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CONFIGURATION CONTROL FOR ADDITIVE MANUFACTURING DIGITAL TWINS

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Abstract

The additive manufacturing workflow is a ductile entity, often varying depending on the design, the product, the process, the material, and the application. Information models and schemas have been developed that can provide structure to data and information throughout the workflow. The result has been a well-characterized outline of an additive manufacturing digital thread. However, implementation-specific details are often missing from these characterizations, creating challenges in establishing part-specific workflows necessary for product configuration control and management. While software vendors are increasingly filling this gap, a software-agnostic workflow is yet to be defined. This paper investigates the additive manufacturing workflow and establishes the fundamentals of a standardized, configuration-control approach including formats and interoperability while addressing versioning, digital rights, and ownership.

Introduction

As industry moves towards the fourth industrial revolution and digital supply chains, the need to establish transparency and accountability across organizations has only grown. Increasingly sophisticated manufacturing processes have led to heightened vigilance and abundance of caution when introducing new parts into a supply chain. The digitalized nature of these processes, however, has created new opportunities to leverage data throughout the product lifecycle for reasons including traceability, improved efficiencies, compliance and innovation [1]. These opportunities are nowhere more apparent than in additive manufacturing (AM), an inherently digital production process.

AM machines fabricate digitized designs using a layer-by-layer process that follows a digitally planned production path. Given the intricate process complexities, additively manufactured parts are often considered "unique" when compared to their traditionally manufactured counterparts. This uniqueness holds true for the digitalization characteristics of the processes as well, in that the extent of the AM digital workflow sets itself apart from other manufacturing workflows. Here, we will call the connection of digital components throughout this workflow the AM digital thread [2]. We will call aggregated data associated with a single instance of a part traversing this thread a digital twin, with the twin "growing" in size from the generation of new data at every layer.

The AM digital thread incites diverse transformations in the digital twin when progressing from a raw design to a qualified product. In transitioning from a design to a manufactured part, the AM digital thread can be defined by several stages including CAD Design, Tessellated Geometry, Sliced Geometry, Build File, Part with Build Data, and Part with Evaluation Data. Each of these stages will introduce new information requirements to be associated with the digital twin. These digital twins provide a snapshot, or representation, of the state of an AM part at any point in time along the workflow path. Managed correctly, these snapshots can provide vital insights into the state of a part, from design to fabrication to inspection.

In quality control for AM, establishing digital provenance has become a necessary part of the part-qualification process. When accepting a final part, it is important to have confidence in the processes used in the fabrication of the part, since differences in implementation can result in differences in part quality. Two parts progressing through the same thread can lead to two different digital twins, even if the process configuration and materials are similar. By providing each part with a unique "signature", the digital twin provides an important resource from which this confidence can be gained. However, the underlying data has its own uncertainty even if it is not well-defined and not well-understood. As a consequence, the digital thread has an uncertainty, which is a combination of these individual uncertainties. When relying on a digital thread to guide the provenance of part, not understanding the context and fidelity of the associated information limits the amount of insight that can be attained.

This paper investigates configuration management and control of data throughout the AM product lifecycle. A data model is presented that defines 1) how critical configuration data throughout this lifecycle can be identified, 2) how the associated data formats can be packaged, 3) how to transform these data packages from one configuration to the next and 4) how the information gains or losses transition through this workflow. This data model provides an approach to identify and control the critical data along the product lifecycle, thereby providing a workflow reference for future AM product-realization endeavors and an architecture for implementing AM digital twins and threads. The model aims at being process and industry agnostic. It also does not dictate which approach is optimal but provides the user with the needed information to make the correct choices and identify the required configuration items for their particular application.

Background

2.1. Additive Manufacturing as a Digital Process

AM is seen as an inherently digital production process. Kim, Witherell, Lipman, and Feng [2] refer to this concept that includes the magnitudes of associated information, formats and software as the "digital spectrum". For a given workflow within this spectrum, the digital thread links the path of the information that is gathered throughout the lifecycle [2]. Understanding and managing this thread is vital to truly take advantage of afforded opportunities and insights into a part and process. Mies, Marsden, and Warde [1] note the importance of infrastructure for data capture, availability, and discovery and how this impacts intellectual property, the tools for data mining, data federation and integration, quality standards and best practices. They further noted the challenges this poses since it requires cultural shifts from traditional manufacturing approaches. Mies et al. [1] coin this broader concept "AM informatics". Ultimately, the digital thread provides an improved vision into the product lifecycle; this, in turn, benefits complex production processes such as AM.

Kim, Witherell, Lu and Feng [3] state that maintaining consistency across AM builds is a challenge, noting that variations in the process, material, or geometry cause such variability between builds. Further contributing factors to such variability include:

- The use of different data formats and schemas.
- Proprietary file formats and software.
- Closed AM machines leading to inconsistencies between AM machine models.
- Lack of a standard for defining the critical data throughout the AM product lifecycle required to reliably reproduce AM parts.

Each of these factors compounds the challenges of creating and maintaining a digital twin that can be consistently accessed and maintained by various stakeholders. This is particularly true when stakeholders are dispersed across an organization or organizations. This is often the case with an AM part since this part is a component of a larger product made by a distributed supply chain. This distributed manufacturing capability is often cited as an advantage of the AM process itself, whereby a component can be designed at a head office and sent out to the locations where the product must be e manufactured on-site. Doing so reduces lead times and the need for large, on-site inventories. This concept of distributed manufacturing can be extended in cases where certain post-processing or component testing and qualification are performed at different locations or by different organisations. Not having a defined and standardized approach for characterizing the AM digital twin poses many challenges for situations such as these just described.

The need for a standardized approach that addresses representations across the AM product lifecycle is identified as a current gap [4], though the AM workflow and digital thread have been characterized previously. Previously published literature on the topic include Nassar and Reutzel [5] who proposed a digital thread for AM, Kim et al. [2] who investigated the information requirements workflow of the AM digital spectrum, Mies et al. [1] provided an overview of AM informatics and how this drives the digital thread, Kim et al. [3] proposed a tiered AM information map including data models and key attributes that span from design through to qualification, and Bonnard, Hascoët, Mognol and Stroud [6] presented a STEP-NC compliant data model for an AM digital thread. While these efforts help establish an accepted flow of information, they did not aim to address how the flow impacts the establishment, or configuration, of the digital twin.

2.2. Configuration Management & the Need Thereof in Additive Manufacturing Production

Configuration-management techniques are required to control and manage data within AM production. Configuration is defined as "a collection of an item's descriptive and governing characteristics that can be expressed in functional and physical terms, this represents the requirements, architecture, design and implementation that define the version of the system and its components" [7]. Whereas configuration management is defined as "a process for establishing and maintaining consistency of a product's performance, functional and physical attributes with its requirements, design and operational information throughout its life" [7]. Configuration-management standards and handbooks such as SAE EIA-649, ISO 10007 and MIL-HDBK-61B define the configuration management process in five key functions. These functions are defined in green in Figure 1 per the MIL-HDBK-61B definition, and subsequently used as guidelines to discuss the adoption of configuration management for AM in subsections of 2.2.1 to 2.2.6

2.2.1. Configuration planning and management

Configuration management for AM should be planned during the earliest project stage. Procedures should be developed for managing the configuration of the design and relevant data through to its disposal. Additional considerations should be made for configuration between organizations to ensure each organisation's approach and coding schemes are consistent and compatible.

2.2.2. Configuration identification

Identification of Configuration Items (CI) requires the knowledge of which items have an effect on the integrity of the component data as well as which data items are required for compliance consistency. All CIs and associated AM formats should be assigned an identifier and revision controlled.

2.2.3. Configuration control (Process required to change a CI and re-baseline it)

Configuration control can be defined as "a systematic process that ensures that changes to released configuration documentation are properly identified, documented, evaluated for impact, approved by an appropriate level of authority, incorporated, and verified" [8]. In documenting a CI change, critical information to be captured includes the nature of the configuration change, the identification of the previous state and the current state of the configuration item, and information of the data transformation and losses.

2.2.4. Configuration status accounting (Traceability)

The configuration data shall be stored in a system that allows for retrieval of configuration statuses. [8]. This allows for the component's full digital twin to be accessed when required anywhere along its digital thread.

2.2.5. Configuration verification and audit

Configuration baselines need to be periodically audited to verify their contents and ensure conformance. This involves a functional and physical verification of the component configuration.

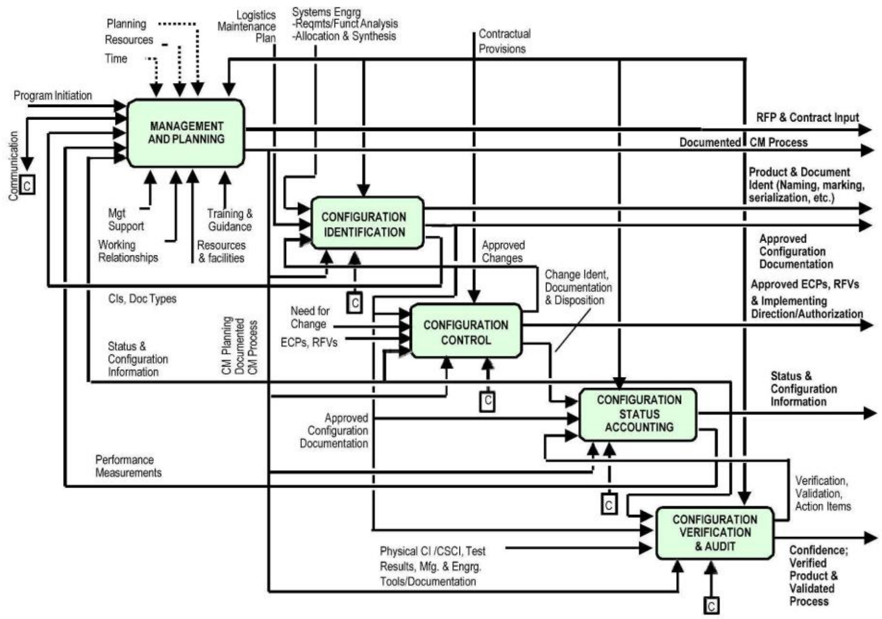

Figure 1: DoD configuration management activity model [8].

2.2.6. Conceptualizing Configuration Management for AM Production

Configuration management is a process that is begun early in the product design phase and aims at ensuring that the design intent is realized by monitoring and controlling the subsequent processes. In digital production processes such as AM, applying configuration management practices requires the configuration of both the physical aspects and their associated digital twins. The resulting digital twins and corresponding digital thread must accurately model their real-world counterparts, leading to full digital traceability and record of the AM product.

Focusing on the AM production digital twin, the application of configuration management must aim at reducing impermissible and unintended changes and monitor/record the permissible changes. Such changes could be increasing the component wall thicknesses in the CAD digital twin to compensate for material removal in post-processing stages, converting the CAD digital twin into an AM machine-readable format or even the orientation and location of the design in the build envelope. These are examples of changes that may have an effect on the design intent of the component and therefore such configurations should be managed. It is not always the case that subsequent processes require each of the preceding configurations, but it is still necessary to maintain configuration control. This concept is presented in Figure 2, where the focus is on what design and data configuration changes are permitted if the final product is to fulfill its original intent, and how should these be defined and controlled.

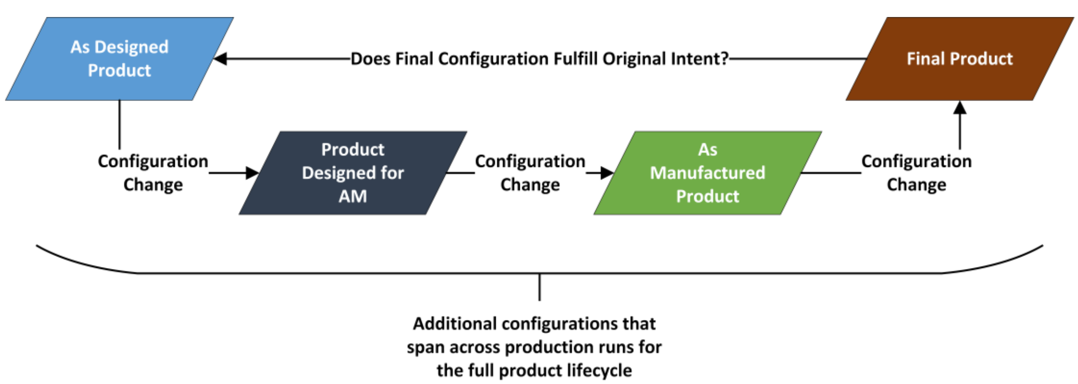

Figure 2: Conceptual diagram of data configuration within AM workflow.

2.3. Towards a Reference Data Model

The success of any digital twin depends on its accuracy when compared to the physical reality it aims to represent. The more real-world data of high fidelity that can be represented by the digital twin the greater its accuracy. The application of digital-twin concepts to AM has its benefits and challenges. The key benefit being that since the AM process is inherently a digital one, the AM process is an excellent candidate for the application of digital twin concepts when compared to some of the more traditional manufacturing processes. Conversely, challenges are created when building digital twins from the large amount, diversity, and complexity of the variety of data involved during the AM process and the product lifecycle as a whole.

As a part transitions through its AM digital thread, it is configured in various ways that provide benefit for the activities being performed at the relevant stages throughout the workflow. There is a need for a definition of:

- The stages in such AM workflows and the relevant product configurations.
- What the data inputs and outputs are exhibited at these stages.
- How the data can be formatted and configured at each of these stages to ensure high fidelity.

A reference data model that addresses these needs provides benefits for planning and managing AM production. Such a reference data model can be used for defining configuration baselines and, in turn, reduces the risk of unintentionally changing data throughout the workflow. Establishing a reference data model does not have to be a universal approach, but instead based on the workflow of a specific organization or a subset of specific stages from the digital thread. The creation of a data package is one way to down-select from the digital thread.

Figure 3 illustrates the relationship between the digital thread and the digital twin. Note that the arrows in Figure 3 indicate that the data package facilitates the selection of data requirements for the digital twin from the digital thread. Left uncontrolled, these relationships pose various challenges, the main being determining what data is required in the data packages that are distributed between the locations or organisations and how is this data to be configured in order for the design to be manufactured and evaluated to fulfil its design intent. Here, configuration management establishes consistency in how the data package requirements are met.

The next section will adopt the concepts put forth in Section 2. The proposed method aims to integrate established data management concepts with specific AM needs. A result is a conceptual approach to establishing configuration management practices for AM.

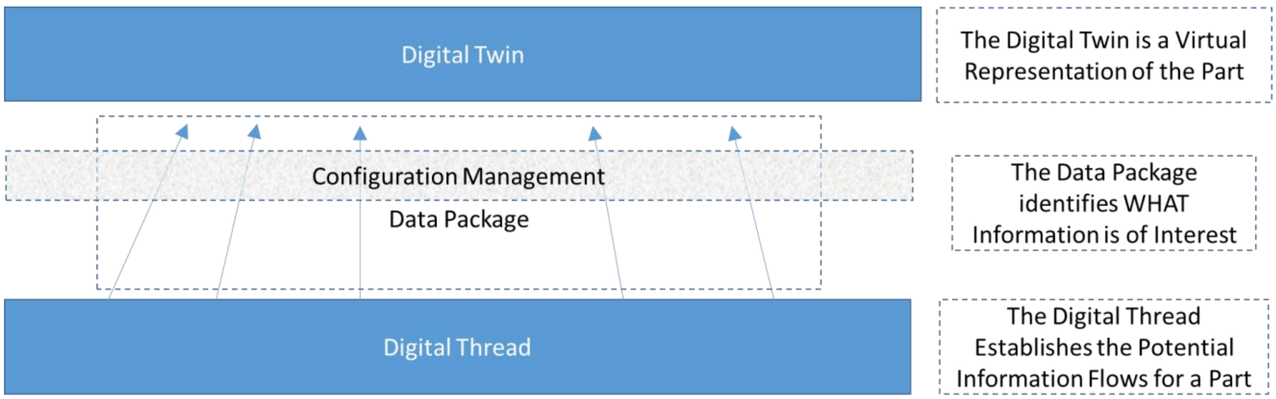

Figure 3. Configuration Management establishes consistency in HOW information requirements are met.

Approach

As alluded to in the previous sections, configuration management is not established as a "one size fits all". Instead, configuration management can be thought of as providing a "filter" when establishing a digital twin, as the plan:

- Defines the allowable representations on which requirements can be met.
- Identifies allowable formats and configurations.
- Establishes consistency in how data is captured and represented.
- Essential for consistent evaluation and qualification of families of AM parts.

In establishing a data reference model, the realization of the configuration management plan is based on the data package requirements and the organizational workflows. As such, configuration management requires a well-defined approach when establishing digital twin requirements. Such an approach is presented as four steps in Figure 4, where the steps are, 1) identifying WHAT information from the "digital spectrum" is leveraged by the workflow and used to establish the digital thread, 2) identifying HOW this information is represented through available format types, 3) establishing specific data requirements based on data package requirements, and 4) mapping data package requirements to appropriate data formats. The steps are designed in such a way that steps one and two may be developed for a general process, while steps three and four are likely to be specific to a given scenario.

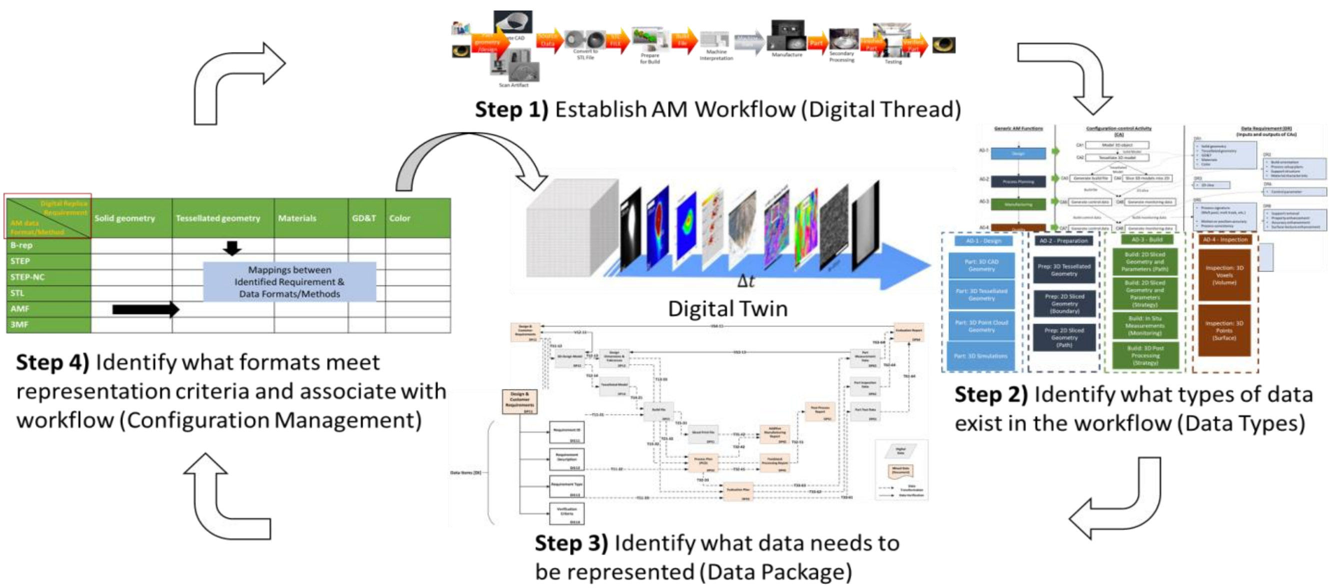

Figure 4: The approach for establishing configuration management for AM production.

The approach is expanded upon in the following subsections:

1. Establish the AM workflow.
2. Identify data types and requirements.
3. Define data packages and identify where configuration changes occur.
4. Associate formats and establish a reference model for control.

3.1. Step 1 - Establish the additive manufacturing workflow

Kim et al. [2] illustrate a typical AM workflow as presented in Figure 5. This workflow starts with design and planning activities, progresses to AM build planning and printing, then secondary manufacturing process and finally testing.

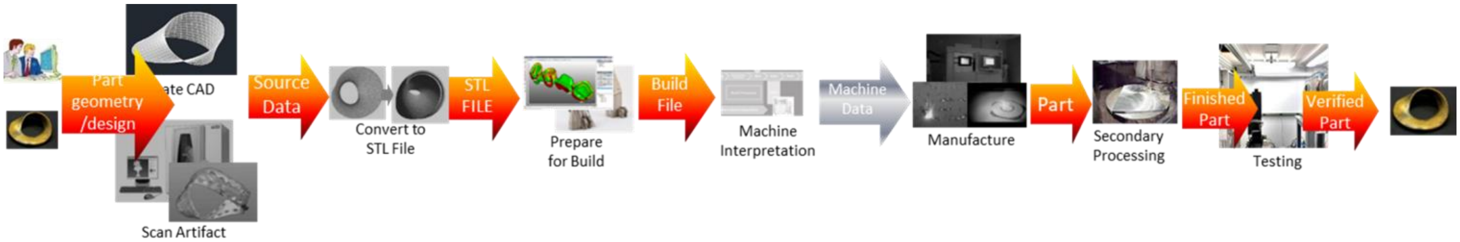

Figure 5: Illustrative additive manufacturing workflow [2].

Through this process, the design as an entity changes from requirements and a conceptual idea to a digital model, then to machine instructions. These phases and the various stages in between are *Digitally Orientated & Planning Focused*. The design as an entity then transitions to a *Physically Orientated & Production Focused* phase whereby the design entity changes from the machine instruction into a physical green or as-built part and representative data of the physical production process. The design then changes through the various post-processing stages such as heat treatments and surface finishing processes and lastly testing and inspection of the final part. The physically orientated phase of the AM workflow contains an important data aspect as well. This data is the data generated and recorded during the physical production process, these data are required for verification and validation purposes.

When formalizing the data flow, manufacturing follows a generic flow of design, process planning, manufacturing and quality evaluation. Figure 6 presents the generic AM workflow that is decomposed from these four manufacturing functions as defined by Kim et al. [3]. This workflow serves as a reference workflow for all AM production runs and the basis for defining AM data requirements and packages.

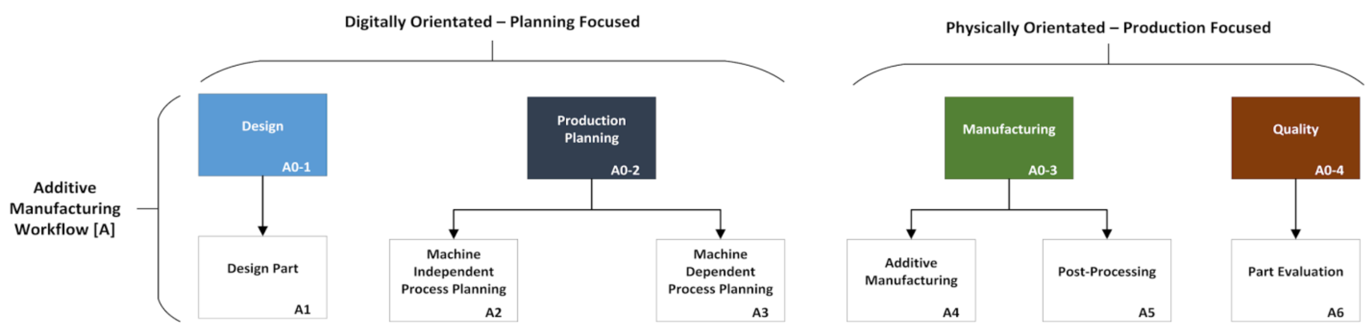

Figure 6: Reference additive manufacturing workflow functions.

This AM workflow is performed at various phases of production, such as prototype, qualification and approved production as well as performed for multiple runs within these phases. This concept is presented in Figure 7. Data requirements can be defined for each of these blocks and data can be generated in each of these blocks. Data generated in blocks that follow in the lifecycle can utilize data from preceding blocks. In certain blocks not all functions in the AM workflow are performed, and example being during the prototype production phase, certain post-processing stages may not be required if only a design mock-up is needed. When production transitions in either of the three dimensions, the data generated in the previous dimension shall be baselined and controlled. Reference to data blocks in this AM production framework can be made as defined in Figure 7. As an example, the heat treatment data from the second qualification production run would be referenced under the P2-A5.B data block.

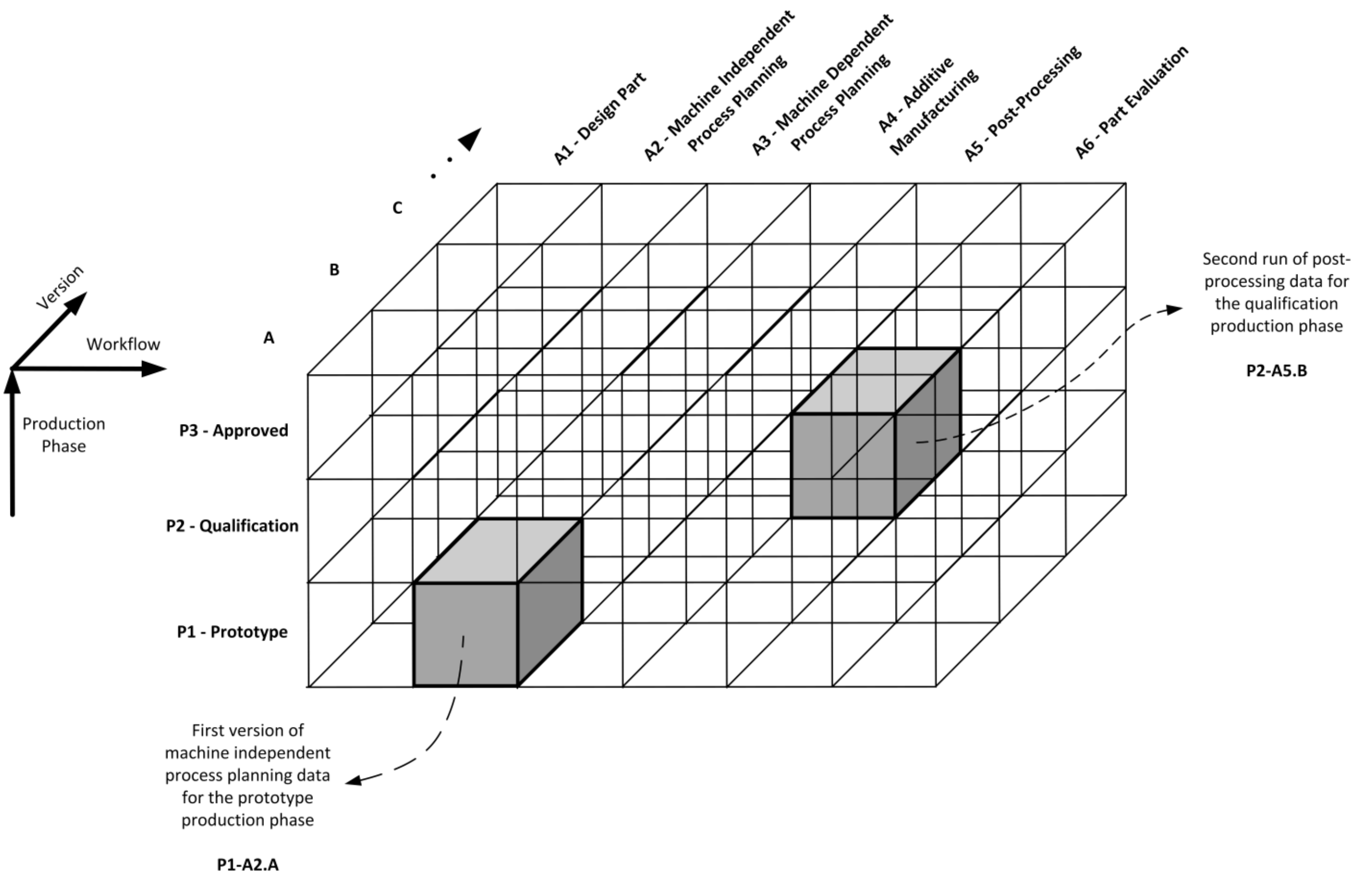

Figure 7: Configurable "blocks" of data within the AM workflow.

3.2. Step 2 - Identify the data types and requirements

This step is an inclusive step, being that is not meant to satisfy a specific application scenario but instead establish allowable formats for meeting data requirements. The goal of this step is to map the "what" needs to be represented to available file formats on "how" this information can be represented. Figure 8 provides an example of the data that may be associated with a simplified workflow. At the highest level, the four-staged workflow in Figure 8 consists of Design, Preparation, Manufacture, and Inspection.

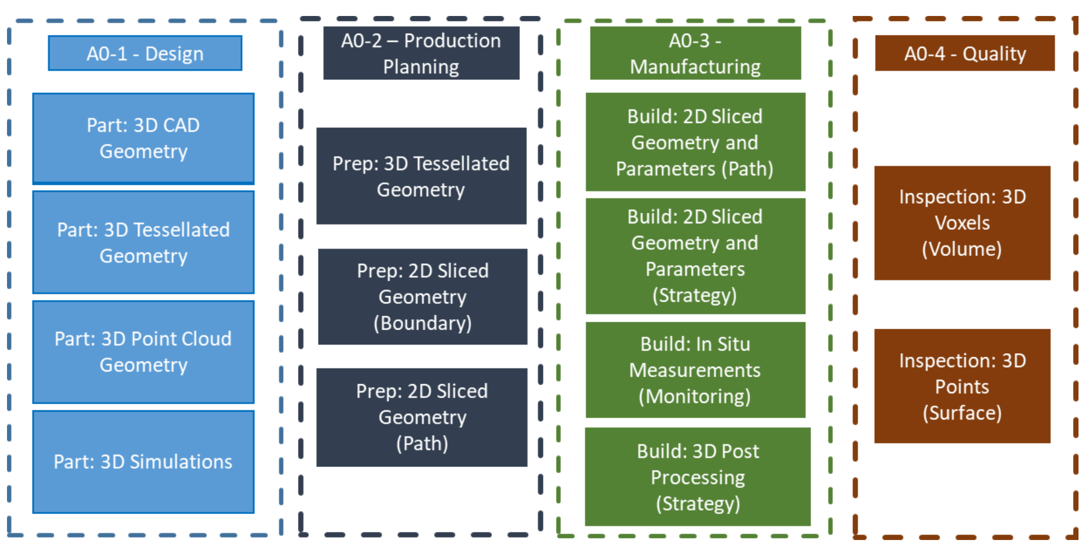

Figure 8: Identification of the data types, the "WHAT".

While the high-level progression of information is helpful to establish a general workflow and scope basic requirements, it is insufficient for establishing a detailed configuration management plan. Each stage of a workflow may consist of various configuration-control activities. Each of these activities may have unique data requirements depending both on AM-function and configuration-control types, and therefore unique data representations. Figure 9 provides an example of how data requirements are established based on the general workflow presented in Figure 8. The sub-activities identified in Figure 9 are representative of activities that may drive data requirements, such as model tessellation and the generation of a build file. This step of the process is vital since it identifies the activities that may dictate data representation requirements.

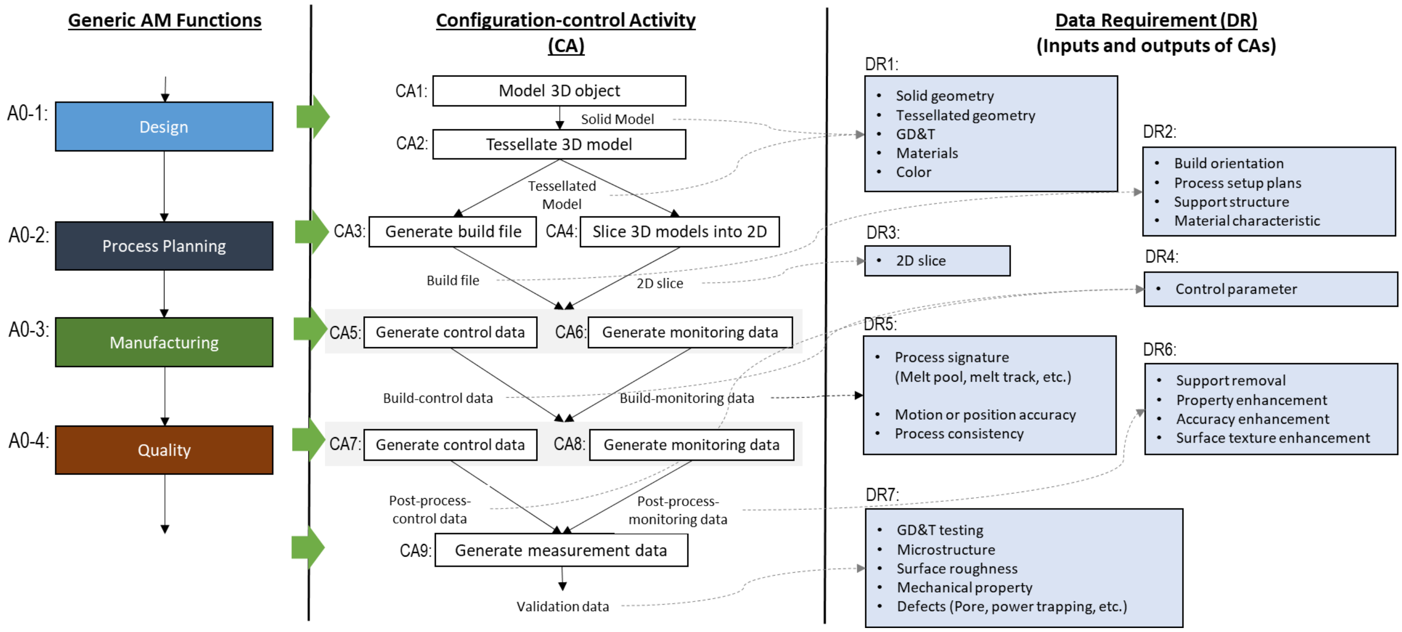

Figure 9: Deriving data requirements for the AM workflow.

3.3. Step 3 - Define data packages and identify where configuration changes occur

Once the data requirements and types have been defined, this data is traced to distinct data packages at the various stages of the AM workflow. Therefore, moving from the WHAT to the HOW. The diagram in Figure 10 presents an example, demonstrating data packages for an AM workflow and the critical locations where data is transformed as well as where verification takes place.

The data packages defined in this diagram are either transformed (changed) into other data packages or verified against previous data packages. This diagram defines the data packages that are the outputs of the AM workflow for a production phase, the configuration between design states and each of their production phases is additionally required. Data packages can be decomposed into sub-data packages or directly into their constituent data items.

Identification of data inputs and outputs within the AM workflow is critical. Data is defined in either a digital or a mixed format such as documents. Physical entities are excluded from this diagram as their data representation is what is important here. Referring to Figure 10, the “3D Design Model”, DP12, can be decomposed directly into data items whereas the “Post-Process Report” data package, DP51, can be decomposed into various sub-data packages such as Heat Treatment Report, Machining Report or Shot Peening Report and these further decomposed into their data items. Such data is application-specific, and the content varies greatly from one production instance to another.

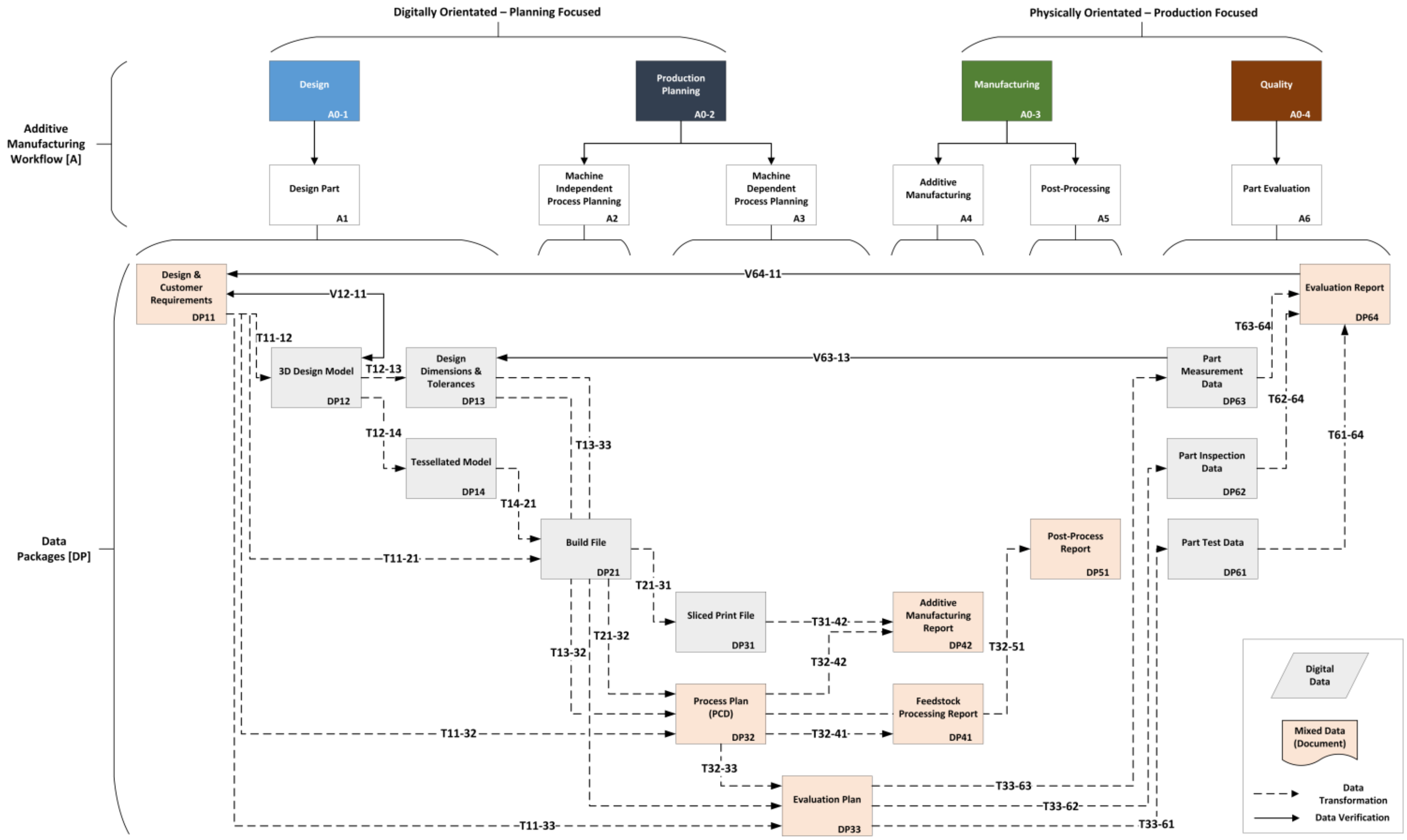

Figure 10: Definition of data packages and changes along the AM workflow.

The data packages and the decomposed data items identifiers lay the foundation for version control. When practicing configuration management, it is imperative to identify changes to the configuration. A change to a data item will require a change to that data package's version identification to ensure integrity. Depending on the criticality of the data items or the data package itself, they can be classified as a configuration item and subsequently baselined and controlled. Figure 11 presents the decomposed data items of the DP11 and DP12 data packages.

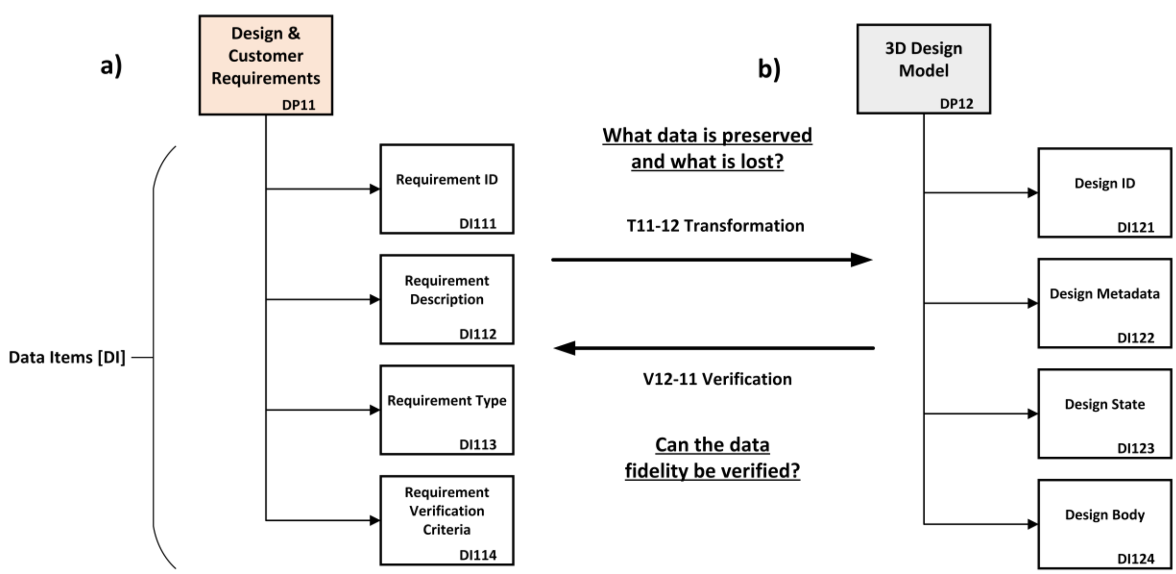

Figure 11: Exemplar definition of data items for the a) "Design & Customer Requirements", and b) "3D Design Model" data packages.

3.4. Step 4 - Associate formats and establish a reference model for control

Figure 12 is an example of mapping "what" to "how", where various design requirements from the design stages are met by various file formats. Additional details are needed to establish which file formats may best suit specific needs. Where step 3 was used to narrow down the data requirements for a given application scenario, step 4 will take this one step further by identifying allowable formats. Figure 12 illustrates how requirements can be mapped to formats at the most general levels, but an acceptable configuration management plan will require significant additional details on both the data requirements and the format capabilities.

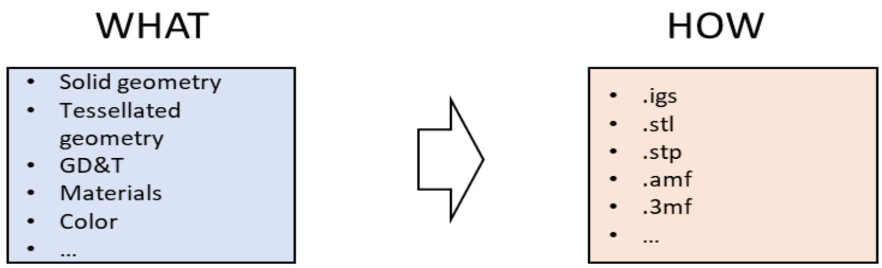

Figure 12: Basis of configuration management in digital production.

The final step involves identifying applicable data formats for the defined data packages and items in Step 3, mapping the data requirements against the identified formats to ensure conformance and characterizing data integrity due to the transformations and verification between data packages and items. Table 1 presents the description of a"Design & Customer Requirements" Data Package with identified applicable formats and Table 2 presents the same for the "3D Design Model" data package.

Table 1: Exemplar description of the "Design & Customer Requirements" data package and applicable formats.

Description	Design and production requirements defined by industry and customer including standards and specifications.			
Purpose	Requirements define what the customer wants and what industry requires produced. They are the first configuration baseline against which manufactured parts can be verified.			
Formats	ReqIF, SysML, CSV, PDF, Text.			
<u>Data Items</u>				
Data Item	All AM?	All Applications?	Configuration Item?	Rationale/Comments
DI111	✔	✔	✔	Each requirement needs an ID to reference it within the workflow and identify where and when it is verified.
DI112	✔	✔	✔	The requirement description defines the details of what is required. It is important that the description is unambiguous and that each person has the same understanding of what is required.
DI113	✔	✔	✔	Various types of requirements can be defined. Requirements can apply to different stages of the workflow, be of different criticality and require different verification approaches.
DI114	✔	✔	✔	Criteria for how the customer or industry requires the requirement to be verified or validated. These criteria are critical for production quality and release to the customer once produced.

Table 2: Exemplar description of the "3D Design Model" data package and applicable formats.

Description	3D design representation modelled in computer-aided software.			
Purpose	The 3D Design Model is the 3D presentation of what the customer wants manufactured. It is used to represent certain requirements in a computer-readable format for analysis and further processing.			
Formats	STEP, STL, IGES, OBJ, AMF, B-rep, 3MF.			
Data Items				
Data Item	All AM?	All Applications?	Configuration Item?	Rationale/Comments
DI121	✔	✔	✔	The design ID is linked to the physical design body.
DI122	✔	✔	✔	Design metadata can include data such as color, material, notes, reference to requirements etc.
DI123	✔		✔	The design state defines the stage of the design's development such as prototype, qualification, or production.
DI124	✔	✔	✔	The design body defines the data of the part's solid geometry. This includes point cloud, boundary, and solid data.

After each data package and their constituent data items are defined and applicable data formats are identified, the data formats are mapped against the data types and requirements in a matrix to identify conformance gaps and determine the conformant data formats as depicted in Figure 13. When conformance gaps are identified, this indicates data from previous data formats need to be preserved.

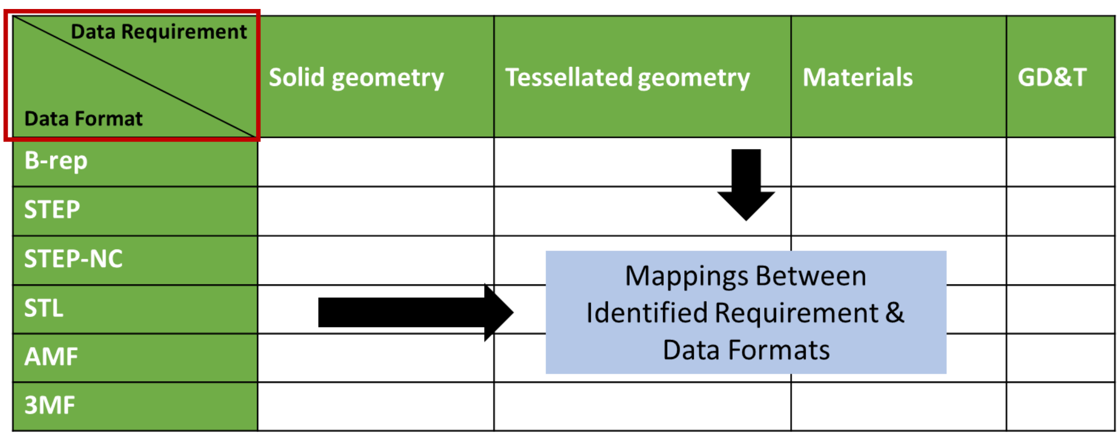

Figure 13: Map data to applicable data formats.

Part of establishing a reference model for a specific scenario includes understanding the transitions between formats for the workflow scenario. As defined in Figure 10, there is a transformation and a verification event that occurs between the two example data packages, DP11 and DP 12, and therefore a configuration change has occurred. These are defined as T11-12 and V12-11 respectively. Table 3 describes the transformation between DP11 and DP12.

Table 1: T11-12 Transformation

Description	Transformation of Design & Customer Requirements into CAD Design
Purpose	Certain requirements are used to create the CAD design model. This transformation is largely performed by engineers and requires application-specific knowledge.
Data Integrity	From requirements to a CAD design poses two key challenges. The first being loss of information due to misunderstanding the requirements. The second challenge is that not all requirements can be fulfilled by a CAD design, this means certain requirements have to be stored along with the CAD design until they are addressed in the workflow.
Conforming Formats	STEP, AMF, 3MF.
Nonconforming Formats	STL, IGES, OBJ, BRep. These formats only partially represent the critical data items defined. If used, data will need to be preserved in additional formats.

Table 4 presents the verification considerations for the exemplar case. The "3D Design Model" needs to be verified that it is conformant with the Design and Customer Requirements. Not all data packages are transformed and not all transformed data packages require verification. Data packages that have been verified are baselined and controlled.

Table 4: V12-11 Verification

Description	Verification that the 3D Design Model data meets defined requirements.
Purpose	Verification that the design data meets the requirements is a critical step before continuing the workflow. This verification can be performed by various means such as simulations and design reviews. Once the design data is verified it is baselined and configuration controlled.
Data Integrity	Potential integrity issues faced are the fidelity of the verification data generated and how well it represents the information it aims at verifying. Additionally, not all information can be verified or to the same degree and certain data requires expert and application knowledge to verify.

Establishing the transformations and understanding the verification needs is the final part of the configuration management plan. A user is left with application-independent scenarios, application-specific scenarios, identification of allowable formats, mappings of these formats to the scenarios, and finally an understanding of the impact of transitioning between formats throughout the workflow.

Discussion

The need for a standardized approach to the AM data workflow that addresses the full AM product lifecycle is identified as a current standardization gap [4]. The ISO/ASTM joint workgroup 73 was set up to address digital product definition and data management. Supplementing the AMSC standardization gaps, the ASTM AM Center of Excellence published a strategic guide identifying the current challenges and gaps related to AM data management and schema as recognized within industry [9]. Noted in this guide is the need for principles defining what data is important to collect and how this data should be processed for utilization and understanding. Additionally, the need for a common data exchange format and determining minimum viable data packages for ensuring data pedigree and quality were identified as high priority topics.

The concept of a “data digital twin” as the data representation of the physical part and process is defined. The MIL-HDBK-61B [8] point out that the concept of a digital twin is formed when these digital models evolve and mature until their behavior and performance become indistinguishable from their physical counterparts. This requires effectively defining configuration and stringent controls to realize this concept and its benefits.

Data versioning and coding is an important aspect of configuration management. In modern computer-integrated and digital production processes, there is a substantial amount of data generated and recorded throughout the production lifecycle. This data is encapsulated in various formats, both digitally and physically, and controlling these various data configurations is ever more prevalent in AM production. The approach presenting in this paper demonstrates how this data can be packaged, assigned a code for referencing to the production phase, workflow location and version, and identification of applicable formats for representing this data. This paper proposes an approach for implementing and addressing configuration management within the AM workflow. Implementing such configuration management principles is imperative for realizing and managing the digital twin and digital thread.

Conclusion

The approach presented in this paper provides a framework for implementing configuration management practices in an AM organisation. The need for configuration management in digitalized production such as AM is justified and the implications this has on realizing the digital thread and twin are defined. A four-step approach is proposed consisting of 1) defining the AM production workflow, 2) identifying the data types and requirements, 3) defining data packages and identify the configuration changes between them, and 4) associate applicable data formats and determine conformant formats for data preservation. Further work is needed to define a standardized reference model for implementing AM configuration management that can be referenced and applied in industry.

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