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Ontology-based knowledge representation for wire arc additive manufacturing and composite extrusion modeling

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ABSTRACT:
Knowledge representation in additive manufacturing (AM) is essential for data management, enabling semantic interoperability and decision-making. Wire arc additive manufacturing (WAAM) and composite extrusion modeling (CEM) are advanced manufacturing methods employed within metal-based additive manufacturing. Although knowledge representation in AM has been widely explored, there is a notable gap in research addressing knowledge representation tailored to WAAM and CEM. Aiming to advance knowledge representation for WAAM and CEM, this paper proposes an ontology-based knowledge representation approach. Two ontologies, the Wire Arc Additive Manufacturing Application Ontology (WAAMAO) and the Composite Extrusion Modeling Application Ontology (CEMAO), are proposed, following a well-known ontology engineering methodology to ensure a rigorous and systematic ontology design process. To validate the proposed approach, a manufacturing information system utilizing both ontologies is presented. The findings highlight the capability of WAAMAO and CEMAO in knowledge representation, enabling efficient data management and supporting semantic interoperability in metal-based AM processes.

KEYWORDS:
Additive manufacturing, metal-based additive manufacturing, wire arc additive manufacturing, composite extrusion modelling, ontology

1. INTRODUCTION

Additive manufacturing (AM) is a fabrication technique leveraging raw materials, product design, and specialized AM methods (Ford, et al., 2016). One branch of AM, metal-based additive manufacturing (MAM), specializes in metal products. Metal-based additive manufacturing involves various AM methods, such as wire arc additive manufacturing (WAAM) (Wu, et al., 2018), composite extrusion modeling (CEM) (Altıparmak, et al., 2022), and powder bed fusion (PBF) (Singh, et al., 2020). Additive manufacturing processes, including MAM processes, utilize and generate heterogeneous data, including 3D models processed by slicing software tools, descriptions of

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manufacturing process as well as various process parameters (Peralta, et al., 2022).

Knowledge representation in AM is critical for data management, enabling semantic interoperability and informed decision-making (Peralta, et al., 2020), and the significance continues to grow with the increasing prevalence of digital twinning (Smarsly, et al., 2024). A prominent approach towards knowledge representation is based on ontologies that enhances data integration and semantic interoperability by utilizing formal logic. Ontologies are collections of concepts and relationships, organizing and formalizing knowledge; for a formal definition of ontologies, the interested reader is referred to Rudolph (2011). Using ontologies, knowledge is represented in the form of Resource Description Framework (RDF) triples (RDF Working Group, 2012), enabling data processing and querying through the SPARQL Protocol and RDF Query Language (SPARQL) (SPARQL Working Group, 2013).

Several ontologies have been proposed in the context of AM. For instance, the Printing Information Modeling Ontology (PIM-O) has been presented by Peralta, et al. (2023), facilitating additive manufacturing of concrete structures, while being adaptable to additive manufacturing of metals. Furthermore, in Bayerlein, et al. (2024), the ontology Platform Material Digital Core Ontology (PMDco) is presented. As an extension of the Provenance Ontology (PROV-O) (Provenance Working Group, 2013), the ontology PMDco serves as a mid-level ontology bridging semantic gaps between materials science and other domains, achieving cross-domain interoperability as well as enabling the representation of processes and process chains in a material-science-specific manner. In Roh, et al. (2021), the Additive Manufacturing Ontology (AMOntology) is introduced. The AMOntology is specialized for metal-based PBF, providing terminology for describing AM processes as well as laser, thermal, microstructure and mechanical properties. In Abd Nikooie Pour, et al. (2024), the ontology Powder Bed Fusion Additive Manufacturing Process Ontology (PBF-AMP-Onto) is introduced, which is a modular ontology specialized for Electron Beam Powder Bed Fusion (EB-PBF). In Kim, et al. (2019) and in Wang, et al. (2024), the Design for Additive Manufacturing Ontology (DFAM ontology) and the Eco-Design for Additive Manufacturing Ontology (EcoDfAM ontology) are presented, respectively. Both ontologies emphasize knowledge representation for design stages preceding AM processes.

Although knowledge representation in AM has been widely explored, there is a notable gap in research addressing knowledge representation tailored to WAAM and CEM. Furthermore, knowledge representation in AM is challenging owing to the lack of metadata as well as ambiguity and inconsistencies in the terminologies, hindering semantic interoperability and data reuse. Aiming to address the gap and to advance knowledge representation tailored to WAAM and CEM, this paper proposes an ontology-based knowledge representation approach, comprising two ontologies: The Wire Arc Additive Manufacturing Application Ontology (WAAMAO) and the Composite Extrusion Modeling Application Ontology (CEMAO) are developed, following a well-known ontology engineering methodology.

The remainder of the paper is structured as follows. First, the ontologies WAAMAO and CEMAO are introduced. Next, a manufacturing information system, incorporating both ontologies, is presented for validation purposes, emphasizing the role of WAAMAO and CEMAO in facilitating knowledge representation and data management in WAAM and CEM. Finally, concluding remarks and an outlook on future work are provided.

2. THE ONTOLOGIES WAAMAO AND CEMAO

As a key contribution of this paper, the ontologies WAAMAO and CEMAO are presented in this section. The section begins with an overview of the ontology design process employed herein, followed by a description of each ontology.

2.1 Ontology design process

To develop the ontologies WAAMAO and CEMAO, the NeOn methodology for ontology engineering is employed, to ensure a rigorous and systematic ontology design (López, 2011). The ontology design process, shown in Figure 1, involves five steps, (i) ***scope definition***, in which clear boundaries and objectives for both ontologies are established, based on the competency questions shown in Table 1, (ii) ***taxonomy definition***, in which terms are specified and structured in a hierarchical manner, (iii) ***ontology development***, in which the ontologies are implemented utilizing the Web Ontology Language (OWL) (OWL Working Group, 2012) and the ontology editor Protégé (Stanford University, 2011), (iv) ***ontology validation***, in which the ontologies are verified and validated to ensure the absence of design flaws as well as capability to answer the competency questions effectively, and (v) ***documentation***, in which a usage guideline is provided to help researchers understand and use the ontologies. As a result of the ontology design process, the ontologies WAAMAO and CEMAO are established, as introduced in the following subsections.

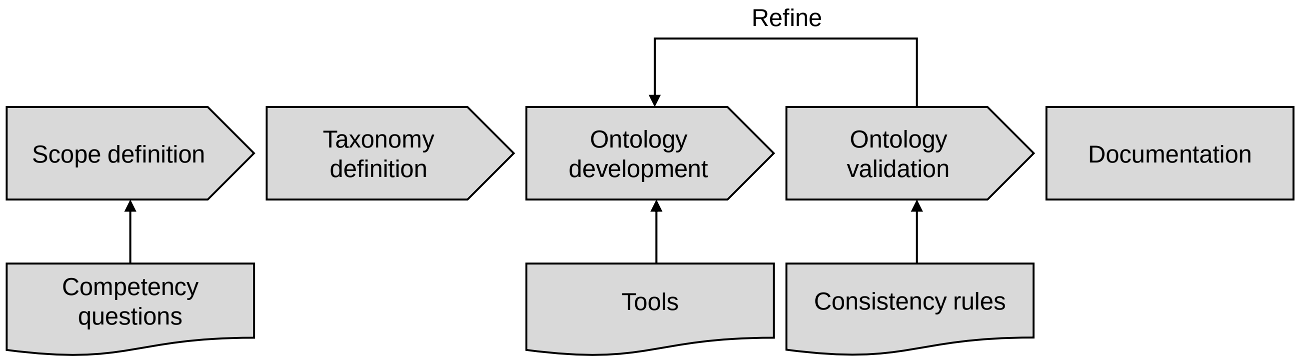

Figure 1: Ontology design process

Table 1: List of competency questions.

ID	Competency questions for WAAM and CEM
CQ1	What type of machine is employed for manufacturing?
CQ2	What are the inputs and outputs during the manufacturing process?
CQ3	What are the sub-processes of the manufacturing process?
CQ4	What is the welding mode used for manufacturing?
CQ5	What are the measurements of the *temperature* and *specific heat capacity* of a particular artifact manufactured by a WAAM process, as determined by a dynamic scanning calorimetry test?

2.2 Wire Arc Additive Manufacturing Application Ontology (WAAMAO)

The ontology WAAMAO provides classes describing manufacturing processes, machines, and parameters within WAAM. The ontology WAAMAO builds upon higher-level ontologies, including the Fraunhofer IGCV AM Application Ontology (AMAO) (Bjarsch, 2024), the Fraunhofer IGCV Manufacturing Application Ontology (MAO) (Bjarsch, 2024), the Common Core Ontologies (CCO) (Jensen, et al., 2022), and the Basic Formal Ontology (BFO) (ISO/IEC 21838-2:2021), enriching the ontologies with classes specialized for WAAM. Figure 2 shows the main classes of the ontology WAAMAO (in green color) as well as the classes relevant to manufacturing processes included from the higher-level ontologies, as presented in the following paragraphs.

Figure 2 is arranged into two parts, the terminological box (T-Box, top part of the figure) and the assertional box (A-Box, bottom part of the figure). The T-Box is devoted to present the main classes of the ontology WAAMAO, while the A-Box illustrates an example instantiation. For clarity, the T-Box is intentionally simplified to include the main classes of the ontology WAAMAO. The ontology WAAMAO comprises a total of 40 classes, each being subclass of the top-class (“*owl:Thing*”). Subclass relationships are expressed via the relation (“*rdfs:subClassOf*”).

Processes in WAAM are modeled utilizing the class (“*waamao:WireArcAdditiveManufacturing*”), which is a subclass of the class (“*bfo:Process*”), inheriting several properties, such as decomposability, into subprocesses, as well as attributes for duration, start time, and end time. To model manufacturing machines, the class (“*waamao:WireArcAdditiveManufacturingMachine*”) is utilized. The WAAM processes are linked to manufacturing machines via the relation (“*cco:has_participant*”). In addition, WAAM processes may have various inputs, such as welding modes, and outputs, such as 3D-printed metal products. The inputs represent parameters of WAAM processes and are modelled utilizing the “*waamao:ActOfWireArcAdditiveManufacturingProcessParameter*” class. The WAAM processes are linked to process parameters via the relations (“*cco:has_input*”) and (“*cco:has_output*”). Finally, as mentioned above, the A-Box demonstrates an instantiation of the ontology WAAMAO. The instances, or “individuals”, are linked to the corresponding classes via the property (“*rdf:type*”). The A-Box describes a particular manufacturing process (“*ex:manufacturing_1*”), which utilizes a manufacturing machine (“*ex:machine_1*”), operates in a welding mode (“*pulsed-AC*”), and is initiated with a starting current of 100 A.

As a result, the ontology WAAMAO provides classes describing manufacturing processes, machines, and parameters for WAAM. To facilitate knowledge representation in CEM, the following subsection introduces the ontology CEMAO.

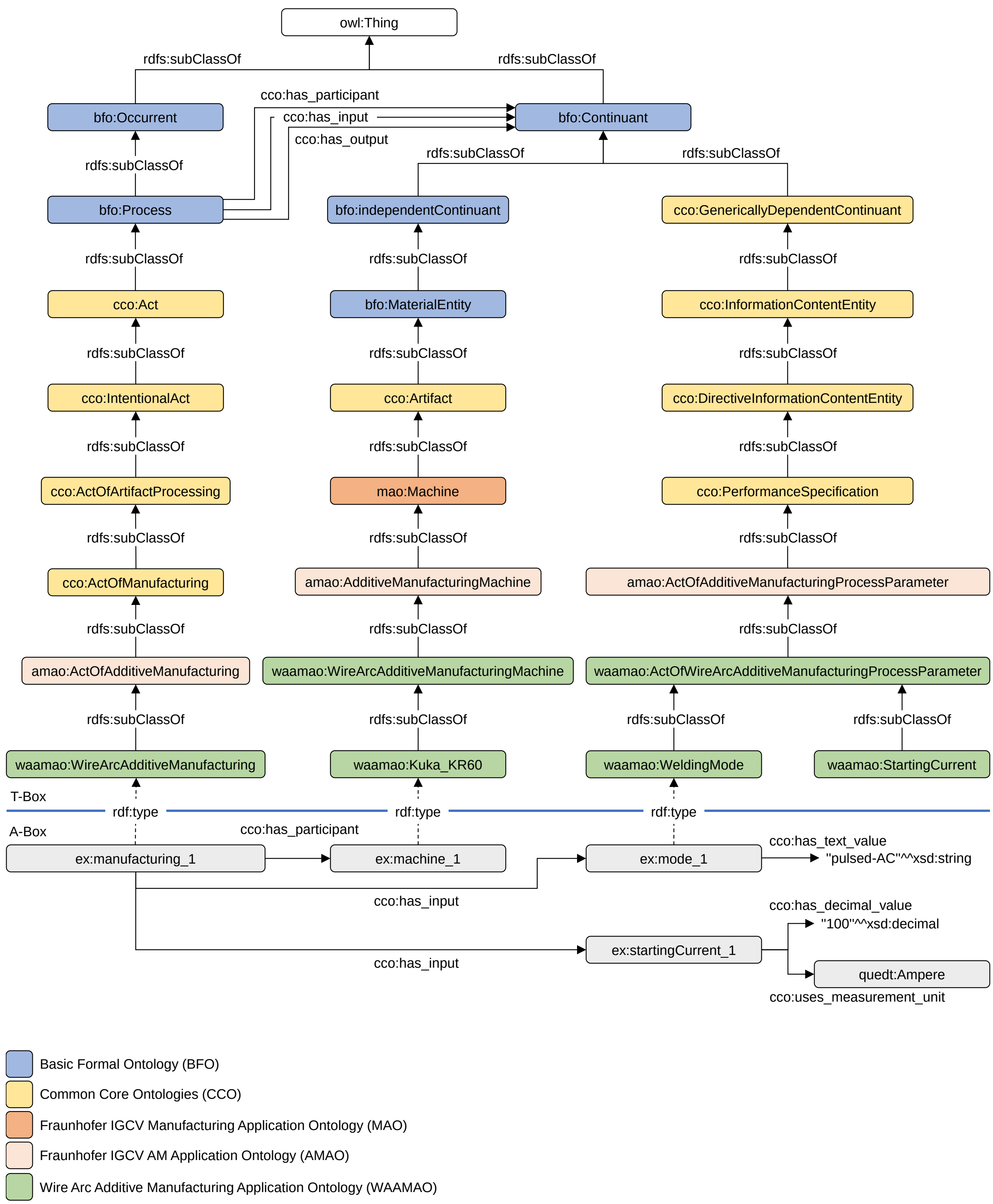

Figure 2: Main classes and relationships of the ontology WAAMAO (in green color).

2.3 Composite Extrusion Modeling Application Ontology (CEMAO)

The ontology CEMAO provides classes describing manufacturing processes, machines, and parameters for CEM. Analogous to WAAMAO, CEMAO builds upon the same higher-level ontologies, i.e., AMAO, MAO, CCO, and BFO.

Figure 3 presents the main classes of CEMAO, denoted with turquoise color. CEMAO comprises a total of 39 classes dedicated to represent CEM processes, CEM machines, and process parameters (e.g., extrusion speed and nozzle diameter). The A-Box demonstrates an instantiation of the ontology CEMAO, representing a particular manufacturing process, ("*ex:manufacturing_2*"), which utilizes a manufacturing machine, ("*ex:machine_2*"), at an extrusion speed of 20.75 mm/s, and a nozzle diameter of 3.15 mm.

To validate the ontology-based knowledge representation approach, the following section presents the manufacturing information system utilizing the ontologies WAAMAO and CEMAO.

3. MANUFACTURING INFORMATION SYSTEM

To validate the proposed approach, the manufacturing information system, incorporating the ontologies WAAMAO and CEMAO, is developed. As shown in Figure 4, the system comprises three major components, (i) a frontend, (ii) a backend, and (iii) an ontology-based database. The ***frontend***, or client side, is responsible for handling user interactions and data visualization. The ***backend***, or server side, hosts business logic and manages communication between the frontend and the ontology-based database. The ***ontology-based database*** stores, organizes, and retrieves AM data related to WAAM and CEM. The AM data is represented as instances of the ontologies WAAMAO and CEMAO. The frontend, the backend, and the ontology-based database are implemented utilizing the web application framework Angular

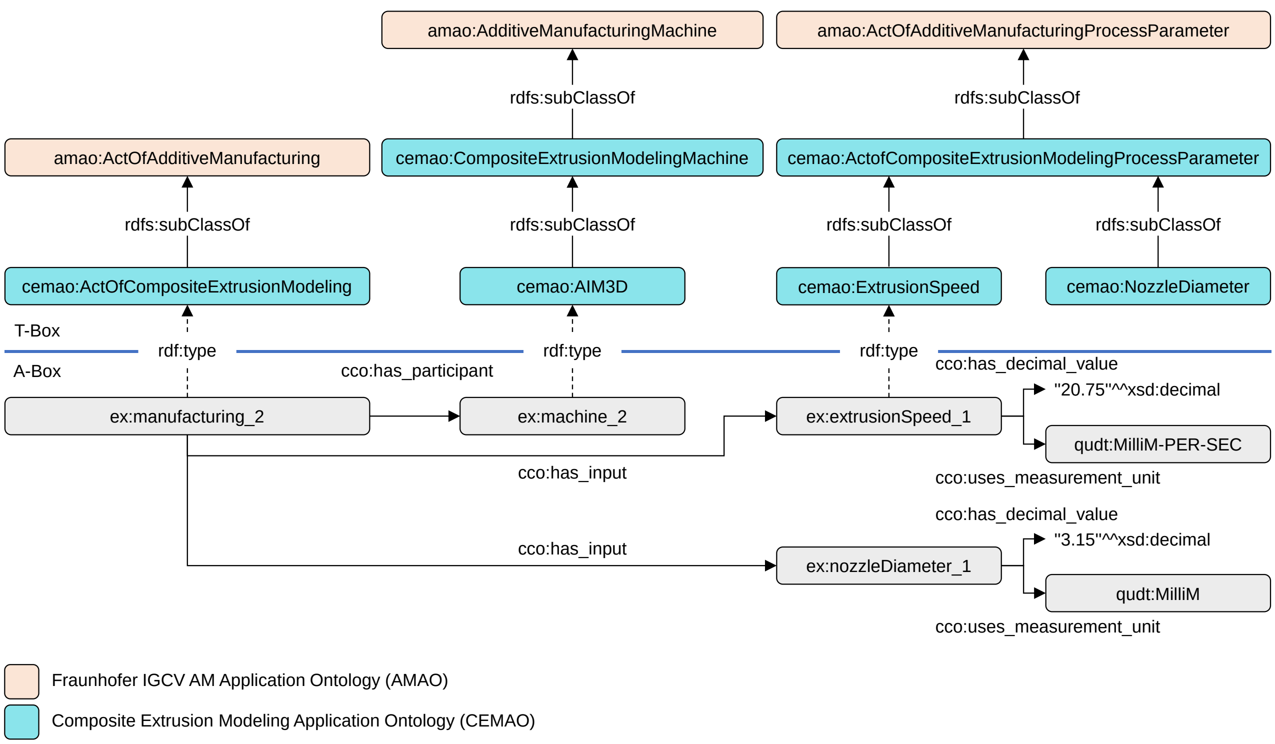

Figure 3: Main classes and relationships of the ontology CEMAO (in turquoise color).

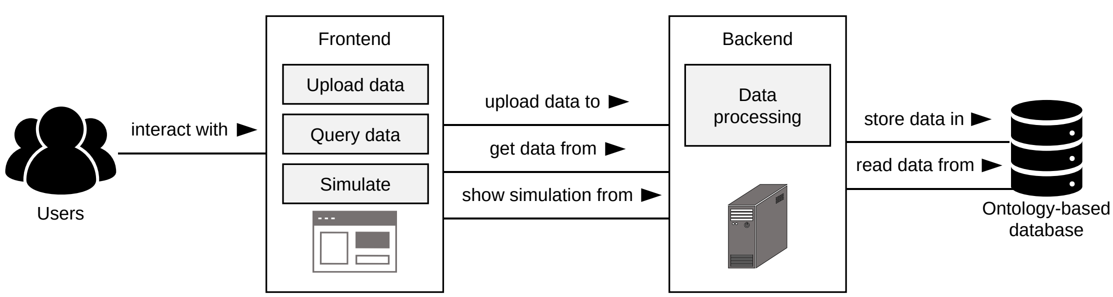

Figure 4: System architecture.

(Angular, 2024), the framework Flask (Pallets, 2024), and the database management system GraphDB (Ontotext, 2024), respectively.

For the validation, data is used, obtained from an experiment involving the manufacturing and testing of a wall structure with a specific parameter set. In the experiment, an industrial robot, type Kuka KR 150-2, in combination with a welding system, type Fronius CMT Advanced 4000, are employed for welding, and a differential scanning calorimeter, type NETZSCH DSC 204 F1 Phoenix, is employed for testing. The data, encompassing manufacturing data as well as testing data, is obtained from the experiment in two Excel files. The manufacturing data is manually inserted into an Excel file, while the testing data is obtained from the testing machine.

The validation procedure is twofold: First, the data is mapped to the ontology WAAMAO as well as to higher-level ontologies (including the ontology MAO) utilizing a Python script. Second, a SPARQL query is performed to validate the ability to query the data. For data mapping, instances are created using the Python script. Thereby, the instances are assigned to classes in accordance with the ontologies WAAMAO and MAO and interlinked with each other (Figure 5).

As shown in Figure 5, the WAAM process ("*ex:manufacturing_1*") is applied to fabricate a wall structure ("*ex:artifact_1*"), utilizing (a) the manufacturing machine ("*ex:machine_1*"), which represents the Kuka robot, and (b) a printing job ("*ex:printing_job_1*"), as inputs. The output of the WAAM process ("*ex:manufacturing_1*") is the wall structure ("*ex:artifact_1*"), which, in turn, is used as an input to the dynamic-scanning-calorimetry test ("*ex:testing_1*"). Furthermore, data describing the temperature dependency of specific-heat-capacity is linked as outputs to the test ("*ex:testing_1*").

As for the SPARQL query, Listing 1 shows the query corresponding to the competency question CQ5 (*What are the measurements of the temperature and specific heat capacity of a particular artifact manufactured by a WAAM process, as determined by a dynamic scanning calorimetry test*). The query is executed through the manufacturing information system. The results obtained from the query are illustrated in Figure 6, indicating the temperature dependency of specific heat capacity. The results highlight the capability of the ontology WAAMAO to address CQ5, emphasizing ability to query the data as well as knowledge representation for WAAM.

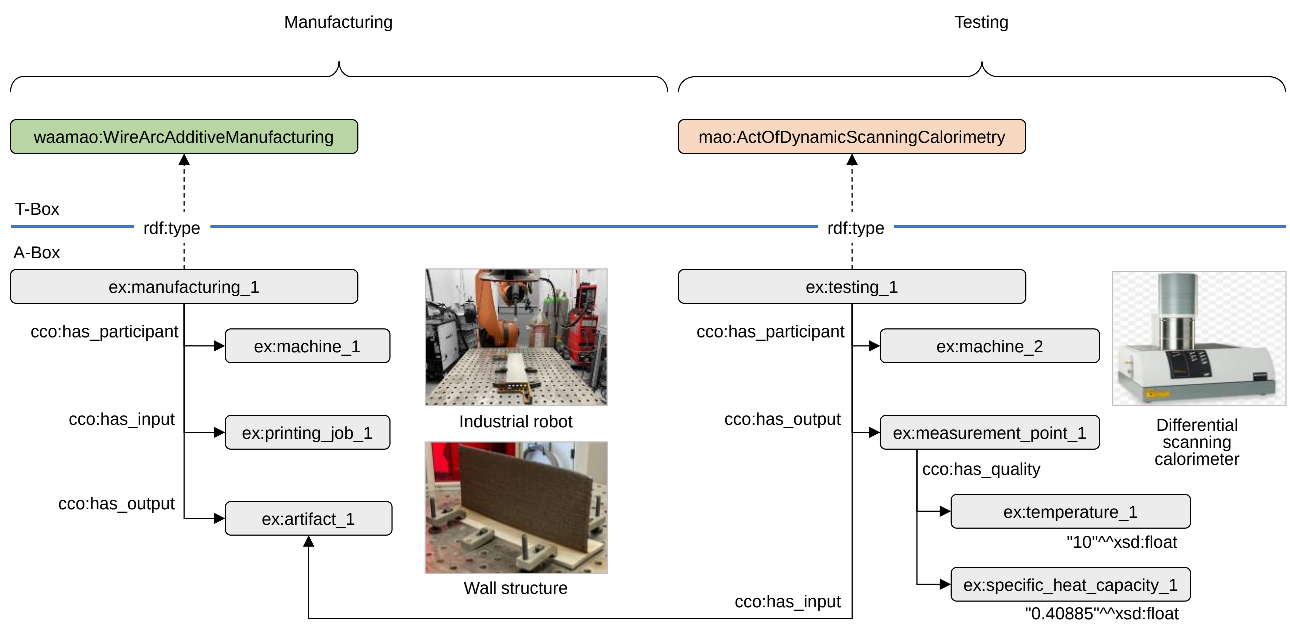

Figure 5: Schematic representation of a process chain for manufacturing and testing a wall structure.

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PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX bfo: <http://purl.obolibrary.org/obo/bfoowl#>
PREFIX cco: <http://www.ontologyrepository.com/CommonCoreOntologies/>
PREFIX mao: <https://w3id.org/ODE_AM/MAO/>
PREFIX waamao: <https://w3id.org/ODE_AM/WAAMAO/>

SELECT ?temperature_value ?specific_heat_capacity_value
WHERE {
  ?manufacturing_process rdf:type waamao:WireArcAdditiveManufacturing .
  ?manufacturing_process cco:has_output ?artifact .
  ?testing_process  rdf:type mao:ActOfDynamicScanningCalorimetry .
  ?testing_process  cco:has_input ?artifact .
  ?testing_process  cco:has_output ?measurement_point .
  ?measurement_point bfo:has_quality ?temperature.
  ?temperature rdf:type cco:Temperature.
  ?temperature cco:has_decimal_value ?temperature_value.
  ?measurement_point bfo:has_quality ?specific_heat_capacity.
  ?specific_heat_capacity rdf:type mao:SpecificHeatCapacity.
  ?specific_heat_capacity cco:has_decimal_value ?specific_heat_capacity_value.
  ?artifact cco:has_text_value ?artifact_name .
  FILTER(?artifact_name = "artifact_1")
}

ORDER BY ?temperature_value
```

Listing 1: SPARQL query for competency question CQ5.

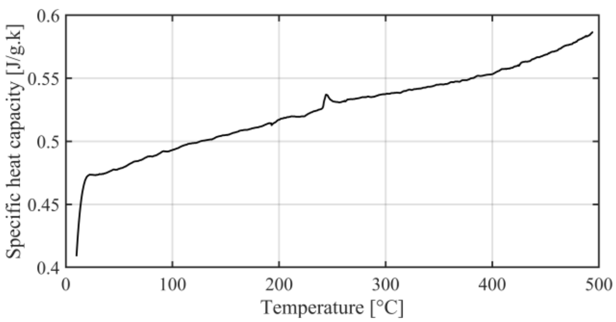

Figure 6: Illustration of the results of the SPARQL query for CQ5, depicting the specific heat capacity as a function of the temperature.

4. SUMMARY AND CONCLUSIONS

Wire arc additive manufacturing and composite extrusion modeling are key manufacturing methods in metal-based additive manufacturing. However, despite the considerable progress made in knowledge representation in additive manufacturing, there is a notable lack of research on knowledge representation tailored to WAAM and CEM. Furthermore, knowledge representation in AM faces inherent challenges owing to ambiguity and inconsistency in the terminology. Aiming to the address the aforementioned challenges, an ontology-based knowledge representation approach has been proposed in this paper. Representing integral cornerstones of the proposed approach, two ontologies have been developed, the Wire Arc Additive Manufacturing Application Ontology (WAAMAO) for WAAM as well as the Composite Extrusion Modeling Application Ontology (CEMAO) for CEM. As has been shown in this paper, the ontologies provide specialized terminology for WAAM and CEM, facilitating the transformation of manufacturing data into an ontology-based, machine-processable format. Moreover, for validation purposes, a manufacturing information system utilizing both ontologies has been developed to facilitate knowledge representation and data management in metal-based additive manufacturing. Future work may be conducted towards developing a framework for digital twins in additive manufacturing, leveraging WAAMAO and CEMAO to enable monitoring and control of AM processes in real time. In addition, future research may be conducted towards an ontology for sustainable additive manufacturing methods, such as clay-based AM, promoting semantic interoperability across diverse AM branches.

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List of acronyms

AMOntology	Additive Manufacturing Ontology
A-Box	Assertional box
AM	Additive manufacturing
AMAO	Fraunhofer IGCV AM Application Ontology
BFO	Basic Formal Ontology
CEM	Composite extrusion modeling
CEMAO	Composite Extrusion Modeling Application Ontology
CCO	Common Core Ontologies
DFAM	Design for Additive Manufacturing
EB-PBF	Electron beam powder bed fusion
EcoDfAM	Eco-Design for Additive Manufacturing
MAO	Fraunhofer IGCV Manufacturing Application Ontology
MAM	Metal-based additive manufacturing
OWL	Web Ontology Language
PBF	Powder bed fusion
PBF-AMP-Onto	Powder Bed Fusion Additive Manufacturing Process Ontology
PMD	Platform MaterialDigital
PMDco	Platform Material Digital Core Ontology
PROV-O	PROV Ontology
QUDT	Quantities, Units, Dimensions and Types
RDF	Resource Description Framework
SPARQL	SPARQL Protocol and RDF Query Language
T-Box	Terminological box
WAAM	Wire arc additive manufacturing

List of ontology prefixes

amao	https://w3id.org/ODE_AM/AMAO/
bfo	http://purl.obolibrary.org/obo/
cco	https://github.com/CommonCoreOntology/CommonCoreOntologies
cemao	https://w3id.org/ODE_AM/CEMAO/
ex	https://example.org/
mao	https://w3id.org/ODE_AM/MAO/
owl	http://www.w3.org/2002/07/owl#
rdf	http://www.w3.org/1999/02/22-rdf-syntax-ns#
rdfs	http://www.w3.org/2000/01/rdf-schema#
qudt	http://qudt.org/schema/qudt/
waamao	https://w3id.org/ODE_AM/WAAMAO/

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