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Streamlining the additive manufacturing digital spectrum: A systems approach☆

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Abstract

Additive manufacturing (AM) promises great potential benefits for industrial manufacturers who require low volume and functional, highly complex, end-use products. Commercial adoption of AM has been slow due to factors such as quality control, production rates, and repeatability. However, given AM's potential, numerous research efforts are underway to improve the quality of the product realization process. A major area of opportunity is to complement existing efforts with advancements in end-to-end digital implementations of AM processes. New paradigms are needed to support more efficient and consistent design-to-product transformations. Systematically configured digital implementations would facilitate informational transformations through standard interfaces, streamlining the AM digital spectrum. Here, we propose the development of a federated, information systems architecture for additive manufacturing. We establish an information requirements workflow for streamlining information throughput during product realization. The architecture is delivered through the development of a solution stack, including the identification of areas where advancements in information representations will have the highest impact. The architecture will specify the stages of the product realization process, and the interfaces needed to link those stages together. Common data structures and interfaces will allow developers and end users of additive manufacturing technologies to simplify, coordinate, validate, and verify end-to-end digital implementations.
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1. Introduction

Additive manufacturing (AM) processes manufacture parts layer-by-layer from a three dimensional (3D) digital geometric model. This still-maturing technology shows great potential for fabricating geometrically complex, value-added, and customer-oriented products [1]. In addition, AM provides multiple advantages over traditional manufacturing processes, especially machining. These advantages may come in the areas of geometric flexibility, assembly requirements, waste production, portability, and ease-of use [2]. For geometrically complex parts, AM offers manufacturing opportunities not afforded by traditional subtractive manufacturing. Intricacies related to the subtractive manufacturing of complex parts can be avoided, such as subjecting a part to many different pieces of manufacturing equipment, with each providing a specific service [3,4]. Due to the advantages of the AM processes, many researchers from government, universities, and industry anticipate that this manufacturing approach will become a major player in the next industrial revolution [5]. A number of research efforts are underway to realize the potential for practical use of AM technologies in various domains (e.g., manufacturing, biomedical, and energy applications) [1].

Though the technology has great promise, several barriers and challenges have hindered AM from becoming a more prevalent manufacturing alternative. Factors such as manufacturing repeatability and reliability, affordability, process time, and lack of standards [2] have prevented AM from being more readily adopted. The manufacturing repeatability and reliability

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challenges must be overcome to provide quality assurance and to avoid part failure. The affordability of AM is a critical issue, as much of the technology is expensive to obtain, especially for processes that use metals. Reductions in machine, material, and processing costs, coupled with increases in technical functionalities (e.g., heterogeneous material properties and multiple colors within a part), would greatly expand the consumer base. In regard to part production, although the lead-time in AM processes is often much shorter than conventional manufacturing processes, considerable time is committed to the AM process itself. Because AM is unique, in that complex parts can be manufactured in the confines of a single machine, we believe underlying systems opportunities exist that can be used to address many of the barriers outlined.

The material, process, and geometry interactions necessary to realize a "part on demand" are quite intricate. Contributions from the geometry, process, and materials associated with a part, along with any part performance requirements, must be integrated to achieve the fine-grain control necessary for the successful creation of a part. From an information management perspective, we recognize opportunities to advance how information is captured, exchanged, managed, and used across AM's digital spectrum. We propose that these areas of opportunity can be addressed simultaneously using a systems engineering (SE) approach. Implementing SE principles will reduce design to production lead-times (quicker design to production), facilitate decision making through the feed-forward and feedback of information, and reduce redundancies in information acquisition to promote consistency and transparency during production. More specifically, we propose that advancements in these areas can be achieved through the development of an integrated information systems architecture to respond to industrial needs.

The proposed architecture will provide and use the fundamental information structures and metrics needed to verify and validate both the information at individual phases of product realization as well as the interactions between them. The concept of federation supports the idea that the phase-specific information will continue to evolve independently, and that the transitions should not be too tightly coupled. Federation also accommodates the many different processes, software, technologies, and materials associated with AM. By verifying and validating information not only within, but also between phases, new crosscutting opportunities will emerge to support both downstream and upstream activities. By providing controlled, granular structure to the information at each phase, and transparency between their interactions, the proposed architecture will support both AM information management and AM decision making. The architecture will facilitate the throughput of AM part and process information, from product concept to qualification, thus streamlining design-to-product transformations in AM.

In this paper, we explore and begin to identify systems-level requirements for the development of an integrated information system architecture, with a focus on metal-based AM. In Sections 2 and 3, we investigate the information requirements at each phase of AM's digital spectrum, from design to product. We explore, from the system integration perspective, which factors need to be taken into account when addressing interoperability between the digital formats used throughout the development of a part for AM. In Section 4, based on a broad literature survey from Section 3, we analyze research gaps and industrial needs in terms of system integration. In conclusion, we propose a conceptual information systems architecture and provide a subsequent discussion around future research plans.

2. Background and related work

2.1. Systems engineering for AM information management

As requirements for AM design and manufacturing evolve toward higher levels of product and process quality and reliability with lower cost, it is expected that next-generation, advanced methodologies will be necessary. We propose that many of these advancements can be achieved in the context of an SE perspective. While there are several authoritative definitions for SE, it is understood as an interdisciplinary field of engineering that focuses on how to design and manage complex engineering projects over their life cycles [6,7]. The SE process is top-down, comprehensive, iterative, and recursive to transform needs and requirements into a set of system product and process descriptions. An SE process model can be used to characterize capabilities and interfaces during the architecture development of a large-scale, complex system in a hierarchical representation manner [7].

2.2. A digital thread of AM process

Where we use the term "digital spectrum" to address all of the information, supporting formats, and supporting software used throughout a design-to-product transformation, the term "digital thread" refers to the information and information path that is gathered and stored when manufacturing a single part. The concept of a 'digital thread' emphasizes interoperability across the supply chain, enhancement of digital capabilities to design and test products, and costs reduction of manufacturing processes in multiple industries [8]. The information captured and maintained in this digital thread enables us to manage and trace "what, how, where, who, when, and why" during the whole AM process. When applied to AM, the context focuses on the digital interactions that occur during design-to-product transformation. This area is still maturing in AM. Bonnard et al. [9] discussed information management in an AM process and proposed to use high-level information to integrate the AM processes in a complete digital chain, comparing it to the STEP-NC standard for representing machine control information. Nassar et al. [10] also proposed a unified paradigm based on Extensible Markup Language (XML) to record and transmit data at stages of the AM process: design, modeling, build plan, monitoring, control, and qualification. As others have noted, there are many opportunities to improve and streamline AM's digital thread and supporting infrastructure, specifically with the application of SE principles.

The primary function of an AM process is to convert raw material into a series of connected solid primitives in a layer-based, additive manner to manufacture a part. During the AM

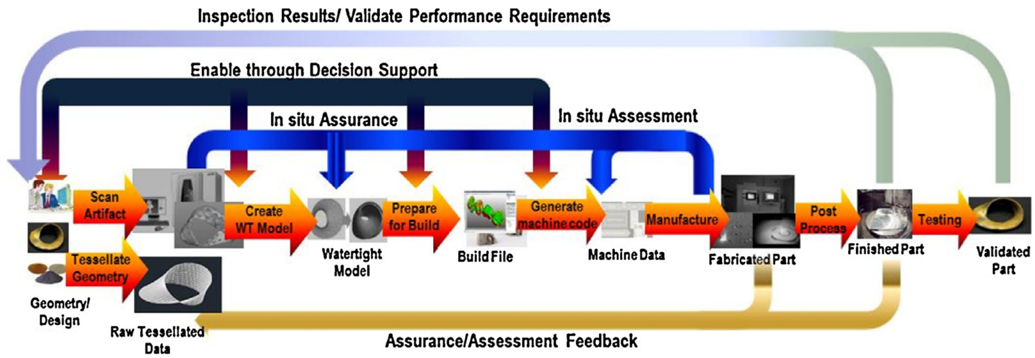

Fig. 1. A deconstructed AM process diagram.

process, different sub-processes are necessary, and the boundaries that define these sub-processes may differ depending on the perspective taken. From an SE perspective, we identify seven activities that change how information is managed and structured in the AM digital spectrum, establishing the provenance of the part. We identify these activities as: tessellation and/or data generation from a design or artifact; the fixing and cleaning of a tessellated model; incorporation of AM-specifics, such as support structures and orientation, into a geometry; generation of code for machine operations; fabrication of a part using processes and materials; post-processing; and testing for part qualification. These activities become "transitions" between different phases of a part's design-to-product transformation. These transitions help to define a supporting infrastructure that covers the standards, methods, techniques, hardware, and software for AM process and analysis. Based on these transitions and findings from related works [2,10,11], we use eight phases to outline the AM digital spectrum from a high-level perspective.

We categorize the end-to-end digital spectrum of AM into the following eight phases: part geometry/design, raw tessellated data, tessellated 3D model, build file (e.g., 'process plan' including build orientation and process parameters), machine data, part (including geometry with final build parameters and information from in situ measurements), finished part (e.g., part information including any post-processing), and validated part. As shown in Fig. 1, information generated from each phase interacts with the information from the previous or next phases. The left-to-right arrows represent transitions (information changes) between phases, while the icons represent the phases. The outlying arrows in Fig. 1 also reveal feedback and feed-forward opportunities such as decision support, in situ assurance and assessment, and part performance assurance and assessment. The feedback/feed-forward of information enables us to simulate, assess, and optimize a part and process.

The following paragraphs describe the eight phases in Fig. 1, providing a brief explanation of what makes the phases distinct, as well as an explanation of the transition between phases.

2.2.1. Phase 1 – *part geometry/design*

This phase addresses the information created during early design, from conceptual to detailed design. This phase represents the "form" of the part, as well as any available design rationale. In this phase, geometry may exist as a CAD (Computer-Aided Design) file or a physical object being prepared for a 3D scan. In addition, material needs to be selected for fabricating the product, since it is fundamental to the quality and manufacturability of the product.

2.2.2. Phase 2 – *raw/tessellated data*

This phase is the result of the creation of "formatted" information from which a 3D part may be created. Currently the transition from Phase 1 to Phase 2 is usually done in two ways, exporting a CAD geometry file as an STL (STereoLithography) file or using a 3D scanner to collect raw 'image' data (then turned into an STL file).

2.2.3. Phase 3 – *tessellated 3D model*

The transition from Phase 2 to Phase 3 requires creating a usable geometry from raw data (tessellated data), and often involves removing duplicate nodes, inserting missing nodes, and creating what can be interpreted as a watertight solid from surface nodes. In some instances, this phase may not be necessary.

2.2.4. Phase 4 – *build file*

The transition from Phase 3 to Phase 4 involves introducing AM-specific information into the digital thread. Phase 4 consists of two parts: the geometry information and the process information. The geometry portion of the build file considers specifics such as support structures, while the process specific information takes into consideration specifics such as build orientation and process parameters. The two parts are interconnected, as support structure locations will depend on part orientation, and part orientation may be influenced by process parameters.

2.2.5. Phase 5 – *machine data*

The transition from Phase 4 to Phase 5 is facilitated by software that incorporates process specifics as dictated by machine capabilities. Phase 5 is where production information is introduced into the digital thread. This phase may include information such as machine code or other direct machine-specific process plans.

2.2.6. Phase 6 – *fabricated part*

This phase occurs when a part is fully realized. The transition from Phase 5 to Phase 6 is an assimilation of all data and information used in the development of a specific part, including geometry, processes, and materials. In this phase, the provenance of the part assumes a more physical nature. The notion of "part

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pedigree" can be introduced, based on the material and process parameters used and measured during the manufacture of a part.

2.2.7. Phase 7 – *finished part*

Phase 7 transitions beyond the AM-manufactured part to a "finished" product. The transition from Phase 6 to Phase 7 may be dependent on part performance requirements and on whether secondary processing, such as heat treatment or surface finishing, is needed. Here is where any information associated with secondary processes may be captured. Information about any post-processing will add to the pedigree of the part.

2.2.8. Phase 8 – *validated part*

This phase addresses the "final product." The information added in this phase may include any mechanical testing or non-destructive evaluation (NDE) on the manufactured part and the results of these tests. In this phase, results from testing will be added to the part pedigree, establishing a reference for any future part performance inquiries.

3. Surveying digital thread of AM

In this section, we survey each of the eight phases outlined from the information management perspective, including notable formats and metrics used.

3.1. Part geometry/design

The first step of product realization is to conceptually design a part in terms of geometric shape and its properties [12]. The conceptualization can come via different forms, such as textual descriptions and sketches. When designing a part to be manufactured with AM technologies, AM's unique capabilities should be considered [2], such as flexibility in geometry, hierarchy, function, and material. This flexibility provides an opportunity to rethink traditional Design for Manufacturing and Assembly (DFMA) methods and allows us to theoretically manufacture any 3D geometric model. In addition, AM enables us to manufacture a complete functional part, including multiple parts and joints, in a single build, which leads to designed reduction of part counts in an assembly. With the concept of functionally graded material or heterogeneous materials [13], different materials can be designed into different points or layers. These aspects create both challenges and opportunities in representation.

One example representation that supports this phase is ISO 10303, known as 'STEP (Standard for the Exchange of Product model data). The ISO 10303 AP (Application Protocol) 242 [14], is known as 'managed model based 3d engineering.' Though currently generic for most design applications, there is interest to include additive manufacturing design information to future editions of AP 242. This information could include curved tessellations, graded materials, internal lattice structures, material properties, build orientation, and process information.

To achieve effective design representation, several types of design information (e.g., purpose, design reasoning, notation, method, communication, options, and background) should be managed for efficiency and traceability. This is known as design rationale [15]. Design rationale can be used to provide a basis to communicate between designers and manufacturers for three specific purposes: (1) record of design process history for traceability, (2) modification and maintenance of existing designs, and (3) new design of a part [16]. As the AM technology evolves, and both processes and materials continue to improve and expand, design rationale allows designers to revisit parts and take advantage of these advances.

3.2. Raw/tessellated data

In this phase, the geometry of a digital model or a scanned physical object is tessellated. A 3D model can be realized by (1) CAD software, (2) reverse engineering (RE) software and hardware (e.g., 3D laser scanner), and (3) obtaining it from an internal/external repository [17]. When a CAD model exists, no scanning is needed. This eliminates the use of raw point cloud data to create the tessellated model, instead using CAD-embedded algorithms to discretize a solid geometry.

If transitioning from a physical object, the geometry information is measured using suitable hardware (e.g., optical sensors or computed tomography) and software and stored as digital point cloud data. The cloud data from optical sensors usually contains vertex coordinates (x, y, z) and possibly color information. Alternatively, it contains normal information for each vertex. The generated information from optical sensors needs to be merged into a single 3D model, called a registration process. A noise reduction step can remove unwanted point samples. From this, a triangular mesh generation is necessary to determine the relationship between point samples and its data structure, achieving tessellation.

Using commercial or open software tools, a solid model from a CAD software or repository can be converted into the STL file format, which is the de facto geometry data exchange standard in AM. Recently, however, the ISO/ASTM 52915 standard was introduced as a more capable alternative. The standard specifies an XML (Extensible Markup Language)-based file format called the Additive Manufacturing File Format (AMF) [18].

3.3. Tessellated 3D model

To create a watertight model, geometry editing methods [19], such as noise reduction or hole filling, are often necessary. The geometric modification of the raw tessellated data is necessary to provide an AM-processable model.

In this phase, the tessellated model exists as a watertight 3D model that may include vertex information, normal information, triangle (topology) information, color information, and material information. The generated 3D model may have not yet been optimized for AM processes. Some optimization algorithms for design topology, lattice structures, and scaling factors can be used to get an improved 3D model. Such algorithms, when appropriate, can often improve resource efficiency (e.g., material and time) and result in a lighter product.

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Table 1
Attributes related to the path plan and process parameters.

Attributes	Path plan/process parameters	Unit
Length	Layer thickness Nozzle diameter Focus diameter (=spot size, e.g., 100–500 μm) Powder size (e.g., 20 μm)	μm
Temperature	Bed temperature Feed temperature	°C
Power	Laser power (e.g., 200 W) Laser spot size	W mm
Density	Internal fill density Powder bed density	% kg/m^3
Speed	Scan speed	m/s
Rate	Feed rate (extrusion) Gas flow rate	mm/s cm^3/s
Pressure	Pressure in the chamber	Pa
Angle	Scan angle (e.g., 0, 45, 90) Part orientation	°

3.4. Build file

In this phase, information specific to AM processes is introduced into the digital thread. This information may include build orientation, support structure location, hatching, and process-specifics such as shrinkage. Build (part) orientation is a key factor in build quality because (1) it influences the amount of support structures required and (2) positioning and resolution are fundamentally different along the *z*-axis (vertical) than the XY (horizontal) due to factors such as stair-stepping effects. Support structures are temporary features that prevent layers from collapsing during the AM build process. To account for part shrinkage a scaling factor may be introduced prior to building.

To prepare for processing, the 3D model is sliced into multiple two-dimensional cross-sections, which are sometimes represented in a layer-based model file format (e.g., SLI and CLI) [20,21]. When slicing the 3D model, geometric information, process information, material information, and machine information are taken into account to generate parameters for each layer. The geometric information of each layer includes machine tool movement related information, e.g., the nozzle movement, axis movement, laser scan position, or layer thickness. The process information of each layer includes manufacturing process parameters. Table 1 shows examples of attributes related to the path plan and process parameters.

To transition to the next phase, a path plan for each layer is determined according to defined information such as machine constraints and rules, processing parameters, and support structure. The inner and outer perimeters and infill information of each slice should be defined.

3.5. Machine data

To execute a build, the previous AM information representations must be converted into machine-interpretable languages [22]. Standard specifications are not available for converting neutral processing paths and parameters into machine-interpreted formats. Many AM machines use proprietary interpretations, which can limit in situ modifications and reuse between machines. Recently, to overcome this limitation, research efforts have been initiated using the STEP-NC concept in accordance with ISO TC 184/SC 1 [9,23]. The RS274D (ISO 6983) G and M code standard [24] has been implemented by some AM system vendors as a standardized means to generate machine interpretable information for their AM processes.

Generally, machine codes consist of machine start and end codes, process paths, and parameters for an AM process. The machine start and end codes are related to the setup (e.g., system on) and teardown (e.g., system off) for manufacturing. Each layer has its process paths and parameters according to the information in the previous phase.

The transition from Phase 5 to Phase 6 is supported by in situ monitoring of the AM process. There are no standard formats for data generation and management while monitoring and controlling the AM process. Table 2 shows example information types used for in situ monitoring and control of AM process parameters. Much research [25–29] on monitoring and controlling processes can be found, since these results are closely related to the mechanical properties and quality of resulting AM parts.

Table 2
Examples of in situ monitoring and control information in the AM process.

Type	Assurance/assessment
Position	Nozzle position information
Process	Deposit layer thickness Powder feed rate Source power monitoring Scan speed and pattern Gas flow parameters
Temperature	Distribution on the workpiece [25,26] Powder bed temperature Powder feed temperature
Melt pool	Melt pool size and shape [27] Melt pool geometry Solidification rate
Sustainability issues	Energy consumption Hazardous emissions

3.6. Fabricated part

In this phase, the concept of part "pedigree" is first introduced into the digital thread. Pedigree-related information refers to the part-related information after a part has been built. This information includes details on the design, the materials, the manufacturing environment, and the process parameters, with the goals of supporting traceability, manufacturability, repeatability, and reducing the risk for part qualification. When describing the environment, the AM process can be categorized into four stages: setup (prepare the required resources such as materials and tools), idle (warm up the AM machine), active (manufacture the designed part), and teardown (cleanup). The

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manufacturing environment information may also include operator name, machine type, build date, ambient temperature, and air pressure.

During the AM process, geometric information is generated related to the output of a specific part. Material (e.g., substrate material specification, substrate manufacturer, material type, composition ratio) is specified, as it relates to process–structure–property dependency and heterogeneous [30] or functionally gradient materials [13]. Any information related to actual process parameters (e.g., scan speed, powder feedrate, and preheat temperature) should also be specified.

3.7. Finished part

The manufactured part often needs post-processing to satisfy design specifications (e.g., surface roughness, mechanical strength). In this phase, information related to post-processes is specified and can also contribute to the pedigree of the part. In AM, the post-processes may include support material removal, surface texture improvements (e.g., shot peening, polishing), accuracy improvements (e.g., machining), esthetic improvements (e.g., painting, priming, polishing), property enhancement using thermal techniques (e.g., heat treatment) [31], or non-thermal techniques (e.g., curing). Any information collected from post-processing will contribute to the pedigree of the part.

Similar to the AM build process, the post-processes can be also specified in terms of four stages. Any necessary information related to the manufacturing environment, geometry, material, and process parameters for post-process should be specified. For example, in the case of machining [32], the manufacturing environment information may include the high-level context for the process, e.g., machine specifications, operator, and cutting tool specifications. The geometric information includes data from the workpiece and output part. The material information includes the workpiece material and its required consumables (e.g., coolants). The process parameters may include cutting speed, spindle speed, depth of cut, or feed per tooth.

3.8. Validated part

In this final phase, information related to the validation and qualification of the manufactured part is documented and incorporated into the part pedigree. Measurements of part properties (e.g., tensile strength, toughness, fatigue strength, surface roughness, and porosity) are often necessary to qualify the part and determine if design requirements have been met [33]. In this phase, information related to the part, testing methods (e.g., NDE or hardness), and test results are generated and documented. A wide variety of non-destructive and destructive evaluation methods can be used to verify and validate the mechanical properties of a part. The test method, its inputs, and results should be documented with any information necessary for further usage (e.g., analysis and traceability).

Recently, considerable research has focused on the relationships between micro-structure [34–36], residual stress [37,38], and mechanical properties [35,39] of manufactured AM parts. Qualification-related information [39] can be categorized into testing environment, input for testing, specific data for testing method, and results. The testing environment may include the testing type (e.g., strength, fatigue, toughness), the hardware (e.g., machine type, model name), any software specifications, and the testing organization. In this phase, the concept of pedigree assumes a greater level of importance, as any information gathered during testing will provide a basis for understanding the capabilities and limitations of a part's performance.

4. Defining a solution stack for information systems architecture for AM

As AM matures, drivers include the desire to improve quality, process consistency, repeatability, and reliability from a variety of materials and at a low manufacturing cost. In this paper, we propose that advancements can be made in each of these areas, both independently and collaboratively, using a systems approach. For the system integration of the digital thread, tight and loose integration should be simultaneously considered. The tight integration focuses on the development of an information management system and supporting interfaces for the eight phases of the AM digital thread. This integrated information management system interacts with the supporting infrastructure (e.g., standards, methods, techniques, hardware, and software) in a loosely coupled way. In Section 3, we decomposed the AM digital spectrum into eight distinct phases. The next step is to describe the system as a whole.

Fig. 2 is a diagram of the end-to-end digital thread discussed in Sections 2 and 3. This figure provides a condensed view of the eight phases and their transitions. With a clear understanding of the different phases of an AM part and the information transitions between each phase, we are now able to establish a systems perspective of the process as a whole. It is through this view that we can identify opportunities to evolve the AM digital footprint and establish the mechanisms and enablers necessary to realize these opportunities. In this section, we propose a solution stack approach (identified as Mechanisms/Enablers in Fig 3), where new capabilities are enabled as Mechanism/Enabler layers are added. The five layers of the stack are as follows: Metrics/Models, Modularity, Interoperability, Composability, and Verification and Validation. These are the main mechanisms/enablers necessary to effectively manage and use the information captured and maintained during the AM digital thread. Together, these layers form a basis for the federated information systems architecture for AM, discussed in Section 5. Each layer, and the function it provides, is discussed in the following sub-sections. In Section 5, we then discuss overarching opportunities (identified as Architecture Functions in Fig. 3) and their implementation within a federated information systems architecture.

4.1. Metrics/models

Although there are many differences among AM process technologies, methods, and tools, significant functional commonality exists among them. This commonality creates an opportunity to propose a central set of metrics that can be

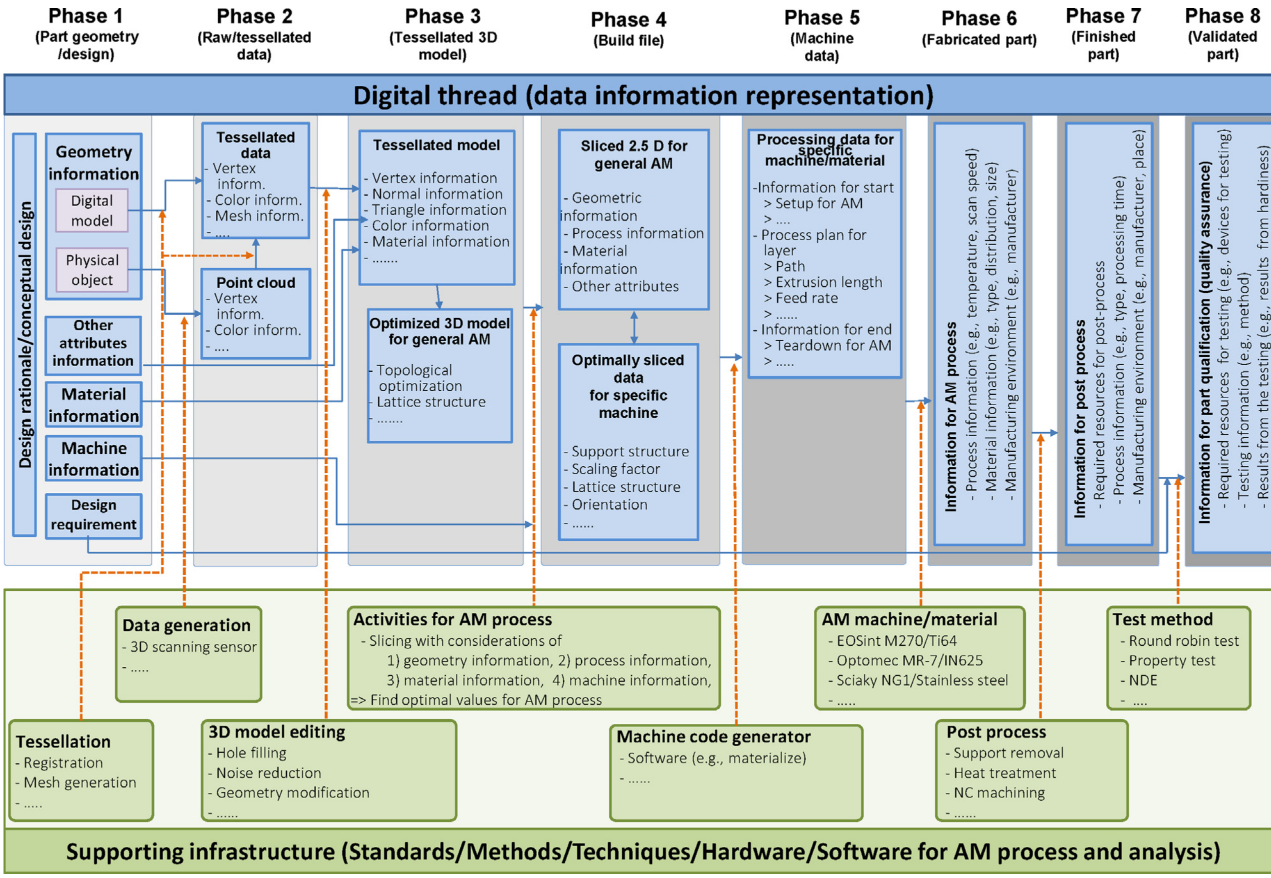

Fig. 2. A diagram of an end-to-end digital thread and its phases and transitions.

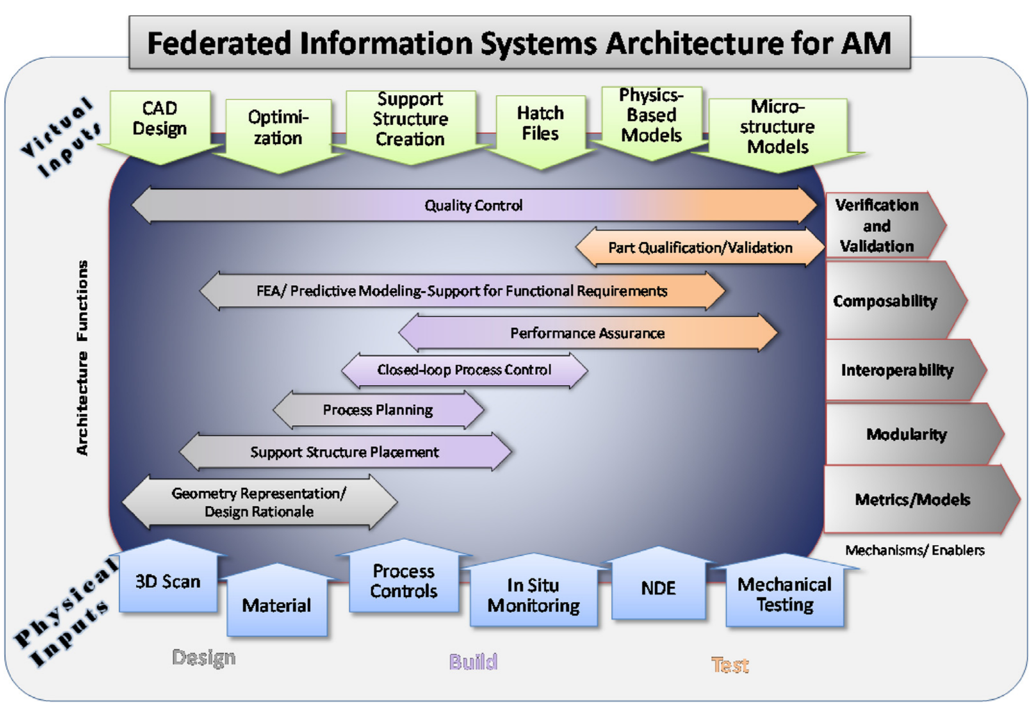

Fig. 3. A conceptual federated information systems architecture for AM.

referenced by different processes. Metrics can be used to define key impacts, outcomes, or issues that determine or influence actionable recommendations for process and part improvements. By selecting the appropriate metrics for a specified goal, accurate assessments can be made. For instance, common metrics can provide a template for the characterization of dimensional accuracy, surface roughness, distortion, density, mechanical properties, and microstructure. In contrast, macro-level metrics may be used to define key performance indicators (KPIs) that evaluate the overall performance of an AM process and simplify process qualification. Thus, consistent metrics and KPIs should be developed in an understandable, meaningful, and measurable way.

Information models can be developed from an arrangement of metrics and used to describe a particular form, function, or behavior [40]. Domain-specific models can be used to support information within a specific domain, for instance a model for "Design Rationale." However, the systems perspective encourages us to identify the inputs and outputs of the system as a whole, not only within phases. For instance, a model for "part qualification" may require information related to each of the eight phases. The first step in supporting crosscutting opportunities is defining common metrics and information models for product development, measurement, modeling, analysis, and inspection within the digital thread.

The deployment of common data metrics and models can simplify information requirements and facilitate faster and more cost-effective ways for streamlining data transformations, leading to reductions in design-to-production time and improved product quality. However, the definition of common data standards and metrics for AM is a difficult task due to the complexity of the material-process relationships. Thus, research efforts on identification, definition, and classification of data metrics and models in a consistent way are necessary to support effective modeling, simulation, and analysis tasks. To improve efficiency and accuracy of AM information exchange, standardized efforts for hierarchically well-structured information models must be established.

4.2. Modularity

Modularity supports the notion that independent information models can be connected in multiple ways for different uses and applications. Modularity, partitioning information entities along a logical boundary into a collection of smaller, independent, and reusable information, is necessary to increase the extensibility and flexibility of the information management for systems integration. The diversity of AM processes, and the different types of parameters, means there are various ways to represent information within a domain, and this creates challenges. When information can be managed in a modularized way for each phase, the information can be manipulated in a reusable and composable way for a specific purpose. Generated information can be grouped within a domain-specific model to serve a specific application, such as a process model or a geometry model. One way to promote modularity is through a classification or taxonomy for AM technologies. While existing classification schemes facilitate the grouping of common techniques, the overall scope is limiting in that they do not identify all of the commonality that exists across the eight phases. Thus, a framework based on the functional decomposition of AM-related activities should be developed.

In addition to providing a common means for capturing and representing knowledge, the notion of modularity also supports knowledge retrieval and reuse in information management. Large amounts of data are dynamically generated by different AM system and process types. Information retrieval methods can benefit from common, reusable data structures. Standard structures will support fast and effective content-based information access with capabilities of storage, maintenance, and searchability. In general, users want the information data to be available whenever needed. For example, availability of previous AM information can provide decision support or guidance for selection of an optimal AM processes/geometry/material before an AM build.

4.3. Interoperability

Interoperability supports the requirement of information transitioning between metrics and models both within and between domains. The systems architecture should be supported by mechanisms for interoperability, meaning that generated input and output formats should be accessible between various application systems pertaining to AM design, materials, and process [23]. For example, modeling and simulation tools may require multidisciplinary support including: (1) topological optimization that can provide the optimal geometric structure design [41], (2) finite element analysis (FEA) methods that can predict thermal stresses [42], and (3) discrete event simulation [DES] that can evaluate the AM process before manufacturing the part. Interoperability is required to support information transparency and reuse in such complex interactions.

From the information management perspective, feed-forward, concurrent, and feedback strategies are all supported by interoperability, and should be leveraged to facilitate decision-making. Feed-forward management is to respond in advance, and focuses on an expected task rather than an occurred one. In contrast, concurrent and feedback occur during and after a task. Regardless of the direction, interoperability is essential in establishing the information flow and transparency necessary to establish these strategies. Further research efforts on the understanding and usage of these strategies will provide insights on how to establish methods to check errors and manage information in a more dynamic and efficient way.

Interoperability, when supported by open architecture and modularity, can be leveraged to support the composition and decomposition of models, each with the ability to function as a group or independently. This notion of using information modularity to create new functionalities enables composability.

4.4. Composability

Composability is an important concept given the expansiveness of AM technology, and variability in processes and materials. Composability offers the ability to select and assemble information or process model components in various combinations for different purposes. For instance, finite element analysis is widely used to simulate the thermal stress from the laser-based AM processes (e.g., laser sintering and laser melting). Interfaces for these analyses should be considered, developed, and integrated into the information management system, allowing models to not only be interchanged but also combined to perform new functions. These interfaces can be used to combine efforts in model generation, both information and process-based, material selection, and property analysis (e.g., simulation and optimization) as necessary. By establishing the modularity, and defining the parameters and methods to be used in any interfacing, the model is supported for reuse in later analysis efforts.

It is increasingly the case that process models are desired "on-demand" as a method for supporting process control. The closed loop monitor/control systems start with data acquisition using various sensors (e.g., optical and acoustic sensors) from the monitored assets. The systems collect, organize, and analyze the status of event real-time information from the machine on the shop floor [25,29]. The data collected from these sensors are then fed back into a model to make in situ corrections. The machines that are self-monitoring and self-calibrating will be able to self-correct and control important equipment performance parameters. To do this in real time, the machine must have access to different scales of models when necessary. Composability supports the multi-scale approach required to achieve this control.

4.5. Verification and validation

Once each of the previous four layers has been realized, leveraging an information systems architecture for verification and validation of AM-related data and information becomes conceivable. Though the extracted results throughout the AM process are deterministic in nature, the results contain uncertainties from a number of sources (e.g., lack of data, loss of data, data assumption, and dynamic change of manufacturing conditions). To reduce discrepancies and have reliable decision guidance, all possible sources of uncertainty should be identified, characterized, and quantitatively estimated for evaluation of the total uncertainty. A comprehensive understanding of the uncertainty can provide guidance on how to manage or reduce it in an efficient and cost-effective manner for quality assurance.

Traceability is an iterative process of tracking and validating that the requirements have been satisfactorily addressed. To support verification and validation during the flow of information, rich and robust traceability must be developed, e.g., a morphological model (e.g., metamodel) with new concepts and ideas. Transparency within the information flow can be leveraged to provide insight into all phases of the digital spectrum, supporting the notion of system-wide functions in an AM information architecture. Development of a holistic approach to support the concepts of transparency and traceability is a notable opportunity for information management improvement.

5. Toward a federated information systems architecture

5.1. Defining the conceptual architecture

Much of the data and information discussed in the previous sections exists in closed or proprietary architectures, making it difficult for users to interact with the data. In these instances, modifications are constrained by the software. Such restrictions make it difficult to independently test new build routines, materials, and so forth. Open architecture controllers, reconfigurable modules, and their interfaces would enable manufacturing flexibility and agility [43]. An open architecture would allow customers to design, develop, and customize a part throughout production with new material and process parameters. In addition, the development of an open architecture supports the customization of a part or product for specific applications. Interoperability mechanisms will provide integration features for exchanging information data between different AM domains (e.g., tools, materials, and processes). Using an open architecture approach, the proposed platform will be developed independently of file formats and implementations and provide the flexibility necessary to recognize and conform to technological advances and a changing environment.

Fig. 3 is a graphical representation of the AM parameters and the abstract functional solution stack discussed in the previous two sections. The X-axis is representative of the design-to-product transformation. Key inputs, from both virtual and physical sources, are mapped to their respective locations during the transformation process. The Y-axis portrays the solution stack described in Section 4, where each layer is representative of different mechanisms/enablers that are available to manage the information within the architecture. In addition to the conceptual representation of a federated information systems architecture, Fig. 3 illustrates several functional opportunities (shown as Architecture Functions). These Architecture Functions are areas where systems engineering principles can be applied to the digital end-to-end implementation of AM processes and advance current state-of-the-art. These opportunities are discussed in Section 5.2.

5.2. Leveraging the architecture: AM opportunities

In the early stages of the design to product transformations, systems opportunities can lead to improved traceability and better decision making. By explicitly identifying information requirements early in the development of an AM part, more informed decisions can be made about whether AM processes are appropriate, which AM processes are appropriate, and what, if any, implications may be realized once a specific process has been selected. This function has been identified as *Geometry Representation/Design Rationale*. Depending on the software implementation, the architecture may provide opportunities to streamline geometry-related transformations prior to machine processing. As methods for process planning and control improve, explicitly identified design rationale can become an important means for modifying designs to meet functional part requirements.

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Increased communication between the design and process stages will provide new insights into process planning, including support structure requirements and locations. For instance, during many AM processes, temperature gradients are present due to the melting of input materials. The gradient causes thermal strains and stresses that can lead to a part failure (e.g., part distortions and delamination). In order to reduce the failure, a methodology for the thermo-mechanical optimization of the support structure design could be developed to reduce the residual stresses and distortions. Currently, incorporating support structures into a design is much more a function of software functionality than process specifics. A *support structure placement* function would leverage systematic configurations of neutral representations to supplement available capabilities. Similar statements can be made about *process planning*, as independent software offers few process-specific considerations and proprietary software supports process generalities. There remain significant opportunities for incorporating process and material specifics into the build files and machine code. Further bridging the information flow between design and process information will lay the foundation for improved support structure placement techniques and process planning.

For the effective utilization of AM processes, post-processing operations are often required. For example, heat treatment is used to form the desired microstructures and to relieve residual stresses. In some cases, special heat treatment techniques are necessary to maintain the fine-grained microstructure within the part while still providing some stress relief and ductility enhancement. As a second example, integration of additive and subtractive post-processing is another method for dimensional accuracy and surface roughness improvements. To anticipate how to satisfy design requirements, research efforts on design and process planning for post-processing is imperative.

Process parameters significantly affect the process cost, part properties, and part quality. As such, process control is a highly researched area in AM. These efforts usually focus on material-process interactions and investigate the techniques for measuring the phenomena associated with these interactions. For instance, as reported in Fateri et al. [44], part quality is different according to different types of scanning paths such as spiral, linear, and random paths. The fluidity of these efforts makes process model verification and validation difficult to achieve in a systems architecture. However, by isolating different modeling spaces, we can create new opportunities for leveraging process control efforts as part of a *closed-loop process control* function. Specifically, we propose that systematic advances achieved by previously identified functions can be leveraged for advancements in *performance assurance*, *predictive modeling*, and subsequently *part qualification*. Advancements in the development of predictive models of different process-structure-property relationships would be influential in determining better parameter values to achieve a desired manufactured part quality. A much better understanding of the fundamental physics and the inter-relationships between process–structure–property is necessary to advance current predictive modeling efforts.

Improved methods for part qualification are highly critical capabilities needed to facilitate a more widespread use of AM. Measurement methods during the AM process, such as mechanical tests, round-robin tests, and NDE techniques, can be leveraged to efficiently validate for a desired output (e.g., part microstructures, dimensional accuracy, and quality). Predictive models, standardized testing, and development of performance metrics and measurement methods are all key aspects in developing this capability.

6. Conclusion

This paper reflects on the need for the systematic integration, management, and analysis of the data/information generated during the different phases of AM design-to-product transformations. It investigates the AM digital spectrum, from design to final part/product, for general adoption in manufacturing industry. The digital thread is defined throughout eight phases: part geometric/design, raw tessellated data, tessellated 3D model, build file, machine data, fabricated part, finished part, and validated part, and their transitions. The information associated with each phase is discussed in detail, as well as examples of the information types found. A solution stack is developed to address research gaps in the information-intensive AM digital spectrum, and discussed in terms of metrics/models, modularity, interoperability, composability, and verification and validation. Finally, guidelines for an information systems architecture to support end-to-end digital implementations in additive manufacturing are presented. Research opportunities, in the context of architecture development for AM information management systems, are also discussed.

The proposed federated information systems architecture will provide a platform that will enable the verification and validation of AM information across the digital spectrum. Systematically configured digital implementations will replicate physical transformation processes with models and simulations, and facilitate information transformations through standard interfaces. Improved information management will allow for more transparent information exchange between the different phases, ultimately supporting the notion of quality control throughout the development, manufacture, and qualification of an AM part. This effort will address current validation and verification methods for data integration and exchange. Related efforts will include industry outreach to facilitate requirements development through needs assessments. NIST will incorporate this feedback into architecture development and focus on areas of high concern and greatest opportunity. By streamlining the methods used during design-to-product transformations, additive manufacturing technologies will become more accessible to small and medium-sized businesses, thereby increasing industrial competitiveness and promoting their widespread adoption.

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