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TOWARDS AN INTEGRATED DATA SCHEMA DESIGN FOR ADDITIVE MANUFACTURING: CONCEPTUAL MODELING

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ABSTRACT

Large amounts of data are generated, exchanged, and used during an additive manufacturing (AM) build. While the AM data from a single build is essential for establishing part traceability, when methodically collected, the full processing history of thousands of components can be mined to advance our understanding of AM processes. Hence, this full body of data must be captured, stored, and properly managed for easy query and analysis. An innovative, AM-specific data model is necessary for establishing of a comprehensive AM information management system.

This paper introduces our work towards designing a complete and integrated data model for AM processes. We begin by defining the scope and specifying the requirements of such a data schema. We investigate how information created and exchanged in the AM process chain is identified based on an AM process activity diagram. A comprehensive survey shows that existing AM standards are unable to provide both the breadth and the depth needed for an integrated AM information model. We propose a conceptual design for an additive manufacturing integrated data model, AMIDM, based on a well-defined product lifecycle management (PLM) data modeling method called PPR (product, process, and resource). The proposed AM model has a core scheme composed of product, process, and resource entities. The process entities play critical roles in transforming product input into product output using assigned resources such as equipment, material, personnel, and software tools. The proposed model has been applied to an information system design for Powder Bed Fusion based AM experimental data management. An XML (eXtensible Markup Language) schema is presented in the paper to demonstrate the effectiveness of the conceptual model.

1 INTRODUCTION

Additive Manufacturing (AM) uses 3D design data to build up a component layer upon layer. AM technology enables the manufacturing of parts with complex shapes and heterogeneous materials that cannot be fabricated using subtractive manufacturing methods. Although past uses of AM technology were mainly for rapid prototyping, AM is now being increasingly incorporated into real production [1].

Whether for prototyping or real production, industry requirements result in large amounts of data generated, exchanged, and used during the AM process. This data includes material information, design models, process data, and measurement data. As the volume of data grows with increased in-situ sensing and nondestructive examination (NDE), the types of data generated by AM activities also become richer [2, 3]. Perhaps more than traditional machining processes, each of the intermediate steps of an AM process - CAD design, tessellation, support and lattice design, building and post-processing, contribute to the finished part quality. For example, differing thermal properties from layer to layer can lead to internal stresses and failures. These property differences may be caused by deposition parameters, but can also be attributed to the build material or even the design of the component. As a result, all the AM data generated during the build of a part should be stored for effective traceability analysis, establishing a digital thread. In addition, empirical AM data helps us build predictive models that support optimal manufacturing decision making and advance our understanding of AM processes for new material and equipment development. Hence, the full processing history of thousands of samples and parts must be captured, stored, and linked to relate designs and process parameters with process outcomes. The management, query, and analysis of this data are considerable challenges [4]. To solve the problem, an innovative, comprehensive, and AM-specific data model is required. Any considered data schema should address not only machine and material information, but also include AM product lifecycle data.

Though a complete implementation of an AM schema has yet to emerge, several activities have been initiated. In the last several years, a few commercial material information management systems have been reportedly built or used for

AM. For example, Granta, has collaborated with four European Framework Seven projects in the field of additive manufacturing [5]. Granta's software, Granta MI, has been designed to focus on the material properties. Similarly, the Senvol Database [6] provides researchers and manufacturers with open access to industrial AM machines and materials. A search on the Senvol Database finds machine information, material information, and information on their compatibility. Beyond software vendors, various collaborative efforts are emerging, including the MSAT database led by Department of Defense (DOD) [7] and a joint effort by members of America Makes [8]. Work from Nassar et al. proposed a unified paradigm, built on Extensible Markup language (XML) to record and transmit data at every stage of the AM process [9]. Nassar's work proposed four data formats based on the Additive Manufacturing File (AMF) format [16] to facilitate information exchange from slicing to process planning to execution and testing.

While an inclusive, comprehensive AM-specific schema has not yet emerged, there is much to learn from more mature, comparable domains. Consider that, in the last ten years, significant progress has been made in lifecycle information modeling. For example, building information modeling (BIM) [10] is a process that involves the generation and management of digital representations of physical and functional characteristics of buildings. These representations support the planning and design phases, as well as the construction and facility operations. The Industry Foundation Class (IFC) is the most internationally accepted BIM standard [11]. However, in general, IFC does not include any operational or test data itself. For traditional manufacturing processes, Li et al [12] proposed a complete and integrated data model to capture product, process, and machining system information for powertrain components using traditional machining methods. A key feature of the proposed model is the use of a product feature classification scheme and parametric feature representations for connecting the geometry of a part to its machining process, which is also linked to manufacturing resources. Although AM presents similar challenges, this model cannot be directly applied here because there are no strict correlations between part features and fabrication processes for AM [13].

This paper presents our initial work towards designing a complete information model, additive manufacturing integrated data model (AMIDM), for AM product and process data management. We first define the scope of the AM schema to be considered, including both role context and use context. We then investigate the information requirements of AMIDM based on an AM process activity diagram. After a brief review of several existing standards, we identify gaps and challenges of developing an AM data schema. We propose a concept model by classifying AM information into product, process, and resource domains. Finally, we discuss the opportunities furthered with the development of such a schema, including a design allowable AM experimental database.

2 SCOPE AND REQUIREMENTS OF AMIDM

Common data structures and interfaces will allow developers and end users of additive manufacturing technologies to simplify and coordinate digital end-to-end implementations. They will also provide timeless access for supply chain stakeholders to apply data analytics in qualifying and advancing AM materials and equipment. Figure 1 shows both the role context and use context of an inclusive AM schema.

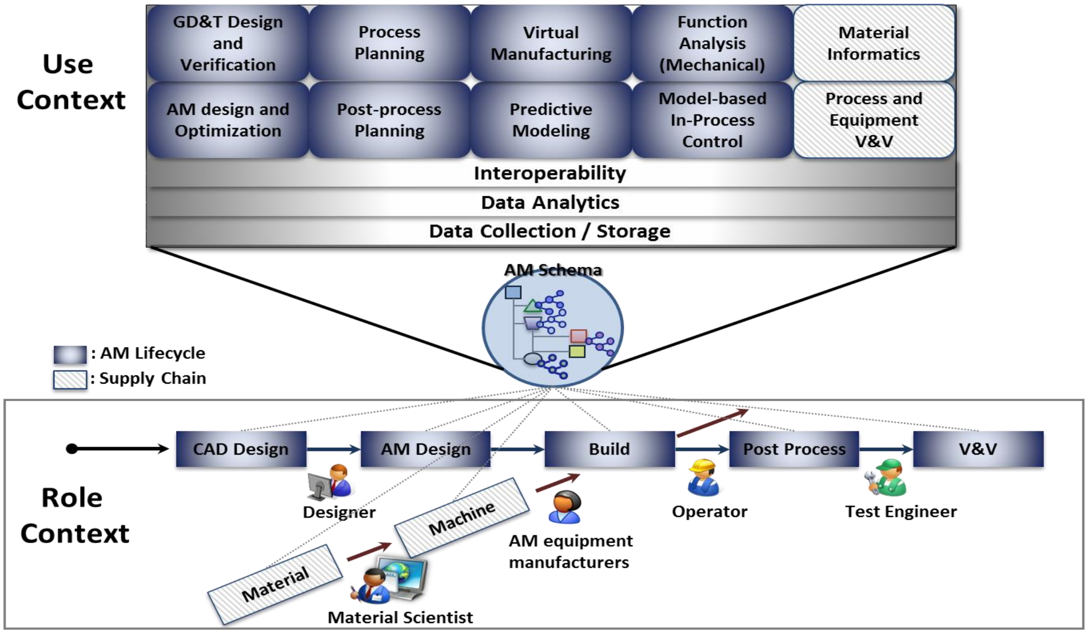

Figure 1 AM Information sharing based on a common data model

The bottom half of Figure 1 indicates that the data model should be comprehensive enough to cover the information needs of multiple stakeholders, such as designers, operators, test engineers, material scientists, and even AM equipment manufacturers. The adoption of a common data schema by stakeholders will enhance information sharing among different teams, improve part quality, facilitate tight and instantaneous collaboration between members of the development team, and ultimately shorten product development time.

The top half of Figure 1 lists potential applications supported by the AM data schema, ranging from design optimization, cost estimation, process planning, to predictive modeling and simulation, function analysis and model-based in-process control. Well-structured quality data with the full processing history of thousands of samples and parts can be mined to improve our understanding of materials and processes. Tools based on material informatics can facilitate the task of relating the powder properties from various suppliers to the process outcomes. Modeling and simulation applications can synthesize material properties for new material development. In addition, AM experimental data can help qualify and validate AM processes, machines, and materials.

Common data schemas that are able to support functionalities such as those described in Figure 1 are difficult to develop. This holds true for the AM process, perhaps more so than other processes, due to the volume and complexity of the data generated and consumed. To address potential challenges in AM schema development, we look to lifecycle data management techniques. For a common schema for lifecycle data management, Geryville [14] has defined three basic functional objectives:

1. Offer a standardized protocol for data interoperability for relevant information sharing through the lifecycle
2. Integrate collaborative lifecycle processes by providing a coherent flow of data within a heterogeneous framework.
3. Coordinate information and data in an open, lightweight, and extensible form.

These requirements will force AMIDM to focus on the aspects of the AM product development process that integrate different product development stages. They require modularity and facilitate upward compatibility between model releases. The requirements also support our development philosophy of leveraging existing modeling efforts and reusing model components to create an open data schema. As such, we adopt these requirements in our proposed schema.

3 AM INFORMATION COLLECTION

The first step in developing the AMIDM is to collect AM information in both role context and use context, as shown in Figure 1. We achieve this through the development and analysis of AM process activity diagrams, such as shown in Figure 2. The decomposition of the AM part lifecycle provides an overview of the types of information that is associated with the development of an AM part, providing insight into how this information may interact.

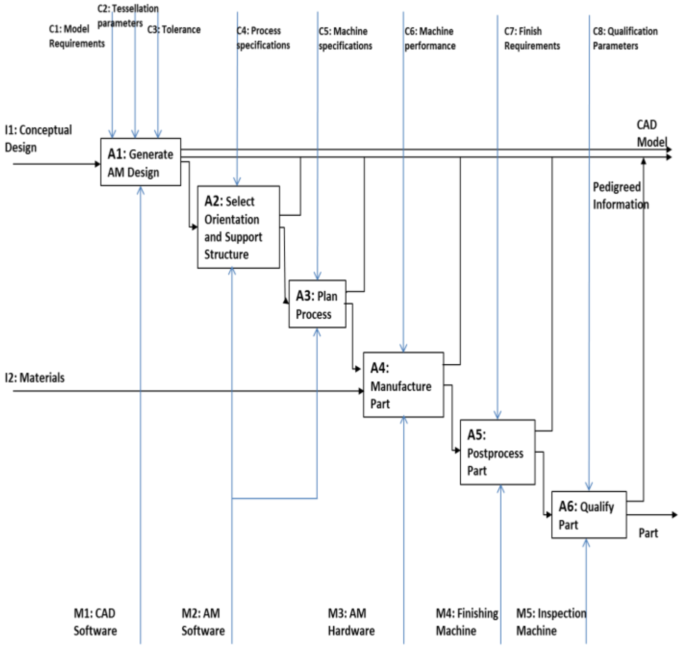

Figure 2 AM process activity overview

Figure 2 represents all the principal technical activities involved in the manufacture of an AM component, including the engineering activities of AM design generation, support structure design, process planning, part building, post processing and part qualification. The six activities identified above were isolated by identifying different “controls” observed in developing an AM part. These controls, identified in Figure 2 as the arrows feeding into the tops of the boxes, were determined based on the basic information requirements to complete each activity. We explain each activity in detail below.

Generate AM Design

This activity transforms a concept design to an AM design, including CAD modeling, model tessellation and repairing, and lattice design. The input to A1 is the conceptual design of the 3D model including shape, form and aesthetics, and the design evaluation results. The output from A1 is a watertight tessellated model. This activity is controlled by design requirements and specifications.

Select Orientation and Support Model

This activity selects build location and the optimal build orientation. Support structures are designed based on multiple criteria. This is a process-specific activity, as different processes may or may not require support structures and may or may not benefit from different orientations. The input of this activity is the watertight tessellated model. The output of this activity is an optimally oriented, watertight model and a support structure model. Process specifications control this activity.

Plan Process

During the process-planning phase, slices are created for both oriented parts and support structures. Machine-specific considerations must be made at this time. Build parameters are set and a final process plan for AM is generated, including the following elements: a scanning strategy, a control plan and measurement parameters, desired work piece quality parameters to describe the target parameters for real time control, and a monitoring plan. Machine specifications control this activity.

Manufacture Part

Based on the process plan from the prior activity, a part is manufactured using AM equipment. The outputs from this activity are the as-manufactured part with support structures and the in-process monitoring and event data. The actual machine settings, provenance data, and material lot and consumption are also included. This activity is controlled by machine performance.

PostProcess Part

Post process activities include support structure removal, surface finish enhancement, and mechanical property enhancement, depending on the part specifications. The information required includes support structure design details, part tolerance, finish requirements, mechanical property requirements, and material properties. The post process pedigreed information is also generated from this phase. Part finish requirements are the controls of this activity.

Qualify Part

The qualification activities involve tolerance and surface tests, porosity and crack tests, mechanical tests, and microstructure analysis tests. High volumes of data are generated during this stage including raw NDE data and part geometry, mechanical testing data, and microstructure analysis data. Qualification parameters control this activity.

The decomposition of the AM lifecycle, as noted above, provides us with a baseline for identifying data management challenges in AM. The schema must be comprehensive enough to address these data needs at the higher levels of abstraction, while being flexible enough to capture varying levels of detail.

4 ANALYSIS OF EXISTING AM INFORMATION STANDARDS

A prioritized criterion of our AM data schema design is to leverage existing standards, which we see as a key to acceptance of the data schema by the AM community. A comprehensive study has been conducted to highlight the features of related standards, and to identify gaps in the existing data standards. This section summarizes the results and presents a set of challenges that must be overcome in order to fill the gaps.

4.1 Survey of AM related data standards

STL (stereolithography) [15] is the most generic data format and de facto standard for AM. AMF was developed as a replacement for the commonly used STL format. AMF communicates design geometry to 3D printers. AMF provides an XML schema for AM and it is an open standard for describing objects for AM processes. The official AMF standard, ISO/ASTM 52915:2013, is an XML-based format designed to allow any computer-aided design software to describe the shape and composition of any 3D object to be fabricated on any AM system [16]. AMF has many additional features compared to the STL format, including curved patches, recursive subdivision, multiple materials, graded materials, internal structures, material properties, colors, graphics, constellations, and metadata support.

Microsoft announced 3MF as a new file format to support 3D printing in Windows 8.1 [17]. The process of 3D printing in Windows 8.1 has several steps. Firstly, the list of available 3D printers is enumerated and the user selects the 3D printer to use. Then, the user selects the print options, and the 3D model is converted to 3MF format. The 3MF data is encapsulated in an OpenXPS [18] document package. In the 3D print pipeline, a 3D printer driver extracts the 3MF package and converts it to a format understood by the printer. Finally, the data is sent to the 3D printer and the 3D model is printed out. 3MF is an XML-based data format and the geometry component is similar to that of AMF. 3MF consists of meshes, slices, components, metadata and attributes including color, material, and texture.

ISO 6983 G-code [19] is the most widely used numerical control (NC) programming language, and it is used in AM machines as well. STEP-NC is a machine tool control language that extends the ISO 10303 standards [20] in ISO 14649 [21]. STEP-NC was developed to replace G-code, the associative communications protocol that connects computer numerical controlled (CNC) process data.

4.2 Analysis of the standards for AM schema development

Although standard file formats have been developed for AM, these standards do not support the entire AM value chain as of today. AMF and 3MF currently focus on geometry representation, and G-code and STEP NC support the machine control of an AM process. Specifically, the standards do not address the desired lifecycle integration capabilities. Lifecycle information coverage of the standards are presented in Table 1. AMF covers the information representation of the AM design stage. 3MF represents AM design and partly covers the process plan and part manufacture. G-code and STEP NC support process planning and part manufacture.

Table 1 Lifecycle information coverage of existing Standard

	Lifecycle Information Coverage					
File Format	**Generate AM Design**	**Select Orientation and Support Model**	**Plan Process**	**Manufacture Part**	**Post process Part**	**Qualify Part**
AMF	O	O	X	X	X	X
3MF	O	O	Δ	Δ	X	X
ISO 6983	X	X	O	O	X	X
ISO 14649	Δ	X	O	O	X	X
O: fully covers, Δ: partially covers, **X**: no coverage						

Table 2 shows the existing standards' coverage of Geryville's three function objectives stated in Section 2. AMF provides a standard protocol for data interoperability and has an open, lightweight, and extensible form. 3MF provides standardized protocols for data interoperability, but its support environment is limited to Microsoft Windows 8.1. STEP NC provides a standardized protocol for data interoperability. However, AM machine vendors have not completely adopted STEP NC to control a machine. So, while G-code is widely used, it only partly satisfies the functional objectives of the schema.

Table 2 Status of existing AM information Standard

File Format	**Schema Functional Objectives [14]**		
	1	2	3
AMF	O	Δ	O
3MF	O	X	Δ
G-Code (ISO 6983)	X	Δ	Δ
STEP NC (ISO 14649)	O	O	Δ

In summary, both tables indicate that existing AM standards do not possess the desired breadth and depth for AM information management. Our methodology focuses on developing a conceptual data model towards achieving the goal of a complete and integrated information model for additive manufacturing parts and processes.

5 AMIDM CONCEPTUAL DESIGN

From product planning, design, production, procurement, and service up to sales, PLM comprehensively manages information related to the entire product lifecycle. PLM can be leveraged to manage data based on product, process, and resource (PPR) information [22]. Given our schema requirements and identified gaps, we investigate product lifecycle management (PLM) schema [14] as a starting point for developing the AM schema. PPR information represents core information of the product development process about the man, machine, material, and method (4M) [23]. PPR information is created, modified, and extended throughout the product development process. In addition, the PPR information links PLM with enterprise resource planning, supply chain management and customer relationship management, and thus PPR information propagates to the whole life cycle of the product.. Table 3 is a summary of the major features of the PLM schemas and an analogy to AM information content.

Table 3 Analogy between PLM and AM information [22, 24]

	PLM Schema	**AM Analogy**
Product Information	- Product information for assembly	- AM specific design, design rules and qualification
Process Information	- A process of manufacture (Routing-based) - Product-process and process-production relationship	- Pre-process (Process Plan) - Build - Post-process
Resource Information	- Machine, Tool, Jig & Fixture, Labors - Resources' sub-assembly	- Build equipment - Post-process equipment - Test equipment
Additional Important Factors	- Human	- Material

In a PLM schema, engineering and manufacturing bill of material (BOM) information representations are important. The correlation between the product information and process at each process sequence has to be clearly represented. The related resources such as machine, tools, and labor are linked in accordance with the process sequence. The labor information included in the resources needs to be separately managed and comprise important information such as industrial accidents and ergonomic analyses. [24]

An AM schema should represent AM specific designs, processes, and resources, and thus can leverage the PPR style. Additionally, material data representation is important for the creation of new materials. The schema has to be developed to be easily understood and implemented, as AM lifecycle data is huge and complex. The concept of AM schema development is explained in detail in the next several sub-sections.

5.1 AM information in PPR Categories

Based on the PPR model, we are able to classify AM information into three domains – Product, Process, and Production.

Product domain information includes any component-related information, from specifications to as-designed and as-built product information. For AM modeling, the domain can be generalized to include all the input and output information of AM process activities. Specifically, it includes design specifications, CAD models, design validation/verification information, tessellated models, sliced models, orientation, support structure/lattice structure information, scanning paths, as-built component models, as-postprocessed component models and as-qualified component models.

Process domain information records the AM activity governance data, for example, process control, as well as dynamic data generated during the activities, such as time series data from in-situ monitoring and testing. A non-exclusive list includes production requests, production job assignments, approvals, actual equipment, production time, subtasks, location, environmental parameters, process control parameters; events for deviation, material handling, in-situ sensor monitoring information such as sampling frequency, trend data, in-process analyses, post-processing procedures, inspection procedures, and NDE results.

Resource domain information can be further categorized into material, equipment, personnel, and software tools. The equipment information includes general machine information, envelope size, component information, material compatibility, system fitness, calibration, and maintenance history. Material information covers both vendor-specified property information and actual material qualification information, including sieving, mixing and distribution data and documents. Personnel information is simplified here, with roles limited to designers, operators, and controllers. Software tool information consists of the basic vendor information, version information and user configuration data.

5.2 A Conceptual Data Model

The three types of AM information define a core schema to establish the most general layer within AMIDM. Entities defined in this layer can be referenced and specialized by most entities. This core layer includes three main types of entities - product, process, and resource; and it provides the fundamental relationships among entities and the common concepts. We have modelled these essential concepts and their relations to each other in Figure 3 using Unified Modeling Language (UML) [29]. The conceptual data model is applicable to different AM technologies. The process and material attributes change based on the process and material type. The following sections describe the information model in Figure 3.

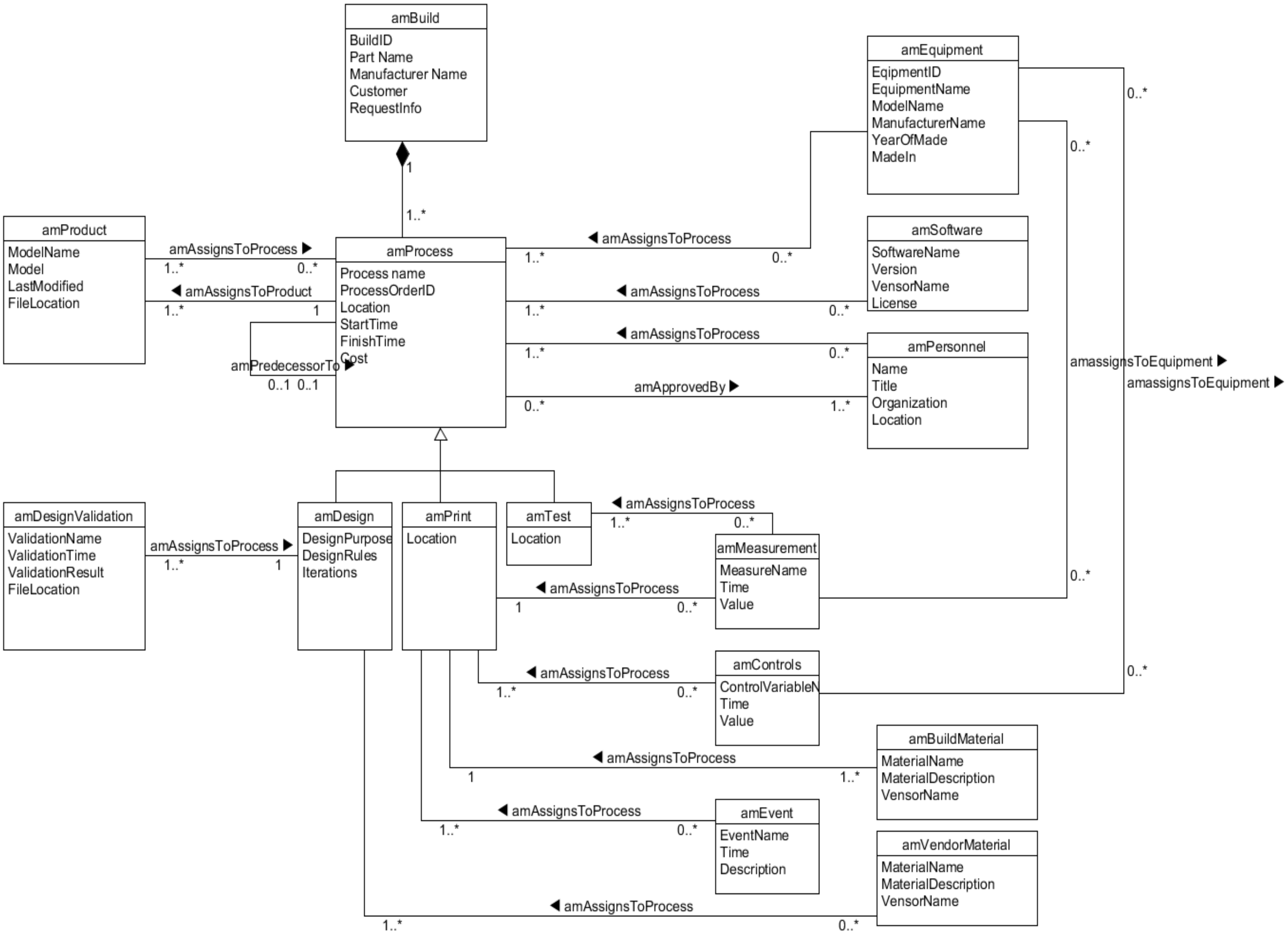

Figure 3 Conceptual Model of an integrated AM data schema

Build

"amBuild" indicates the undertaking of design, process planning, printing, and testing leading towards an AM part. The build establishes the context for information to be exchanged or shared, and it may represent a complete AM build project but does not have to. The amBuild's main purpose as an exchange structure is to provide the root instance and the context for all other information items.

A subset of the context provided by the amBuild includes build ID, the responsible manufacturer's name, customer name, and build request information.

Process

As shown in the Figure 3, processes play critical roles in transforming product input into product output, and connect to other processes through the input-output relationships. Resources like equipment/tools, materials, and personnel are assigned to the processes. Processes are composed of three subtypes: amDesign, amPrint and amTest. amDesign covers the first three design-related activities, and amPrint and amTest cover the latter three AM activities in the IDEF0 diagram shown in Figure 2. The differentiation comes from their associations. The design activities associate with design analysis and validation, while the build and test activities generate large amounts of time series data during the process, including in-situ control, measurement and event data. At the same time, the control and measurement data are directly associated with the equipment as shown in Figure 3.

Control

Though AM equipment control configurations are usually generated during a process planning phase, the actual data of real motion control, laser control and test equipment control could be different from as-planned. This data plays a critical role in faulty part analyses. The control variable data is expected to be at high sampling rates with time stamps recorded.

Measurement

Measurement data includes in-situ sensing and NDE testing data, which could be multi-dimensional or unstructured. Timestamps are very important for all data record. For highly dimensional data such as images, links to the files are recommended in the AM information model.

Event

amEvent is used to capture the information about particular interrupts that have happened or could happen. Particularly developed for the build/postprocess/test process maps, they identify a point at which an operator's command to disrupt the process, or a rule or constraint is invoked.

Product

The amProduct entity is a representation of any object that relates to a part shape/geometric representation, including customer-provided design requirements, CAD/CAM design models, as well as the 3D objects scanned from qualifying activities. Products are defined by their properties and representations. The proposed data schema does not intend to define a product model from scratch. Instead, existing models such as the ISO 10303 AP238/AP 242 [25], and ASTM F2915 (AMF) standards [16] can be adopted to describe original parts, support structures and manufacturing plans. Additional effort is required to implement models for lattices and heterogeneous materials, which is beyond the scope of this paper.

Results from design analyses, such as finite element analysis, are also included in the Product domain. The details are not included in the conceptual model, other than an attribute named FileLocation to specify a link to the design analysis.

Resources

The Resource domain includes entities like amMaterial, amEquipment, amPersonnel, and amSoftware. Many existing standards are applicable to this domain. Our future work includes identifying the most appropriate one to model AM resources.

Equipment

amEquipment has a multiple layer subtype structure as shown in Figure 4. AM equipment classification is based on existing standards, such as ASTM: F2792 − 12a [26].

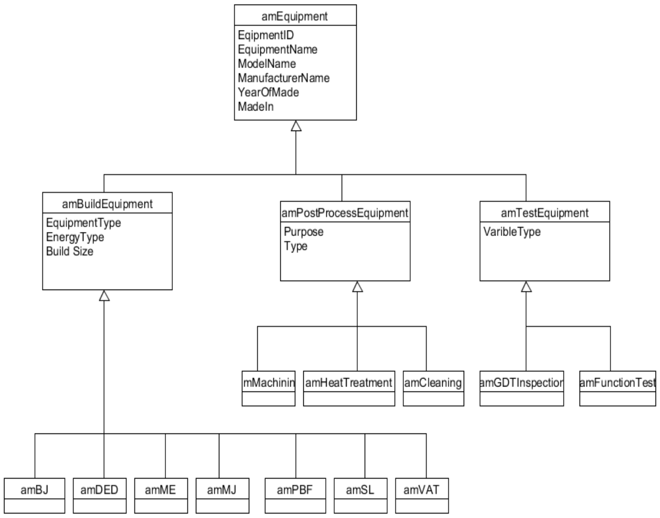

Figure 4 An example amEquipment data model

Software

The context provided by the amSoftware entity includes software name, version number, vendor name, the license agreement.

Personnel

amPersonnel represents an individual human being who has an active role in the AM process. The role a person plays is differentiated by associations when he or she is assigned to a process, either as an operator/designer (amAssignsToProcess) or as a controller (amAppovedBy).

Material

Material is assigned to both design activities and to build/test activities, but in different representations. During the design phase, only vendor material information is given, captured by amMaterial, which has numerous properties. During the build/test phases, actual material information is collected, including material lot/sublot information, actual consumption, sieving, mixing, distribution, qualification information, and chemistry certificates etc. Figure 5 shows a conceptual design of the material entity.

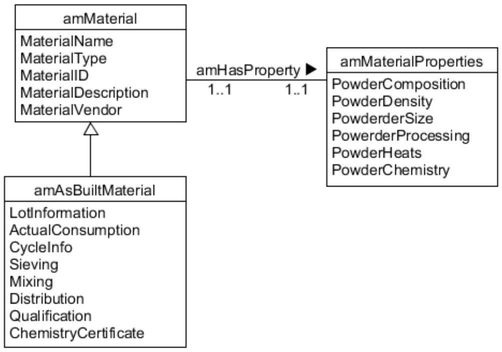

Figure 5 An example material data model

Relationships

Defining entities is only half of the effort for data schema development. In the real world, entities have relationships with other entities. A well-defined relationship model will not only link entities together for easy query and data search, but also improve data storage capacity and data access performance

UML diagrams distinguish between different types of relationships – inheritance, composition, and association – as shown in Figure 3. Subtyping, one application of inheritance, is often found in data models. An example of subtyping is the relationship between amProcess and amDesign, amBuild and amTest. Composition is another common type of relationship requiring no special definition, for example, the relationship between amBuild and amProcess. All other UML association types are model-specific, and the semantics have to be defined for database implementation or software construction. The cardinality and optionality of a relationship are combined into simple multiplicity definitions in the UML model. Figure 3 shows that subtyping and composition relationships usually have 1 to n mappings while associations could be m to n relationships.

Four association types are highlighted in our AM conceptual model. amAssignsToProcess handles the assignment of one or many objects to a process or activity. An object can be the item the process operates on, or a resource object the processes operates with, or a control or measurement object the process generates. amAssignsToProduct assigns a process to a product, which indicates that the product is an output of the process. amAssignsToEquipment links the control and measurement data to the hardware equipment. amApprovedBy represents the approval relationship between a process and a human being

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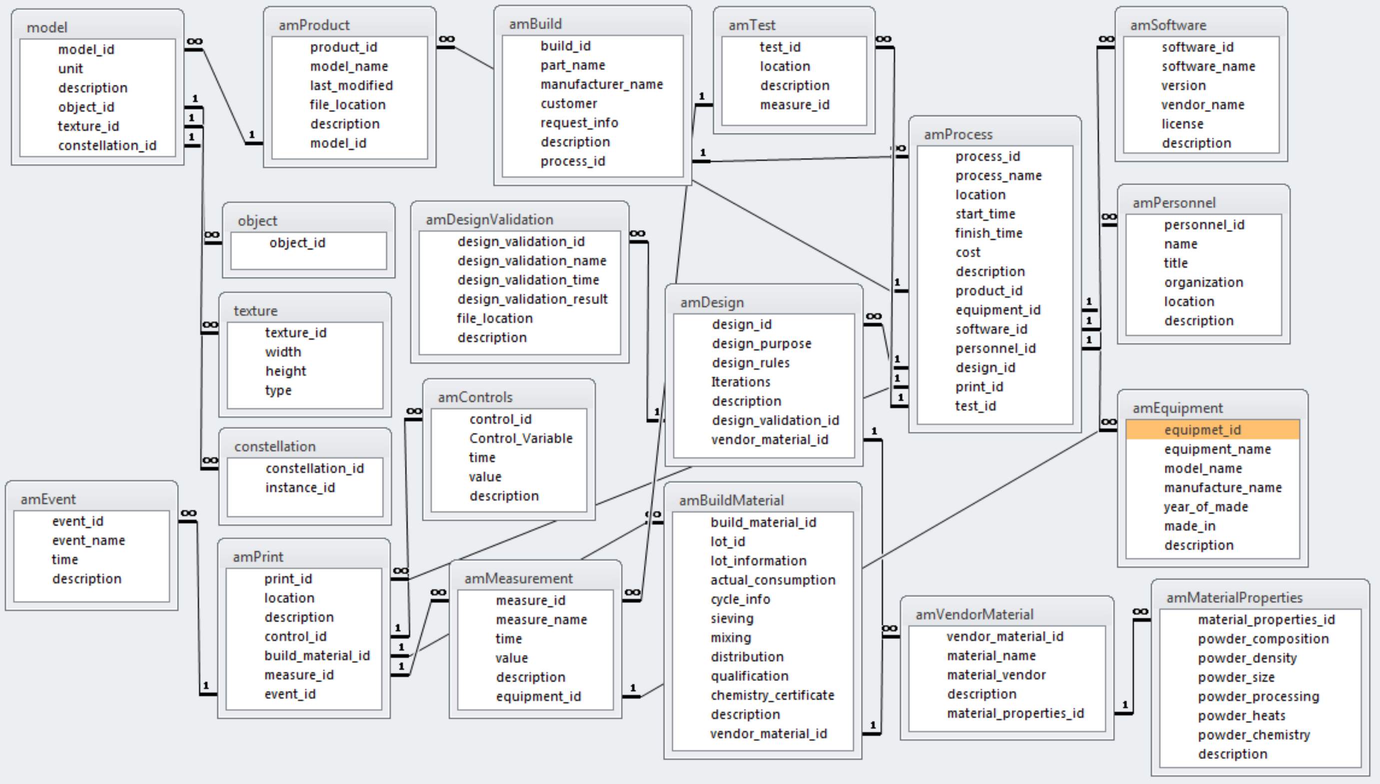

Figure 6 Database relationship model for NIST AM experimental data management

5.3 A Case Study

A NIST internal study is being conducted to develop a method called the Manufacturing Plan and report for a specific metal AM process known as laser powder bed fusion (L-PBF) [28]. The goal of the project is to confirm the effectiveness of a controlled data generation method on the characterization of material and mechanical properties of AM manufactured parts. The method specifically demonstrated for nickel alloy 625 produced using EOS M270 Direct Metal Laser Sintering machines. The Manufacturing Plan is broken into two main sections, one to define the production process and one to record it. The Manufacturing Plan was demonstrated with two controlled variables: machine serial number and build environment. All other conditions were the same including build geometry, powder lot, process parameter sets, and heat treatment. To this end, four total L-PBF builds were produced on three different serial number machines and in argon or nitrogen environments. The build coupons received a stress relief at 1038°C, followed by a hot isostatic pressure thermal treatment at 1121°C. Large volumes of structured and unstructured data were generated from the four builds. The data exists in various formats, such as CAD models, STL files, excel data sheets and pdf documents. To effectively store and analyze the data generated from the project, we applied our integrated AM information model to capture the data with an XML schema and developed a relational database using the relationship model shown in Figure 6.

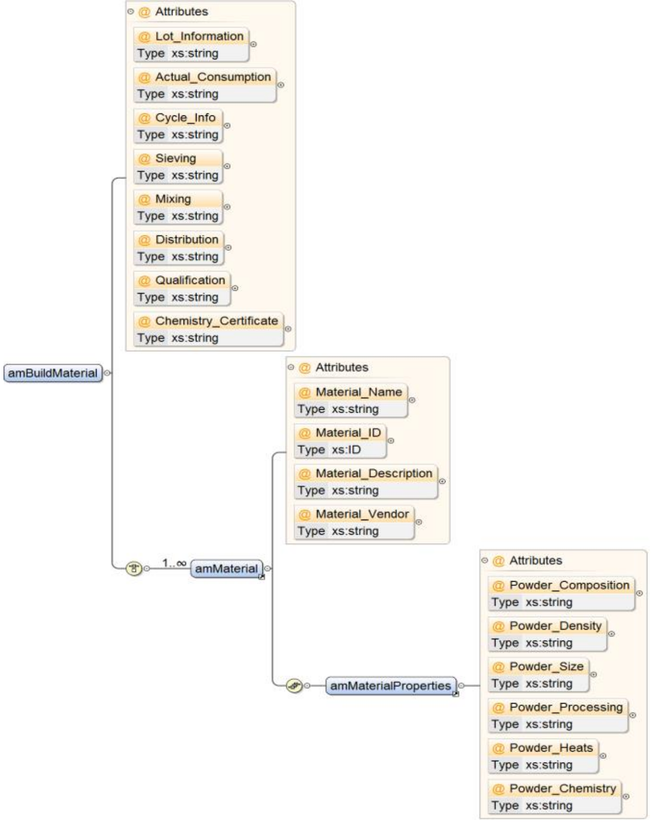

Figure 7 Build material XML schema

Figure 7 shows the details of AM material XML schema. The build material schema has properties of Lot_Information, Actual_Consumtion, Cycle_Infomation, Sieving, Mixing, Distribution, Qualification, and Chemistry_Certificate as attributes. The amMaterial is a general entity that captures vendor material information including a unique material ID, the material name, the material description and the vendor name. The attribute amMaterialProperties links to amMaterial. It manages powder information such as composition, density, processing, heats, size, and chemistry.

For the case study, the database is being implemented in Microsoft Access. **RStudio** [27], a free and open source integrated development environment (IDE) for **R**, is used to connect to the database and perform statistical analysis of the experimental data. Future work will further discuss the implementation of the described database and lessons learned.

6 CONCLUSION

Many of the standards discussed in Section 4 can support AM information. However, none of the existing standards support the complete AM development lifecycle and supply chain. This paper has taken an integrated PLM approach to design the AM data schema AMIDM, which supports AM data collection, storage and usage over the entire AM value chain. The proposed data model has advantages over the listed standards, not only in comprehensiveness, but also because of the AM-specific navigable structure. The AM-based relationship models enable easy query and data analytics. Because the proposed concept model is generalized and extensible, it is applicable to all the AM processes and tools. To demonstrate the possibilities, we have created a prototype of implementable XML schemas and a relational database for AM experimental data management that can be used effectively to test the repeatability of direct metal laser sintering (DMLS) based AM processes.

Future efforts will focus on extending the conceptual schema to a fully implementable data model. Data analytics are beginning to play a large role in AM progress. From modeling, to closed-loop control, to design allowable databases, how information is structured, stored, accessed, and analyzed will play a significant role in potential applications of AM data. We believe that further schema refinement, especially refined and expanded relationships, will facilitate the identification and extraction of correlations in AM data. When extended across the design-to-product transformation, the proposed AM schema will support the sharing, retrieval, exchange, access, and reuse of AM information; ultimately, streamlining the information flow and reducing AM cycle times.

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