PBF-AMP-Onto: an ontology for powder bed fusion additive manufacturing processes

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Abstract

Additive manufacturing is an innovative production approach aimed at creating products that traditional techniques cannot produce with the desired quality and requirements. Throughout the additive manufacturing process, data is either used (such as materials properties, printer characteristics and settings) or generated (such as monitoring data during printing, slicing strategies setting parameters). However, managing such data with complex relationships remains a significant challenge in both research and industry in the additive manufacturing field. To address this issue, we developed a modular ontology that can be used as the basis for a framework that supports decision-making systems, facilitate semantics-aware data management, and enhance the understanding and optimization of additive manufacturing processes. In this paper we focus on one of the state-of-the-art additive manufacturing approaches, i.e., powder bed fusion. To show the use and the feasibility of our approach, we created a knowledge graph for an actual additive manufacturing experiment based on our ontology, and show how queries relevant to domain experts can be answered using this knowledge graph.

Keywords

Ontology, Additive Manufacturing Process, Powder Bed Fusion, Electron Beam Powder Bed Fusion

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, is a production method to create three-dimensional objects based on respective 3D models in an automatic way. There are several benefits to use AM for manufacturing [1]. The 3D model design can be easily modified based

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on requirements, manufacturing constraints and be shared as a digital model. Furthermore, it is reasonable to create a limited number of product samples using AM (e.g. for research purposes), whereas establishing an entire production line with dedicated tools using traditional manufacturing techniques may not be practical. Also, it may be easier to meet sustainability goals.

To print 3D models with high quality and resolutions, different AM methods were developed, such as *Fused Deposition Modeling (FDM)*, *Powder Bed Fusion (PBF)*, *Inkjet printing and contour crafting*, and *Stereolithography (SLA)* [2]. The choice of method for AM depends on several factors, including the material used for printing, the desired quality, and any constraints during production (such as whether the model can be printed with or without adding a support part based on the printing angle). In this paper, our focus lies on Electron Beam Powder Bed Fusion (EB-PBF). EB-PBF represents a state-of-the-art technology that leverages a focused electron beam to melt and fuse metal powder layers [3]. This method offers several advantages, including the capability to fabricate intricate geometries with high precision and exceptional material properties. Notably, the electron beam technique is well-suited for processing high-temperature metals and alloys (e.g., stainless steel), rendering it indispensable in industries such as aerospace, automotive, and medicine.

Typically, AM processes follow a number of steps, which may be different for different AM techniques. Some common steps are: (1) designing digital models using Computer-Aided Design (CAD) software, (2) configuring parameters such as printing angle and speed using slicing software, (3) the actual printing using 3D printing machines, and (4) inspecting and testing the printed objects. During each step, different types of data are used and generated [4, 5, 6]. For instance, data representing a 3D model is generated by CAD software in the design step and used for configuring printing parameters by slicing software. However, there is no standardized way to store and format such data. Also, data in materials science and engineering is frequently sparse or incomplete [7]. For instance, metadata and provenance information is often lacking when storing information about AM experiments. Therefore, standardized formats may guide how to store data as well as provide information about what data is lacking. Further, it would allow for the development of design and analysis tools that would alleviate the design and quality assurance of AM products. Further, there is no formal model based on domain knowledge to represent and interpret such data. These issues bring challenges in semantics-aware data search and data analytics applications. They also relate to the FAIR (Findable, Accessible, Interoperable, and Reusable) principles [8, 9] which aim to enable machines to automatically find and use the data, and help individuals easily reuse the data.

Ontologies can address these issues by formally representing domain knowledge in AM. Therefore, in this paper we propose a first version of a modular ontology, PBF-AMP-Onto, for PBF processes. We describe the ontology and its development in Section 3. We created two modules: one with core concepts for PBF and a specialized module for EB-PBF. Further, in Section 4.1 we show how a knowledge graph (KG) based on the ontology can be used to describe a particular 3D printing experiment for printing screws. We also exemplify how this KG can be queried to find information about, e.g., the sub-processes and materials in this experiment which are relevant to the experiment developers. We describe related work in Section 2, and conclude the paper Section 5.

The ontology, KG and queries that are described in this paper are available at https://github.

com/LiUSemWeb/PBF-AMP-Onto.

2. Related work

Although much research has been performed regarding the modeling of processes in general, for the sake of brevity, we focus here on related work in the AM domain.

In [10] AM ontologies are categorized based on whether they contain information on products, processes, resources and parameters. The authors also define the upper levels of an AM ontology based on these concepts.

The Platform Material Digital Core Ontology (PMDco) [7] is a mid-level ontology that aims to bridge semantic gaps between high-level materials science and engineering-specific, and other science domain semantics. It defines processes, processing nodes which execute processes, and objects which are inputs and outputs to processes. These core concepts can then be further specialized for different types of processes.

The Additive Manufacturing Ontology (AMOntology) attempts to model the knowledge and terminology within Metal AM [11]. As different types of laser beam models produce different heat distribution and flux, and different thermal models use different analyses, AMOntology represents relationships between AM modeling parameters regarding different laser, thermal, microstructural, and mechanical property models for metal-based AM. The ontology can be used for process control and predicting effects of changes.

In [12], the Innovative Capabilities of Additive Manufacturing (ICAM) ontology is presented. It is based on a review of AM manufacturers and machines that identified the capabilities that they possess. These capabilities can relate to such things as fabrication method, manufacturing scale and shapes. This knowledge can be used to find, e.g., machines that allow for printing products with specific properties.

The Design for Additive Manufacturing Ontology (DFAM Ontology) [13] aims to represent knowledge needed in a general fabrication scenario. A process is represented by an AM event. Different parameters for things such as builds, design and processes are concepts on their own. Similarly, parts are represented as concepts. We make other choices as these are better represented as relations and there seem to be confusions between is-a and part-of [14, 10]. For instance, an object becomes a part only in relation to another object. It is often not an inherent property of the object. Another DFAM ontology is presented in [15] with processes, capabilities, features and parameters.

Our work aims to represent knowledge about PBF printing processes to guide the storage and analysis of AM process data. The closest works to this paper are [7] and [10]. We specialize the process concepts in [7] by focusing on PBF printing. Further, our ontology has a larger focus on the sub-processes of the AM process than [10].

3. Ontology development

We employed the NeOn ontology engineering methodology [16] to develop our modular ontology. This approach allows for the flexible extension of the ontology to accommodate various future scenarios. A team of knowledge engineers and domain experts collaborated to gather requirements and gain insights into the specific needs of the AM field. There are many AM techniques with different sub-processes and strategies. Therefore, we decided to model the AM domain knowledge in a modular way. We chose to start with PBF and in particular EB-PBF, as it is a state-of-the-art technique and our results will be directly applicable in the development of databases and KGs in ongoing research in EB-PBF.

We used Protégé[1] as ontology development tool. We reused some concepts from the PROV-O Ontology[2]. We note that in future versions we will reuse more ontologies. For instance, in this first version we have used strings to represent the values and units of quantities. A natural next step is to reuse an ontology such as Quantities, units, dimensions and data types ontologies (QUDT)[3] for representing these.

3.1. Competency questions

Conform to the methodology, we formulate competency questions that our developed ontology should be capable to answer:

- **CQ1**: What is the material used for each printed build in an EB-PBF printing process?
- **CQ2**: Who is the manufacturer of the metal powder used in an EB-PBF printing process?
- **CQ3**: What are different sub-processes in an EB-PBF process?
- **CQ4**: What are the inputs and outputs of each sub-process in an EB-PBF process?
- **CQ5**: What are the properties of the layer melting strategy used in an EB-PBF slicing sub-process?
- **CQ6**: Which 3D printing machine has been used for an EB-PBF printing process?
- **CQ7**: What types of sensors are utilized in an EB-PBF 3D printing machine?
- **CQ8**: What is the total number of layers used in an EB-PBF printing process?
- **CQ9**: What is the layer thickness used in an EB-PBF printing process?
- **CQ10**: What is the start and end date and time for an PBF-AM process?
- **CQ11**: What is the typical beam power for the energy source used in an EB-BPF printing process?

3.2. PBF-AMP-Onto_Core

The first module, PBF-AMP-Onto_Core, models the core concepts and relationships in PBF processes. A visualization of PBF-AMP-Onto_Core is presented in orange in Figure 1.

The `Powder_Bed_Fusion_Additive_Manufacturing_Process` is modeled as a sub-concept of `Additive_Manufacturing_Process` which in its turn is a sub-concept of `Process`, and inherits temporal information from that concept. A `Process` is supervised by at least one `Prov:Agent` and has a start and an end date and time.

In general, a `Powder_Bed_Fusion_Additive_Manufacturing_Process` has sub-processes which are performed in a specific order: `3D_Model_Design_Process` where a 3D model is created, the `Slicing_Process` where the 3D model is sliced to layers and a digital twin is

[1] https://protege.stanford.edu/
[2] https://www.w3.org/TR/prov-o/
[3] https://qudt.org/

created for each layer, the `Printing_Process` where the actual physical objects are printed, and the `Post_Printing_Process` where the physical objects undergo various post-processing methods such as cleaning off excess powder and detaching the printed objects from the build plate. Further, the `Monitoring_Process` is carried out during the printing process to monitor and document each layer, collecting data for future decisions or potential adjustments. The `Inspection_And_Quality_Management_Process` investigates the printed build using various analysis methods, such as microstructural analysis. In some specific PBF processes some of the sub-processes may be missing. For the first steps in the PBF workflow (part of) `Files` in different formats are used as input and output for the sub-processes. The printing sub-process has a physical object (`Printed_Build`) as output.

3.3. PBF-AMP-Onto_EB

PBF-AMP-Onto_EB focuses on a specific kind of PBF, namely EB-PBF. The concepts that are specific for PBF-AMP-Onto_EB are presented in blue in Figure 1. For EB-PBF, the sub-processes

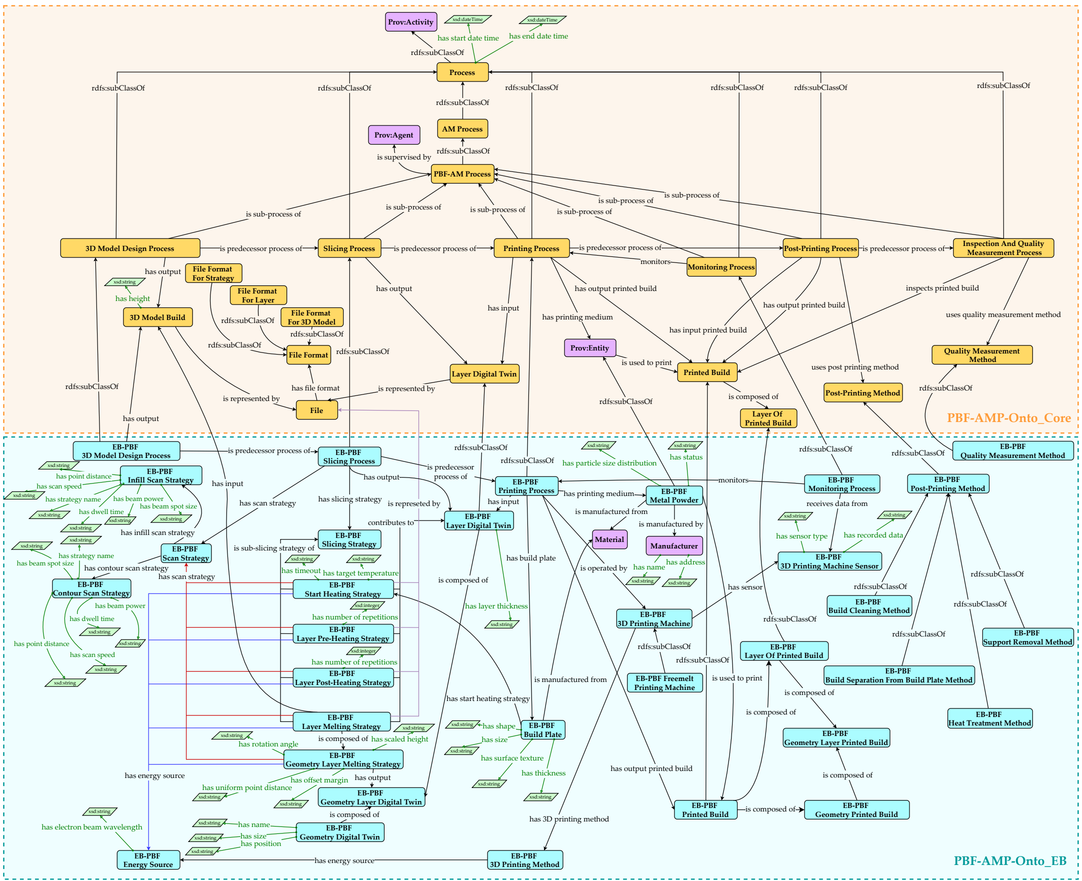


Figure 1: PBF-AMP-Onto including the Core and EB modules.

of PBF are specialized. We describe here the two most complex sub-processes.

An `EB-PBF_Slicing_Process` has a slicing strategy (`EB-PBF_Slicing_Strategy`) and strategy for scanning (`EB-PBF_Scan_Strategy`). At the beginning of the printing process, the `EB-PBF_Start_Heating_Strategy` is applied once and defines how to heat the build plate. Each layer is prepared before melting the metal powder as defined in the `EB-PBF_Layer_Pre-Heating_Strategy`. Further, the `EB-PBF_Layer_Melting_Strategy` defines the strategy for melting the metal powder spread on the previous layer. Finally, the `EB-PBF_Layer_Post-Heating_Strategy` guides the heating of the melted layer in different repetitions. Each of these strategies are represented in (part of) `Files` in different formats. They use an `EB-PBF_Energy_Source` (an electron beam). Further, they have an `EB-PBF_Scan_Strategy` which is composed of an `EB-PBF_Infill_Scan_Strategy` and an `EB-PBF_Contour_Scan_Strategy` where infill strategies focus on the interior part of a layer, while contour strategies deal with the outer part of a layer. All these strategies are part of the `EB-PBF_Layer_Digital_Twin`.

As different geometries (e.g., different screws) can be printed at the same time and we like to store information and reason about these, we define an `EB-PBF_Geometry_Digital_Twin` which is composed of `EB-PBF_Geometry_Layer_Digital_Twins` which are produced by an `EB-PBF_Geometry_Layer_Melting_Strategy`.

The `EB-PBF_Printing_Process` uses an `EB-PBF_Printing_Machine` that allows for certain `EB-PBF_Printing_Methods`. It uses an `EB-PBF_Build_Plate` that is heated using the `EB-PBF_Start_Heating_Strategy`. The process uses `EB-PBF_Metal_Powder`. The actual printing is performed based on the information in the `EB-PBF_Layer_Digital_Twin`. The output is a `Printed_Build`.

4. Use case and evaluation

In this section, we describe an example use case where we construct a KG for an EB-PBF experiment and demonstrate how competency questions in Section 3 can be answered using SPARQL queries.

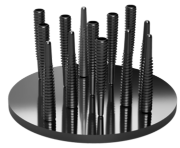
4.1. Use case

We used the data from an EB-PBF printing experiment where 13 screws were printed. As printing medium, *stainless steel* was used. Also the build plate was manufactured from *stainless steel*. Figure 2a shows a Python file where the first line reads the 3D model in *.stl* format of a single screw. Then, the locations of the 13 different copies (*part1* to *part13*) on the build plate are defined. Figure 2b shows the 3D model of the 13 screws on the build plate.

Once the geometries are located on the build plate, they are sliced into layers using various slicing strategies. Figure 3a shows part of the *Python* code for the layer melting strategies used to slice each geometry in the experiment. For instance, all 13 parts have a *spot size*, i.e., the size of the electron beam after passing through the gun, of 1 µm. However, the *beam power* of *part7* is set to 720 kW, while for the other parts it is set to 660 kW. Additionally, each part has a different *dwell time*, representing the duration the beam stays on a point. There are other parameter settings as well that reflect various settings for the beam power and its movements such as the *scan speed* (speed of the beam), and *point distance* (distance between adjacent spots).

```
part01 = pv.read(r"C:\Users\Linköpingsuniversitet\Projekt\2024_04_16\swemac_screw.stl")
part01 = center_mesh(part01)
part1 = part01.translate([2*d,0,0])
part2 = part01.translate([d,d,0])
part3 = part01.translate([d,0,0])
part4 = part01.translate([d,-d,0])
part5 = part01.translate([0,2*d,0])
part6 = part01.translate([0,d,0])
part7 = part01.translate([0,0,0])
part8 = part01.translate([0,-d,0])
part9 = part01.translate([0,-2*d,0])
part10 = part01.translate([-d,d,0])
part11 = part01.translate([-d,0,0])
part12 = part01.translate([-d,-d,0])
part13 = part01.translate([-2*d,0,0])
```

(a) Parts placement on the build plate.



(b) 3D model of the experiment.

Figure 2: A build with 13 geometries (parts).

print_2024_04_15.py

```
build = SimpleBuild(
    meshes = [part7, part1, part11, part5, part8, part13, part3, part9, part6,
    part2, part12, part4, part10],
    spot_size = [1],
    beam_power = [720, 660, 660,  660, 660, 660, 660, 660, 660, 660, 660, 660, 660],
    scan_speed = [1700000],
    dwell_time = [58333, 570000, 570000, 700000, 700000, 186122, 186122, 228571,
    228571, 46530, 46530, 57142, 57142],
    infill_strategy = ["point_random"],
    infill_settings = [{}],
    infill_point_distance = [0.1, 0.35, 0.35, 0.35, 0.35, 0.2, 0.2, 0.2, 0.2, 0.1, 0.
    1, 0.1, 0.1],
    layer_height = 0.07,
    rotation_angle = [0],
    bse_melt = True,
    bse_step = 1,
    )
build.prepare_build(r"C:\Users\antwi87\OneDrive - Linköpings
universitet\Projekt\Testbädd\prints\2024 04 16\build 2024 04 16")
```

(a) Layer melting strategies.


```
build:
  start_heat:
    file: /home/freemelt/Desktop/Anton/build_2024_04_16/PlateHeat950W_SS100_S3000.obp
    temp_sensor: Sensor1
    target_temperature: 900
    timeout: 3600
  preheat:
    file: /home/freemelt/Desktop/Anton/build_2024_04_16/LowCurrentPreheat_PT_V.obp
    repetitions: 10
  postheat:
    file: /home/freemelt/Desktop/Anton/build_2024_04_16/PostMelt_IdleScan.obp
    repetitions: 0
  build:
    layers: 642
    files:
      - - /home/freemelt/Desktop/Anton/build_2024_04_16/layer0.obp
        - /home/freemelt/Desktop/Anton/build_2024_04_16/BSE_Scan_PT.obp
      - - /home/freemelt/Desktop/Anton/build_2024_04_16/layer1.obp
        - /home/freemelt/Desktop/Anton/build_2024_04_16/BSE_Scan_PT.obp
      - - /home/freemelt/Desktop/Anton/build_2024_04_16/layer2.obp
        - /home/freemelt/Desktop/Anton/build_2024_04_16/BSE_Scan_PT.obp
```


(b) Input to printing sub-process.

Figure 3: Files used in the EB-PBF process.

The layers may have different layer *thicknesses*. The *rotation angle* represents the angle which a geometry is rotated. The *infill strategies* and *contour strategies* represent the methods for scanning the surface, focusing on the interior part of a layer, and the outer part of the layer, respectively. If no contour strategy is specified, then the infill strategy is also used for the outer part. The number of layers is computed from the layer thickness and the height of the `3D_Model_Build`.

In addition to the layer melting strategy, each layer needs a pre-heating and post-heating strategy. In our experiment, there is one pre-heating strategy and one post-heating strategy that is used for all layers, respectively. The different strategies contribute to the layer digital twins which are represented in *.obp* files. All these strategies are combined in *Python* by domain experts[4]. While printing, sensors in the printing machine record data that can be used to generate images from the electrons scattered off the surface which is used to monitor the printing process.

We created a KG by instantiating PBF-AMP-Onto_EB with the collected data from the experiment. Figure 4 shows part of this KG. It shows, for example, that *build_2024_04_16_Experiment* is an instance of the `PBF-AM_Process` concept in PBF-AMP-Onto_Core and has *build_2024_04_16_Experiment_SlicingProcess* and *build_2024_04_16_Experiment_PrintingProcess* as sub-processes. The *build_2024_04_16_Experiment* started on *2024-05-31T14:30:00Z* and finished on *2024-05-31T23:30:00Z*. One of the geometry layer melting strategies (*build_2024_04_16_Geometry_layer_melting_Strategy_geometry1*) has energy source *Electron-*

[4]https://github.com/wiberganton/obpcreator/tree/main

BeamEnergySource1. Moreover, *build_2024_04_16_Geometry_layer_melting_Strategy_geometry1* has *build_2024_04_16_Scan_Strategy_geometry1* as the `EB-PBF_Scan_Strategy` that has *Infill_Strategy_2* and *Contour_Strategy_2* as `EB-PBF_Infill_Scan_Strategy` and `EB-PBF_Contour_Scan_Strategy`, respectively. *Infill_Strategy_2* has a *beam power* of 660 kW, and a *beam scan speed* of 1700000 μm/s with *dwell time* 570000 ns.

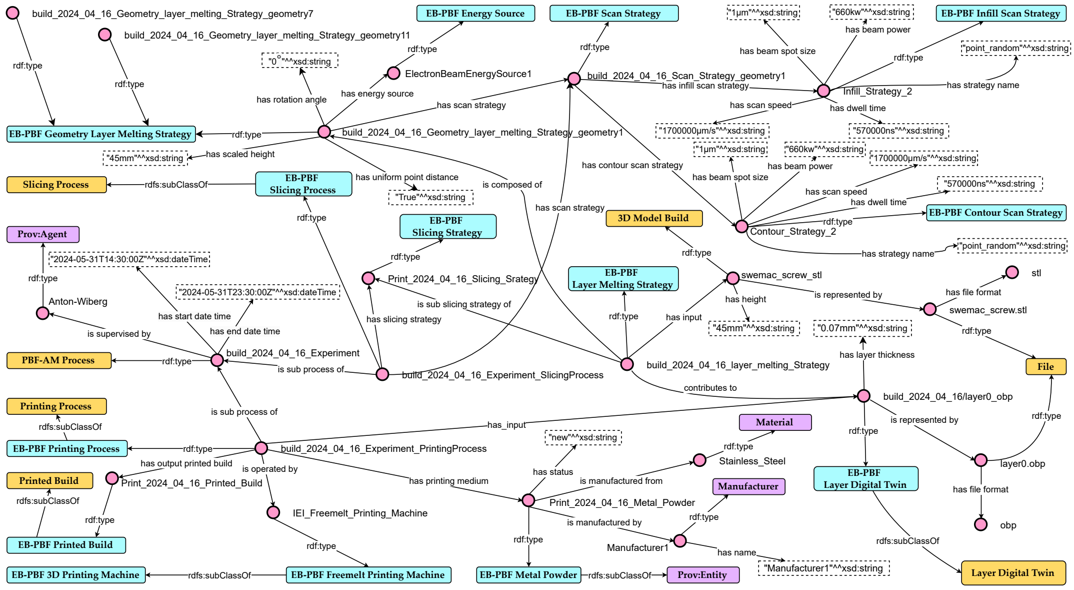


Figure 4: Part of the KG for the printing experiment.

4.2. SPARQL query examples

To show the use and the feasibility of our approach, we implemented SPARQL queries based on competency questions (see Section 3.1). To execute these queries, we used blazegraph[5] which is an ultra high-performance graph database supporting RDF/SPARQL APIs.

As examples, we show the SPARQL queries for the competency questions CQ1, CQ7, CQ8, and CQ10 in Tables 1, 2, 3, and 4 respectively. The retrieved results for each query are presented in Table 5. For example, executing the SPARQL query for CQ1 in Table 1 returns the result that the printed build in *build_2024_04_16_Experiment_PrintingProcess* has used *Stainless_Steel* as the metal powder. The result of the SPARQL query CQ7 (Table 2) indicates that the *IEI_Freemelt_Printing_Machine* is equipped with four temperature sensors (*Temp_Sensor_1* to *Temp_Sensor_4*). The SPARQL query for CQ8 (Table 3) returns that there are five layers for the EB-PBF printing process in the KG. The SPARQL query for CQ10 (Table 4) reveals the start and end date and time of *build_2024_04_16_Experiment*. We note that all CQs could be formulated using PBF-AMP-Onto_EB. Table 6 shows the concepts and relationships used for each CQ.

[5]https://github.com/blazegraph/database/releases/tag/BLAZEGRAPH_2_1_6_RC

Table 1
An example SPARQL query CQ1 (What is the material used for each printed build in an EB-PBF printing process?).

```
PREFIX pbfampocore: <http://www.semanticweb.org/minab62/ontologies/2024/4/PBF-AMP-Onto_Core#>
PREFIX pbfampoeb: <http://www.semanticweb.org/minab62/ontologies/2024/5/PBF-AMP-Onto_EB#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT ?printing_process ?printed_build ?material
WHERE {
  ?printed_build rdf:type pbfampoeb:Electron_Beam_Powder_Bed_Fusion_Printed_Build.
  ?printing_process rdf:type pbfampoeb:Electron_Beam_Powder_Bed_Fusion_Printing_Process.
  ?printing_process pbfampoeb:has_output_printed_build ?printed_build.
  ?metal_powder rdf:type pbfampoeb:Electron_Beam_Powder_Bed_Fusion_Metal_Powder.
  ?printing_process pbfampocore:has_printing_medium ?metal_powder.
  ?metal_powder pbfampoeb:is_manufactured_from ?material. }
```

Table 2
An example SPARQL query for CQ7 (What types of sensors are utilized in an EB-PBF 3D printing machine?).

```
PREFIX pbfampocore: <http://www.semanticweb.org/minab62/ontologies/2024/4/PBF-AMP-Onto_Core#>
PREFIX pbfampoeb: <http://www.semanticweb.org/minab62/ontologies/2024/5/PBF-AMP-Onto_EB#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?printing_machine ?sensor ?sensor_type
WHERE {
  ?printing_machine_subclass rdfs:subClassOf
  pbfampoeb:Electron_Beam_Powder_Bed_Fusion_3D_Printing_Machine.
  ?printing_machine rdf:type ?printing_machine_subclass.
  ?printing_machine pbfampoeb:has_sensor ?sensor.
  ?sensor pbfampoeb:has_sensor_type ?sensor_type. }
```

5. Conclusion

In this paper we developed a modular ontology for PBF with a specialized module for EB-PBF. We showed the use of the ontology for describing and querying information on EB-PBF processes.

In the future we will propose a standardized way to (store and) integrate information from different sources regarding PBF processes to enable semantic and integrated access to these different sources based on our ontology. We will take inspiration from our previous work on integrating materials computation databases [17, 18]. This will be the basis for advanced design and analysis tools that guide the design and provide quality assurance of AM products.

Another important task will be to align our ontology with other ontologies. For instance, we will investigate the connection between our process concept and PMDco's [7] process concept, and our material concept with, e.g., the material concept in EMMO (Elementary Multiperspective Material Ontology)[6]. In [10] several attributes are defined that can be connected to our ontology.

[6] https://github.com/emmo-repo/EMMO

Table 3
An example SPARQL query for CQ8 (What is the total number of layers used in an EB-PBF printing process?).

```
PREFIX pbfampocore: <http://www.semanticweb.org/minab62/ontologies/2024/4/PBF-AMP-Onto_Core#>
PREFIX pbfampoeb: <http://www.semanticweb.org/minab62/ontologies/2024/5/PBF-AMP-Onto_EB#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT ?printing_process  (COUNT(?layer_digital_twin) AS ?numberofLayers)
WHERE {
   ?printing_process rdf:type pbfampoeb:Electron_Beam_Powder_Bed_Fusion_Printing_Process.
   ?printing_process pbfampocore:has_input ?layer_digital_twin.
   ?layer_melting_strategy rdf:type
        pbfampoeb:Electron_Beam_Powder_Bed_Fusion_Layer_Melting_Strategy.
   ?layer_melting_strategy pbfampoeb:contributes_to ?layer_digital_twin. }
GROUP BY ?printing_process
```

Table 4
An example SPARQL query for CQ10 (What is the start and end date and time for an PBF-AM process?).

```
PREFIX pbfampocore: <http://www.semanticweb.org/minab62/ontologies/2024/4/PBF-AMP-Onto_Core#>
PREFIX pbfampoeb: <http://www.semanticweb.org/minab62/ontologies/2024/5/PBF-AMP-Onto_EB#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT ?process ?startTime ?endTime
WHERE {
   ?process rdf:type pbfampocore:Powder_Bed_Fusion_Additive_Manufacturing_Process.
   ?process pbfampocore:has_start_date_time ?startTime.
   ?process pbfampocore:has_end_date_time ?endTime. }
```

For this alignment, we will need to investigate possible ontological commitments. We will also reuse an ontologies for quantities.

Further, we will investigate other AM processes and extend the ontology with new modules accordingly.

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Table 5
Results of the SPARQL queries for CQ1, CQ7, CQ8, and CQ10 presented in Tables 1, 2, 3, and 4.

CQ — **Result of the SPARQL query**

CQ1

printing_process	printed_build	material
pbfampoeb:build_2024_04_16_Experiment_PrintingProcess	pbfampoeb:Print_2024_04_16_Printed_Build	pbfampoeb:Stainless_Steel

CQ7

printing_machine	sensor	sensor_type
pbfampoeb:IEI_Freemelt_Printing_Machine	pbfampoeb:Temp_Sensor_1	Temperature
pbfampoeb:IEI_Freemelt_Printing_Machine	pbfampoeb:Temp_Sensor_2	Temperature
pbfampoeb:IEI_Freemelt_Printing_Machine	pbfampoeb:Temp_Sensor_3	Temperature
pbfampoeb:IEI_Freemelt_Printing_Machine	pbfampoeb:Temp_Sensor_4	Temperature

CQ8

printing_process	numberofLayers
pbfampoeb:build_2024_04_16_Experiment_PrintingProcess	5

CQ10

process	startTime	endTime
pbfampoeb #build_2024_04_16_Experiment>	2024-05-31T14:30:00.000Z	2024-05-31T23:30:00.000Z

Table 6
Coverage of concepts and relationships in CQs from Section 3.1.

CQ	Relevant Concepts	Relevant Relationships
CQ1	EB_PBF_Printed_Build, EB_PBF_Printing_Process, EB_PBF_Metal_Powder,Material	has_output_printed_build, has_printing_medium, is_manufactured_from
CQ2	EB_PBF_Printing_Process, EB_PBF_Metal_Powder, Manufacturer	has_printing_medium, is_manufactured_by
CQ3	PBF_AM_Process	is_sub_process_of
CQ4	PBF_AM_Process	is_sub_process_of, has_input,has_output, has_input_printed_build, has_output_printed_build
CQ5	EB_PBF_Slicing_Process, EB_PBF_Slicing_Strategy, EB_PBF_Layer_Melting_Strategy, EB_PBF_Infill_Scan_Strategy, EB_PBF_Contour_Scan_Strategy, EB_PBF_Energy_Source	has_slicing_strategy, is_sub_slicing_strategy_of, contributes_to, has_layer_thickness, has_scan_strategy, has_infill_scan_strategy, has_contour_scan_strategy, has_energy_source
CQ6	EB_PBF_3D_Printing_Machine, EB_PBF_Printing_Process	is_operated_by
CQ7	EB_PBF_3D_Printing_Machine,EB_PBF_3D_Printing_Machine_Sensor	rdfs:subClassOf, has_sensor, has_sensor_type
CQ8	EB_PBF_Printing_Process, EB_PBF_Layer_Digital_Twin, EB_PBF_Layer_Melting_Strategy	has_input,contributes_to
CQ9	EB_PBF_Printing_Process, EB_PBF_Layer_Digital_Twin	has_input,contributes_to, has_layer_thickness
CQ10	EB_PBF_Process	has_start_date_time, has_end_date_time
CQ11	EB_PBF_Printing_Process, EB_PBF_Slicing_Process, EB_PBF_Process,EB_PBF_Scan_Strategy, EB_PBF_Infill_Scan_Strategy, EB_PBF_Contour_Scan_Strategy	is_sub_process_of, has_scan_strategy, has_infill_scan_strategy, has_contour_scan_strategy, has_beam_power

References

[1] S. Ford, M. Despeisse, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, Journal of Cleaner Production 137 (2016) 1573–1587. doi:10.1016/j.jclepro.2016.04.150.

[2] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Nguyen, D. Hui, Additive manufacturing (3d printing): A review of materials, methods, applications and challenges, Composites Part B: Engineering 143 (2018) 172–196. doi:10.1016/j.compositesb.2018.02.012.

[3] D. D. Singh, T. Mahender, A. R. Reddy, Powder bed fusion process: A brief review, Materials Today: Proceedings 46 (2021) 350–355. doi:10.1016/j.matpr.2020.08.415.

[4] Y. Qin, Q. Qi, P. J. Scott, X. Jiang, Status, comparison, and future of the representations of additive manufacturing data, Computer-Aided Design 111 (2019) 44–64. doi:10.1016/j.cad.2019.02.004.

[5] D. B. Kim, P. Witherell, Y. Lu, S. Feng, Toward a digital thread and data package for metals-additive manufacturing, Smart and sustainable manufacturing systems 1 (2017) 75–99. doi:10.1520/SSMS20160003.

[6] A. Wiberg, J. A. Persson, J. Ölvander, A design automation framework supporting design for additive manufacturing, in: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, volume 87295, American Society of Mechanical Engineers, 2023, p. V002T02A083. doi:10.1115/DETC2023-116415.

[7] B. Bayerlein, M. Schilling, H. Birkholz, M. Jung, J. Waitelonis, L. Mädler, H. Sack, PMD Core Ontology: Achieving semantic interoperability in materials science, Materials & Design 237 (2024) 112603. doi:10.1016/j.matdes.2023.112603.

[8] M. D. Wilkinson, M. Dumontier, I. J. Aalbersberg, G. Appleton, M. Axton, A. Baak, N. Blomberg, J.-W. Boiten, L. B. da Silva Santos, P. E. Bourne, J. Bouwman, A. J. Brookes, T. Clark, M. Crosas, I. Dillo, O. Dumon, S. Edmunds, C. T. Evelo, R. Finkers, A. Gonzalez-Beltran, A. J. Gray, P. Groth, C. Goble, J. S. Grethe, J. Heringa, P. A. 't Hoen, R. Hooft, T. Kuhn, R. Kok, J. Kok, S. J. Lusher, M. E. Martone, A. Mons, A. L. Packer, B. Persson, P. Rocca-Serra, M. Roos, R. van Schaik, S.-A. Sansone, E. Schultes, T. Sengstag, T. Slater, G. Strawn, M. A. Swertz, M. Thompson, J. van der Lei, E. van Mulligen, J. Velterop, A. Waagmeester, P. Wittenburg, K. Wolstencroft, J. Zhao, B. Mons, The FAIR Guiding Principles for scientific data management and stewardship, Scientific Data 3 (2016) 160018:1–9. doi:10.1038/sdata.2016.18.

[9] P. Lambrix, R. Armiento, A. Delin, H. Li, FAIR Big Data in the Materials Design Domain, in: A. Y. Zomaya, J. Taheri, S. Sakr (Eds.), Encyclopedia of Big Data Technologies, Springer, Cham, 2022. doi:10.1007/978-3-319-63962-8_293-2.

[10] E. M. Sanfilippo, F. Belkadi, A. Bernard, Ontology-based knowledge representation for additive manufacturing, Computers in Industry 109 (2019) 182–194. doi:10.1016/j.compind.2019.03.006.

[11] B.-M. Roh, S. R. Kumara, P. Witherell, T. W. Simpson, Ontology-based process map for metal additive manufacturing, Journal of Materials Engineering and Performance 30 (2021) 8784–8797. doi:10.1007/s11665-021-06274-2.

[12] T. J. Hagedorn, S. Krishnamurty, I. R. Grosse, A knowledge-based method for innovative design for additive manufacturing supported by modular ontologies, Journal of Computing

and Information Science in Engineering 18 (2018) 021009. doi:10.1115/1.4039455.
[13] M. Dinar, D. W. Rosen, A design for additive manufacturing ontology, Journal of Computing and Information Science in Engineering 17 (2017) 021013. doi:10.1115/1.4035787.
[14] P. Lambrix, Part-Whole Reasoning in an Object-Centered Framework, volume 1771 of *Lecture Notes in Computer Science*, Springer, 2000. doi:10.1007/3-540-46440-9.
[15] S. Kim, D. W. Rosen, P. Witherell, H. Ko, A design for additive manufacturing ontology to support manufacturability analysis, Journal of Computing and Information Science in Engineering 19 (2019) 041014. doi:10.1115/1.4043531.
[16] M. C. Suárez-Figueroa, A. Gómez-Pérez, M. Fernández-López, The NeOn Methodology for Ontology Engineering, in: Ontology engineering in a networked world, Springer, 2011, pp. 9–34. doi:10.1007/978-3-642-24794-1_2.
[17] H. Li, R. Armiento, P. Lambrix, An Ontology for the Materials Design Domain, in: The Semantic Web - ISWC 2020 - 19th International Semantic Web Conference, Athens, Greece, November 2-6, 2020, Proceedings, Part II, volume 12507 of *Lecture Notes in Computer Science*, Springer, Athens, Greece, 2020, pp. 212–227. doi:10.1007/978-3-030-62466-8_14.
[18] P. Lambrix, R. Armiento, H. Li, O. Hartig, M. Abd Nikooie Pour, Y. Li, The materials design ontology, Semantic Web 15 (2024) 481–515. doi:10.3233/SW-233340.