

A Product Life Cycle Ontology for Additive Manufacturing

Munira Mohd Ali^{a,*}, Rahul Rai^a, J. Neil Otte^b, Barry Smith^b

^a*Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Buffalo, NY, USA*

^b*National Center for Ontological Research, State University of New York at Buffalo, Buffalo, NY, USA*

Abstract

The manufacturing industry is evolving rapidly, becoming more complex, more interconnected, and more geographically distributed. Competitive pressure and diversity of consumer demand are driving manufacturing companies to rely more and more on improved knowledge management practices. As a result, multiple software systems are being created to support the integration of data across the product life cycle. Unfortunately, these systems manifest a low degree of interoperability, and this creates problems, for instance when different enterprises or different branches of an enterprise interact. Common ontologies (consensus-based controlled vocabularies) have proved themselves in various domains as a valuable tool for solving such problems. In this paper, we present a consensus-based Additive Manufacturing Ontology (AMO) and illustrate its application in promoting re-usability in the field of dentistry product manufacturing.

Keywords: additive manufacturing ontology, manufacturing process ontology, ontology engineering, product life cycle, dentistry product manufacturing

^{*}Preprint version of article published in *Journal of Computers in Industry*, Volume 105, February 2019, Pages 191-203. (<https://doi.org/10.1016/j.compind.2018.12.007>) .

^{**}Only to be used for personal use, copyright belongs to the authors and Elsevier Science.

^{*}Corresponding author

Email addresses: munirabi@buffalo.edu (Munira Mohd Ali), rahulrai@buffalo.edu (Rahul Rai), jeffotte@buffalo.edu (J. Neil Otte), phismith@buffalo.edu (Barry Smith)

1. Introduction

The economic model of the manufacturing industry is increasingly based on the modularization of industrial processes and digitally mediated collaboration between modules both internally, within the enterprise, and externally, through subcontracting and off-shoring. The sharing of information is crucial for facilitating such collaboration across all phases in the life of a product from development and design, through production and sale, to use and disposal [1, 2, 3]. As industrial processes come to be further modularized and distributed throughout the entirety of the manufacturing pipeline, more powerful and more intelligent software solutions are required to support the different components and phases of the product life cycle (PLC).

The Economist Intelligence Unit [4] reports that the need for knowledge representation of manufacturing processes is increasing exponentially as technology expedites the rapid exchange of information. In information science, an ontology is a controlled vocabulary implemented in a semantic or knowledge representation language such as the Web Ontology Language (OWL). Ontologies have been successfully used, for example, in military domains and biomedicine. In the design and manufacturing domains, in contrast, the use of ontologies has not lived up to initial expectations, due not least to a lack of coordination among industrial enterprises. *The focus of this paper is to present the Additive Manufacturing Ontology (AMO), an ontology designed to represent the Additive Manufacturing (AM) Product Life Cycle.*

AMO is a modular ontology that employs Basic Formal Ontology as its top level, while also drawing from the Common Core Ontologies and three other ontologies from the Coordinated Holistic Alignment of Manufacturing Process Ontologies that represent manufacturing processes: the Manufacturing

Process Ontology, the Design Ontology, and the Testing Process Ontology. As an illustrative example, the use of AMO is illustrated in the dentistry manufacturing domain.

30 **2. Related Work**

2.1. Ontology Development in the Manufacturing Domain

Many manufacturing ontologies have been developed in recent years. For example, Lemaignan et al. [5] developed the Manufacturing Semantics Ontology (MASON), which employs three top-level classes of *entities*, *operations*, and
35 *resources*. *Entities* in MASON comprise a broad class including geometric entities (for example, shape), raw materials, and costs. *Operations* class attempts to cover all processes involved in manufacturing, and *resources* attempt to represent tools, human resources, and geographic resources. MASON was developed as an upper-level ontology to accomplish two goals:

- 40 1. Developing an architecture and tools for automatic cost estimation, and
2. Linking a high-level ontology written in OWL with a multi-agent framework for manufacturing simulation.

Unfortunately, MASON's tripartite division of classes into entities, operations, and resources are lack of classificatory coherence. *Entity* in MASON, for instance,
45 is introduced as comprising the common helper concepts used to specify a product. However, *entity* as defined in the OWL Web Language Guide [6] and OWL2 Web Ontology Language Structural Specification [7] does not limit the definition in specific concept of specifying product only but also include classes, datatypes, object properties, data properties, annotation properties, and named individuals
50 are entities.

Kjellberg et al. [8] introduces the Machine-Tool Model (MTM) as an ontology focusing on the machine tool as a central part of a manufacturing system as

well as on the way machine tool information is used throughout the design and operation of such systems. Process planning, for instance, requires information
55 on the functional properties of machine tools, such as the ability to perform different types of machining operations.

Both MASON and the MTM were developed from scratch, each in its ad hoc way, and they do not use a common upper-level ontology nor do they reuse the content of other domain ontologies. In this way, they re-create the very lack of
60 interoperability that they were designed to address, but now this lack occurs between ontologies rather than between data systems. Even though MASON was intentionally developed as an upper-level ontology to represent manufacturing information, the entities in MASON are identifiable and concrete to represent manufacturing as the specialized domain of interest instead of being an ontology
65 that is domain neutral. According to Musen [9], upper-level ontology is defined as an ontology at a sufficiently high level of abstraction such that it does not refer to identifiable, concrete entities in the domain of interest.

MASON's contribution as an upper-level ontology is undeniably has contributed to the development of other ontologies in manufacturing domain. For
70 instance, Ramos [10] introduces the Machine Ontology (MO), which elaborates the representation of machines in terms of the *market*, *material*, and *operation* features. The resultant redundancy between MASON, MTM, and MO led Ramos et al. [11] to present a method for integrating ontology reuse with ontology validation, and they applied this method to the three ontologies in question, using
75 Protégé-Prompt to find common content and overlapping terms between them. The Machine of a Process Ontology (MOP) was developed as a result of this work with the goal of facilitating the buying and selling of industrial machinery; it employs MASON as its reference ontology while drawing in relevant classes and relations from MTM and MO. The CDM-Core Ontology, presented by Mazzola

80 et al. [12] is another ontology that was developed by reusing MASON as one of the upper-level ontology. CDM-Core Ontology includes both the general manufacturing domain applicability and the specific project use cases that can be a guidance for developing other specific applications in manufacturing domain.

Another ontology, the Manufacturing Service Description Language (MSDL),
85 was introduced by Ameri et al. [13], who employ a methodology relying on the incremental enhancement of an initial set of definitions constructed on the basis of a formal ontology. MSDL is an upper-level ontology that supports the semantic framework for representing conventional manufacturing processes outlined in Kjellberg et al. [8]. The original purpose of MSDL was to serve as
90 the ontology in an agent-based framework for supply chain deployment; for this reason, it employs an analysis of manufacturing capabilities across several levels: the supplier, shop, machine, device, and process.

Mesmer and Olewnik [14] proposes a Part-Focused Manufacturing Process Ontology (PMPO) designed around the idea that a classification of manufacturing
95 processes can be developed on the basis of an account of the desired features and attributes of the products they will be used to manufacture. The ontology thus develops a representation of the qualities used in specifying product requirements, including material composition, cost, shape, size, the surface finish of the product, thickness, and so forth. Users can describe the features and attributes based on
100 the qualities defined in PMPO, and select appropriate manufacturing processes according to the information provided.

Most ontologies designed for the manufacturing domain thus far have been put together with a focus narrowly directed to some specific sub-domain of manufacturing engineering and with little attention to interoperability with
105 other ontologies in related domains. Among the ontologies discussed, MOP and PMPO stand out because they build on prior work. PMPO is especially

interesting in that it utilizes not only Basic Formal Ontology but also MSDL, the Ontology for Biomedical Investigations (OBI), and the Common Semantic Model Ontology (COSMO). It is thus, at least to some degree, able to achieve
110 interoperability among data systems deriving from external sources. On the other hand, PMPO is small in scale and has been designed only for traditional machining and molding processes thus it cannot be applied to more modern manufacturing processes such as additive manufacturing.

Ideally, a representation of the manufacturing domain should deal with
115 commonly collected product-related information. Moving forward, we hold that an ontological representation of products and the PLC is a prerequisite for integrating data across systems in the manufacturing domain. Therefore, developing an ontology with a focus on AM products - their qualities, functions, the production, use, and end-of-life is the main objective of this paper. However,
120 our ontology is intended to form part of a larger suite of modular ontologies within the framework of the Industrial Ontologies Foundry (IOF) initiative, and it will accordingly be modified in tandem with IOF development. IOF is an initiative that was proposed to promote interoperability of high quality and non-redundant ontologies in industrial domains or manufacturing specializations
125 [15].

2.2. Manufacturing Processes and the Product Life Cycle (PLC)

As customer demands diversify, the complexity of products and product repertoires increases, and this gives rise to demand for increasingly innovative manufacturing processes [16]. Understanding the nature of such processes and
130 creating computational systems that can understand and reason about them is crucial, and this means understanding and reasoning across the entire product life cycle (PLC) in the Product Life Cycle Management (PLM). Moreover, Product, Process and Resource (PPR) are the key elements of engineering

domain in any manufacturing industry [17]. The information about PPR that
 135 is structured in PLM systems requires explicit mapping among the PPR for
 a complex decision purpose. Therefore, an ontology that provides common
 vocabularies in representing knowledge could facilitate the full potential of the
 PLM by supporting information exchange between the PPR in different phases
 in PLC[17, 18].

140 Cao and Folan [19] divide PLC models into two groups:

1. Marketing Product Life Cycle (M-PLC) models that focus primarily upon marketing needs and conceptions;
2. Engineering Product Life Cycle (E-PLC) models that integrate design and manufacturing with marketing needs and conceptions.

145 Figure 1 represents the successive phases of the PLC taken as the basis of ontology development in many recent works, including Young et al. [3], Chen et al. [16], Borsato [18], Matsokis and Kiritsis [20], Chungoora et al. [21], Usman et al. [22], Urwin [23], Urwin et al. [24], and others.

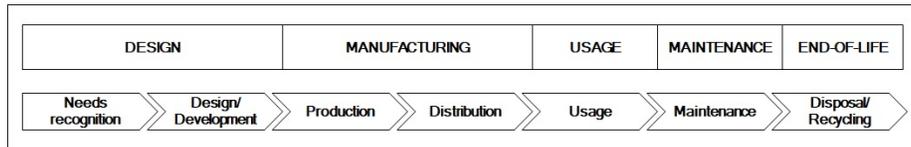


Figure 1: Phases in the PLC.

Table 1, from Chen et al. [16], extends this representation to create a more
 150 granular perspective. Here, the PLC is depicted as consisting of seven stages
 each with a number of sub-stages.

Chen et al. [16], Borsato [18], Matsokis and Kiritsis [20], Chungoora et al.
 [21], Usman et al. [22], Urwin [23] and Urwin et al. [24] have demonstrated
 good concept of information integration and sharing between the design and
 155 manufacturing phases in PLC through ontology. Borsato [18] for instance,

Table 1: Seven stages of the PLC presented by Chen et al. [16]

Stages	Sub-stages
Product design	Requirement analysis, Conceptual design, Preliminary design, Detail design
Process development	Part description, Generative process planning, Variant process planning
Product manufacturing	Equipment layout, Production management, Quality control
Sales	Chance analysis, Target market choice, Sell combination development
Product in use	Operation instructions establishment, Product installation and execution
Post sell service	User problem reaction, Problem identification, Service support
Product retirement	Decomposition, Recycling

believes that ontology could bridge the gap between manufacturing and PLC. Chungoora et al. [21] presents the Interoperable Manufacturing Knowledge System (IMKS) model-driven concept that was built on the ideas of extensible core ontologies of manufacturing. Usman et al. [22] forms the Manufacturing Core Concepts Ontology (MCCO) by identifying core set of concepts formalized in the upper-level ontology that serve as foundation ontology to provide the first stage of a common understanding before developing the domain specific concepts of design and production.

In what follows, we will adopt this granular perspective in conceiving of the PLC as having a scope that includes processes of design and development, manufacturing, usage, maintenance and disposal, as well as the information, materials, qualities, and functions that participate in these processes.

In particular, we take into account also the following key areas of interest regarding the PLC identified by Young et al. [3]:

- Information regarding products including product geometry,
- Potential supply chain capability,

- Knowledge of what has been done in the past, and
- Potential legislation, catalog data, and standards that affect decision making.

175 *2.3. Previous Work on Additive Manufacturing Ontology*

Additive manufacturing (AM) is defined by the American Society for Testing and Materials (ASTM) as: the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [25]. AM is nowadays widely used in industrial product
180 development, and its ability to create almost any possible shape through a process of building up a product layer by layer.

Existing work on the ontology for AM includes SAMPro, for Semantic Additive Manufacturing Process Planning, described by Eddy et al. [26]. SAMPro is extended from the MSDL; it provides the starting point for a module that
185 includes types of AM such as the Binder Jetting and Directed Energy Deposition as its classes and focuses on the products which are the output of such processes, representing in detail product features such as surface finish, accuracy, tolerance, and so forth.

By contrast, The Design for Additive Manufacturing Ontology (DFAM),
190 presented in Dinar and Rosen [27], focuses on the detailed representation of different types of AM processes in terms of what it calls process parameters such as printing orientation angle. However, DFAM, too, suffers from the fact that it has been developed with its own peculiar vocabulary for the included classes.

NIST [28], Roh [29] and Liang [30] are some other ontologies for AM that
195 have been developed recently. Roh [29] develops an ontology for AM to represent information for different process models for laser, thermal, micro structure, and mechanical properties for metal-based AM of Ti-6-6Al-4V. Liang [30] develops the AM-OntoProc ontology that promote the modeling and reutilization of

knowledge towards the AM process planning where AM process is supposed to
200 begin from the utilization of CAD software during the design stage until the
final AM prototype is developed.

Finally, there is recent work by Hagedorn et al. [31], which uses BFO as
the platform for an AM ontology called Innovative Capabilities of Additive
Manufacturing (ICAM). ICAM also reuses the BFO-conformant ontology - the
205 Information Artifact Ontology (IAO) - to provide the higher-level representation
of information-related types that serves as its backbone. The information in
ICAM covers basic product attributes from the NIST Core Product Model
(CPM) relating to materials, geometry and designed function as well as types of
manufacturing processes and services taken over from MSDL. It also incorporates
210 the SAMPro model of AM and a set of formal description of parts and features
from Functional Basis Ontology (FBO). ICAM is thus able to provide extensive
coverage of the AM domain and since our version of AMO also reuses the BFO-
conformant ontology - the Common Core Ontologies (CCO), we will be looking
forward for the opportunity to develop future versions of AMO to be consistent
215 with the ICAM content that focus on the application of AM. The CCO is a
suite of ontologies that was released to the public recently that adds general
contents to the BFO structure and at the same time are also common to many
domain of interest, especially to manufacturing engineering domain. We feel
that Information Entity Ontology (IEO) that is part of CCO seems to be able to
220 represent information-related types to manufacturing domain in a more accurate
way than IAO. However, there are still works to be done in making the IEO and
IAO to be compatible to each other.

3. Approach for Ontology Development

Although there are is no standard methodology for developing ontologies,
225 Natalya F and Deborah L [32] outlined a simple knowledge-engineering method-
ology in developing ontology which was followed as a guideline in our work. The
methodology include: determining ontology domain and scope, considering on-
tology reuse, enumerating important terms, defining classes and class hierarchies,
defining class properties, defining values for properties, and creating instances of
230 classes.

We adopted a top-down approach in most of the ontology development
process where the AMO as the domain ontology was constructed by downward
population from a common upper-level ontology in the multi-tiered network
connected in the following way [33]:

- 235 1. A single, small, domain-neutral upper-level ontology;
2. Mid-level ontologies covering broad domains having root nodes that are
either direct children of classes from the upper-level ontology or of a term
drawn from another mid-level ontology within the network;
3. Lower-level ontologies representing specialized domains having root nodes
240 that are either direct children of classes from one of the mid-level ontologies
or of a term drawn from another domain level ontology within the network;.

BFO and Descriptive Ontology for Linguistic and Cognitive Engineering
(DOLCE) are some of the upper-level ontology that have been used as the
foundation ontologies in the domain ontology development [34, 35, 36]. Both
245 ontologies in fact grew out of a common philosophical orientation, and thus some
parts of the ontologies overlapped with each other. Since our work is part of the
Coordinated Holistic Alignment of Manufacturing Processes (CHAMP) project
founded by Digital Manufacturing and Design Institute (DMDII) which focuses
on constructing an efficient scheme to manage discordant manufacturing data

250 source, BFO is already selected as one of the project requirement. However, despite of the selection of BFO due to the CHAMP project requirement, BFO's well-documented guidelines and training material, it's extensive use in in hundreds of projects in biomedical and military domains, and increasingly being adopted in industry as a top-level framework are another factors that contribute to the selection of BFO. ICAM [31], CCO [37] and Functional Graded Material Ontology (FGMO)[38] are some of the ontologies that have been developed by adopting BFO as foundation of the ontology development. These factors make its use a key enabler in promoting the secondary use of our ontology by others. Therefore, we selected BFO¹ as an upper-level ontology to serve as starting point in the ontology development of AMO. In addition, we have wherever possible reused content taken from the Common Core Ontologies (CCO)², which were also built as conservative extensions of BFO.

BFO contains the top class *entity* that contains two subclasses: *continuant* and *occurrent* [34]. A *continuant* is an *entity* that is wholly present at every time during the course of its existence. Examples of *continuant* entities include objects, such as tables and people, as well as spatial regions and portions of matter, qualities, such as the length of an airplane wing, and dispositions, such as the tensile strength of a steel sheet. An *occurrent*, by contrast, is an *entity* that occurs or happens by unfolding itself through time in successive phases (for example of a beginning, middle, and end). Manufacturing processes fall under this heading, as also do the temporal regions during which such processes occur. A fragment of the BFO class hierarchy is provided in Figure 2.

An AM process is a *process* that involves certain sorts of *material entities* as its participants. A *Portion of Material* is a subclass of *material entity*, and

¹See <https://github.com/BFO-ontology/BFO/blob/master/bfo.owl>

²See <https://github.com/CommonCoreOntology/CommonCoreOntologies>

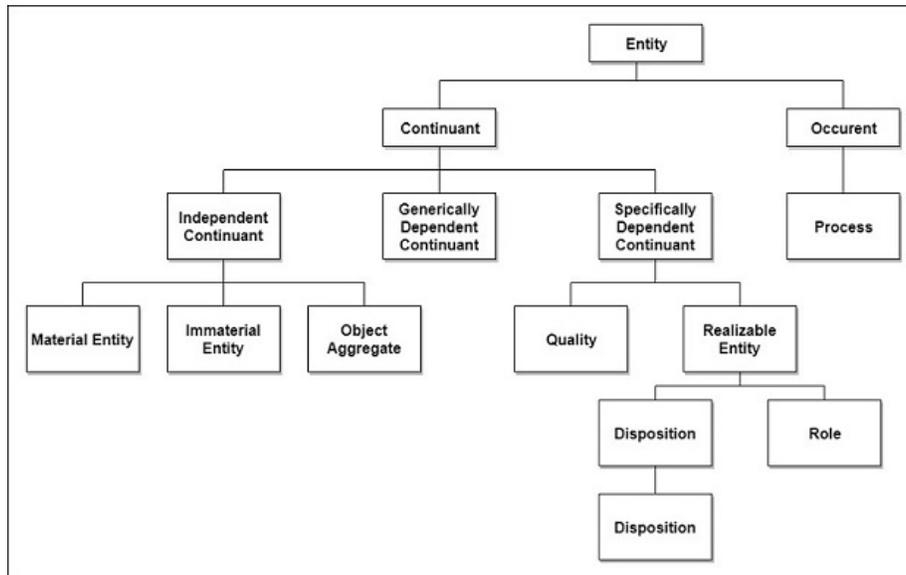


Figure 2: A fragment of the BFO class hierarchy [39].

275 instances of *Portion of Material* are the inputs for instances of AM process.

Both *processes* and *material entities* are distinct from the third type of *entity* in BFO comprising *generically dependent continuants*. These are, roughly, patterns that can be exactly copied - they are entities that depend on the existence of at least one bearer at any time during which they exist, but not on
 280 any particular bearer. The most important subclass of *generically dependent continuant* is *Information Content Entity*, whose instances stand in a relation of *aboutness* to some *entity* [40]. Importantly, for our purposes, this class includes instances of reports, sentences, and data values that are about the processes and materials of a manufacturing process. Such information is not itself material,
 285 nor is it a process, though it may participate in processes [34].

The Common Core Ontologies (CCO) form a set of conservative extensions of BFO with the goal of representing the mid-level entities involving agents, artifacts, actions, and measurements [41]. The ontologies in the CCO include:

- Agent Ontology, representing agents, especially persons and organizations,
290 and their roles.
- Artifact Ontology, representing deliberately created material entities along
with their models, specifications, and functions.
- Currency Unit Ontology, representing currencies in different countries.
- Extended Relation Ontology, representing relations (i.e. object properties)
295 holding between entities.
- Event Ontology, representing processes.
- Geospatial Ontology, representing sites, spatial regions, and other entities,
especially those that are located near the surface of Earth, as well as the
relations that hold between them.
- 300 • Information Entity Ontology, representing generic types of information as
well as the relationships between information and other entities.
- Quality Ontology, representing a range of attributes of entities, including
qualities, realizable entities such as dispositions and roles, and process
profiles.
- 305 • Time Ontology representing temporal regions and the relations that hold
between them. A temporal region, as defined by BFO, is an occurrent
entity that is part of time as defined relative to some reference frame.
- Units of Measure Ontology, representing standard units used when mea-
suring various attributes of entities.

310 Figure 3 shows the CCO ontologies with the import structure between them.
Every class in CCO is the subclass of some class in BFO, and general relations
used in BFO are also adopted by the CCO.

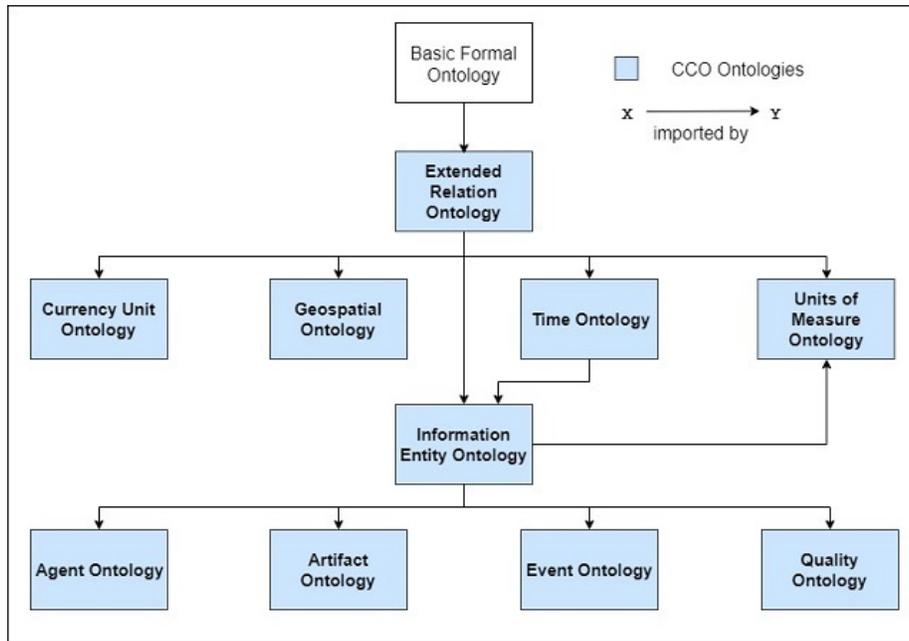


Figure 3: The Common Core Ontology import structure [37].

Although CCO served as the mid-level ontology that reduce the generality of BFO, having direct children from CCOs' classes to represent the specific domain in AM are not sufficient. There is a need of another level of ontology
 315 after the CCO so that it can increase the granularity of domain before moving towards the concrete entities that represent AM. The Coordinated Holistic Alignment of Manufacturing Processes (CHAMP) is a project funded by the Digital Manufacturing and Design Innovation Institute (DMDII). The CHAMP
 320 project has developed a suite of ontologies whose objective is to aid industrial organizations in overcoming the problem of data heterogeneity. The CHAMP³ ontologies are an extension of CCO representing the mid-level classes relating to the design, manufacturing, use, and maintenance phases of the PLC. These ontologies include:

³See <https://github.com/NCOR-US/CHAMP>

- 325 • Product Life Cycle Ontology
- Commercial Entities Ontology
- Design Ontology
- Manufacturing Process Ontology
- Testing Process Ontology
- 330 • Tool Ontology
- Maintenance Ontology

Figure 4 shows the CHAMP ontologies and their import structure.

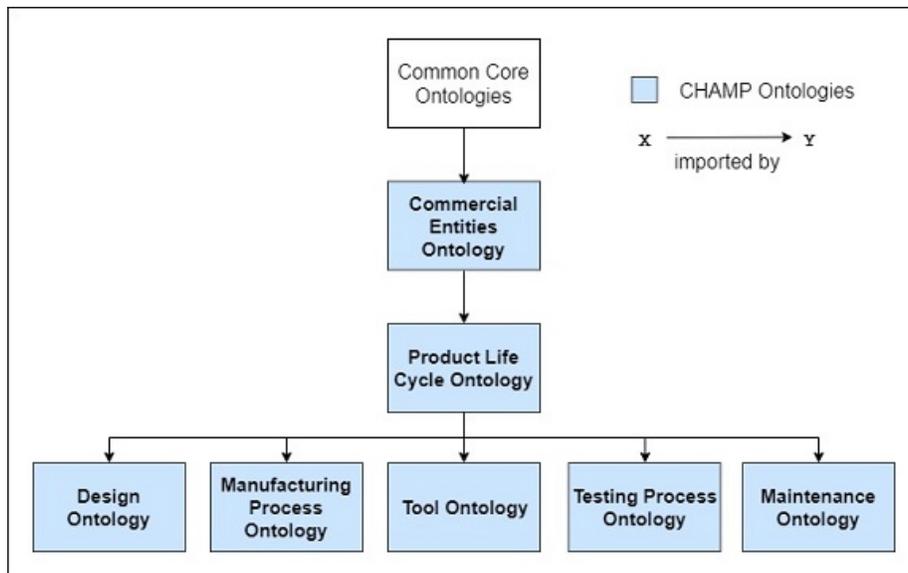


Figure 4: The CHAMP Ontologies

Ideally, we planned to extend the whole set of CHAMP ontologies for the development of AMO. However, since the CHAMP ontologies are still in initial
 335 implementation, we decided to import only a fragment of the CHAMP ontologies that are related to the AM processes. We imported manually some of the

classes from the Design Ontology, Manufacturing Process Ontology, and Testing Process Ontology without changing its' class structures and URI from its' original ontologies. Figure 5 shows the framework for the AMO development.

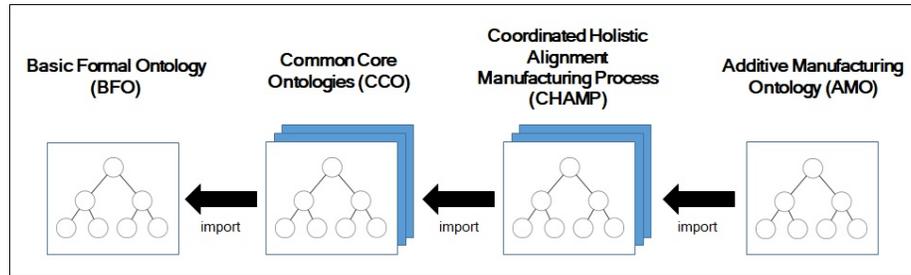


Figure 5: An overview of AMO development.

340 4. The Additive Manufacturing Ontology (AMO)

Existing classes from BFO, CCO, and CHAMP are imported into AMO and new classes are added in a process of downward population. This ensures that AMO utilizes commonly used terms and definitions and thereby increases the chances that AMO will itself be re-used and integrated with other ontologies.

345 4.1. Process

There is a canonical order to processes that occur within AM, and that the processes represented in the AMO were selected in order to account for this canonical representation. From a mechanical perspective, AM often uses numerically controlled (NC) machines that are integrated with CAD and process
 350 planning software. The canonical AM process flow consists of six steps [42]:

1. 3D CAD model generation;
2. Conversion of the CAD Model into AM machine acceptable format (STL file);
3. Setting the process parameters;

- 355 4. The process of printing;
5. Support removal; and
6. Post-processing.

The class *process* is defined in BFO as an *occurrent* entity that exists in time by occurring or happening, has temporal parts, and always depends on
360 some (at least one) *material entity* [34]. Each of the steps listed by Yang et al. [42] corresponds to the instantiation of a certain type of *process* entity. *Process* entities in AMO include:

1. Design Ontology: *ActOfDescribingClientNeed*
2. Design Ontology: *ActOfAnalysisOfClientNeed*
- 365 3. AMO: *ActOfCADModelDevelopment*
4. AMO: *ActOfDataTransformation*
5. Design Ontology: *ActOfManufacturingRequirementIdentification*
6. Manufacturing Process Ontology: *ActOfAdditiveManufacturing*
7. AMO: *ActOfSupportRemoval*
- 370 8. AMO: *ActOfPostProcessing*

As can be seen, some of these classes are imported from the Design Ontology and the Manufacturing Process Ontology. Figure 6 shows the taxonomy of the process classes in AMO. *IntentionalAct* as can be seen from the figure is the subclass of *Act* class where both *Act* and *IntentionalAct* are the CCO classes,
375 extension of *Process* class in BFO. The definition of both class as follows:

- *Act* is a process in which at least one agent plays a causative role.
- *IntentionalAct* is an Act in which at least one agent plays a causative role and which is prescribed by some Directive Information Content Entity held by at least one of the Agents.

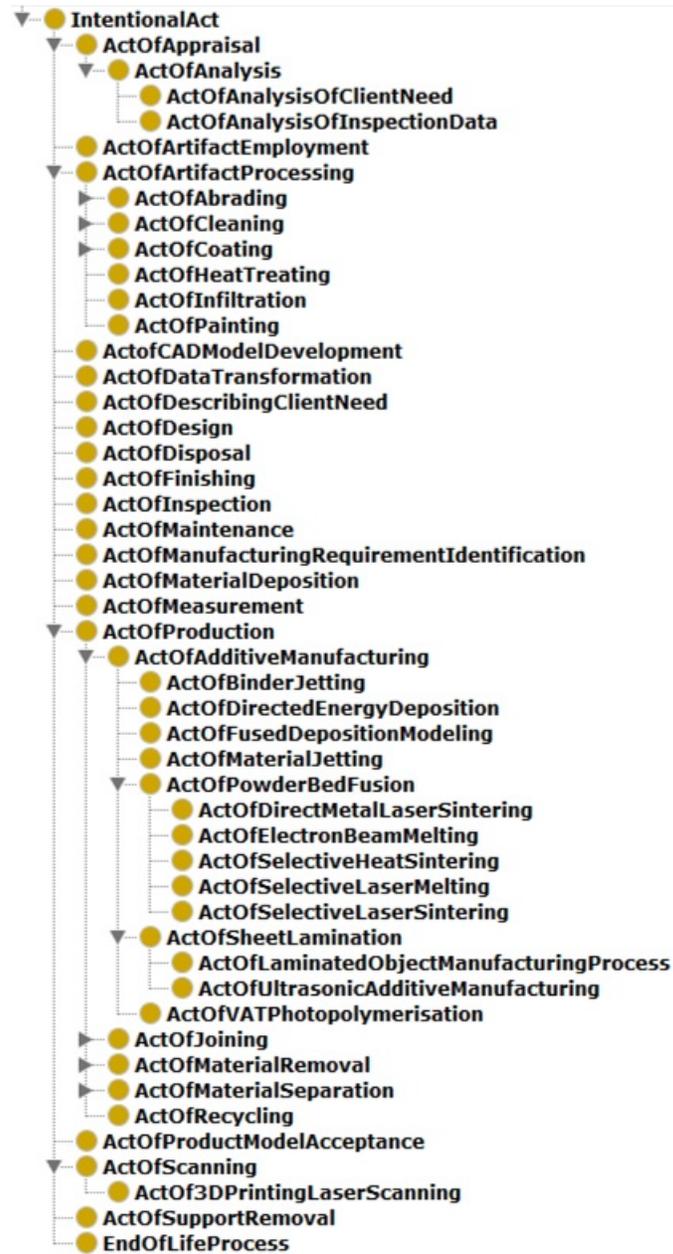


Figure 6: *Process* classes in AMO.

380 In addition to the eight main *process* classes, there are also conditions where main *process* classes at the instance level has other *process* as part of the main

process. However, it is not right to put that *process* class as the subclass of the main *process* since this process part relations only hold in some cases and not all the time. Figure 7 shows the example of some *ActOfSupportRemoval* that
 385 *has_process_part* an *ActOfMaterialRemoval* and an *ActOfPostProcessing* that has an *ActOfAbrading* and an *ActOfJoining* as process parts.

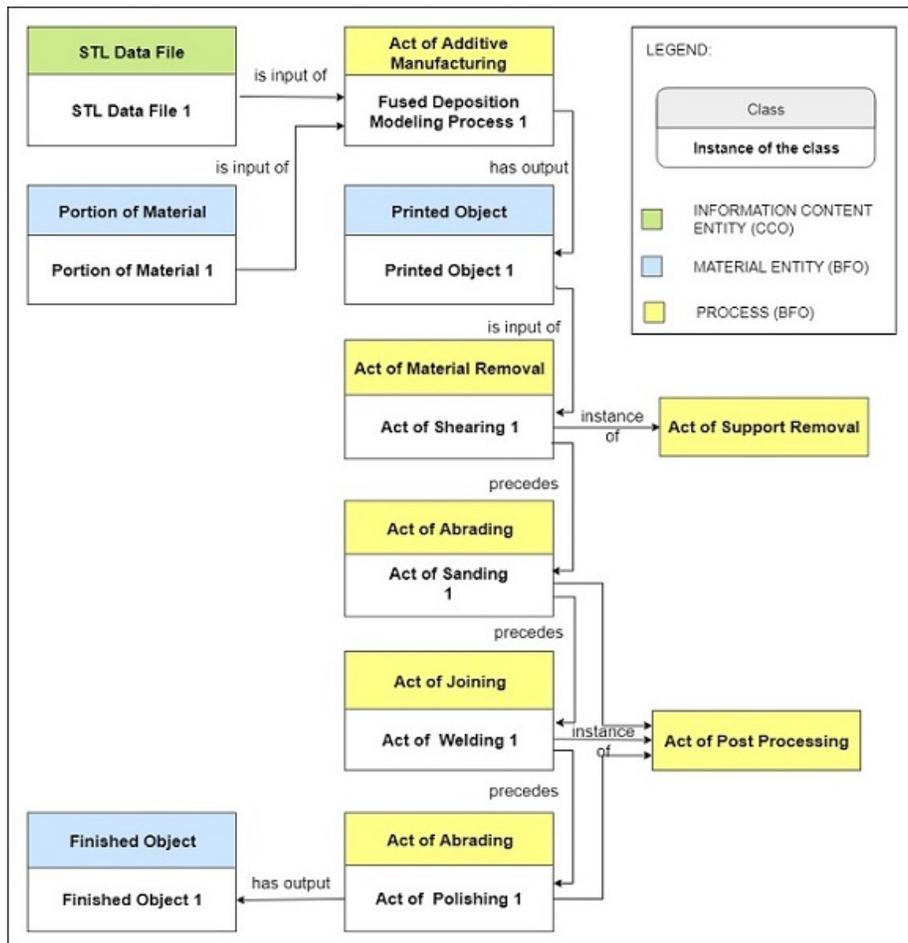


Figure 7: Example for process parts of *Act of Support Removal* and *Act of Post Processing*.

4.2. Material Entity

BFO defines a *material entity* as an *independent continuant* that has some portion of matter as part [34]. Three types of *material entity* are recognized by
390 BFO: *object*, *fiat object part*, and *object aggregate* [34]. BFO does not assert that all *material entities* fall under one or other of these headings. Thus, portions of liquid, gas, and plasma are classified (in the current version of BFO) as immediate descendants of *material entity*.

Resources involved in the AM process can all be classified as *material entities*
395 in the AMO. These resources are:

- *Portion of Material*
- *3D Printing Machine*
- *Printed Object*
- *Finished Object*

400 *Portion of Material* in AMO is a direct child of *material entity* because it may describe those *material entities* that are not *object aggregates*. *Material entity* classes in AMO are shown in Figure 8. Meanwhile, *3DPrintingMachine*, *PrintedObject*, and *FinishedObject* are types of *object* in BFO [43]. *PrintedObject* and *FinishedObject* are defined classes with definitions as follows:

- 405 • *PrintedObject* is an *object* that is an output of some *Act of Additive Manufacturing*.
- *FinishedObject* is an *object* that is an output of some *Act of Post-Processing*.

4.3. Information Content Entity

An *Information Content Entity* as defined by the CCO is "a *Generically*
410 *Dependent Continuant* that generically depends on some *Information Bearing*

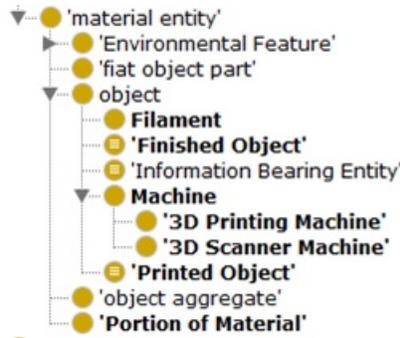


Figure 8: *Material Entity* classes in AMO.

Entity and stands in the relation of *aboutness* to some *entity*⁴". The CCO also provides three sub-relations of ‘*is_about*’, including: describing, prescribing, and designating.

The AMO makes use of these distinctions provided in the CCO to provide
 415 a series of classes of information that either prescribe, designate, or describe
 various AMO processes and resources. These are displayed in Figure 9 and newly
 added classes appear in bold. *CADSoftwareProgram*, *CADModel*, *STLDataFile*,
 and *TechnicalDrawing* are *InformationContentEntity* in AMO. Thus, all are
generically dependent continuants in BFO. A *CADModel*, for example, contains
 420 information pertaining to the qualities that must inhere in a solid model of the
 sort that is represented in an *ArtifactModel*. An *ArtifactModel* in the CCO is a
 subclass of *ArtifactDesign*. Both classes are defined in the CCO⁵ as follows:

- *ArtifactDesign* is a *Directive Information Content Entity* that is a specification of an *object*, manifested by an agent, intended to accomplish goals,
 425 in a particular environment, using a set of primitive components, satisfying
 a set of requirements, subject to constraints.

⁴See <https://github.com/CommonCoreOntology/CommonCoreOntologies/blob/master/AllCoreOntology.ttl>

⁵See <https://github.com/CommonCoreOntology/CommonCoreOntologies/blob/master/AllCoreOntology.ttl>

- *ArtifactModel* is an *Artifact Design* that prescribes a common set of functions and qualities that are to inhere in a set of artifact instances.

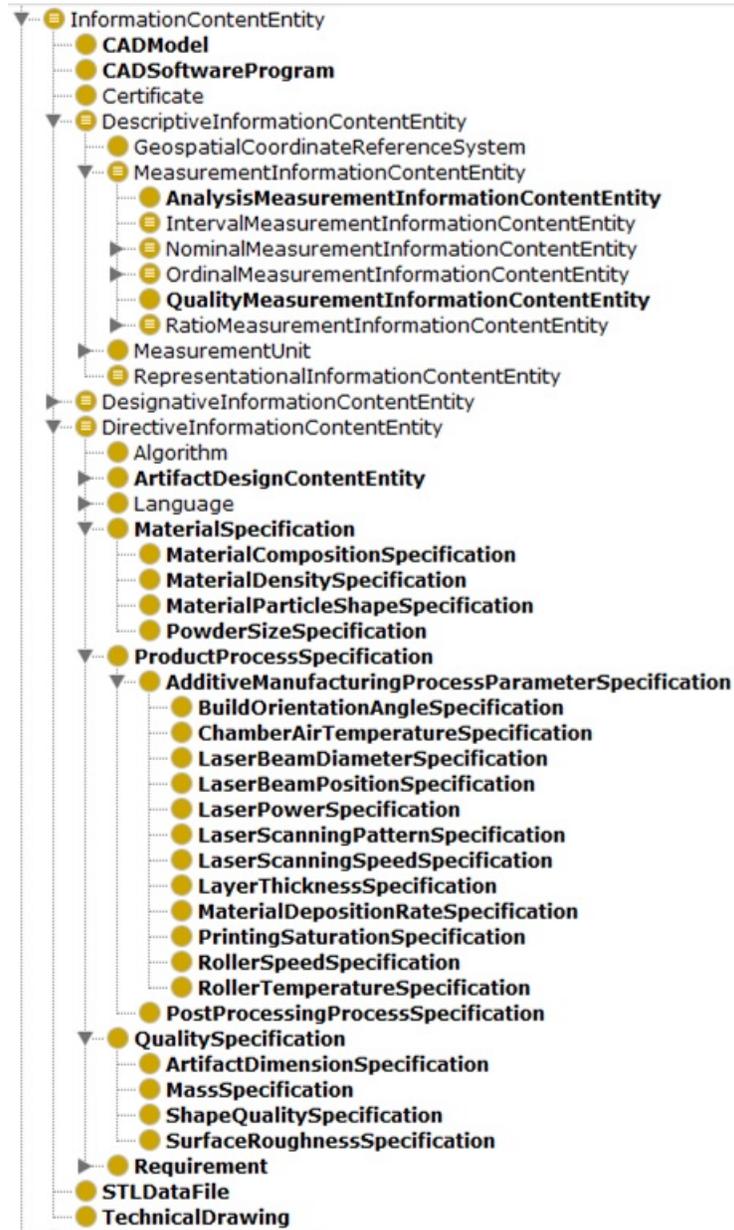


Figure 9: *Information Content Entity* classes in AMO.

The CCO class, *Directive Information Content Entity* is defined as an *Information Content Entity* that prescribes some *entity*. Specifications, for example, are classified under *Directive Information Content Entity*, as for example where some *Additive Manufacturing Process Specification* prescribes some *Act of Additive Manufacturing*.

Requirements, too, are classified under *Directive Information Content Entity*, for example when a *Customer Requirement* prescribes certain *qualities* that must inhere in a product. Standards documents such as ISO 3923, the International Standard for Metallic Powders, prescribes the level of quality that a metallic product must have if it is to satisfy the standard.

4.4. Relations

Figure 10 provides an overview of the relations used in AMO, in addition to *process_part_of* discussed in Section 4.1.

Definitions from BFO and the CCO are as follows:

- *has_participant* is a primitive instance-level relation between a *process*, a *continuant*, and a *time* at which the *continuant* participates in some way in the *process*.
- *is_input_of* is a relation between a *continuant* and a *process* in which the *continuant* participates. The presence of the *continuant* at the beginning of the *process* is a necessary condition for the initiation of the *process*.
- *is_output_of* is a relation between a *continuant* and a *process* in which the *continuant* participates. The presence of the *continuant* at the end of the *process* is a necessary condition for the completion of the *process*.
- *prescribes* is for all types T1 and T2, if T1 prescribes T2, then there is some instance of T1, t1, that serves as a rule or guide to some instance of T2, t2.

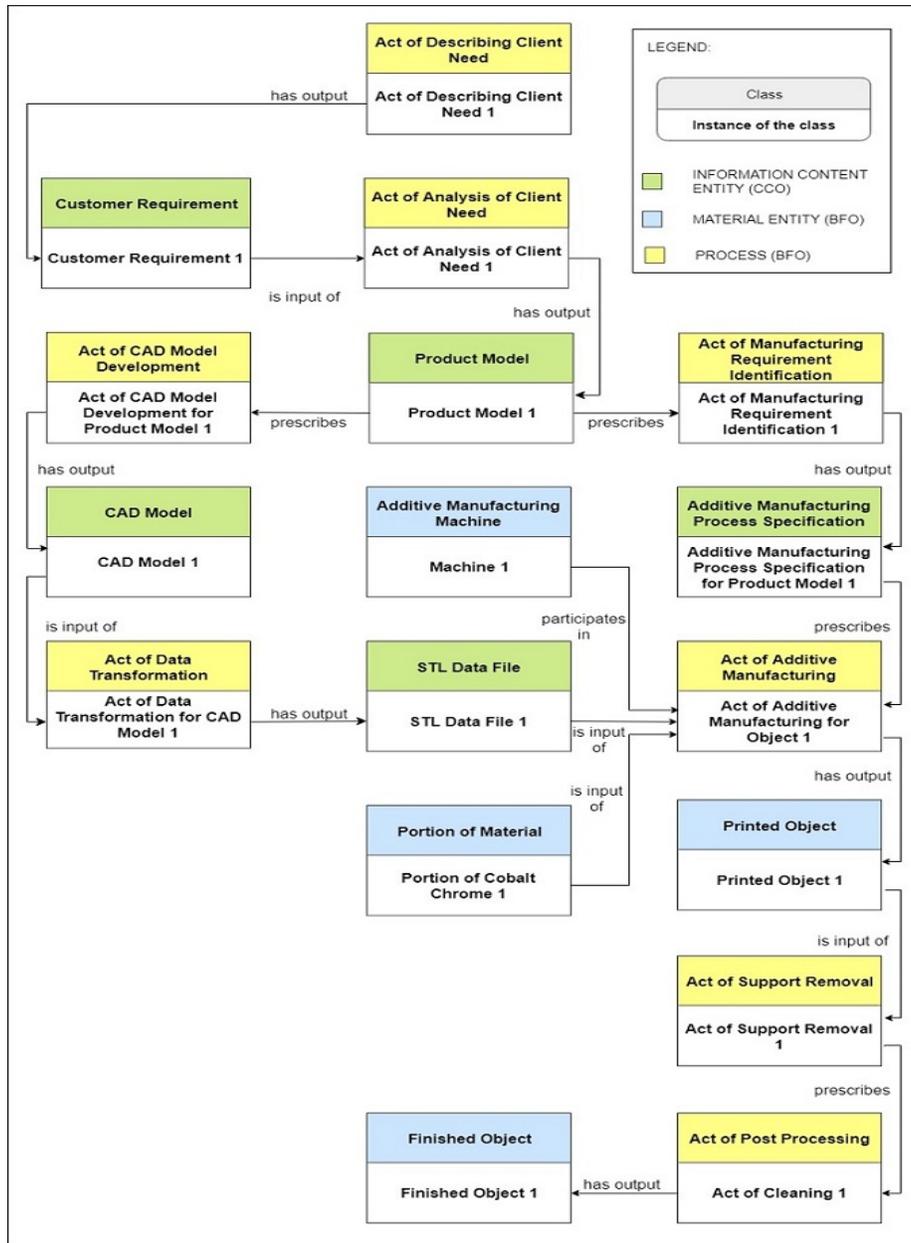


Figure 10: An overview of AMO entities and relations.

455 **5. Application of AMO to the Dentistry Product Manufacturing**

AMO was developed to serve as a mid-level ontology that can be re-utilized for multiple different types of additive manufacturing. By providing terms for all processes within the AM organized process flow, we feel that AMO is particularly well suited for PLC applications. Besides, to ensure generality of AMO, the properties interrelating objects of different ontologies are only defined directly
460 in the AMO at the instance level. To show the utility of the developed AMO for developing application-specific ontologies, a case study applying AMO to dentistry manufacturing application termed Additive Manufacturing for Dental Product Ontology (AMDO) is discussed next.

465 *5.1. Additive Manufacturing (AM) in Dentistry*

AM has established itself in the dentistry field as a promising alternative to the conventional manufacturing processes. AM has the advantage of yielding accurate one-off fabrication of complex structures in a variety of materials having properties highly desirable for both dentistry and surgery [44]. AM
470 even becoming a feature of many dental surgeries [45], where it allows direct fabrication of dental prostheses such as crowns and bridges.

As a case study, an application ontology extending AMO with new classes related to the dentistry product manufacturing field has been developed. This application ontology is titled the Additive Manufacturing for Dental Product
475 Ontology (AMDO) and is depicted in Figure 11 (newly added classes are highlighted in bold). As can be seen from the figure, the newly added classes are the extension of the existing classes from the imported ontologies. This shows the re-usability of AMO in the developing the application ontology. No new object properties are needed to be created as well.

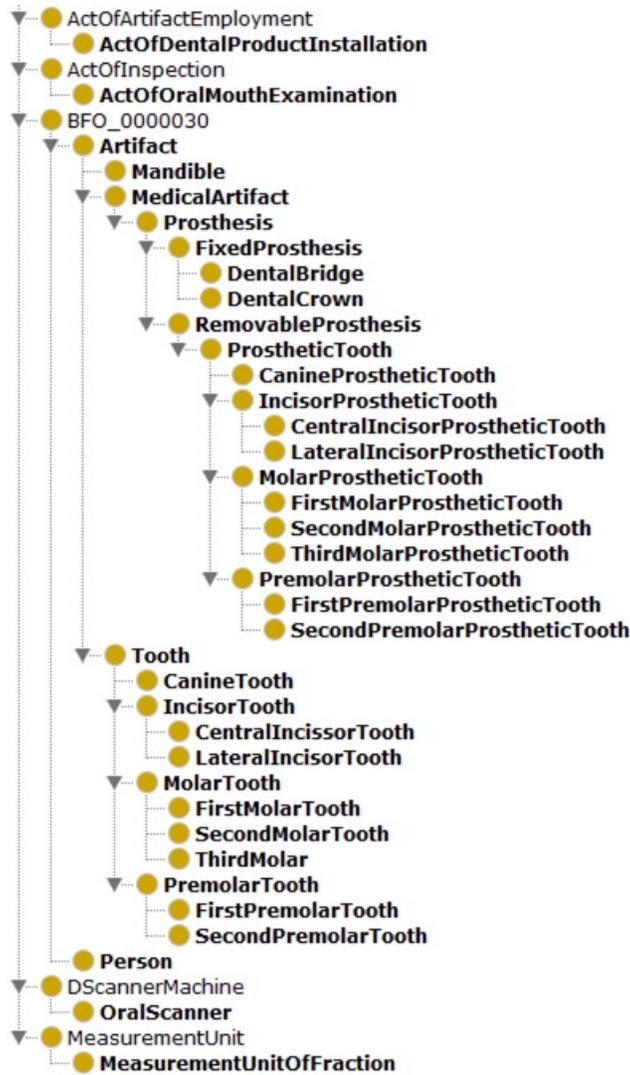


Figure 11: Active classes in AMDO.

480 5.2. Case Demonstration

This section demonstrate an example of the practical uses of the AMDO guided by the work outlined in Khalil et al. [46]. In their work, they evaluate dimensional differences between natural teeth and the printed models using three different AM processes. The process starts with the scanning of three premolars

485 dimension from two dry adult human mandibles by means of an optical scanner
to yield the three-dimensional data needed for the dental model. Table 2 shows
the specifications of the four 3D printers used in the study Khalil et al. [46].

Table 2: Specification of 3D Printers used

Machine	SLA	Objet Eden 250	Objet Connex 350	UP Plus 2
Printing type	SLA	Polyjet	Polyjet	FDM
Layer thickness (μm)	50	16	16	150
Material used	Resin	Resin	Resin	ABS

24 printed premolar tooth were produced in total and the volume of each
replicas are measured and compared against the original premolars. Table 3
490 shows the overview of the volume measurements of each printed premolar tooth
with the percentage of volume difference with the original premolars.

Table 3: Volume and Percentage of Volume Differences Data

Group	Tooth No.	UP Plus 2	Objet Connex 350	Objet Eden 250	SLA
M1	34	509.2(4.2%)	502.1(2.7%)	482.6(-1.3%)	484.2(-0.9%)
M1	44	616.7(18.5%)	521.2(0.1%)	516.2(-0.9%)	519.3(-0.3%)
M1	54	440.5(-1.6%)	438.8(-2.0%)	446.2(-0.3%)	448.0(0.1%)
M2	34	376.5(-4.4%)	421.6(7.0%)	398.2(1.1%)	388.9(-1.3%)
M2	44	340.2(-6.8%)	351.0(-3.8%)	361.0(%-1.1%)	362.1(-0.8%)
M2	54	416.4(-12%)	464.2(-1.9%)	482.6(%-0.9%)	471.1(-0.4%)

For the testing purposes of AMDO, we populated all data from Table 2 and
Table 3 as instances for the classes in AMDO. Following are the three queries
that we have made for the AMDO to provide the inferred information:

- 495
1. What are the 3D Printers used in the study?
 2. What type of materials used for each machine and what are the layer
thickness specification in fabricating the printed tooth?
 3. What are volume differences of the printed tooth with the uses of different
3D printers?

500 The queries have been created using an Resource Description Framework (RDF)
query language, SPARQL that is a plugin to Protege. SPARQL is a semantic
query language that is able to retrieve and manipulate data stored in the

RDF format where the entities and its relations are expressed in the form of subjectpredicateobject. For each queries, following are the namespace and its

505 binded prefixes that were used to identify the URI of the classes:

rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>

owl: <http://www.w3.org/2002/07/owl#>

rdfs: <http://www.w3.org/2000/01/rdf-schema#>

xsd: <http://www.w3.org/2001/XMLSchema#>

510 bfo: <http://purl.obolibrary.org/obo/>

ros: <http://www.obofoundry.org/ro/ro.owl#>

ccos: <http://www.ontologyrepository.com/CommonCoreOntologies/>

plco: <http://www.semanticweb.org/no/ontologies/2017/1/PLC-ontology/>

mpos: <http://www.semanticweb.org/ontologies/ManufacturingProcessOntology/>

515 y/

dos: <http://www.semanticweb.org/no/ontologies/2017/6/DesignOntology/>

amos: <http://www.semanticweb.org/munira/ontologies/2017/6/AdditiveManufacturingOntology#>

amdo: <http://www.semanticweb.org/munira/ontologies/2018/1/AdditiveManufacturingDentalOntology#>

520

Query 1: Identifying 3D printers used in the study.

The SPARQL Query for this question is as follow:

```

SELECT ?Machine
525 WHERE {
    ?Machine rdf:type amos:3DPrintingMachine }

```

As can be seen from Table 2, there are four 3D printers used in the study. Even though there are only four data, this simple query represents those with large

530 input and low selectivity and does not assume any hierarchy information or
inference. Figure 12 shows the result of this query.

Machine
ObjetEden2501
ObjetConnex3501
SLA1
UPPlus2

Figure 12: Query 1 Result

Query 2: Identifying type of materials used for each machine and what are the
layer thickness specification in fabricating the printed tooth.

535 To identify the type of materials used for each machine and with the layer
thickness specification for the printing process, the relations between the process,
machine, materials and also the process specification are defined at the instance
level. To increase the selectivity of the inferred information, we limited type of
printing process to only to the Vat Photopolymerisation Process. The SPARQL
540 Query for this question is as follow:

```
SELECT ?Machine ?Material ?LayerThickness ?MeasurementUnit
WHERE {
    ?a rdf:type amos:ActOfVATPhotopolymerisation .
    ?Machine ros:agent_in ?a .
    545 ?Machine rdf:type amos:3DPrintingMachine .
    ?b ccos:is_input_of ?a .
    ?b rdf:type amos:PortionOfMaterial .
    ?b ccos:has_text_value ?Material .
    ?c ccos:prescribes ?a .
    550 ?c rdf:type amos:LayerThicknessSpecification .
    ?c ccos:inheres_in ?d .
    ?d rdf:type ccos:InformationBearingEntity .
```

```

?d ccos:has_integer_value ?LayerThickness .
?d ccos:uses_measurement_unit ?MeasurementUnit }

```

555 This query increases in complexity where there are four classes are involved and it has high selectivity due to the constraint added to one of the class. Figure 13 shows the result of this query.

Machine	Material	LayerThickness	MeasurementUnit
SLA1	"Photopolymer Resin"@	"50"^^<http://www.w3.org/2001/XMLSchema#integer>	'Micrometer Measurement Unit'
SLA1	"Photopolymer Resin"@	"50"^^<http://www.w3.org/2001/XMLSchema#integer>	'Micrometer Measurement Unit'
SLA1	"Photopolymer Resin"@	"50"^^<http://www.w3.org/2001/XMLSchema#integer>	'Micrometer Measurement Unit'
SLA1	"Photopolymer Resin"@	"50"^^<http://www.w3.org/2001/XMLSchema#integer>	'Micrometer Measurement Unit'
SLA1	"Photopolymer Resin"@	"50"^^<http://www.w3.org/2001/XMLSchema#integer>	'Micrometer Measurement Unit'

Figure 13: Query 2 Result

Query 3: Identifying volume differences of the printed tooth with the uses of
560 different 3D printers?

To identify the volume differences of the printed tooth with the uses of different 3D printers, the relations between the process, machine, and also the volume measurements with the volume difference analysis data are defined at the instance level. The illustration of the relations between instances of each class is
565 shown in Figure 14.

To increase the selectivity of the inferred information, we limited type of printing process to only to the Vat Photopolymerisation Process. The SPARQL Query for this question is as follow:

```

570 SELECT?Machine?ProstheticTooth?ProstheticToothVolume?VolumeDifference
Percentage
WHERE {
?a rdf:type amos:ActOfMaterialJetting .
575 ?Machine ros:agent_in ?a .

```

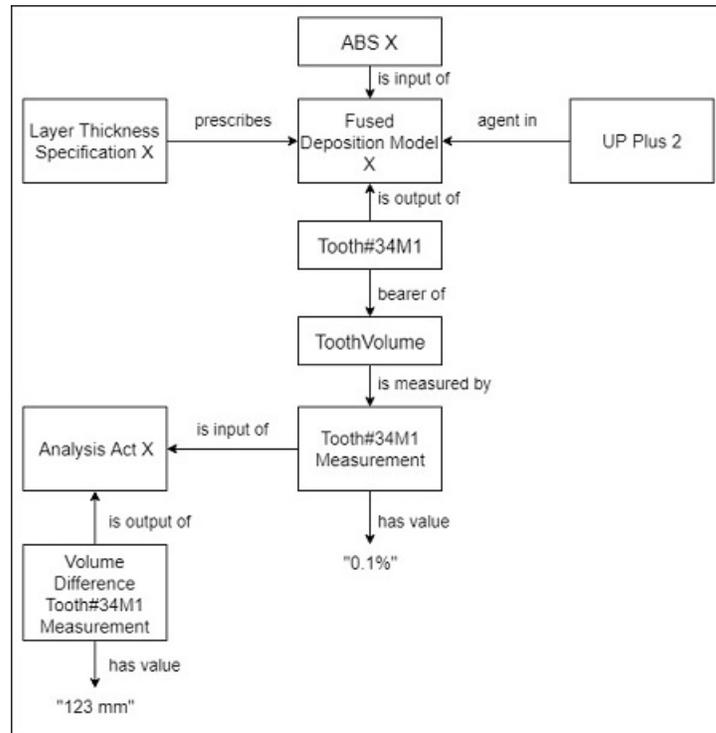


Figure 14: Instances in AMDO

```

?Machine rdf:type amos:3DPrintingMachine .
?ProstheticTooth ccos:is_output_of ?a .
?ProstheticTooth rdf:type amdo:PremolarProstheticTooth .
?ProstheticTooth ccos:bearer_of ?d .
580 ?d rdf:type amos:VolumeCapacity .
?d ccos:is_measured_by ?e .
?e rdf:type amos:QualityMeasurementInformationContentEntity .
?e ccos:inheres_in ?f .
?f rdf:type ccos:InformationBearingEntity .
585 ?f ccos:has_decimal_value ?ProstheticToothVolume .
?e ccos:is_input_of ?g .
?g rdf:type amos:ActOfAnalysisOfInspectionData .

```

```

?h ccos:is_output_of ?g .

?h rdf:type amos:AnalysisMeasurementInformationContentEntity .

590 ?h ccos:inheres_in ?i .

?i rdf:type ccos:InformationBearingEntity .

?i ccos:has_decimal_value ?VolumeDifferencePercentage }

```

Figure 15 shows the result of this query.

Machine	ProstheticTooth	ProstheticToothVolume	VolumeDifferencePercentage
ObjetEden2501	'Premolar Tooth 34 Mandible1 (OE250)'	"482.6"^^<http://www.w3.org/2001/XMLSchema#"1.3"^^<http://www.w3.org/2001/XMLSchema	
ObjetEden2501	'Premolar Tooth 44 Mandible1 (OE250)'	"516.2"^^<http://www.w3.org/2001/XMLSchema#"0.9"^^<http://www.w3.org/2001/XMLSchema	
ObjetEden2501	'Premolar Tooth 45 Mandible1 (OE250)'	"446.2"^^<http://www.w3.org/2001/XMLSchema#"0.3"^^<http://www.w3.org/2001/XMLSchema	
ObjetEden2501	'Premolar Tooth 34 Mandible2 (OE250)'	"398.2"^^<http://www.w3.org/2001/XMLSchema#"1.1"^^<http://www.w3.org/2001/XMLSd	
ObjetEden2501	'Premolar Tooth 44 Mandible2 (OE250)'	"361.0"^^<http://www.w3.org/2001/XMLSchema#"1.1"^^<http://www.w3.org/2001/XMLSc	
ObjetEden2501	'Premolar Tooth 45 Mandible2 (OE250)'	"469.1"^^<http://www.w3.org/2001/XMLSchema#"0.9"^^<http://www.w3.org/2001/XMLSc	
ObjetConnex3501	'Premolar Tooth 34 Mandible1 (OC350)'	"502.1"^^<http://www.w3.org/2001/XMLSchema#"2.7"^^<http://www.w3.org/2001/XMLSd	
ObjetConnex3501	'Premolar Tooth 44 Mandible1 (OC350)'	"521.2"^^<http://www.w3.org/2001/XMLSchema#"0.1"^^<http://www.w3.org/2001/XMLSd	
ObjetConnex3501	'Premolar Tooth 45 Mandible1 (OC350)'	"438.8"^^<http://www.w3.org/2001/XMLSchema#"2.0"^^<http://www.w3.org/2001/XMLSc	
ObjetConnex3501	'Premolar Tooth 34 Mandible2 (OC350)'	"421.6"^^<http://www.w3.org/2001/XMLSchema#"7.0"^^<http://www.w3.org/2001/XMLSd	
ObjetConnex3501	'Premolar Tooth 44 Mandible2 (OC350)'	"351.0"^^<http://www.w3.org/2001/XMLSchema#"3.8"^^<http://www.w3.org/2001/XMLSc	
ObjetConnex3501	'Premolar Tooth 45 Mandible2 (OC350)'	"464.2"^^<http://www.w3.org/2001/XMLSchema#"1.9"^^<http://www.w3.org/2001/XMLSc	

Figure 15: Query 3 Result

595 The answers to the example of queries show the ability of the ontology to retrieve information that matched to the queries even though the classes in AMDO are imported from different ontologies. This is because, AMDO is an extension of AMO and AMO is an extension of CHAMP which are extended from the CCO and BFO. We use the import process in developing the ontology

600 to maintain the URI of the classes so that the naming of the class, the class structure, the class definition and the class relations will be standardized in all related ontologies. This will ensure re-usability of the ontology. Even though, we have not tested the interoperability of the ontology yet, but aiming for the re-usability of the ontology is a starting point in achieving interoperability of

605 the ontology.

Nevertheless, due to the import structure of the AMDO with the AMO,CHAMP, CCO and BFO, we will have CCO terms available in AMDO. The CCO terms

may then extend the reach of AMDO to cope with corresponding data concern-
ing persons and organizations, roles of persons (for instance dental technician,
610 patient), measurement units, and cost factors. Thus, the functionality of AMDO
can be extended to cope with a digital record or a patients history record in such
a way as to document the process of maintenance of the dental crown, comparing
susceptible of wear of the crown and of associated dental disorders in different
patients, perhaps incorporating also terms from the OBOFoundry⁶.

615 **6. Conclusion and Future Work**

The AMO was developed within the context of a more general treatment
of the PLC. It will be helpful to users who employ AM in their work, and who
face the challenge of data integration faced by most modern industries today.
It can assist the designer in designing a new product, by enabling access to
620 bodies of data across the entire dentistry product manufacturing domain, for
example relating to materials used, patient experiences, maintenance costs, and
so forth. The framework is also sufficiently general that it may accommodate
the generation of more fine-grained application ontologies in other areas where
AM technology is applied.

625 As the manufacturing industry is evolving rapidly and becoming more com-
petitive, quality and cost are major factors that need to be focused on by the
manufacturers. These factors are affected closely by the process and the material.
We concentrated here primarily on the process aspect in the AM process but
in the next stage, we will work on integrating the AMO with the ontology that
630 represents the types of material used in AM and their associated attributes.
This will build on work on the ontology of material that is part of the CHAMP
ontologies, where each ontology in CHAMP constitutes a mid-level ontology that

⁶See <http://www.obofoundry.org/ontology/ohd.html>

imports the whole of the CCO, as well as BFO.

References

- 635 [1] X. Chang, R. Rai, J. Terpenney, Development and utilization of ontologies in design for manufacturing, *Journal of Mechanical Design* 132 (2010) 021009.
- [2] A. Gunasekaran, E. Ngai, Knowledge management in 21st century manufacturing, *International Journal of Production Research* 45 (2007) 2391–2418.
- [3] R. Young, A. G. Gunendran, A.-F. Cutting-Decelle, M. Gruninger, Manufacturing knowledge sharing in plm: a progression towards the use of heavy
640 weight ontologies, *International Journal of Production Research* 45 (2007) 1505–1519.
- [4] T. Economist, Knowledge management in manufacturing, 2007. URL: [www.01net.it/wp-content/uploads/sites/14/2014/10/siemens_ugs_](http://www.01net.it/wp-content/uploads/sites/14/2014/10/siemens_ugs_Knowledge_management.pdf)
645 [Knowledge_management.pdf](http://www.01net.it/wp-content/uploads/sites/14/2014/10/siemens_ugs_Knowledge_management.pdf).
- [5] S. Lemaignan, A. Siadat, J.-Y. Dantan, A. Semenenko, Mason: A proposal for an ontology of manufacturing domain, in: *Distributed Intelligent Systems: Collective Intelligence and Its Applications*, 2006. DIS 2006. IEEE Workshop on, IEEE, 2006, pp. 195–200.
- 650 [6] C. Welty, D. L. McGuinness, M. K. Smith, Owl web ontology language guide, W3C recommendation, W3C (February 2004) <http://www.w3.org/TR/2004/REC-owl-guide-20040210> (2004).
- [7] B. Motik, P. F. Patel-Schneider, B. Parsia, C. Bock, A. Fokoue, P. Haase, R. Hoekstra, I. Horrocks, A. Rutenber, U. Sattler, Owl 2 web ontology language: Structural specification and functional-style syntax, W3C
655 recommendation 27 (2009) 159.

- [8] T. Kjellberg, A. von Euler-Chelpin, M. Hedlind, M. Lundgren, G. Sivard, D. Chen, The machine tool modela core part of the digital factory, CIRP annals 58 (2009) 425–428.
- 660 [9] M. A. Musen, Upper Level Ontology. In: Dubitzky, W., Wolkenhauer, O., Yokota, H., Cho, K-H.(eds)Encyclopedia of systems biology, Springer Publishing Company, Incorporated, 2013.
- [10] Ramos, 2011. URL: https://downloads.sourceforge.net/project/ontomanufacture/mop/Machine_Ontology.owl.
- 665 [11] L. Ramos, R. Gil, D. Anastasiou, M. J. Martin-Bautista, Towards a machine of a process (mop) ontology to facilitate e-commerce of industrial machinery, Computers in Industry 65 (2014) 108–115.
- [12] L. Mazzola, P. Kapahnke, M. Vujic, M. Klusch, Cdm-core: A manufacturing domain ontology in owl2 for production and maintenance, in: KEOD, ????, pp. 136–143.
- 670 [13] F. Ameri, C. Urbanovsky, C. McArthur, A systematic approach to developing ontologies for manufacturing service modeling, in: Proc. 7th International Conference on Formal Ontology in Information Systems (FOIS 2012), Graz, Austria, Citeseer, 2012.
- 675 [14] L. Mesmer, A. Olewnik, Development of a part-focused manufacturing process ontology: Exploring use and applications, in: ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, 2015, pp. V01BT02A034–V01BT02A034.
- 680 [15] B. Smith, 2017. URL: https://emmc.info/wp-content/uploads/2017/12/EMMC-IntOp2017-Cambridge_Smith_Buffalo.pdf.

- [16] Y.-J. Chen, Y.-M. Chen, H.-C. Chu, Development of a mechanism for ontology-based product lifecycle knowledge integration, *Expert Systems with Applications* 36 (2009) 2759–2779.
- 685 [17] M. B. Raza, R. Harrison, Ontological knowledge based system for product, process and resource relationships in automotive industry, in: *Proceedings of the 1st International Workshop on Ontology and Semantic Web for Manufacturing*, Heraklion, Crete, Greece, 2004, pp. 23–36.
- [18] M. Borsato, Bridging the gap between product lifecycle management and sustainability in manufacturing through ontology building, *Computers in Industry* 65 (2014) 258–269.
- 690 [19] H. Cao, P. Folan, Product life cycle: the evolution of a paradigm and literature review from 1950-2009, *Production Planning & Control* 23 (2012) 641–662.
- [20] A. Matsokis, D. Kiritsis, An ontology-based approach for product lifecycle management, *Computers in industry* 61 (2010) 787–797.
- 695 [21] N. Chungoora, R. Young, G. Gunendran, Z. Usman, N. Anjum, C. Palmer, J. Harding, K. Case, A. CuttingDecelle, A model driven ontologybased approach for manufacturing knowledge sharing in plm, *Enterprise Interoperability: IESA'12 Proceedings* (2012) 197–204.
- 700 [22] Z. Usman, R. I. M. Young, N. Chungoora, C. Palmer, K. Case, J. Harding, A manufacturing core concepts ontology for product lifecycle interoperability, in: *International IFIP Working Conference on Enterprise Interoperability*, Springer, 2004, pp. 5–18.
- 705 [23] E. Urwin, Deliverable D3.2: Initial formal ontologies, Report,

2014. URL: <http://www.flexinet-fof.eu/Documents/FLEXINET%20D3.2%20Initial%20Formal%20Ontologies.pdf>.
- [24] E. Urwin, C. Palmer, B. Young, E. Palacios, J. M. Pinazo, A. Font, R. Al-
marcha, Deliverable D3.5: Product-service-production ontologies report, Re-
710 port, 2016. URL: <http://www.flexinet-fof.eu/Documents/FLEXINET%20D3.5%20Product-Service-Production%20Ontologies.pdf>.
- [25] A. Standard, Iso/astm 52900: 2015 additive manufacturing-general principles-terminology, ASTM F2792-10e1 (2012).
- [26] D. Eddy, S. Krishnamurty, I. Grosse, M. Perham, J. Wileden, F. Ameri,
715 Knowledge management with an intelligent tool for additive manufacturing,
in: ASME 2015 International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference, American Society
of Mechanical Engineers, 2016, pp. V01AT02A023–V01AT02A023.
- [27] M. Dinar, D. W. Rosen, A design for additive manufacturing ontology,
720 Journal of Computing and Information Science in Engineering 17 (2017)
021013.
- [28] NIST, Nist’s owl ontology for additive manufacturing, 2016. URL: <https://github.com/iassouroko/AMontology>.
- [29] B.-M. Roh, Ontology-Based Laser Metamodels and Visualization for Metal-
725 Based Additive Manufacturing, Thesis, 2017.
- [30] J. S. Liang, An ontology-oriented knowledge methodology for process plan-
ning in additive layer manufacturing, Robotics and Computer-Integrated
Manufacturing 53 (2018) 28–44.
- [31] T. J. Hagedorn, S. Krishnamurty, I. R. Grosse, A knowledge-based method
730 for innovative design for additive manufacturing supported by modular

ontologies, *Journal of Computing and Information Science in Engineering* 18 (2018) 021009.

[32] N. Natalya F, M. Deborah L, *Ontology development 101: A guide to creating your first ontology*, 2001.

735 [33] 2016. URL: <https://github.com/CommonCoreOntology/CommonCoreOntologies/blob/master/Best%20Practices%20of%20Ontology%20Development.pdf>.

[34] R. Arp, B. Smith, A. D. Spear, *Building ontologies with basic formal ontology*, Mit Press, 2015.

740 [35] V. Mascardi, V. Cord, P. Rosso, A comparison of upper ontologies, in: *Woa*, volume 2007, ????, pp. 55–64.

[36] S. Borgo, P. Leito, The role of foundational ontologies in manufacturing domain applications, in: *OTM Confederated International Conferences” On the Move to Meaningful Internet Systems”*, Springer, 2004, pp. 670–688.

745 [37] CUBRC, *Common Core Ontologies for Data Integration*, 2017. URL: <https://www.cubrc.org/index.php/data-science-and-information-fusion/ontology>.

[38] F. Furini, R. Rai, B. Smith, G. Colombo, V. Krovi, Development of a manufacturing ontology for functionally graded materials, in: *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, 2016, pp. V01BT02A030–V01BT02A030.

750 [39] B. Smith, *Basic Formal Ontology 2.0 Specification and User’s Guide*, 2015. URL: <https://github.com/BFO-ontology/BFO/raw/master/docs/bfo2-reference/BFO2-Reference.pdf>.

755

- [40] W. Ceusters, B. Smith, Aboutness: Towards foundations for the information artifact ontology, in: Proceedings of the Sixth International Conference on Biomedical Ontology (ICBO), volume 1515, CEUR, 2015, pp. 1–5.
- [41] CUBRC, An Overview of the Common Core Ontologies, 2017. URL:
760 [https://github.com/CommonCoreOntology/CommonCoreOntologies/
blob/master/An%20overview%20of%20the%20Common%20Core%
20ontologies%201.0.pdf](https://github.com/CommonCoreOntology/CommonCoreOntologies/blob/master/An%20overview%20of%20the%20Common%20Core%20ontologies%201.0.pdf).
- [42] L. Yang, K. Hsu, B. Baughman, D. Godfrey, F. Medina, M. Menon, S. Wiener, Additive Manufacturing of Metals: The Technology, Materials,
765 Design and Production, Springer, 2017.
- [43] B. Smith, On classifying material entities in basic formal ontology, in: Interdisciplinary Ontology: Proceedings of the Third Interdisciplinary Ontology Meeting, Keio University Press, 2012, pp. 1–13.
- [44] A. Barazanchi, K. C. Li, B. AlAmleh, K. Lyons, J. N. Waddell, Additive
770 technology: update on current materials and applications in dentistry, Journal of Prosthodontics 26 (2017) 156–163.
- [45] A. Dawood, B. M. Marti, V. Sauret-Jackson, A. Darwood, 3d printing in dentistry, British dental journal 219 (2015) 521.
- [46] W. Khalil, M. EzEldeen, E. Van De Castele, E. Shaheen, Y. Sun, M. Shah-
775 bazian, R. Olszewski, C. Politis, R. Jacobs, Validation of cone beam computed tomographybased tooth printing using different three-dimensional printing technologies, Oral surgery, oral medicine, oral pathology and oral radiology 121 (2016) 307–315.