

Fundamental Requirements for Data Representations in Laser-based Powder Bed Fusion

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ABSTRACT

Additive Manufacturing (AM) processes intertwine aspects of many different engineering-related disciplines, such as material metrology, design, in-situ and off-line measurements, and controls. Due to the increasing complexity of AM systems and processes, data cannot be shared among heterogeneous systems because of a lack of a common vocabulary and data interoperability methods. This paper aims to address insufficiencies in laser-based Powder Bed Fusion (PBF), a specific AM process, data representations to improve data management and reuse in PBF. Our approach is to formally decompose the processes and align PBF process-specifics with information elements as fundamental requirements for representing process-related data. The paper defines the organization and flow of process information. After modeling selected PBF processes and sub-processes as activities, we discuss requirements for the development of more advanced process data models that provide common terminology and process knowledge for managing data from various stages in AM.

Keywords: additive manufacturing, powder bed fusion, process data interoperability, and systems integration.

1. INTRODUCTION

Additive Manufacturing (AM) technology has been evolving rapidly, as more and more researchers and technology developers are developing and implementing these systems [1–3]. Systems that support different activities in AM, such as design, process planning, fabrication, measurement, and control, become more sophisticated in order to meet market demands. Due to the rapid growth in magnitude and intricacy of AM systems and processes, users are facing islands of technologies that are not fully compatible, and hence impede the progress of making systems interoperable for collaborative projects in different phases of AM.

As AM becomes more accessible to small and medium enterprises and demands for mass customization increase [7], common data sets are becoming increasingly desirable, with process data serving a key role. Many are investigating ways to effectively capture process parameters to support material databases for AM [8,9]. Manufacturers are tasked to independently decide how the process performance is measured and how the data is recorded. The different AM machines, control parameters, measurements, and even personnel will influence how process-related data is generated, captured and stored. These variances make it extremely challenging to share and reuse the quality data sets that are generated by industrial collaborators using heterogeneous software systems.

A fundamental issue is that data cannot be shared among heterogeneous systems because there is a lack of common data structure, vocabulary management systems, and data interoperability methods. This lack of interoperability impedes the use and re-use of AM process data. Transparent access to and deliberate structuring of this process data is essential to furthering the development of process-material-geometry relationships in additive manufacturing. As industry continues the trend of adopting AM technologies [7], issues associated with the availability of data are becoming increasingly important. Process data lies at the center of this, as quality process data is essential for repeatability in AM part production. However, there are several factors that impede the sharing of the data, including (1) undefined key parameter sets, (2) inconsistencies in measurement techniques, (3) ambiguities in data representations, and (4) the proprietary nature of the process data. The proprietary nature of the data plays a large role in impeding the sharing of data, as industry is hesitant to share any headway they may make for fear of losing competitive advantages.

In this paper we investigate the challenges faced when capturing process information, and attempt to address the root causes through methodical information modeling techniques in the context of design, process planning, fabrication, inspection,

and quality control. Our goal is to lay a foundation for a common understanding of how the laser-based Powder Bed Fusion (PBF) process and equipment performance is measured, and process data is captured, stored, and accessed. The organization of the paper is as follows. Section 2 reviews the current state in PBF process data representation. Section 3 provides an overview of a generic AM process to set context for data sharing and exchange. The section also describes the fundamental data requirements. Section 4 discusses the more advanced requirements and opportunities in systems integration and limitations of the input, output, control, and mechanism data in activity diagrams. Section 5 concludes the paper.

2. REVIEW OF LASER-BASED POWDER BED FUSION (PBF) DATA REPRESENTATION AND CHALLENGES

Different materials and processes require different ways of capturing and managing information, as data may be vastly different. The variations that are observed in AM processes are well documented [10]. Large manufacturers, by capturing enormous amounts of data, have had incremental success in duplicating builds in production scenarios [11]. For a specific process, process-related information can fall into one or more of the following two categories: 1) process planning and 2) process monitoring and control. Each of these creates their own challenges in data representation.

Process planning using available tools (e.g. Slic3r [4], Magics [5], Netfab [6]) is a critical task in AM since it provides the basis for process control that leads to quality of final products [12, 13]. A process plan has four major components that can influence the quality of products: orientation determination, support structure design, slicing, and scanning plan. These four components can significantly influence the manufacturing cost, time, geometric tolerance, surface quality, and mechanical properties of the product. Scan path planning includes the determination of path, speed, laser power, and hatching width [14, 15]. These process parameters are determined by either trial-and-error, or using empirical process models [16] or physics-based process models [17, 18, 19].

Process monitoring and control information will refer to the data that are collected or accessed during the build of the part. In a study on process monitoring and control for PBF, some key factors that affect layer and part quality are revealed, such as laser power, spot size, and hatching space [20]. Three key categories of measured data can influence the quality of the product: powder layer filling, powder fusion, and monitoring the fusion process including measurements. In research on the control of PBF quality, based on the analysis of photodiode images, the monitored data includes melt pool temperature and size [22]. A control loop for PBF using thermal sensors identifies a need for radiation data in data sharing [23]. In the research of on-line detection of defects in PBF, using pulsed laser transient thermography techniques, laser pulsed data and defects measurement data are shared by the infrared sensors, control system, thermographic software tool, and quality analysis system [24]. Process monitoring and control related to the specification of the sensors and their setup has been recognized as a key enabler for qualification and certification

in AM [25]. From this review, we identified sets of data elements and categories related to process planning, process monitoring, and control for powder bed fusion. We also determined that there has been little study in information requirements for data representation.

3. PBF PROCESS DATA REQUIREMENTS

To organize the exchange and flow of information among the various activities mentioned in the previous section, we decompose the PBF process into specific activities, represented as activity diagrams using the IDEF0 (Integrated Definition for Functional Modeling - the 0th level) methodology [26]. Activity decomposition helps identify specific input and output data associated with each sub-activity, including how information can be used or aggregated through the PBF process chain. It allowed us to methodically cluster process parameter sets to establish key information in process planning and process monitoring and control. Based on these activity diagrams, we developed an activity model for describing requirements on the representation of PBF processes' planning and fabrication data. The information model development consists of three major tasks: (1) defining the scope of process information in PBF, (2) analyzing process planning, fabrication, and in-process measurement, and (3) organizing the input/output data through activity diagrams.

A focus on activity decomposition, irrespective of specific resources used in the process, is necessary to address differences in the various types of process data collected, and make correlations between them. The aggregation of the information allows us to draw similarities between different measurements of a specific phenomenon in a process. How the parameters are aggregated helps us understand how to model the data.

To scope our modeling efforts, as shown in Figure 1, we describe a PBF process, using a commercial software system. Note that a diagram consists of rectangles and arrows. An activity is represented by a rectangle. When the rectangle is shaded, it means that the activity is decomposed into subactivities. Input data (e.g., design specification) is consumed by the activity and transformed into output data. An output (e.g., product) represents the data resulting from the activity. Control and constraint data (e.g., design and planning rules) are used to regulate the activity. Resource and mechanism data (e.g., machine and powder specifications), coming from the bottom, can be software, hardware, and/or data that support the execution of the activity. A PBF process fabricates a part by adding and joining powders track after track and layer upon layer, as opposed to subtracting materials from the feedstock material [27]. Although Figure 1 shows six activities in a typical PBF process (designated as A1 to A6), the focus of this paper is activities associated with process planning and process monitoring and control (A3 and A4). However, since these activities use information generated in the previous activities, and provide information for the other downstream activities, brief descriptions of these activities are given below.

One output of the Model Product (A1) is the information that defines the product. A product model is created through product design. The other output of A1 is information about

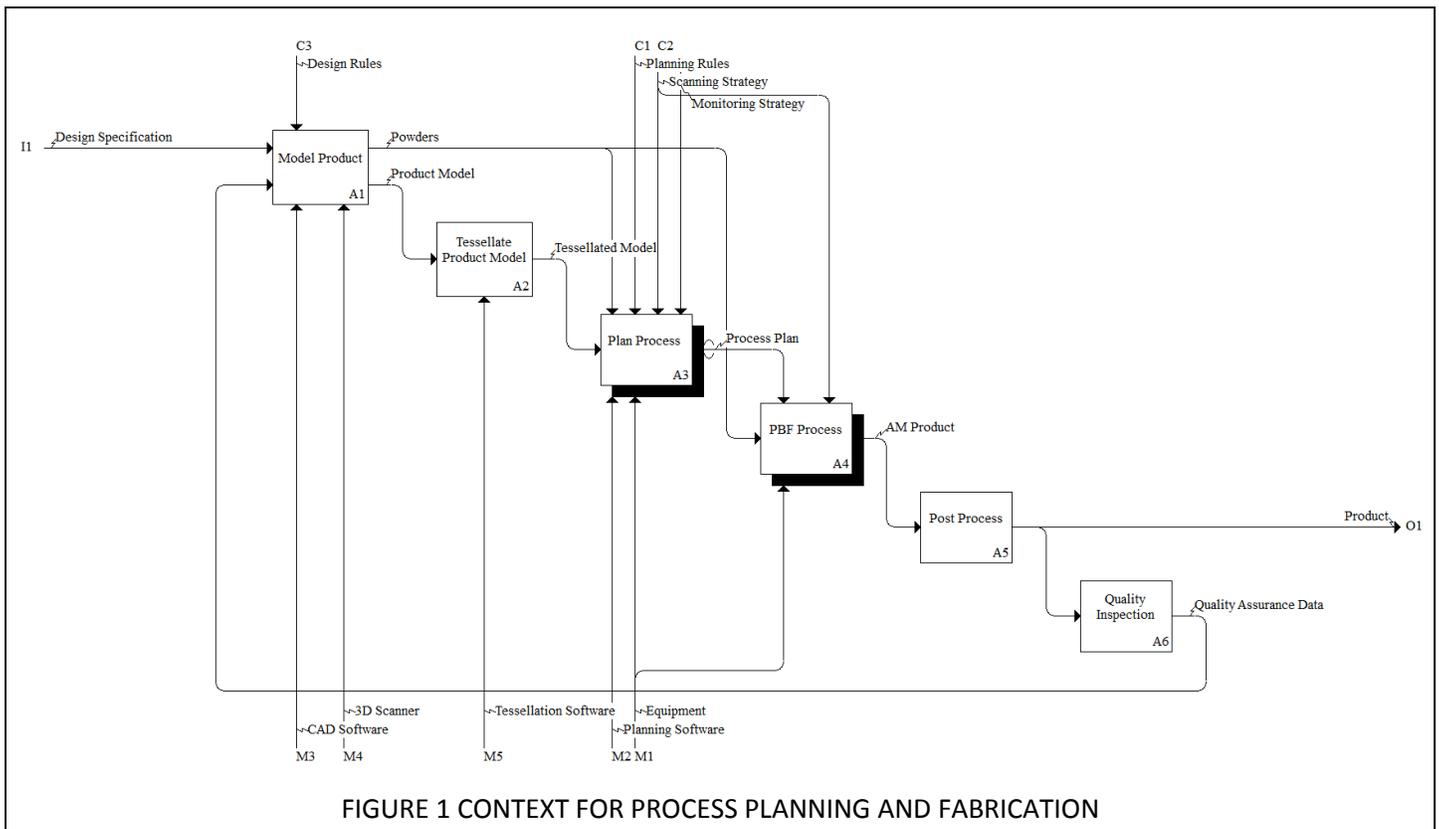


FIGURE 1 CONTEXT FOR PROCESS PLANNING AND FABRICATION

the selected powders for fabrication. A1 uses the constraints defined by Design Rules (C3) (Design Rules is a general term for rules that designers use to define a product model based on functions and constraints.). The output of Tessellate Product Model (A2) is a Tessellated Model, the representation of the product using three-dimensional triangulated surfaces.

Information generated by process planning, monitoring and control (A3 and A4) is used by the activities downstream (A5 and A6). Post Process (A5), describes further processing of the additively manufactured product to meet the design specifications. Lastly, Quality Inspection (A6) is associated with detecting defects of AM products.

Some subactivities in A3 and A4 do not reflect the present technological state, such as monitoring planning in A34 (Figure 2) and in-process powder fusion monitoring in A43 (Figure 7). These subactivities and associated data are developed for meeting the anticipated new process monitoring technology in the future.

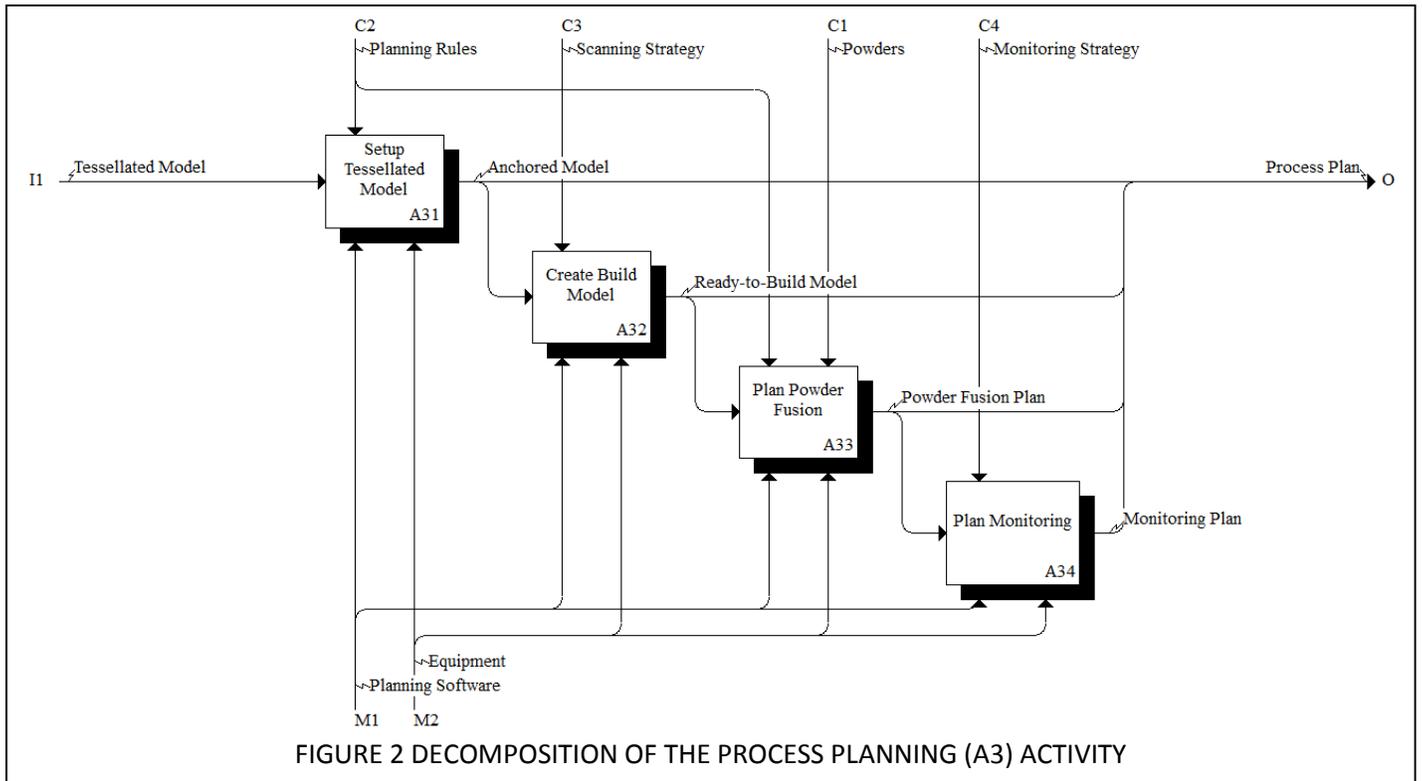
3.1 Process Planning

Process planning (A3) is an activity to determine the desired track, layer, and product quality and process control plan based on a tessellated model, which is created from the product model. The tessellated model has no “leaks” in the model (water-tight) and is ready for layer generation (slicing) and can be in the format of the stereo lithography (STL) format or the Additive Manufacturing format (AMF). The output of A3 is a process plan defining machine commands for a specific PBF machine. A PBF process plan includes the following elements: a ready-to-build model created from the tessellated model, powder fusion plan with control and measurement parameters, and a monitoring plan (future technology). Planning Rules, Scanning

Strategy, Powders, and Monitoring Strategy are used as controls of A3. Planning Rules is a general term for rules that are used in process planning, including product setup rules, and control parameters selection rules. Scanning Strategy is used to plan the movement of the laser, including machine components. We identify Powders as a control in this context, as we are referring to the processing requirements of a specific material. Monitoring Strategy provides guidelines, rules, and methods to monitor the PBF process. Equipment specifications are used as a resource in A3 including the properties of machine components, such as product chamber, powder container, working space, laser, and sensors. Planning Software is a software tool used for generating a process plan. Details of input, output, control, and resources data will be decomposed below. Figure 2 shows four sub-activities of A3.

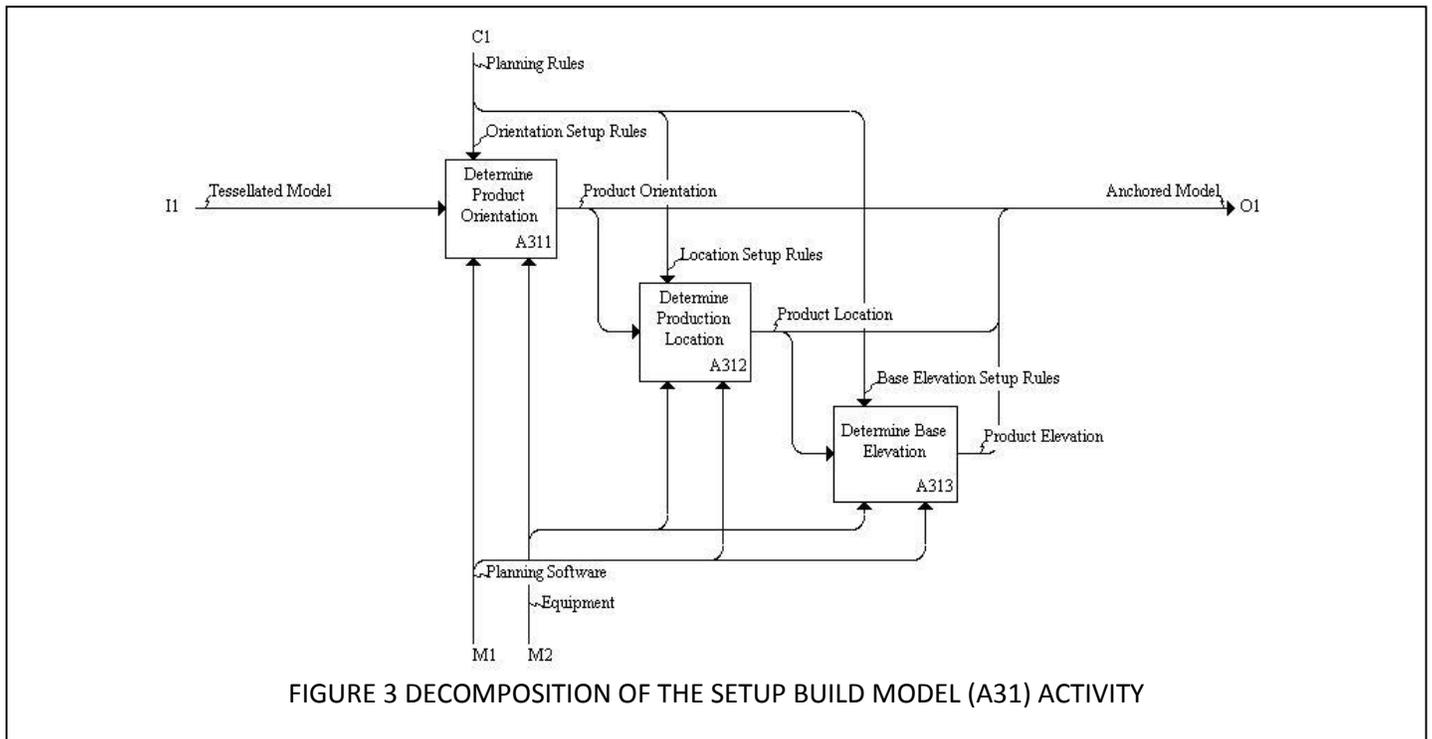
Setup Tessellated Model sub-activity (A31) is to determine product placement on the build plate with respect to the machine coordinate system. A31 uses Setup Rules, and it is a part of Planning Rules, as shown in Figure 2. The output of A31 is an Anchored Model, ready for creating a build model in A32. The attributes of Anchored Model will be described next in the three sub-activities (see Figure 3) of A31.

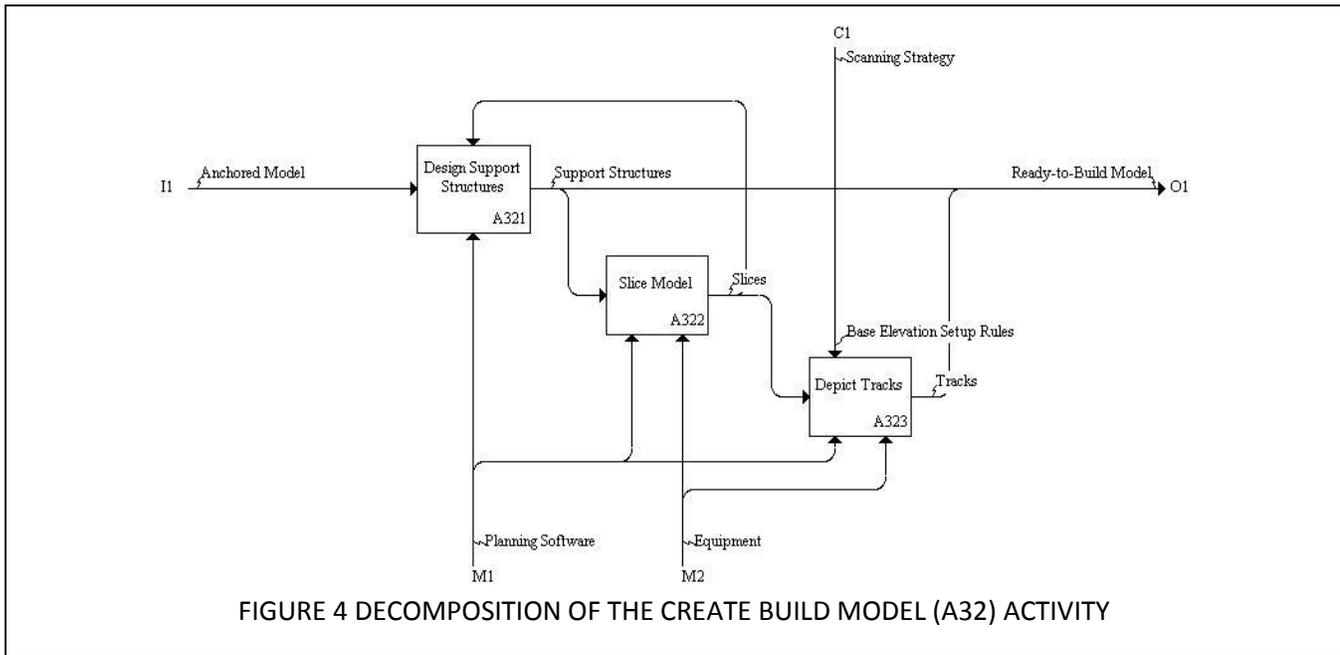
The first sub-activity of process planning is determining the orientation of the tessellated model on the build plate (A311). The control is Setup Orientation Rules, which are a subset of Planning Rules. The Mechanism of A311 includes Error Maps, Laser Spot Size, Laser Power, and Build platform Size, and they are subsets of Equipment in Figure 3. Error Maps refers to the machine position and orientation errors in the work volume. The output is the product’s orientation on the build plate. A312 is to determine the location of the tessellated model



on the build plate. This sub-activity has the control of Location Setup Rules, which is a subset of Planning Rules. A312 has the mechanisms of Build Height Limit, which is describing a parameter in Equipment. A313 is to determine the base elevation for defining the clearance of the additively manufactured product so that it can be removed from the build plate without being damaged. This sub-activity has the control of Setup Base Elevation Rules, which is a subset of Planning

Rules. The Output is Product Elevation, which is the distance between the product base and the build plate. The output of A31 is Anchored Model that is the Tessellated Model with the determined orientation, location, and base clearance. A32 is Create Build Model, a model that has necessary information for starting the powder fusion process. The input is Anchored Model from A31. The Scanning Rules are a control. The mechanism includes Planning Software and Equipment. A32 is

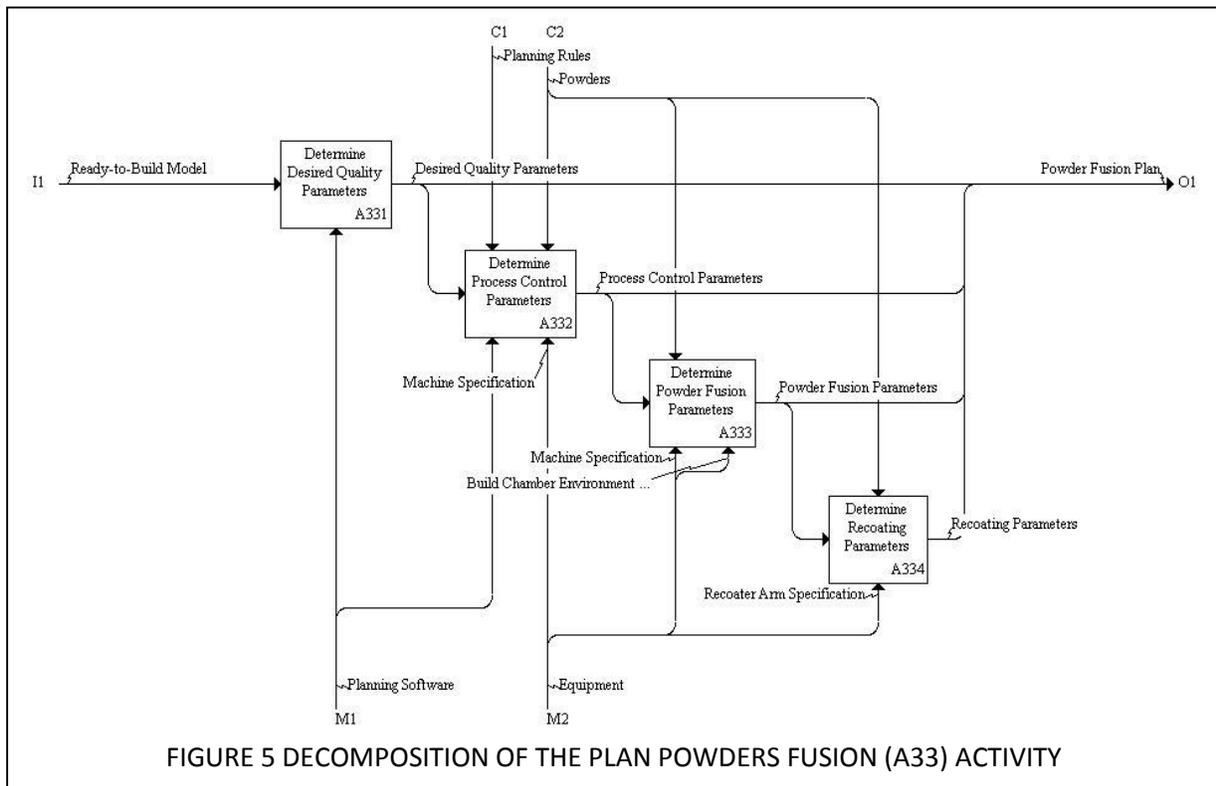




decomposed into three sub-activities (see Figure 4). A321 is Design Support Structures and supports the building of overhanging features. The activity takes the output of A322, Slices, as a control. The output is Support Structures that are needed to support the fabrication of the product. A322 is Slice Model to generate layers to fabricate. The output is a set of defined Slices, which are layers in the fabrication process. A323 is to depict tracks on each layer to define laser scanning tracks. The output is Tracks, a set of track patterns on each slice that the laser scans in the fabrication process. The result from A32 is a ready-to-build model, which combines the anchored

model with designed support and lattice structures, slices, and tracks. The ready-for-build model is the output of A32 to the following activity Plan Powders Fusion (A33) (see Figure 5).

A33 is to plan the powder fusion process (i.e., heating, melting, cooling, and solidification). Planning Rules and Powders are the control of A33 and used to guide the planning process. Powders is the term representing the data about the selected powders, including chemical composition, and physical properties, to be used in powder fusion planning. This data determines the processing requirements of the powder.



The input is Ready-to-Build Model. The mechanism data are Planning Software and Equipment, including Machine Specification, Build Chamber Environment (temperature and insert gas used in the chamber), and Recoating Arm Specification (including relevant parameters used in the activity, such as arm moving speed, blade type, and associated sensor specification if exist). A33 is decomposed into four sub-activities. A331 is to Determine Desired Quality Parameters. The output is Desired Quality Parameters, which include desired track and layer quality parameters, such as geometric, physical, and metallurgical parameters. A332 is the activity of Determine Process Control Parameters. The output is Process Control Parameters, which include laser, scanning, and powder layer parameters. A333 is the activity of Determine Powders Fusion Parameters. The output is Powders Fusion Parameters. These parameters are for process monitoring, and they include parameters related to melt pool, voids, and microstructure. A334 is Determine Recoating Parameters. The output is Recoating Parameters. These parameters describe moving powders from the powder box into the build chamber, such as recoating speed and layer thickness. The output of A33 is the Powder Fusion Plan, which includes Desired Track Quality Parameters, Process Control Parameters, Powders Fusion Parameters, and Recoating Parameters.

A34 is Plan Monitoring, including specifying sensors and their setups for in-process measurement of the powders fusion process. The input is the Powder Fusion Plan. The mechanism includes Sensor Specifications and Planning Software. Sensors Specifications describe setups for in-situ process monitoring for quality control and assurance. Major sensors that may be

available to select in the future include dimensional measuring sensors, thermal measuring sensors, porosity measuring sensors, residual stress sensors, and chemical composition sensors, as shown in Figure 6. Specifically, they are as follows:

- (1) A341: thermal imaging system for temperature measurement (the output of A341 are dimensional and shape Sensors and Setups),
- (2) A342: video camera to detect track irregularity, layer deformation, and part accuracy (the output of A342 are Thermal Sensor and Setups),
- (3) A343: ultrasonic sensors to detect cracks and pores (the output of A343 are Porosity Sensors and Setups),
- (4) A344: stereo-imaging system to detect bending due to thermal stress (the output of A344 are Stress Sensors and Setups),
- (5) A345: spectral analysis system to detect chemical composition (the output of A345 are Material Composition Sensor and Setups).

The description of the sensors includes sensor type, functionality, limitation, uncertainty sources, and speed. The description of a setup is the measuring direction and distance relative to the object, such as melt pool and the track. Also, setups specifications include the locations, orientation, and mounting methods of the sensors. The control is Monitoring Strategy that provides guidance, rules, and methods for performing A34. The output is Monitoring Plan that includes the specifications of the selected sensors and their setups. Planning for post processes can be considered as a sub-activity of process planning, but it is considered to be out of the scope of this paper.

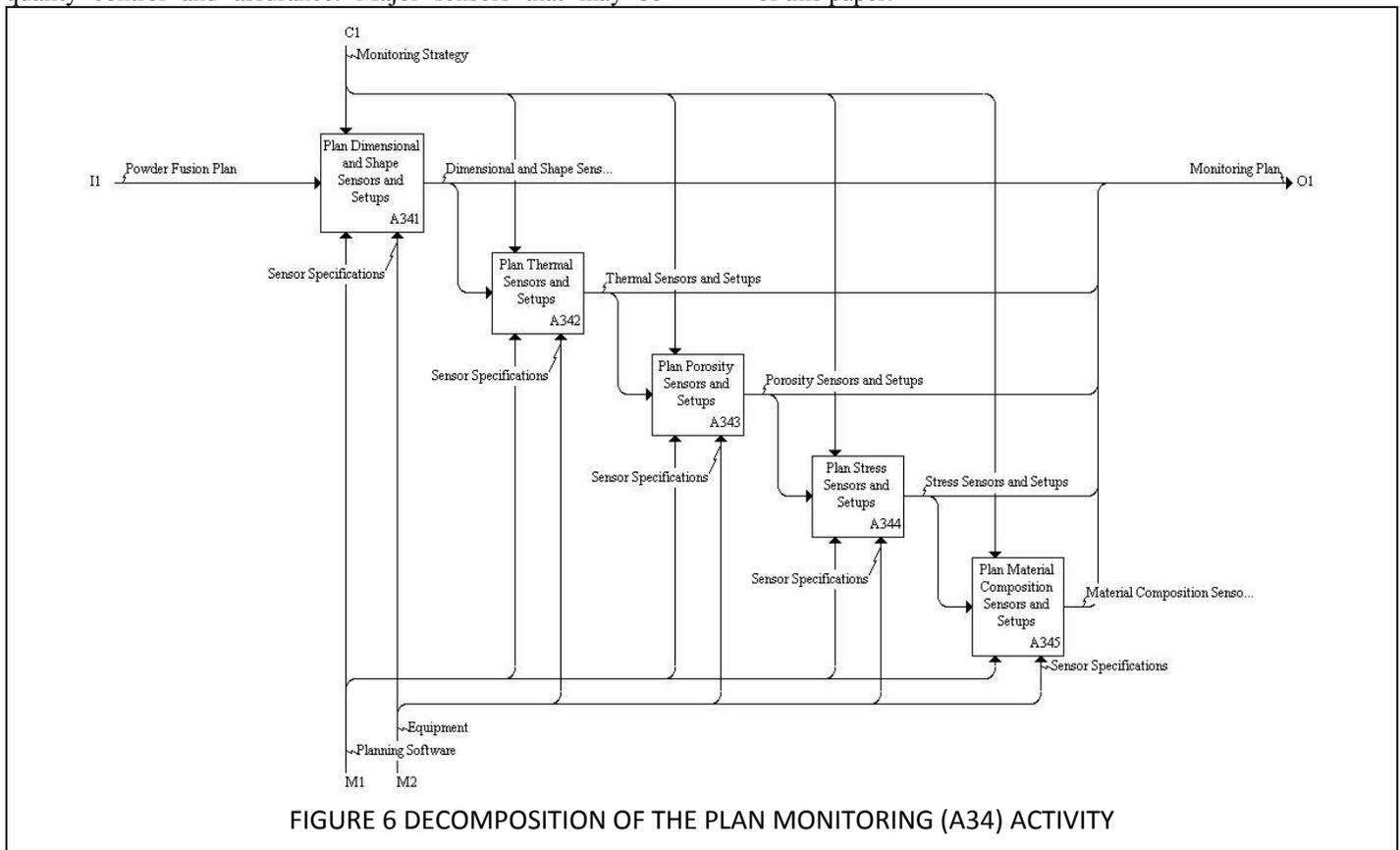


FIGURE 6 DECOMPOSITION OF THE PLAN MONITORING (A34) ACTIVITY

3.2 PBF Process

PBF Process (A4) is the activity of fabricating the product in a layer-by-layer powder fusion process. Figure 7 shows the PBF Process and its three sub-activities. A4 takes Powders as input, as in this context the planning for materials has been completed and the process is to be executed. Control includes Process Plan, Layer Thickness (it can be derived from Slices, the output of A322. Layer Thickness is channeled into A41, with parentheses at the top of the arrow), and Scanning Strategy. Process Plan includes Ready-to-Build Model and Desired Quality Parameters generated in A3. Layer Thickness is an element of the Process Plan.

Scanning Strategy provides knowledge and methods for appropriately setting up the scanning operations. Additionally, an AM process can be either a physical process or represented by a virtual process. A virtual process involves process models and simulation. A physical process takes place in a PBF machine. A4 has the mechanism of Equipment, including Recoater Arm, Powder Container, Build Chamber, Build Chamber Environment, Laser, and Sensors. The Recoater Arm specification includes the form, dimensions, and operational limits of the recoater. Powder Container Specification is the area of the container and the depth of the powder container. The Build Chamber Specification has the area of the chamber and the depth of the chamber. Build Chamber Environment has the attributes of the working volume of the build chamber and the working temperature limit of the chamber. Both Laser Specification and Sensors Specifications have been described previously. The output of A4 includes AM Product and Measured Data. Details in Measured Data will be described below.

Fill Powder Layer is activity A41. This activity is to spread a layer of powders with specified thickness to the build chamber for new layer fabrication. A41 has the control data of Layer Thickness, Scanning Strategy, and Process Plan. Measured Data is the feedback control as an input from A43. A41 has no decomposition. The output of A41 is information about Powder

Layer. Fuse Powders is activity A42. The input includes information about the Powder Layer and Measured Data. The controls are Scanning Strategy and Process Plan. The mechanism data include Build Chamber Environment and Laser Specification. Figure 8 shows the decomposition of A42, which has two sub-activities. Melt Powders is activity A421. It refers to the heat radiation and heat absorption needed to melt powders in the track and has the output of Melt Pool that describes the geometric and temperature characteristics of a melt pool. Solidification is activity A422. It describes material changes during cooling. During cooling, the material transforms from liquid state to a solid state with microstructural change, porosity formation, residual stress development, and geometric irregularities (balling, discontinuity, etc.). The output is fabricated track or layer of the workpiece with metallurgical, physical, and geometric characteristics.

Monitor Fusion is activity A43. It is to collect data from sensors for measuring process variability and workpiece quality monitoring during laser scanning. The inputs are Powder Layer from A413, Melt Pool from A421, and Workpiece from A422. The control data are Monitoring Powder Filling Plan, Monitoring Melt Pool Plan, Monitoring Defects' Plan, Monitoring Residual Stress Plan, and Monitoring Material Microstructure Plan. They are all parts of Monitoring Plan. The mechanism is Sensor, which is decomposed into Powder Layer Sensor, Noncontact Temperature Sensor, Ultrasonic Detector, Strain Measurement Instrument, and Microscope. The output Measured Data describes the in-process measurement data that are used to determine (1) local powder properties, (2) melt pool shape and temperature, (3) pores and cracks to affect the quality of the track, layer, and part, and (4) thermal stresses, and (5) microstructure. Sensor data are used to determine the state of the process including temperature change versus time, melt pool dimensions, thermal stress on the platform, and porosity in the heat- affected zone. The measured data are necessary for

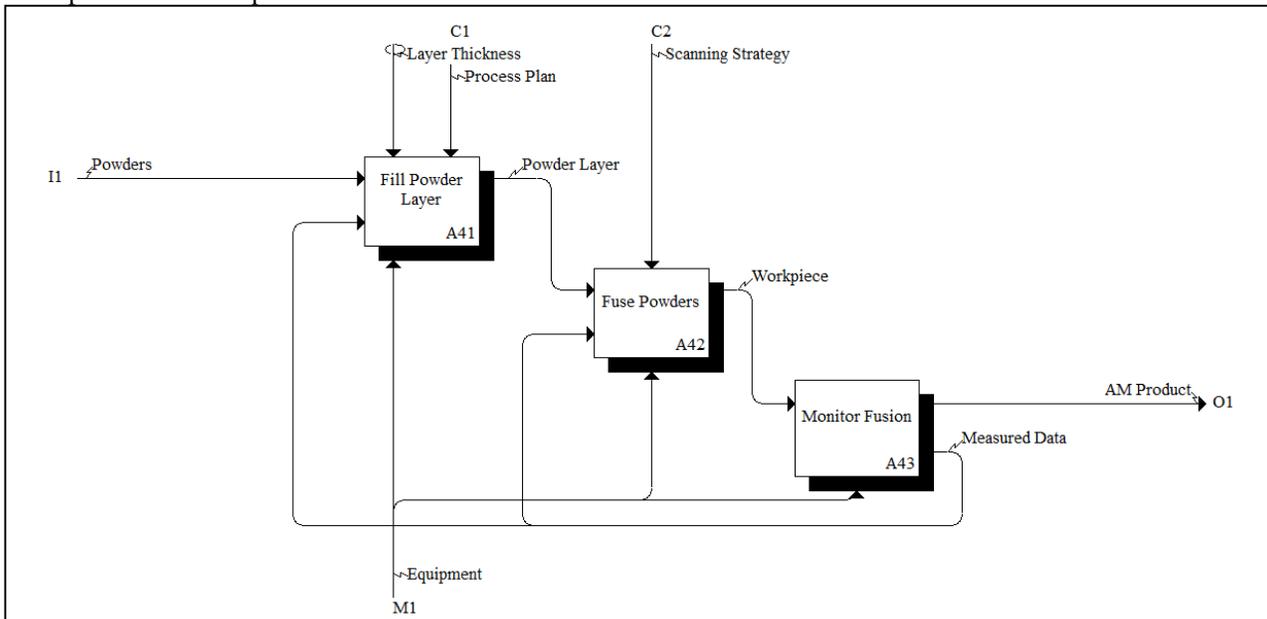
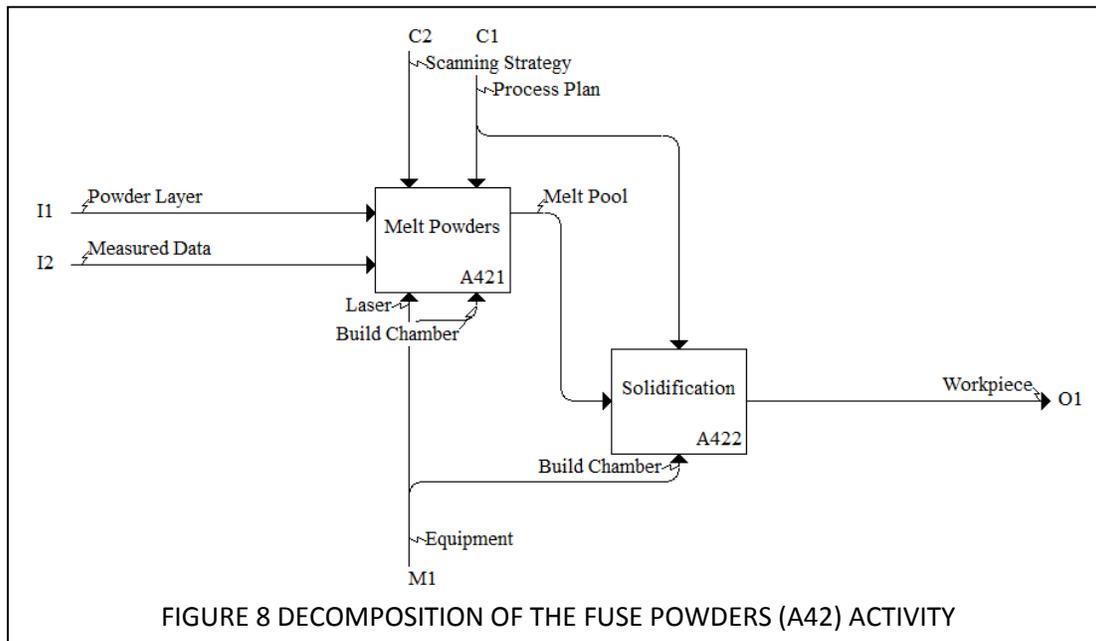


FIGURE 7 DECOMPOSITION OF THE PBF PROCESS (A4) ACTIVITY



feedback control to improve quality. A43 is decomposed into five subactivities, as shown in Figure 9. A43 has not been commonly implemented, and it is specified for desired future technology. A431 is the activity of Measure Powder Layer. It has the output of Local Powder Properties. These properties are local powder density, local powder size distribution, and local powder temperature distribution. A432 is the activity of Measure Melt Pool. It has the output of Melt Pool Shape and Temperature that describe the characteristics of the melt pool in scanning. A433 is the activity of Measure Defects. It has the output of Pores and Cracks that describe the sizes and locations of these defects. A434 is the activity of Measure Residual Stresses. It has the output of Stresses (desired future technology), including the stress distribution of the workpiece in progress or the final AM product. A435 is the activity of Measure Material Microstructures. It has the output of Microstructures of the fabricated layers (workpiece).

On the Feedback from A43 to both A42 and A41 (Figure 7), measured data are processed and analyzed to indicate the actual quality parameters. The measured parameters determine can be compared with the desired quality parameters. Error is the result of the comparison. The error is used by the controller for revising the control parameters for real-time process control in A41 and A42.

The activities A41, A42, and A43 can be part of a real-time feedback control loop, including in-process control and in-situ measurement. After it is fabricated, the product goes through a quality inspection activity (A6), as shown in Figure 1. The inspection is to determine whether the fabricated part meets the design specification. If not, the quality issues are addressed by revising part design, e.g., to compensate deviations in the process. This feedback loop is off-line and post-process.

The generic process monitoring and control activity diagram in this Section shows two feedback loops. The diagrams in Figures 1 and 7 can be used to develop a control architecture for PBF. Major characteristics of this control

architecture include real-time, in-process measurement feedback, off-line, post process quality inspection feedback, and in-situ sensor-based process measurement. The activity diagrams described above are designed to serve as the basis for the description of data flow.

4. DISCUSSION ON DATA MODELING OPPORTUNITIES

Section 3 provided comprehensive breakdowns of various activities associated with the PBF process. The detailed breakdowns of each activity are necessary to identify methodically the inputs and outputs associated with each activity. The models developed in Section 3 will provide a foundation for further decompositions moving forward. Many variations and customizations may occur in PBF process planning, processing, and testing. By identifying the process fundamentals, we can establish where variations and customizations occur, and can begin to establish a core data structure for the PBF process information.

Based on the activity diagrams in IDEF0, data modeling is a logical next step. When developing a data model to represent PBF process data, there are two major technologies to consider: relational data modeling and object-oriented data modeling. Relational data modeling is based on the entity-relation model [28]. It is used for developing a commonly used relational database. Object-oriented data modeling can be based on the Unified Modeling Language (UML) [29]. UML data modeling is logically approvable and rigorous for representing the PBF data discussed in this paper.

Given these different types of modeling technologies, structured representation of process data presents several opportunities. One such opportunity is the development of data models for describing and communicating PBF process planning, and fabrication information is another opportunity.

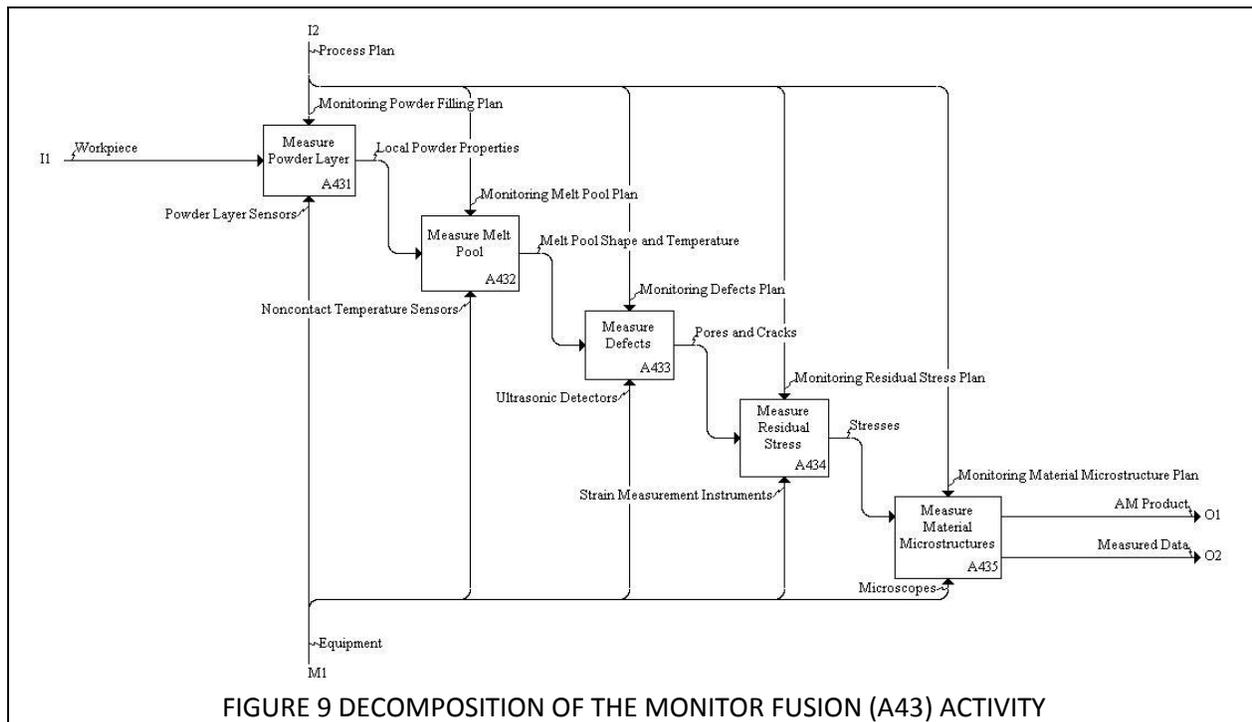


FIGURE 9 DECOMPOSITION OF THE MONITOR FUSION (A43) ACTIVITY

To support structured data, a proposed ontology development can consist of three major tasks: (1) defining the hierarchical structure for aggregation/decomposition in PBF, (2) establish relationships among input, output, mechanism, and control data, and (3) develop queries for users to make inferences and manage process knowledge. Along similar lines, advances in process data representation could greatly improve how material-process-geometry relationships are established and captured in PBF. While much has been made about associating process and material data in PBF, little progress has been made in creating a structure from which data correlations can be mined. Many efforts have focused on identifying the data based on what can be measured. By decomposing process relationships as shown here, we can provide additional insight into what should be measured. We can also begin to establish the relationships between data that will help derive correlations between materials, processes, and parts.

5. CONCLUSIONS

We have identified a comprehensive set of currently available fundamental data elements and the potential future data requirements to address the data interoperability barrier in PBF. Advancements in data structure will enable systems integration that cuts across part design, process planning, in-process measurement, process control, and qualification in the next generation of PBF process control and part quality assurance.

The challenges in developing an activity model lie primarily in the (i) information variability in PBF processes, (ii) differences in materials and their physical properties, and (iii) intricate equipment specifications and limitations. The activity decomposition is necessary to simplify the complexities of PBF models and reduce the many-to-many mappings used in their development. Consequently, we believe that an extension of the approach to detailed process analysis and simulation can

provide a foundation for part and process verification and validation.

Future work includes the validation of the fundamental data requirements with virtual cases and development of meta-data models and ontology - a logical next step to provide data models for data sharing among heterogeneous AM systems.

DISCLAIMER

Certain commercial software products or services may be identified in this paper. These products or services were used only for demonstration purposes. This use does not imply approval or endorsement by NIST, nor does it imply that these products are necessarily the best for the purpose.

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