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A Reference Activity Model for Additive Manufacturing

Powder Bed Fusion

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A Reference Activity Model for Additive Manufacturing

Powder Bed Fusion

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Abstract

Additive manufacturing is a complex and inherently digitally orientated manufacturing technology. This technology has become popular as it offers certain benefits when compared with traditional manufacturing technologies such as the ability to produce unique and complex geometries, reduced turnaround time from design to final product, reduced material waste, and the ability to process a wide range of materials. There are however challenges to the qualification and industrialization on this technology. These include the potential variability in both inputs and outputs, control of the many variables and process parameters, and the lack of process understanding, guidance material, and the steep learning curve for new users.

This report proposes a reference activity model that defines generic activities and data items across the additive manufacturing workflow, from design through to part evaluation. The reference activity model is modeled in accordance with the IDEF0 language. Data items are defined and mapped against industry standards to provide users with the required information to develop their specific production processes and controls. This model aims to improve additive manufacturing product and production data exchange and detail a reference architecture for the development of digital twins and threads.

Keywords

Activity Model; Additive Manufacturing; Digital Manufacturing; IDEF0; Manufacturing Data; Model-Based Control; Powder Bed Fusion; Production Control.

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Acknowledgments

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1. Introduction

When producing a part via an additive manufacturing (AM) process, an inherently digital manufacturing process, not only is the physical part created from raw materials, but also large amounts of data are generated. Such data can be related to the design, process planning, build, post-processing, and testing activities of the part production process. An as-built part is transformed when it is post-processed; however, information is generated and transformed throughout all the activities related to a production process. The digital data associated with the physical part can be output to create a digital twin of the part throughout its lifecycle [1]. The data generated by the production process across the product lifecycle provides a record of all information related to the activities used to create the part, this is referred to as the digital thread [2]. The identification of information flows between various activities is necessary to define data exchange standards.

The activities related to the design, process planning, build, post-processing, and testing of a part and its associated information can be modeled with the Integration Definition for Function Modeling (IDEF0) language. IDEF0 is a language (syntax and semantics) and methodology to model activities, actions, processes, and operations performed by a system and the functional relationships and information or objects that support the integration of those functions [3]. A review of the IDEF0 modeling approach is presented in Appendix B. The IDEF0 language and notation is standardized in ISO/IEC/IEEE 31320-1 [4]. IDEF0 has been used to model various aspects of manufacturing including dimensional inspection planning [5], metal machining [6], reference architectures for the integration of manufacturing software applications and smart manufacturing [7, 8], AM machine qualification [9], manufacturing diagnosis [10], manufacturing planning and execution [11], a planning model for part measurement [12], seamless production planning [13], and ISO 9001 quality management systems [14]. The IDEF0 methodology has also been used to model a digital chain for AM processes [15] and an AM decision support system [16, 17]. Previous research at NIST developed an IDEF0 model for data representations in laser-based powder bed fusion (PBF) processes [18, 19]. This report revises and expands on this previous work.

As AM is an inherently digital process, the aim is to model the AM activities from a digitally focused perspective. As an example, design requirements can be documented in physical paper form and passed around to those that require them. Although such information is included in this model, the digital format of such information, such as PDF or CSV formats, was imposed during the modeling approach. This facilitates the reduction of human information processing and interpretation errors and enables digital engineering concepts such as the Digital Twin and the Digital Thread to be realized. The AIØ WIN® IDEF0 model-based systems engineering software tool was used for developing the AM activity model presented in this document. This tool aids information traceability and configuration management of both the diagrams and the activity model itself.

1.1. Purpose

The activity model for PBF production defined in this document defines the key functions, activities, and production entities required to produce a part using PBF and associated technologies. This model proposes a standard architecture for metal AM data definition with the primary aim of improving AM production data exchange [20]. The model does not intend to define how such products shall be produced. The purpose of this model is to define, at a high-level, the type, scope, and identification of information used during such production activities. Potential uses of this model include:

- Development of procurement agreements and specifications.
- Controlling subcontractors and outsourced production.
- Development and implementation of digital production and management systems such as MES, PLM, and QMS for AM.
- Development of production Digital Twin architectures and product Digital Thread models.
- Integration and interfacing between production system elements.
- Communication with stakeholders to better understand the complexities of the AM production process and the implications on design, planning, and manufacturing.
- Define, impose, and conform to requirements.
- Detail production controls to improve quality.
- Structuring of product development activities and process planning.
- Providing interoperability requirements of data exchange and communication between different stages of the AM processes.
- Modeling unit manufacturing processes (UMP) and characterizing their environmental aspects [21].

1.2. Scope

This document provides a reference[1] activity model of the PBF production process and associated data. This model is developed for the production of discrete metal parts [23]. The focus of the model is on the products of the AM production system in its various forms and states as it progresses through the product lifecycle. The physical products of the AM production system may change depending on the type of production performed. During production qualification, typically test specimens and structural elements will be produced, whereas during ongoing production actual components with witness specimens will be produced.

This model does not address the production system or equipment lifecycles. At a high level, the activity models aim at being process agnostic, whereas at a lower level, the models are specific to the PBF production process. The model is machine and software make and model agnostic. Verification activities whereby production data is analyzed for decision-making purposes such as design simulation or mechanical test result evaluation are excluded from the scope of this model. These activities are performed at the manufacturing operations and control level of the

[1] DIN SPEC 91345 defines a reference model as a “model that is generally used and recognized as being suitable (has recommendation character) for deriving specific models” [22].

enterprise, the controlling level, using the **D.4: Digital Twin Data**, see Figure 2, generated by the AM production system as the input for such verification and decision-making activities [24].

Personnel are key resources in an AM production system. Personnel are not included in the model diagrams, but they are mechanisms for the activities and functions in the model. Software are the digital tools used in the AM production. The associated hardware to be able to use such software is also excluded from the model diagrams. This hardware is always associated with the software entities, and they cannot be separated. Similarly, control system software is not modeled separately from machine type equipment.

1.3. Modeling Concepts

Three key information flows are modeled in the activity model presented in Section 3. These flows provide information for production planning, qualification, and operation activities that directly relate to **P.2: AM Part** quality and extend the IDEF0 modeling language. Data items that do not directly relate to the **P.2: AM Part** are represented in black. The three information flows are:

- **Material Flow** – The material flow defines where the physical material interacts with the physical production system. This flow is colored blue in the model diagrams.
- **Data Flow** – The data flow defines the key production data required for the development of Digital Twins. This data flows through the production system and creates a Digital Thread associated with the part being produced. This flow is colored red in the model diagrams.
- **Resource Allocation** – The resource allocation defines the production system resources required to produce the product. Such resources typically require significant capital investment, but also require qualification, maintenance, and calibration to maintain their operational status. Such resources are prime targets for cyber-attacks and adequate security controls should be implemented to reduce these risks. This allocation is colored magenta in the model diagrams.

The item **P.2: AM Part** is used as a generalized term for all possible physical products or outputs of an AM-centric production system, the product of the production process. The type of output will differ depending on the production phase and application. A **P.2: AM Part** can be either of the following or a combination thereof:

- *Component* – Reference or prototype, qualification, first article, or production parts [25]. Components are the primary output of an AM-centric production system and serve a functional purpose for a specific application.
- *Specimen* – Test specimen, witness specimen, or design element. Such specimens are used to determine material properties or determine part-representative properties.
- *Test Artifact* – Benchmarking test piece geometries used to assess the performance of AM manufacturing systems [26, 27]. Such artifacts are typically produced during early AM production system qualification phases that aim at qualifying AM machines [28].

In addition to these three types of **P.2: AM Part** is the concept of a workpiece. This term draws upon traditional manufacturing terminology and is used to represent a work-in-process **P.2: AM Part**. Such a workpiece could be the full **P.2.2: AM Build** before support removal or an **P.2.5.1: As-Built Workpiece** that may still require post-processing.

2. Function Decomposition

The functional decomposition of the **A0: Produce AM Part** activity is depicted in Figure 1. Three levels of decomposition are modeled, each detailing increased specificity. Further decomposition is dependent on the specific application and production facilities used. Hence **A3** is decomposed a further level lower as these activities are critical for the PBF technology and associated processes.

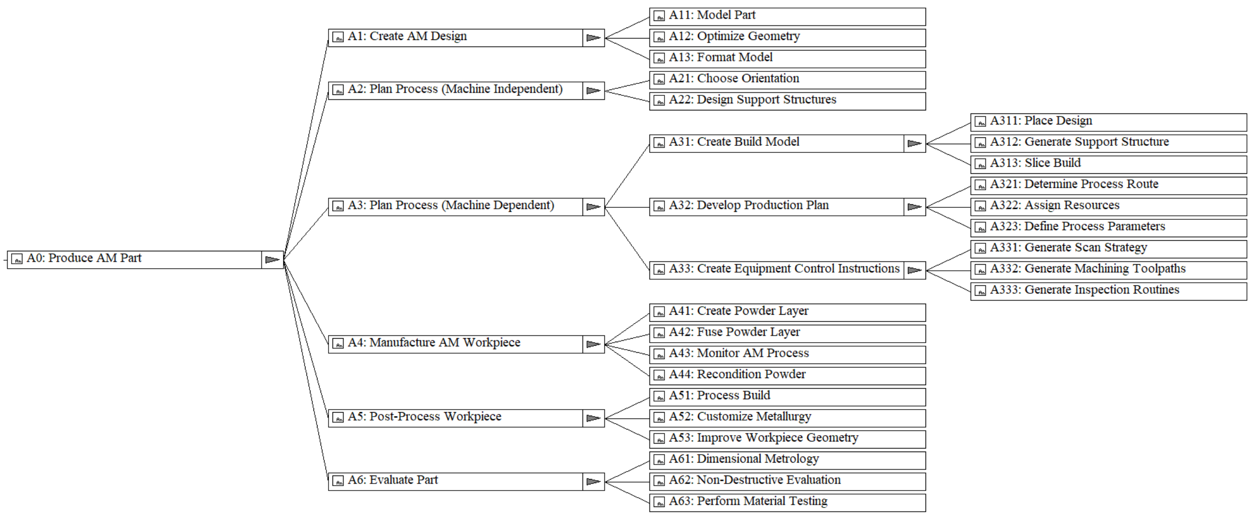

Figure 1: Functional Decomposition Diagram.

3. Activity Model

The primary function of an AM-centric production system is to **A0: Produce AM Parts**. Figure 2 depicts the primary function in the IDEF0 context diagram. This is the highest level of abstraction and the A0 diagram defines the key production system inputs, controls, outputs, and mechanisms (ICOMs)[2]. The **A0: Produce AM Part** activity transforms the **P.1: Feedstock Material** into an **P.2: AM Part** with its associated **D.4: Digital Twin Data**. This activity is controlled by the **D.1: Design Requirements**, **D.2: Production Controls**, and **D.3: Standards**.

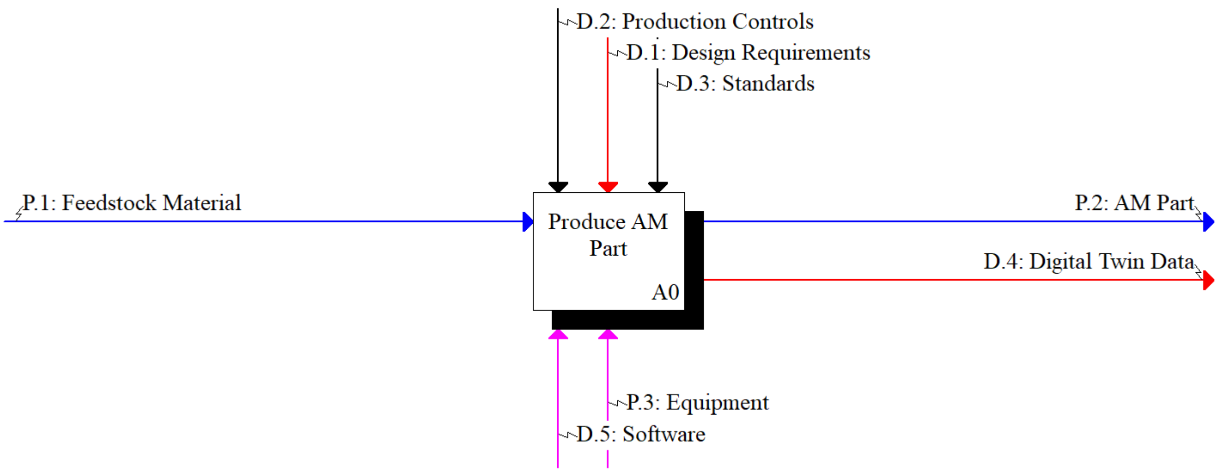

Figure 2: Primary Function to **A0: Produce AM Part**.

The primary function is decomposed into the following six activities:

1. **A1: Create AM Design**
2. **A2: Plan Process (Machine Independent)**
3. **A3: Plan Process (Machine Dependent)**
4. **A4: Manufacture AM Workpiece**
5. **A5: Post-Process Workpiece**
6. **A6: Evaluate Part**

The decomposition of **A0: Make AM Part** into the six sub-activities is depicted in Figure 3. These six activities are generic to AM production. Process planning is separated into two activities, the first for machine independent process planning activities, and the second for machine-dependent process planning. It shall be noted that the **A2: Plan Process (Machine Independent)** activity is not process-independent. The collection of all digital information that is generated by the activities that relate to the **P.2: AM Part** forms a digital thread. The **D.4: Digital Twin Data** is output to form a digital replica of the **P.2: AM Part** at the critical stages of its product lifecycle.

The activities required to produce an **P.2: AM Part** are facilitated by **D.5: Software** and **P.3: Equipment** type resources. Personnel are key resources in an AM production system. Personnel

[2] See Appendix B for an overview of the IDEF0 modeling language.

are not included in the model diagrams, but they are mechanisms to all the activities and functions in the model. **D.5: Software** are the digital tools used during AM production. The associated hardware to be able to use such **D.5: Software** are also excluded from the model diagrams. This hardware is always associated with the software entities, and they cannot be separated. Similarly, the control system software is not modeled separately from machine-type equipment. The ICOM data items are defined in Section 4. As depicted in Figure 3, activities **A1** through **A3** are planning-focused and digitally orientated, whereas activities **A4** through **A6** are production implementation-focused and physically orientated.

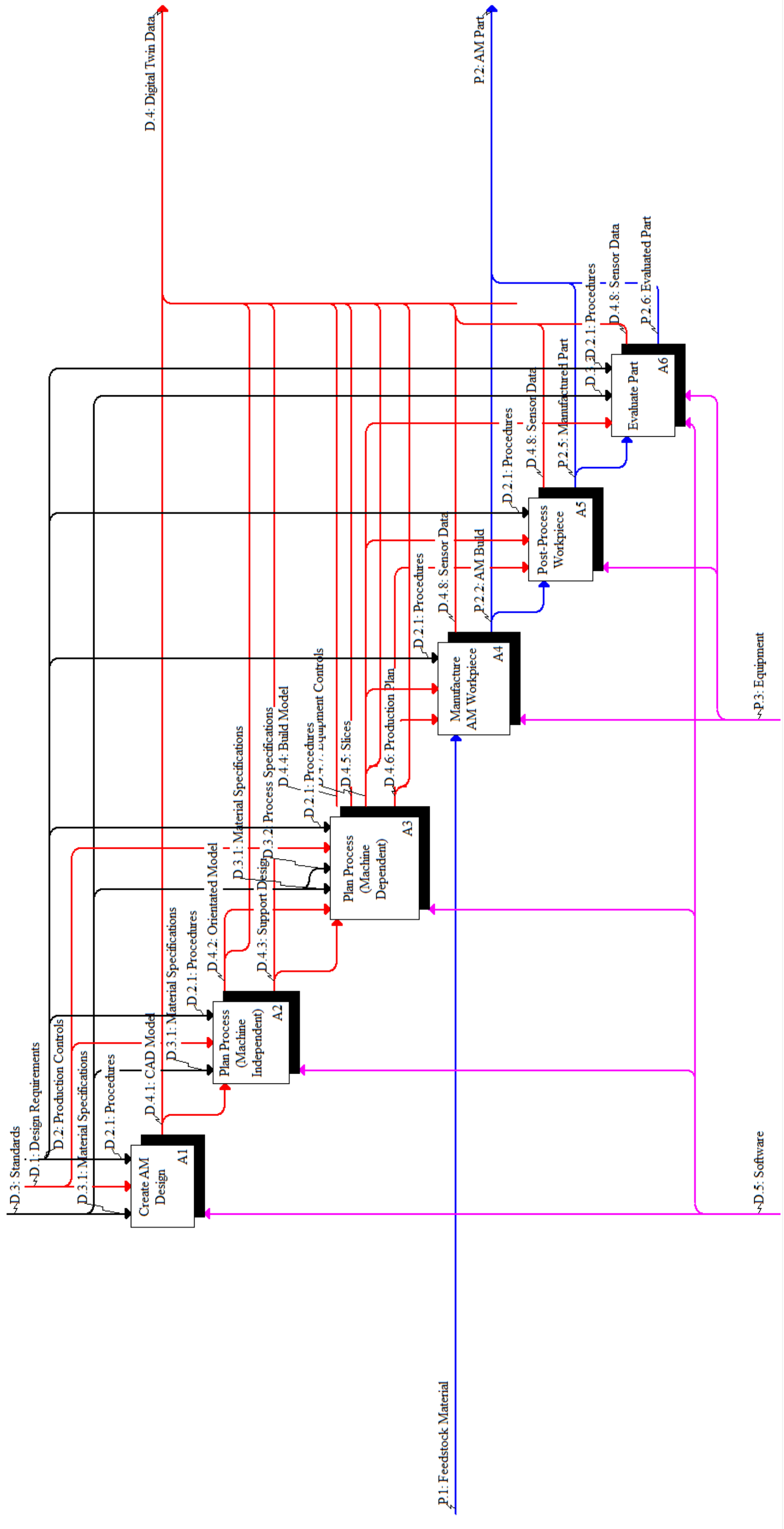

Figure 3: Decomposition of **A0: Produce AM Part**.

3.1. A1: Create AM Design

The decomposed activities for the **A1: Create AM Design** activity are shown in Figure 4. This activity transforms **D.1: Design Requirements** into a **D.4.1: CAD Model** that has been designed for the AM process and material. The **D.4.1: CAD Model** can be output in various formats such as STL, AMF, 3MF, or STEP. The format of the **D.4.1: CAD Model** is dependent on the specific **D.5: Software** and **P.3: Equipment** used in the production system.

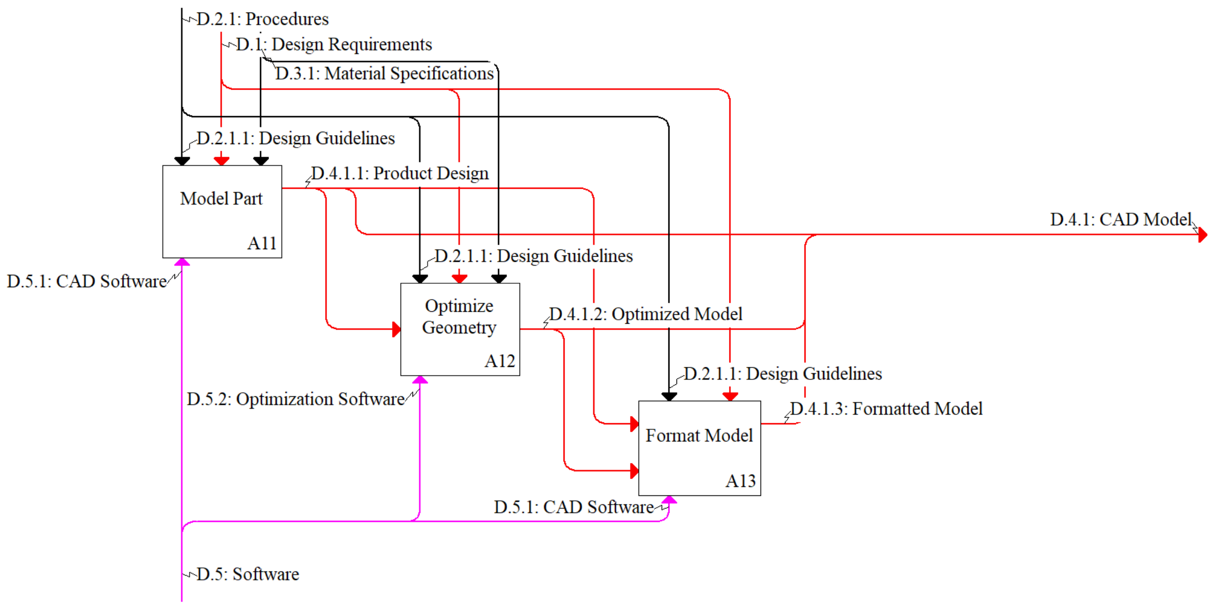

Figure 4: Decomposition of **A1: Create AM Design**.

3.1.1. A11: Model Part

The **A11: Model Part** activity applies a design process to create one or several **D.4.1: CAD Models** that meet the input **D.1: Design Requirements**. This activity is controlled by **D.2.1.1: Design Guidelines**. This activity aims at fulfilling the **D.1: Design Requirements** imposed by the wider production system, such as mating surfaces, system integrations, loads, and other constraints. This activity is also controlled by the **D.3.1: Material Specifications** which specify the material properties and allowables that the designer shall design the part to.

3.1.2. A12: Optimize Topology

The **A12: Optimize Topology** activity optimizes the **D.4.1.1: Product Design** using topology optimization algorithms and generative design functions within a **D.5.2: Optimization Software** package. Such an activity typically aims at reducing the volume of the design body while conforming to expected structural loads. The **D.3.1: Material Specifications** specify the material properties and allowables that control the **A12: Optimize Topology** activity. Topology optimization and generative design activities can be performed using specialized **D.5.2: Optimization Software** or modern **D.5.1: CAD Software** that have such capabilities built in.

3.1.3. A12: Format Model

The **A13: Format Model** activity is performed to format either a **D.4.1.1: Product Design** or an **D.4.1.2: Optimized Model** for the specific application and production process. Formatting can include:

- Repairing mesh errors or other CAD related errors.
- Adding manufacturing or machining tolerances.
- Converting between data formats, such as STEP to STL.

3.2. A2: Plan Process (Machine Independent)

The decomposed activities performed as part of the **A2: Plan Process (Machine-Independent)** activity are shown in Figure 5. This activity is performed with knowledge of the specific manufacturing processes but without specific machine information. AM processes can be susceptible to quality issues such as irregular surface roughness. Adequate process planning shall be performed to reduce the risk of such issues and fulfill **D.1: Design Requirements**. The **D.4.2: Orientated Model** is a control to the **A22: Design Support Structures** meaning this activity can only be performed after the **A21: Choose Orientation** activity has been completed.

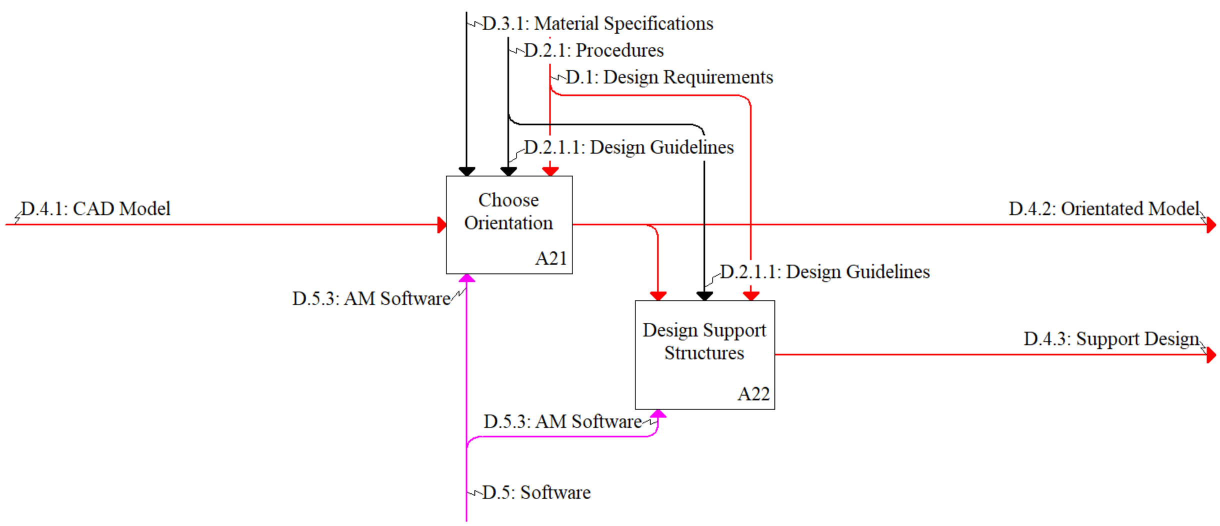

Figure 5: Decomposition of **A2: Plan Process (Machine Independent)**.

3.2.1. A21: Choose Orientation

Using the information specified in the **D.1: Design Requirements** and **D.3.1: Material Specifications**, the design shall choose an appropriate orientation for the design following the **D.2.1.1: Design Guidelines**. An **D.4.2: Orientated Model** is output from the **A21: Choose Orientation** activity. The orientation shall be chosen in relation to the build plate and platform in accordance with ISO/ASTM 52921 requirements [29]. The orientation significantly affects residual stress and material orthotropy or anisotropy. Such aspects shall be carefully considered when choosing an orientation.

3.2.2. A22: Design Support Structures

Based on the **D.4.2: Orientated Model**, the designer then performs the **A22: Design Support Structures** activity. The **D.2.1.1: Design Guidelines**, such as ISO/ASTM 52911-1 [30], shall provide guidance on how to design such supports. This activity shall also be performed based on the specific **D.1: Design Requirements** as the location and type of support structures can have an impact of the surface roughness, dimensions, and residual stresses of the produced **P.2: AM Part**. This activity may be omitted if the part can be printed directly on the build plate or if support structures are designed as part of the original **D.4.1: CAD Model**.

3.3. A3: Plan Process (Machine Dependent)

Figure 6 shows the decomposed **A3: Plan Process (Machine Dependent)** activity. This activity is not only process-specific but also dependent on the specific machines and equipment used for production. The **A32: Develop Production Plan** is dependent on the contents of the **D.4.4: Build Model**, and the **A33: Create Equipment Control** Instructions is dependent on the **D.4.6.2: Production Resources** and **D.4.6.3: Process Parameters** defined as part of the **D.4.6: Production Plan**.

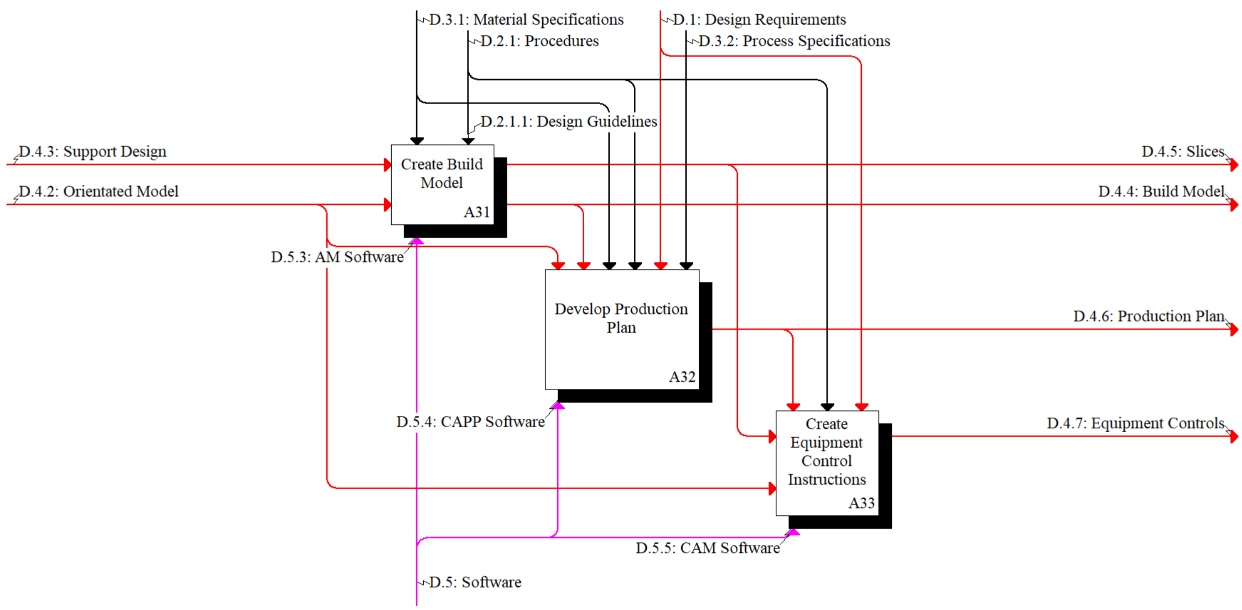

Figure 6: Decomposition of **A3: Plan Process (Machine Dependent)**.

3.3.1. A31: Create Build Model

The sub-activities of the **A31: Create Build Model** activity are shown in Figure 7. The **D.4.2: Orientated Model** is placed in the build volume and located in 3D space during **A311: Place Design** resulting in a **D.4.4.1: Located Design**. This model then either acts as a control for the **A312: Generate Support Structure** activity or as a direct input to the **A313: Slice Build** activity if the design is placed directly on the build plate without the need for **D.4.4.2: Support Structures**.

The **D.4.4: Build Model** consists of the **D.4.4.1: Located Design** and the optional **D.4.4.2: Support Structures**. The **D.5.3: AM Software** can be commercial build preparation software or machine-specific OEM build software.

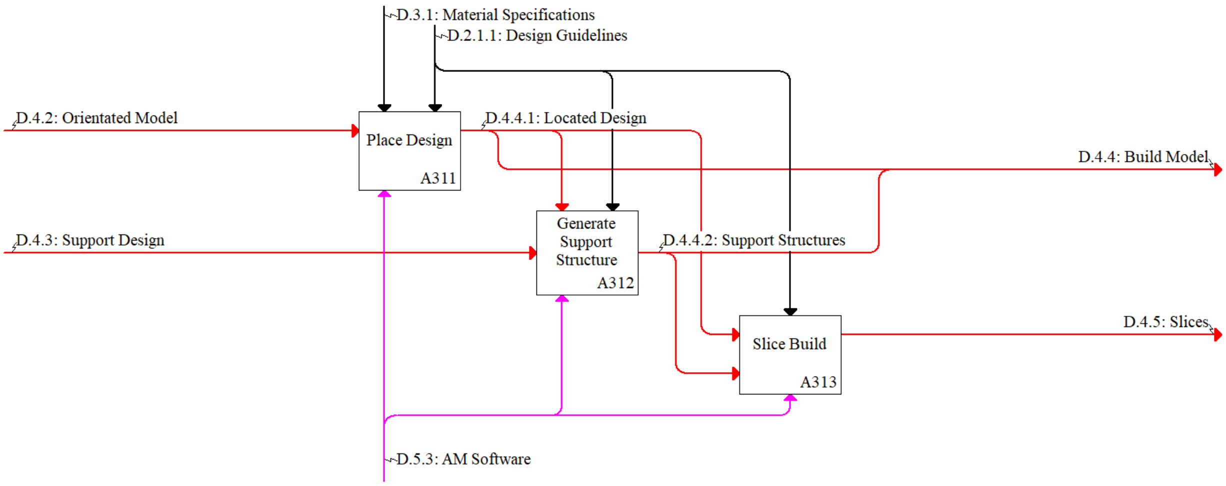

Figure 7: Decomposition of **A31: Create Build Model**.

3.3.2. A32: Develop Production Plan

The decomposed **A32: Develop Production Plan** activity is presented in Figure 8. Firstly, the production process route is defined. The defined **D.4.6.1: Process Route** controls the **A322: Assign Resources** activity. By assigning resources to the production process steps, the machine and equipment-specific capabilities are detailed for the specific production instance. The defined **D.4.6.2: Production Resources** data item then subsequently controls the **A323: Define Process Parameters** activity. The developed **D.4.6: Production Plan** consists of:

- **D.4.6.1: Process Route** which defines the full production sequence and process flow.
- **D.4.6.2: Production Resources** which defines the specific equipment, software, and associated operators required to perform manufacturing and evaluation operations.
- **D.4.6.3: Process Parameters** for each of the assigned **D.4.6.2: Production Resources** and their design values. Examples include build plate temperature of 150°C or annealing dwell temperature of 920°C.

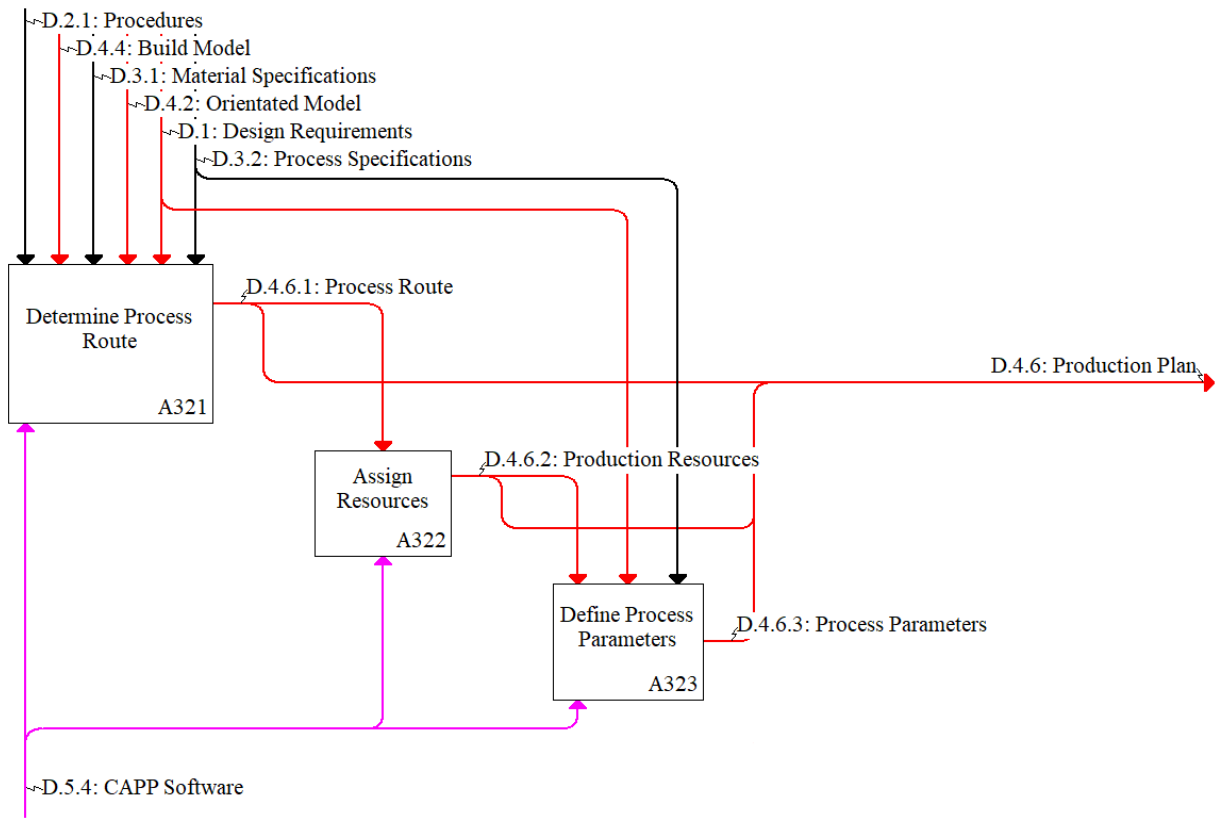

Figure 8: Decomposition of **A32: Develop Production Plan**.

3.3.3. A33: Create Equipment Control Instructions

The decomposition of the **A33: Create Equipment Control Instructions** is depicted in Figure 9. The development of such **D.4.7: Equipment Controls** is controlled by the specific **D.4.6.2: Production Resources** and D.4.6.3: **Process Parameters** specified as part of the **D.4.6: Production Plan**. The **A331: Generate Scan Strategy** transforms the **D.4.5: Slices** into a PBF machine-readable **D.4.7.1: Scan Strategy**. Additionally, the **D.4.2: Orientated Model** can be transformed into **D.4.7.2: Machining Toolpaths** and/or **D.4.7.3: Inspection Routines** by activities **A332** or **A333** respectively. It is important that the **D.4.2: Orientated Model** be used here as opposed to the **D.4.1: CAD Model**, as the orientation of the design in the build can drive the need for location-specific finishing and inspection operations.

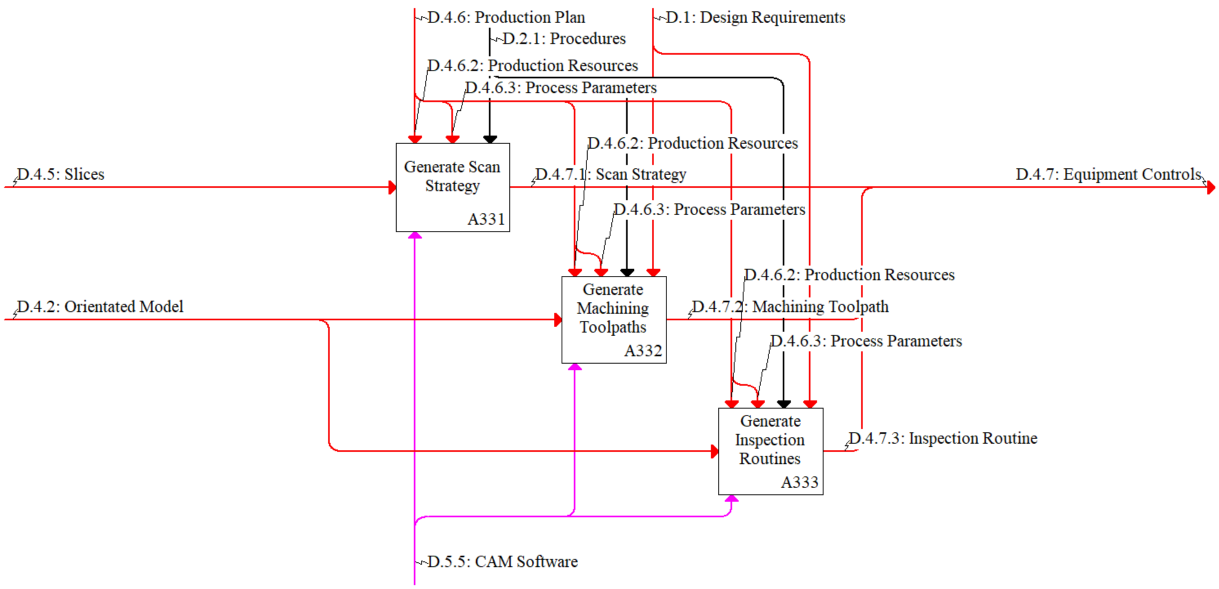

Figure 9: Decomposition of **A33: Create Equipment Control Instructions**.

3.4. A4 Manufacture AM Workpiece

The decomposed activities of the **A4: Manufacture AM Workpiece** activity are shown in Figure 10. This activity includes the fundamental functions required to manufacture an **P.2.2: AM Build** using PBF technology. This activity transforms the **D.4.7.1: Scan Strategy** and either **P.1: Feedstock Material** or P**.2.4: Reconditioned Powder**, or a combination thereof, into an **P.2.2: AM Build** and its associated **D.4.8: Sensor Data**. This activity is where production transitions from a digitally orientated activity to a physical and digital activity. PBF machine functions such as gas flowrate and build plate temperature are specified by the **D.4.6.3: Process Parameters** which control multiple sub-activities as depicted in Figure 10.

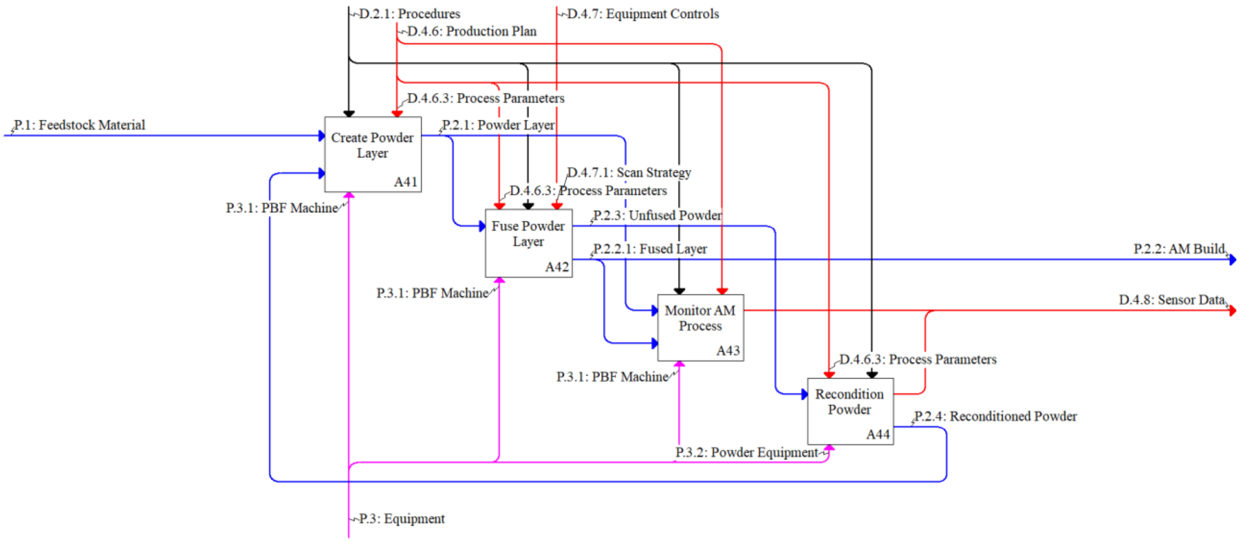

Figure 10: Decomposition of **A4: Manufacture AM Workpiece**.

3.4.1. A41: Create Powder Layer

The **A41: Create Powder Layer** activity is performed by the **P.3.1: PBF Machine** to lay an ideally uniform and homogenous layer of metal powder over the build area. This typically involves dosing powder from a hopper and then coating the powder over the build using a recoating mechanism. The **D.4.6.3: Process Parameters** specify the layer thickness that controls this activity.

3.4.2. A42: Fuse Powder Layer

The **P.2.1: Powder Layer** created during the **A41** activity is then fused into a **P.2.2.1: Fused Layer** by the fusion source in the **P.3.1: PBF Machine**. The **P.2.2: AM Build** consists of one or more **P.2.2.1: Fused Layer/s**. This activity is controlled by the defined **D.4.7.1: Scan Strategy** which specifies important parameters such as laser powder and scan speed, as well as the structure and coordinates of the scan paths such as contouring, hatching, etc.

3.4.3. A43: Monitor AM Process

The **A43: Monitor AM Process** activity is performed to monitor the **P.2.2.1: Fused Layer** and/or the **P.2.1: Powder Layer**. This activity utilizes sensors and instruments within or fitted onto the **P.3.1: PBF Machine** to transform the physical layers into representative **D.4.8: Sensor Data**.

3.4.4. A44: Recondition Powder

P.2.3: Unfused Powder reclaimed from the AM build process can be reconditioned for reuse in subsequent builds. The **A44: Recondition Powder** activity typically involves sieving powder to remove agglomerates and mixing and/or blending the powder to form a homogenous bulk. The resulting **P.2.4: Reconditioned Powder** can then be feedback into the AM process for subsequent builds.

3.5. A5: Post-Process Workpiece

The **A5: Post-Process Workpiece** activity is shown in Figure 11. This activity transforms the **P.2.2: AM Build** into a **P.2.5: Manufactured Part** that is dependent on the specific production application. This model allows for either As-Built, Heat Treated, or Finished type **P.2.5: Manufactured Parts** and any combination thereof.

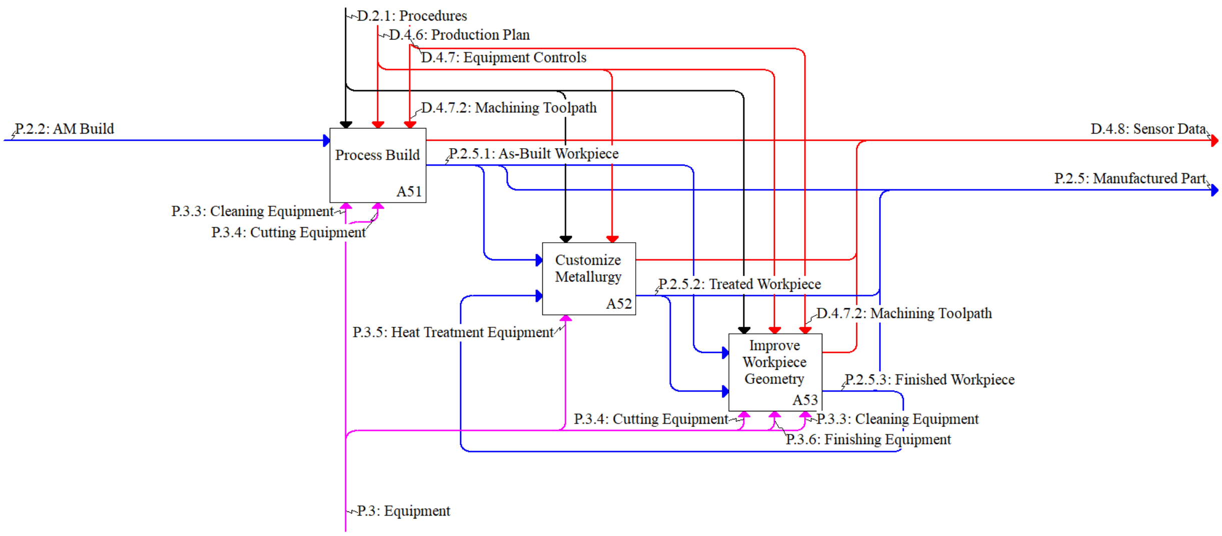

Figure 11: Decomposition of **A5: Post-Process Workpiece**.

3.5.1. A51: Process Build

The **A51: Process Build** activity is performed for all production runs. At the very least all **P.2.2: AM Builds** require cleaning before subsequent activities. Other **A51: Process Build** activities that may be performed include cutting from the build plate and support removal.

3.5.2. A52: Customize Metallurgy

The **A52: Customize Metallurgy** transforms the **P.2.5.1: As-Built Workpiece** into a **P.2.5.2: Treated Workpiece**. It is common practice to finish AM workpieces after performing heat treatments to remove surface oxidation, surface-connected defects, and other reasons. Although there are instances where one might want to **A52: Customize Metallurgy** after performing the **A53: Improve Workpiece Geometry** activity, such as when case hardening is required. The **P.2.5.3: Finished Workpiece** is therefore also a possible input to the **A52: Customize Metallurgy** activity.

3.5.3. A53: Improve Workpiece Geometry

The **A53: Improve Workpiece Geometry** activity can utilize various **P.3.4: Cutting Equipment** such as bandsaws or wire electrical discharge machines (EDM) and/or **P.3.6: Finishing Equipment** such as mills, lathes, barrel finishing equipment, or abrasives and polishing equipment to transform the workpiece into a **P.2.5.3: Finished Workpiece**. The **P.3.3: Cleaning Equipment** is also a mechanism to this activity as cleaning is required after the finishing processes, whether it be to clean cutting fluid from the workpiece or to clean away abrasives after polishing operations.

3.6. A6 Evaluate Part

The **A6: Evaluate Part** activities are shown in Figure 12. These activities are controlled by standardized test methods such as those published by ASTM International or ISO. The **A6: Evaluate Part** activity transforms a **P.2.5: Manufactured Part** into an **P.2.6: Evaluated Part** and its associated **D.4.8: Sensor Data**. Some degree of part evaluation is typically required for all AM production applications, whether it be simple visual type non-destructive evaluation (NDE) and dimensional measurements, or more complex computed tomography (CT) analyses.

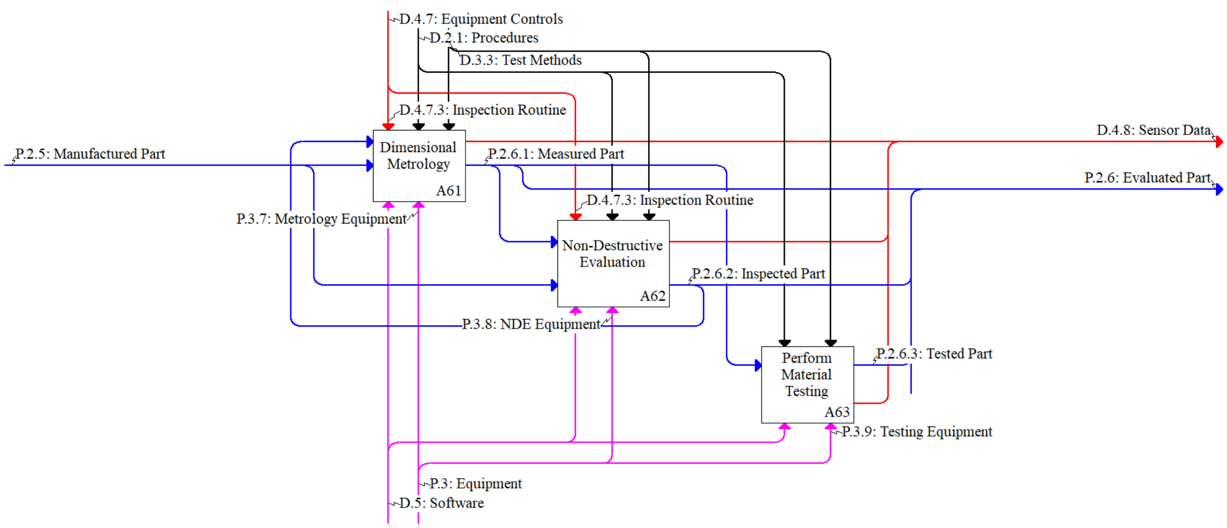

Figure 12: Decomposition of **A6: Evaluate Part**.

3.6.1. A61: Dimensional Metrology

This activity measures the part dimensions such as length, diameter of holes, and surface roughness, and is performed to assess conformance to design tolerances. The **A61: Dimensional Metrology** activity transforms either a **P.2.5: Manufactured Part** or an **P.2.6.2: Inspected Part** into a **P.2.6.1: Measured Part**. This allows for performing either of **A61** or **A62** first. For instances such as fluorescent penetrant, the user may want to apply the penetrant by performing **A62** first and then measure any identified cracks by performing the **A61** activity thereafter. The modeled feedback for **P.2.6.2: Inspected Part** allows for such instances.

3.6.2. A62: Non-Destructive Evaluation

The **A62: Non-Destructive Evaluation** activity is performed to evaluate products for nonconformances and/or quality assurance purposes. NDE can range from visual inspections to radiographic and volumetric CT analyses. ASTM E3166 provides a standard guide for the NDE of AM parts [31].

3.6.3. A63: Perform Material Testing

A63: Perform Material Testing is a generic activity that can be executed if specific testing is required. Such testing may include tensile testing per ASTM E8/E8M [32], microhardness testing per ASTM E384 [33], metallographic evaluations per ASTM E112 [34], or even density testing per ASTM B311 [35]. The **A63: Perform Material Testing** can be performed on **P.2: AM Part** in its various forms and is highly dependent on the production application and phase, such as operational qualification, part and performance qualification, or even ongoing production [28]. The model assumes that testing is performed on a **P.2.6.1: Measured Part** such as tensile specimens after having their gauge length and diameter measured, or metallographic sections after measuring the distance of the sectioned plane from the surface of the manufactured structure.

4. Data Item Definitions

Data items are classified as either of the four ICOMs to a function or activity. These classifications can change depending on the context. As an example, a plan can be an output of one activity and a control to another. Data items are categorized as either digital[3] or physical. Digital data item definitions are provided in Table 1 and physical data items are defined in Table 2. The data items are mapped to the relevant ASTM F3490 AM information modules [36].

Table 1: Digital Data Item Definitions.

ID	Name	Description	ASTM F3490
D.1	Design Requirements	The conceptual design of a part and related design requirements. The availability of design requirements indicates the need for production.	Module 1 & 3
D.2	Production Controls	Instructions (computer and/or human readable) that control production operations (design, planning, manufacturing, testing, etc.).	Module 1
D.2.1	Procedures	Specified way to carry out an activity or a process [37]. Intentionally described for human interpretation.	Module 1
D.2.1.1	Design Guidelines	Guidelines for performing computer-aided design activities. Such guidelines specify the formatting and model transformation heuristics to be able to fulfill **D.1: Design Requirements**.	Module 1
D.3	Standards	Documents that provide requirements, specifications, guidelines, or characteristics that can be used consistently to ensure that materials, products, processes, and services are fit for their purpose.	Module 1
D.3.1	Material Specifications	Documents stating technical material requirements and allowables [37].	Module 1
D.3.2	Process Specifications	Documents stating technical process requirements and variables [37].	Module 1
D.3.3	Test Methods	Standardized methods and associated procedures for testing and evaluating materials and structures.	Module 1
D.4	Digital Twin Data	Dataset used to create virtual information constructs that mimics the structure, context, and behavior of an individual and unique physical asset, or a group of physical assets. It is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value [38].	Module 3, 8 & 9
D.4.1	CAD Model	Computer-generated model of a part that is developed using **D.5.1: CAD Software**.	Module 3
D.4.1.1	Product Design	Model of the part (component, specimen, or test artifact) using **D.5.1: CAD Software** to fulfill **D.1: Design Requirements.**	Module 3
D.4.1.2	Optimized Model	Design optimized for the specific AM technology and post-processes.	Module 3
D.4.1.3	Formatted Model	The transformation of the design model into a data format specific for process planning activities. This includes any alterations to the model due to aspects such as mesh repairs or manufacturing tolerances.	Module 3

[3] We assume that documents are used in their digital form. E.g. standards are in PDF format and read digitally using a computer.

D.4.2	Orientation	The selected orientation of the part as placed in the build volume. This could be used as a reference to choose an orientation for a specific machine.	Module 3 & 4
D.4.3	Support Design	Design of the support structures to support the chosen orientation of the part for a particular AM process. Such supports may be used for fixturing during post-process operations.	Module 3
D.4.4	Build Model	Project file containing the build design and associated data.	Module 2 & 4
D.4.4.1	Located Design	Design located in the build volume in 3D space.	Module 2 & 4
D.4.4.2	Support Structures	Generated support structures in the build volume with reference to the **D.4.4.1: Located Design**.	Module 2
D.4.5	Slices	Build model sectioned horizontally to facilitate the layer-by-layer additive manufacturing process.	Module 2
D.4.6	Production Plan	A planning document that specifies how to control variation in key characteristics [39]. This document can reference both human and machine controls.	Module 1, 2, 4, 7 & 13
D.4.6.1	Process Route	Definition of the production process route and flow detailing key decision gates.	Module 2 & 4
D.4.6.2	Production Resources	List of production resources required to produce the **P.2: AM Part**. Resources are defined by their unique ID with reference to their capabilities.	Module 2
D.4.6.3	Process Parameters	Parameters and their designed values for controlling the operation of process equipment such as machines.	Module 7 & 13
D.4.7	Equipment Controls	Instructions defining how equipment shall operate and utilize tools. Examples include STEP-NC and G-code for CNC machines.	Module 7
D.4.7.1	Scan Strategy	The toolpath strategy for the fusion source used to create the **P.2: AM Part** and builds.	Module 7
D.4.7.2	Machining Toolpath	Numerical code for instructing and controlling CNC machine operations.	Module 7
D.4.7.3	Inspection Routine	Code for instructing and controlling inspection instrumentation such as CMM probes.	Module 7
D.4.8	Sensor Data	Data generated by sensors placed on equipment or in facilities to monitor processes. Examples include powder bed images, furnace thermocouple data, CMM probe coordinates, human operator readings, etc.	Module 8
D.5	Software	Digital tools used to plan and manage part and production operations and associated data.	Module 14
D.5.1	CAD Software	Software used to design products and define geometrical dimensions and tolerances.	Module 14
D.5.2	Optimization Software	Software and associated algorithms used to optimize structures for the AM process.	Module 14
D.5.3	AM Software	Refers to the software tools used to design AM builds and generate a **D.4.4: Build Model** and **D.4.5: Slices**. Some **D.5.3: AM Software** packages can be used to perform CAM activities and generate **D.4.7.1: Scan Strategies**.	Module 14
D.5.4	CAPP[4] Software	Software used for computer-aided process planning. Such software is used to plan process routes and assign production resources.	Module 14

[4] CAPP capabilities are often provided as part of other manufacturing software packages such as PLM software. CAPP can be performed using various software tools such as Excel, Visio, etc.

D.5.5	CAM[5] Software	Software used for computer-aided manufacturing. Such software is used to generate machine toolpaths, generate coordinate controls, and assign process parameters.	Module 14

Table 2: Physical Data Item Definitions.

ID	Name	Description	ASTM F3490
P.1	Feedstock Material	Feedstock material of uniquely identifiable characteristics used to produce the **P.2: AM Part**.	Module 6
P.2	AM Part	The product of the production system. The **P.2: AM Part** is the primary physical output of the system in its final form before shipping to the customer.	Module 2, 4, 6 & 8
P.2.1	Powder Layer	The formed layer of powder that has been spread across the build plate and platform by a recoater arm and blade at a specified thickness.	Module 8
P.2.2	AM Build	Work in process workpiece that is produced by the AM machine. Consists of one or more **P.2.2.1: Fused Layers** on a build plate.	Module 2
P.2.2.1	Fused Layer	Layer of metal powder that has been coated over the powder bed and subsequently fused by the energy source (typically a laser or electron beam).	Module 8
P.2.3	Unfused Powder	Powder that has been recoated in the build chamber but has not subsequently been fused into a solid. Such powder can be processed for reuse for subsequent builds.	Module 8
P.2.4	Reconditioned Powder	Powder that has been reclaimed from the build chamber and processed to improve its condition and enable powder reuse.	Module 6
P.2.5	Manufactured Part	Part produced by AM and post-processed as specified by a **D.4.6: Production Plan**.	Module 4
P.2.5.1	As-Built Workpiece	Workpiece as it is produced by the AM machine before heat treatments and/or finishing.	Module 4
P.2.5.2	Treated Workpiece	Work in process part that has been heat treated to alter its metallurgy.	Module 4[6]
P.2.5.3	Finished Workpiece	AM produced workpiece that has been finished to improve its geometry and surface condition.	Module 4[5]
P.2.6	Evaluated Product	AM produced part that has been evaluated for conformance or production information.	Module 9
P.2.6.1	Measured Product	AM produced part that has been measured for metrological characteristics such as dimensions, surface roughness, and topology.	Module 9
P.2.6.2	Inspected Product	AM produced part that has been inspected for defects. Such inspection can include inspection of aesthetics, inspection of surface defects such as cracks, or volumetric inspection for internal voids.	Module 9
P.2.6.3	Tested Product	AM produced part that has been tested to evaluate its material and/or mechanical properties.	Module 9

[5] CAM in this model refers to any software used for toolpath generation and machine control instructions, not necessarily specific to manufacturing operations. Examples of non-manufacturing specific operations include the generation of CMM probe routines and other coordinate inspection systems.
[6] ASTM F3490 focuses on the AM part in its as-built state. Reference to the part in its treated and/or finished state may require further information.

P.3	Equipment	Production resources including any attached or integrated sensors used to perform production activities.	Module 5 & 13
P.3.1	PBF Machine	Manufacturing equipment that fuses powder into solid products.	Module 5
P.3.2	Powder Equipment	Equipment used to process powder for reuse. Such equipment can include sieves, blending and mixing equipment, and scales.	Module 13
P.3.3	Cleaning Equipment	Equipment and consumables used to clean AM builds and products of powder, soot, and other dirt.	Module 13
P.3.4	Cutting Equipment	Manufacturing equipment that can cut through metal. Examples include support removal tools, bandsaws, and wire EDM machines.	Module 13
P.3.5	Heat Treatment Equipment	Equipment used to heat metal in a controlled environment (temperature, pressure, atmosphere, liquid media, etc.) to achieve desired metallurgical properties. Examples include a HIP furnace, argon gas, and dividers.	Module 13
P.3.6	Finishing Equipment	Equipment used to improve the geometry and/or appearance of metal AM parts. Examples include mills, lathes, barrel finishing machines, polishing equipment and consumables, and abrasive blasting equipment.	Module 13
P.3.7	Metrology Equipment	Equipment and instrumentation used to measure metrological characteristics of products. Examples include calipers, CMM machines, and profilometers.	Module 9 & 13
P.3.8	NDE Equipment	NDE equipment and instrumentation used to inspect the part volume and surface for defects. Examples include fluorescent penetrant consumables, x-ray CT equipment, and visual aids.	Module 9 & 13
P.3.9	Testing Equipment	Equipment and instrumentation used to perform material testing of products to determine some material property. Examples include universal testing machines, extensometers, and indentation machines.	Module 9 & 13

References

[1] ISO (2021) Automation systems and integration - Digital twin framework for manufacturing Part 1: Overview and general principles (ISO 23247-1) (ISO), ISO 23247-1.

[2] Additive Manufacturing Requirements for Spaceflight Systems (NASA-STD-6030) (2021) (NASA), NASA-STD-6030.

[3] Integration Definition for Function Modeling (IDEF0) (FIPS PUB 183) (1993) (NIST), FIPS PUB 183.

[4] Information technology - Modeling Languages - Part 1: Syntax and Semantics for IDEF0 (ISO/IEC/IEEE 31320-1) (2012) (IEEE), ISO/IEC/IEEE 31320-1. https://doi.org/10.1109/IEEESTD.2012.6363476

[5] Feng SC (1993) Dimensional inspection planning based on product data standards. (National Institute of Standards and Technology, Gaithersburg, MD), NISTIR 5183, p 10. https://doi.org/10.6028/NIST.IR.5183

[6] Ang CL, Luo M, Gay RKL (1994) Development of a knowledge-based manufacturing modelling system based on IDEFO for the metal-cutting industry. International Journal of Production Economics 34(3):267–281. https://doi.org/10.1016/0925-5273(94)90157-0

[7] Barkmeyer EJ (1996) SIMA Reference Architecture: Part 1: Activity Models. (NIST), NISTIR 5939, p 84.

[8] Barkmeyer EJ, Wallace EK (2016) Reference Architecture for Smart Manufacturing: Part 1: Functional Models. (NIST), NIST AMS 300-1, p 47. https://doi.org/10.6028/NIST.AMS.300-1

[9] Gibbons DW, van der Merwe AF (2020) Towards a Standard Procedure for the Qualification of Metal Laser Powder Bed Fusion Equipment in the Aerospace Industry using Functional Models. 21st Annual International RAPDASA Conference (Stellenbosch, RSA), pp 97–106.

[10] Khoo LP, Ang CL, Zhang J (1998) Adapting IDEF0 modelling to perform manufacturing diagnosis. The International Journal of Advanced Manufacturing Technology 14(12):928–934. https://doi.org/10.1007/BF01179083

[11] Feng SC (2000) Manufacturing Planning and Execution Software Interfaces. Journal of Manufacturing Systems 19(1):1–17. https://doi.org/10.1016/S0278-6125(00)88886-X

[12] Lin Z-C, Chow J-J (2001) Integration Planning Model of IDEF0 and STEP Product Data Representation Methods in a CMM Measuring System. The International Journal of Advanced Manufacturing Technology 17(1):39–53. https://doi.org/10.1007/s001700170208

[13] Reference process for seamless production planning - Standardized procedure for production systems engineering (2012) (VDMA), VDMA 66421. Available at https://www.beuth.de/en/technical-rule/vdma-66421/167792271

[14] Gingele J, Childe SJ, Miles ME (2003) Incorporating links to ISO 9001 into manufacturing process models using IDEF 9000. International Journal of Production Research 41(13):3091–3118. https://doi.org/10.1080/0020754031000101312

[15] Bonnard R, Mognol P, Hascoët J-Y (2010) A new digital chain for additive manufacturing processes. Virtual and Physical Prototyping 5(2):75–88. https://doi.org/10.1080/17452751003696916

[16] Ghazy MM, Dalgarno KW (2009) Structured Analysis of a Layered Manufacturing Decision Support System. Available at https://www.researchgate.net/publication/268348197_Structured_Analysis_of_a_Layered_Manufacturing_Decision_Support_System
[17] Ghazy MM (2012) Development of an Additive Manufacturing Decision Support System (AMDSS). Dissertation (Newcastle University).
[18] Feng SC, Witherell PW, Ameta G, Kim DB (2015) Fundamental Requirements for Data Representations in Laser-Based Powder Bed Fusion. Volume 1: Processing (American Society of Mechanical Engineers, Charlotte, North Carolina, USA), p 10. https://doi.org/10.1115/MSEC2015-9439
[19] Feng SC, Witherell P, Ameta G, Kim DB (2017) Activity model for homogenization of data sets in laser-based powder bed fusion. Rapid Prototyping Journal 23(1):137–148. https://doi.org/10.1108/RPJ-11-2015-0160
[20] Abeye B, Barkmeyer E, Denno P (2014) Product Data Sheet Ontology (NISTIR 8035). (NIST, Gaithersburg, MD), NISTIR 8035, p 176. https://doi.org/10.6028/NIST.IR.8035
[21] Guide for Characterizing Environmental Aspects of Manufacturing Processes (ASTM E3012) (2022) (ASTM International), ASTM E3012. https://doi.org/10.1520/E3012-22
[22] Reference Architecture Model Industrie 4.0 (RAMI4.0) (DIN SPEC 91345) (2016) (DIN), DIN SPEC 91345.
[23] Batch Control Part 1: Models and Terminology (ANSI/ISA-88.01) (1995) (ANSI, Research Triangle Park, North Carolina), ANSI/ISA–88.01.
[24] Enterprise-Control System Integration Part 1: Models and Terminology (IEC 62264-1) (2013) (ISO), IEC 62264-1.
[25] Standard Guide for Additive Manufacturing General Principles Requirements for Purchased AM Parts (ISO/ASTM 52901) (2016) (ASTM International), ISO/ASTM 52901. https://doi.org/10.1520/F3167-16
[26] Additive Manufacturing - Test Artefacts - Geometric Capability Assessment of Additive Manufacturing Systems (ISO/ASTM 52902) (2023) (ASTM International), ISO/ASTM 52902.
[27] Moylan S, Slotwinski J, Cooke A, Jurrens K, Donmez MA (2014) An Additive Manufacturing Test Artifact. Journal of Research of the National Institute of Standards and Technology 119:429. https://doi.org/10.6028/jres.119.017
[28] Additive Manufacturing - Qualification Principles - Installation, Operation and Performance (IQ/OQ/PQ) of PBF-LB Equipment (ISO/ASTM 52930) (2021) (ASTM International), ISO/ASTM 52930.
[29] Standard Terminology for Additive Manufacturing - Coordinate Systems and Test Methodologies (ISO/ASTM 52921) (2019) (ASTM International), ISO/ASTM 52921.
[30] Additive Manufacturing - Design - Part 1: Laser-Based Powder Bed Fusion of Metals (ISO/ASTM 52911-1) (2019) (ASTM International), ISO/ASTM 52911-1.
[31] Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build (ASTM E3166) (2020) (ASTM International), ASTM E3166.
[32] Test Methods for Tension Testing of Metallic Materials (ASTM E8/E8M) (2022) (ASTM International), ASTM E8/E8M. https://doi.org/10.1520/E0008_E0008M-22

[33] Test Method for Microindentation Hardness of Materials (ASTM E384) (2022) (ASTM International), ASTM E384. https://doi.org/10.1520/E0384-22

[34] Test Methods for Determining Average Grain Size (ASTM E112) (2021) (ASTM International), ASTM E112. https://doi.org/10.1520/E0112-13R21

[35] Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity (ASTM B311) (2022) (ASTM International), ASTM B311. https://doi.org/10.1520/B0311-22

[36] Standard Practice for Additive Manufacturing General Principles Overview of Data Pedigree (ASTM F3490) (2021) (ASTM International), ASTM F3490. https://doi.org/10.1520/F3490-21

[37] Quality management systems - Fundamentals and vocabulary (ISO 9000) (2015) (ISO), ISO 9000.

[38] AIAA (2020) Digital Twin: Definition & Value. (AIAA & AIA), p 16.

[39] Aerospace Series - Quality Management Systems - Variation Management of Key Characteristics (SAE AS9103) (2022), SAE AS9103.

Appendix A. Abbreviations

AM	Additive Manufacturing
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CAPP	Computer-Aided Process Planning
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CSV	Comma-Separated Values
CT	Computed Tomography
EDM	Electrical Discharge Machining
HIP	Hot Isostatic Pressing
ICOM	Input, Control, Output, Mechanism
ID	Identifier
IDEF0	Integrated Definition for Functional Modeling
MES	Manufacturing Execution Software
NDE	Non-Destructive Evaluation
PBF	Powder Bed Fusion
PDF	Portable Document Format
PLM	Product Lifecycle Management
QMS	Quality Management System
UMP	Unit Manufacturing Process

Appendix B. IDEF0 Modeling Approach

IDEF0 is a modeling language (syntax and semantics) and methodology. IDEF0 modeling provides a means to model the functions (activities, actions, processes, operations) required by a system and the functional relationships and data (information or objects) that support the integration of those activities [3]. The two primary modeling components are functions, represented on a diagram by boxes, and the data items (digital and physical entities) that relate to those functions, represented by arrows, as shown in Figure 13.

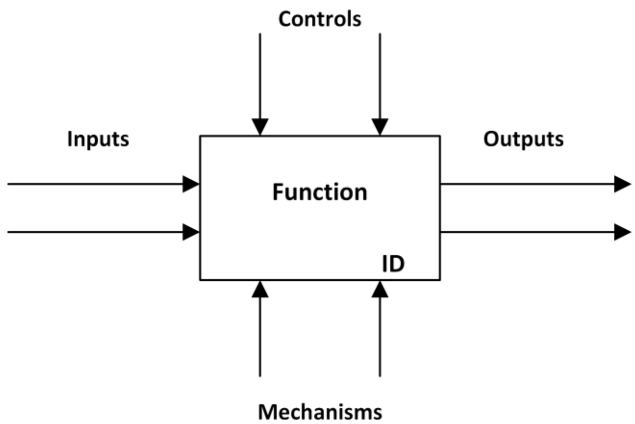

Figure 13: Generic IDEF0 modeling components.

The text in the box that represents a function typically takes the form of a verb-noun pair, for example, “Create AM Design”. There are five[7] types of concepts represented by the arrows: Inputs, Controls, Outputs, and Mechanisms also known as ICOMs. An input is the data, objects, or materials that are transformed by the function or activity [4]. Examples of inputs are CAD models and feedstock materials. Output is the result of the input being transformed by the function [4]. Examples of outputs are an AM build and sensor data. Controls are the conditions necessary for the function to produce the correct output [4]. Examples of controls are standards, specifications, and plans. Mechanisms are the means used by the function to transform input into output, examples include software, equipment, and personnel [4]. An input can be bundled as a control. Each function or activity must be provided a control and must produce an output [4].

Each function is assigned an ID. The primary function ID for the entire system being modeled is referred to as **A0**. Functions and activities are decomposed into lower-level functions and activities that provide further specificity to the model. The functions at the first level of decomposition have IDs **A1**, **A2**, and so on. Decompositions typically do not have more than six activities. When activity **A1** is decomposed, the subsequent activities will have IDs **A11**, **A12**, **A13**, and so on. Activities are decomposed to a level sufficient to create the required outputs for a system. ICOMs are too assigned an ID. The approach for identifying ICOMs in this model differs from the approaches suggested by ISO/IEC/IEEE 31320-1 [4]. As ICOMs in this model can change their type, each ICOM is assigned a unique ID that does not change even if the item’s type does. As an example, the **D.4.1.1: Product Design** data item is an output from **A11** but also an input to

[7] Call references between IDEF0 models were not used for this application [4].

A12 and **A13**. The data item itself is the same but its context is different, hence its ID remains the same throughout the model. Not all outputs from an activity necessarily become inputs to subsequent activities. Outputs can become controls or mechanisms. ICOM data items associated with an activity must be used with the activities of its decomposition. Such items can also be joined (bundled) or separated (unbundled). For example, a generic equipment mechanism can be separated into specific types of equipment or specific subcomponents of that equipment. It can also be bundled into a single equipment mechanism. This makes higher-level activities easier to read and leaves the details to the lower-level decompositions. Bundling outputs creates larger groupings of output from multiple types.

IDEF0 modeling is not a flowchart, nor is there any temporal aspect to the modeling approach. The execution of activities is determined by the control type items. IDEF0 does not allow for modeling logical constructs such as “if-then” decision-making in the diagram, however, decision and logic can be modeled internally to a function based on its inputs, controls, and mechanisms [13]. IDEF0 allows for modeling at different levels of abstraction. Functions can be decomposed when further specificity is required. IDEF0 enables traceability from high-level abstract functions down to their associated lower-level decomposed functions.