturing processes have fundamentally changed how parts can be designed and fabricated. Characteristics of these processes often include new processing technologies, increased automation, and increased digitalization [1]. While the term "advanced" is most often associated with "improved," in practice, advancements over "established norms" welcome increased scrutiny. As new unknowns are introduced into the fabrication of parts that have otherwise benefited from long established legacies, there is need for additional scrutiny of parts and the processes used to create them. With industries increasingly incorporating advanced manufacturing processes, industry sectors with high-threshold, part-acceptance criteria are facing new challenges in part qualification [2-5].

While thresholds for acceptance will vary greatly depending on applications, industry sectors with safety-critical applications, such as aerospace, energy, or medical, set the most stringent requirements. The reason is that a failed part could have a detrimental impact. Consequently, such industries are understandably risk averse when incorporating changes into accepted procedures. The preference is almost always to remain with the "tried and proven" legacy approaches over those less established. Subsequently, parts developed with unproven or still maturing manufacturing technologies face significant hurdles when vying for acceptance.

This work posits that by using a digital-twin approach, a digital manufacturing process has the potential to be more risk averse than many of today's more established processes. By deconstructing physical parts into sets of discrete digital representations, the digital twin should be able to provide almost "on-demand" insight into the state of the part at any given point along its production process. In addition, the discretized nature of the digital twin provides a unique mechanism for decoupling intrinsic, part characteristics from instances of observed part behaviors. This decoupling supports the normalization of observed behaviors across different parts and processes with similar characteristics, creating new resources on which acceptance criteria can be established. It is under this premise that the true effectiveness of the digital twin can be realized in facilitating the acceptance of parts.

In exploring part acceptance applications, some basic acceptance criteria for the fabrication of a part with a manufacturing process are reviewed. Part and process criteria in the context of a part's functional requirements and its manufacturing process signatures are discussed. A method for

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[1] https://www.merriam-webster.com/dictionary/qualify

establishing a digital twin in consideration of all aforementioned criteria is presented. Finally, the case study postulates how a digital twin may be used to provide better insight into an advanced manufacturing process than what is achievable with more traditional manufacturing processes.

Background

The digital nature of advanced manufacturing processes lends itself well to the still-maturing concept of the "digital twin." At its core, "digital twin" refers to the notion that a "thing" can be represented through a "digitized, virtual counterpart." Grieves and Vickers [6] originally defined the digital twin as ''a digital informational construct of a physical system as an entity on its own." A digital twin can be further defined as "*a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making.*[2]" This still broad definition allows for various interpretations of implementations, or adaptations, on which the basic premise of a digital twin can be developed. This basic premise of any adaptation of a digital twin includes 1) the creation of a virtual representation and 2) a link to a system throughout its entire lifecycle, on which analyses can be performed [7].

In manufacturing, the digital twin can provide flexibility in what otherwise may often be considered rigid scenarios. Shao et al [7] note that "Applying the digital concept to manufacturing allows manufacturers to create fit-for-purpose digital representations of their production systems and processes using collected data and information to enable analysis, decision making, and control for a defined objective and scope." In exploring the digital twin as a tool to support manufacturing, they note that different scales—such as machine, facility, or supply chain—can be adopted. The authors pose that a digital twin depends on context and viewpoint, including the process, product, and system viewpoints. In this sense, the concept of a digital twin can also be considered scalable, since new contexts and viewpoints do not necessitate new digital twins. Instead, they scope the twin to a specific application.

Understanding that the concept of a digital twin is both scalable and adaptable lends itself to many different application scenarios. As noted above, for a given scenario, the appropriate adaptation of a digital twin very much depends on the context for which the digital twin is being developed and adopted. One common distinction between the applications of digital twins is the ability to serve as both a simulation and an emulation [7]; and, which of these defines the twin's behavior may very much depend on the scale at which it is being implemented. For instance, a digital twin of a machine may be used to emulate the fabrication of a simulated part. That same digital twin of the machine may be later used to simulate the machine's behavior in an emulated factory setting. The following paragraphs explore some of the emerging adaptations in the manufacturing industry, and how these adaptations may be leveraged to support qualification.

Digital twins are increasingly being deployed in the operations and maintenance (O&M) stages of the product lifecycle, from deployment to retirement, for both parts and the machines used to create them [8-10]. These applications are often used to monitor the health of a part or machine and exploit the ability of sensors to provide real-time data to evaluate system performance. Such real-time awareness can provide detailed information about the state of a system on demand. The adoption of digital twins in the O&M context has allowed for unintrusive monitoring of field-deployed systems through

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[2] https://www.ibm.com/blogs/internet-of-things/iot-cheat-sheet-digital-twin/*)*

commercial sensors, sensor data, and data analytics. Such applications can provide newfound assurance that a deteriorating part or machine can be repaired or replaced prior to failure.

Another increasingly common adaptation of a digital twin involves the design and analysis of complex systems [11-13]. These systems may range from production environments, such as a facility, to complex products, such as an airplane. In such applications, the digital twin provides an environment in which components can be configured and reconfigured, unattached from their physical counterpart. Using a digital twin, the performance of components can be tested 1) within the system scope and 2) within the behaviors of larger systems. Such adaptations of a digital twin allow organizations to reduce reliance on trial and error on more cumbersome physical systems. When integrated into the system, these digital twins can be used to support system reconfiguration "on the fly" by modifying system behaviors to adapt to changing environments. Such applications support the evaluation of behaviors of complex systems, and how changes in constituents or environments impact the behavior of the system as a whole.

Finally, an emerging adaptation of the digital twin focuses on the development and manufacture of individual parts. Alongside the introduction of the digital twin in [14], the appropriateness of using the digital twin concepts for the qualification of advanced manufacturing processes and parts was first discussed by Witherell et al in [15]. In exploring additive manufacturing, the authors note that the complexity of the process-part interactions lend themselves well to the digital twin concept. This observation can be extended beyond additive manufacturing to advanced manufacturing. In advanced manufacturing adaptations, the digital twins mirror the systems and processes that create the part and/or the process used to fabricate the part. Scoping a digital twin to the complex part-process interactions in advanced manufacturing allows for observing how changes in process behaviors affect part quality. Understanding these changes provides a basis for which both part and process qualification may be achieved.

The following section explores the idea of using these digital twins to capture the development and manufacture of a part fabricated using advanced manufacturing processes. The intent is to investigate how the digital, piecewise nature of these processes can be exploited to account for process variances during the manufacture of the part. By establishing acceptable baselines, or thresholds, these digital twins can be used to provide assurance after, or ex situ, and during, or in situ, the development and manufacture of parts. While these assurances stray from the traditional legacy requirements, when properly articulated, they can offer uninhibited insight into parts and their manufacture.

Establishing Digital Twins to Facilitate Part Acceptance

By scoping a digital twin to the facilitation of part acceptance, both the scale and application of the digital twin can be constrained, allowing for the further refinement of its definition. For successful adoption of any digital twin to support qualification, regardless of the adaptation, a baseline of expected performance must be established. Here, to establish a baseline, the digital twin requires two types of criteria, the incorporation of 1) the physical environment in which it is being developed and 2) the physical environment in which it is being deployed. Establishing these criteria types allow for the development of a digital twin that 1) is representative of the part-process interactions that occur during part fabrication and 2) accounts for the conditions set forth by an operating environment in which the part or process is deployed. Posing these requirements as two separate types of criteria supports the notion that both "qualification" and "acceptance" must be contextualized. Additionally, parts must be qualified against both the process used to create them and the application for which they are intended. This separation is key to establishing the use of digital twins as a means for facilitating part acceptance in various sectors.

A proposed five step methodology for developing a digital twin for part acceptance involves 1) establishing purpose through context and scope, 2) establishing basic, fundamental criteria and context specific criteria, 3) correlating metrics between the two types of criteria, 4) establishing equivalent target criteria, or thresholds, between the two types of criteria, and 5) establishing the target digital twin. Figure 1 outlines the proposed methodology, which is further detailed in the case study.

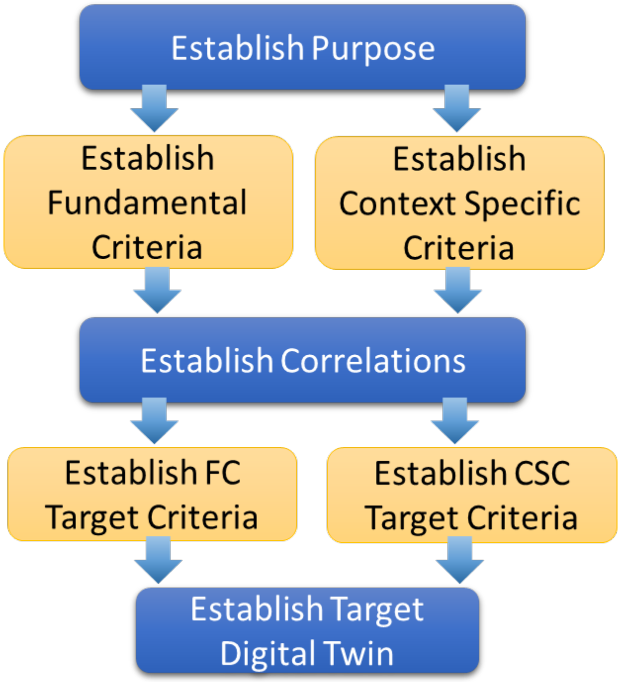

Figure 1. Method to develop digital twins for part acceptance.

The uniqueness of the proposed methodology is centered around the development of two sets of criteria that must be met in developing a digital twin for part acceptance: fundamental criteria (FCs) and context-specific criteria (CSCs). The fundamental criteria focus on observing, capturing, and analyzing the part-process interactions during the fabrication of a part. These criteria are meant to help establish a digital twin that reflects the build of the part, irrespective of the application. The context-specific criteria focus on the context and application for which a part is to be developed. The CSCs are meant to be process agonistic, and thus focus on part characteristics that will influence performance requirements. While the FCs and CSCs can be established separately, they are by no means independent. Successful application of the digital twin for part acceptance requires careful definition and integration from both sets.

Establish FCs- To facilitate part acceptance, five fundamental criteria (FCs) are proposed for establishing a digital twin. They include 1) definition of characteristics associated with a successful execution of the fabrication process (e.g., validation against an established predictive model), 2) definition of the characteristics for a "quality" part (e.g., no crack formation), 3) established linkage (e.g. data registration plan) to establish correlations between process characteristics and part characteristics, 4) identification of available process or part signatures to quantify relevant part characteristics, (e.g. microstructure, surface roughness, or localized temperatures), and 5) determination of acceptable metrics and measurement techniques that can be used to quantify part characteristics (e.g. grain orientation, average roughness). These five criteria form the fundamental basis on which a well-characterized digital twin can be established for the part fabrication process. In addition, a basis is formed to which additional criteria, CSCs, can be associated.

Establishing CSCs- Context-specific criteria (CSCs) associate performance requirements to the fabrication of the part. CSCs essentially help to normalize part and performance characteristics through the digital twin. The five criteria for establishing the CSCs are 1) identification of performance requirements that must be met for part qualification (e.g. cyclic loading requirement), 2) identification of part properties/characteristics that directly or indirectly determine part performance (e.g. surface roughness), 3) identification of metrics to quantify those part properties identified (e.g. average roughness), 4) establishment of baseline thresholds for identified metrics that must be satisfied to ensure the part is able to meet requirements defined in 1), and 5) incorporation of uncertainty into thresholds identified in 4).

Establishing correlations – Clearly, FCs and CSCs are highly correlated. Establishing those correlations, however, requires a well-defined scope. In leveraging CSCs to facilitate part acceptance, the scoping of both the CSCs and FCs must be complementary, where there is clear overlap in context and metrics. To leverage the digital twin for part acceptance, established CSCs should be used to inform desired FCs. Characteristics related to the performance of the part during deployment should be used to inform the expected properties of the part during fabrication. In this scenario, an emphasis is placed on developing the FCs to meet the thresholds established by the CSCs. The target digital twin will incorporate inputs from both FCs and CSCs. While FCs are determined by the advanced manufacturing process, the following section explores some of the factors that may influence the establishment of CSCs in regulatory scenarios.

Using Digital Twins under Regulatory Considerations

In adopting a digital twin approach for qualification, the establishment of correlations is the quintessential component. Correlations provide the ability to recognize how changes in observed behavior affect the expectations of quality throughout. Strong, well-defined correlations are desired, with the expectation that implications from minor changes in observed behavior can be well articulated throughout the digital twin. The ability to establish such correlations requires 1) precise, granular data management, 2) observed, controlled repeatability and reproducibility in measurements and behaviors, and 3) well-formed, deliberately scoped analytics. How these three requirements are met are often subjective and will ultimately dictate the ability to implement any digital twin.

In regulated industry sectors, past performance often triumphs over anything else. For example, the introduction of new materials can often take years, or even decades [16], since understanding material performance over time is critical. The adoption of new parts and systems has shown to be an equally daunting task [17]. Part acceptance in regulated environments is complicated by factors such as criticality, safety, and risk. Subsequently, regulatory sectors rely heavily on prolonged testing methodologies where reliability is established over prolonged periods of time.

While technology supports ample data creation in the development of FCs, the establishment of CSCs benefits from established track records. In the testing phases of a part, the digital twin can provide a platform for which testing results can be curated and expressed through the establishment of CSCs. Establishing a digital twin on existing parts with measured performances creates valuable data that can be leveraged in the introduction of any new part. This approach uses the premise that when a new material or system is to be put into development, performance measurements from related legacy parts should play a key role in their acceptance. This premise emphasizes the notion that establishing correlations between the FCs and CSCs provides valuable insight into expected part performance.

By normalizing performance expectations with CSCs, performance requirements at the part's macroscale can be reduced to intrinsic part characteristics that can be measured at the mesoscale. When establishing correlations between the CSCs and FCs, the goal is to establish a sense of equality between the new part and established parts that have previously met similar performance criteria. While the processes used to create the parts may be different, the goal is to establish similarities in measurable mesoscale characteristics such as microstructure, porosity, or surface roughness. With established similarities, the digital twins can be used to instill/develop confidence in the pre-deployment stages of parts. The objective is to develop "parity" in the production processes, while also introducing baseline acceptance criteria for anticipated performance requirements. Such a scenario is described in the following section where a part is created for the energy sector using additive manufacturing (AM) technologies.

Case Study: Digital Twin in Additive Manufacturing

AM technologies epitomize digitalization in advanced manufacturing processes as they generate substantial amounts of data at each stage of their design-to-product transformation. This data can be used to create a digital twin of the manufactured part and thus address challenges associated with uncertainties in these processes that have created general trepidation about their acceptance. This section articulates this concept using AM as an example of addressing legacy requirements by leveraging a new paradigm in part acceptance.

Metals AM processes have significantly matured in the past decade. AM processes are providing new design freedoms and new processing freedoms for both legacy and new part designs. These designs are particularly attractive for low volume, high complexity parts. Additive manufacturing, also referred to as 3D printing, is a digital manufacturing process that creates a part layer-by-layer until a full part is realized. While these layer-by-layer processes offer numerous design and process flexibilities [18], they also introduce new uncertainties into the part. Given the nature of the layer-by-layer process, material properties are formed locally as the metal is melted and solidified. As a result, parts created with these processes are subject to increased variability, even with additional post-processing steps [19].

Two AM processes that are being increasingly adopted by industry to create parts in safety-critical sectors are Powder Bed Fusion (laser and electron beam) and Directed Energy Deposition (DED). Each process comes with advantages: powder bed fusion (PBF) is better for smaller parts with tighter tolerances and DED is better for larger parts. While the two processes take different approaches to part fabrication, their digitally driven, layer-by-layer natures remain the same. Subsequently, AM processes are subjected to additional scrutiny when submitted for acceptance to certification authorities and thus have created a disruption in how manufactured parts are evaluated. Their piecewise, digital natures, offer unique opportunities for observing, measuring, quantifying, and analyzing the parts as they are being fabricated [20-22].

As noted in the previous sections, the establishment of "quality" can be subjective, and the introduction of new parts and new applications can create additional challenges. Here, we will go step by step through the creation of a target digital twin for part acceptance, following the stages shown in Figure 1.

Establishing Purpose-In this scenario, the assumption will be that a legacy part deployed in a well-studied environment will be replaced with a similar part fabricated by AM. This assumption allows for the focus of the digital twin to be placed on demonstrating production equivalency to that of a pre-existing part. The scope of the digital twin will thus be limited to the part production phase of a traditional part. The emphasis will be on building confidence in the process and confidence that a part made with AM is equivalent to one made with more traditional parts (i.e., reducing risk of adoption). We will assume the traditional part must have a specified surface hardness and performance under extreme heat.

Establishing Fundamental Criteria- In establishing the FCs for a digital twin for an additive manufacturing process, we will define the "quality" threshold based on studies of a traditionally manufactured counterpart. For brevity, we will focus on the creation of part geometry with a homogeneous microstructure.

Here, we will define the five fundamental criteria as the following:

1. *Performance Threshold*- The process should be powder bed fusion with standard Hot Isostatic Pressing procedures performed prior to support structure removal. Support structures should be removed with EDM. No process interruptions should occur during the build. A process model to relate process performance to process observations will be developed and validated for later in situ measurements.
2. *Part Threshold (macroscale)*- The part should be developed with a geometry equivalent to its traditional counterpart with a homogenous microstructure.
3. *Part Characteristics (macro and mesoscales)*- The part should meet geometric dimensioning and tolerancing (GD&T) requirements of the traditional part. The microstructure should be homogenous with minimal deviation in any intricate geometries.
4. *Comparable Metrics*- GD&T will be defined using the appropriate ASME Y14 standards documents. Microstructure will be quantified by average grain size, specified grain orientations, and quantified residual stresses.
5. *Acceptable Measurements*- Initial GD&T will be quantified using a coordinate measuring machine (CMM) to evaluate the external shape and x-ray computed tomography (XCT) to evaluate any internal features. Later, GD&T may be demonstrated with layerwise imaging registered to the path plan and original geometric model [23], with alternative acoustic measurements as a supplement [24]. Microstructure will be measured with scanning electron microscopy (SEM) and residual stresses will be evaluated. Later, microstructure may be demonstrated with co-axial, melt-pool-monitoring techniques with observed temperatures and temperature deviations [25-26].

Key enablers when defining the FCs are understanding what measurements and measurement techniques are available. Note that as confidence is built in the process, FCs may be redirected to in situ measurements, potentially reducing inspection times. In additive manufacturing, sensors are increasingly incorporated into the build environment, providing line-by-line and layer-by-layer measurements of a part during its fabrication [27]. The data collected by these sensors can be digitized and become part of a digital twin that correlates to the final fabricated part.

Establishing Context Specific Criteria- In establishing CSCs, the performance requirements of the part become the focus. As noted earlier, the new part will replace an existing part that has specific hardness and heat-tolerance requirements.

1. *Performance Criteria*- The part to be made will be used to replace an existing part in a nuclear energy application. Specific performance criteria include the ability to withstand high temperatures for prolonged periods of time. The part must also meet specific hardness requirements.
2. *Performance Details*- The part geometry must not warp along specified dimensions, with allowable deformation in unspecified dimensions. The identified surfaces must meet specified hardness requirements, all other surfaces must fall within the specified range.
3. *Performance Metrics*- The part must meet thermal-loading conditions and hardness conditions; therefore, specific metrics will focus on both the microstructure of the part and how the microstructure performs under required loading conditions. Metrics may include average grain size and grain orientation. Additional metrics may include establishing stress-strain curves in directions where warping must be tightly controlled. Hardness tests are required for all surfaces.
4. *Performance Specifications*-Specifications will reflect threshold numbers that must be met for identified performance metrics. These thresholds are determined by initial acceptance criteria as well as measured performance.
5. *Uncertainty Quantification*- Here the average grain size is estimated, and therefore some measure for uncertainty is introduced. Uncertainty quantification can be established through the ASME verification, validation, and uncertainty quantification (VVUQ) standards documents or proprietary documentation. Here an additional safety factor is added to accommodate any necessary assumptions or idealizations made.

In establishing the CSCs, the focus is on the intended application. The CSCs were established for the given application scenario, and the criteria is set based on initial acceptance or qualification criteria as well as observed performance of the legacy part. Note, FC metrics were taken into consideration of CSC metrics.

Comparing Criteria- In this step, the established CSCs are mapped to the process-specific FCs. In this example, microstructure has been identified as a common metric. Hardness and stress-strain curves were not identified in the FCs; therefore, these additional criteria must now be included to accurately compare the legacy part with the new part. This step is the initial step in mapping the performance specifications of the CSCs to the measurables in the FCs.

Establishing Equivalency – After mapping metrics, and establishing new metrics within the FCs, specific performance thresholds and relationships must be established. In this example, because new FCs were established, all performance criteria can be directly mapped. This step is an iterative process, since the FCs must now evolve to satisfy the requirements of a specific application. This is the first step in establishing the Target Digital Twin. Here, the process used to establish the FCs must be modified until a new, fabricated part can meet all Performance Specifications. The resulting configuration, as well as the specified performance criteria, provide the base for which the Target Digital Twin must be established.

Establishing Target Digital Twin- The Target Digital Twin (TDT) becomes the final output of this exercise. The TDT is a virtual representation of all FCs and CSCs. The contents of the TDT include the final measurements used to establish a part that was able to satisfy all FCs and CSCs. Since this is the final product, careful consideration must be given to how this information is curated. To use the TDT in future scenarios, all steps must be repeatable. The metadata associated with the TDT must include the final system configuration upon which the acceptable part was produced, including process specifications. Here, this includes the PBF machine used, its specifications, the process parameters used, and the material specifications. The metadata must also include Performance Criteria and Performance Specifications, since these criteria were used to establish acceptable thresholds.

Data curation is necessary and includes the environments in which all measurements were taken, including sample locations, sample sizes, sampling techniques, and sample formats. Each of these characteristics are important to facilitating the registration of the TDT. The data registration procedures must be established based on available standards, either in-house or externally. Data registration is used to establish temporal and spatial relationships between all sets of sampled data. The data registration techniques used will also influence the final format and/or platform established for the TDT.

Upon completing the above steps, a TDT can be developed for this AM case study. This TDT serves as an authoritative reference for the designated scenario, as well as a reference for future iterations of similar parts or scenarios.

Discussion

This work established a method for using the digital twin concept to facilitate part acceptance. The case study investigated how this approach may be adopted in a regulatory environment, namely the nuclear energy sector. Because the approach decoupled part fabrication from performance specification, special considerations were afforded for how additional performance requirements can be integrated into a digital twin for part acceptance.

While there was substantial literature available to support the establishment of a digital twin for part fabrication, the inclusion of performance requirements requires additional work. The establishment of CSCs requires in depth knowledge of the application scenario, including detailed measurements of legacy parts. While the mapping of CSC metrics can be facilitated by evolving the FCs, establishing thresholds for these metrics is a nontrivial task. Confidence bounds must be established for the identified metrics; and, they must be well representative of the performance requirements.

Establishing ex situ correlations between parts is an initial step to adopting a digital twin for part acceptance. The incorporation of in situ measurements into the TDT would ultimately allow for greater assurance in part fabrication, as well as new parts to potentially be “born qualified.” Research into performance metrics of traditionally manufactured parts must be correlated with multiple stages of observed process behaviors during the fabrication of the part to achieve such an objective.

Finally, the establishment of digital twins for part acceptance supports the development of new practice for part analysis. While this work focused on the ex-situ establishment of CSCs, future works may include the incorporation of performance monitoring. Such an inclusion would result in new opportunities to develop direct correlations between the manufactured part and the performance of the part. For instance, the case study part could use sensors to monitor real-time behaviors during performance, providing critical feedback to how the smallest discrepancies in fabrication influence the overall performance of the part. Such a future, supported by the digital twin concept for part acceptance, could provide newfound assurance into advanced manufacturing technologies for almost limitless applications.

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