



A product life cycle ontology for additive manufacturing

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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.

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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 [1–3]. 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.

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's Semantics Ontology (MASON), which employs three top-level classes of *entities*, *operations*, and *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

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geographic resources. MASON was developed as an upper-level ontology to accomplish two goals:

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, 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 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 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 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 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 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 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 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), 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 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 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 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 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 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 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, 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 [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 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 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].

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.

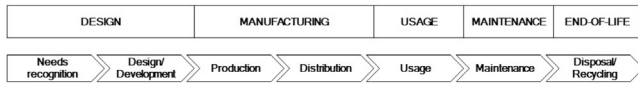


Fig. 1. Phases in the PLC.

Fig. 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.

Table 1, from Chen et al. [16], extends this representation to create a more 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 manufacturing phases in PLC through ontology. Borsato [18] for instance, 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.

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 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 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), 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 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-6-4Al-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 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 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 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 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 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, Natalya F and Deborah L [32] outlined a simple knowledge-engineering methodology in developing ontology which was followed as a guideline in our work. The methodology

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

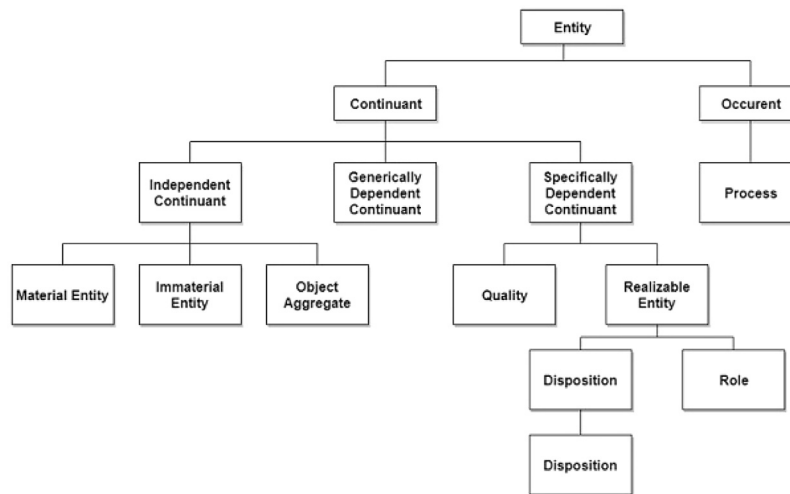


Fig. 2. A fragment of the BFO class hierarchy [39].

include: determining ontology domain and scope, considering ontology reuse, enumerating important terms, defining classes and class hierarchies, defining class properties, defining values for properties, and creating instances of 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]:

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 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 [34–36]. Both 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 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 *occurent*, 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 Fig. 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 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 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, 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, and their roles.

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

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

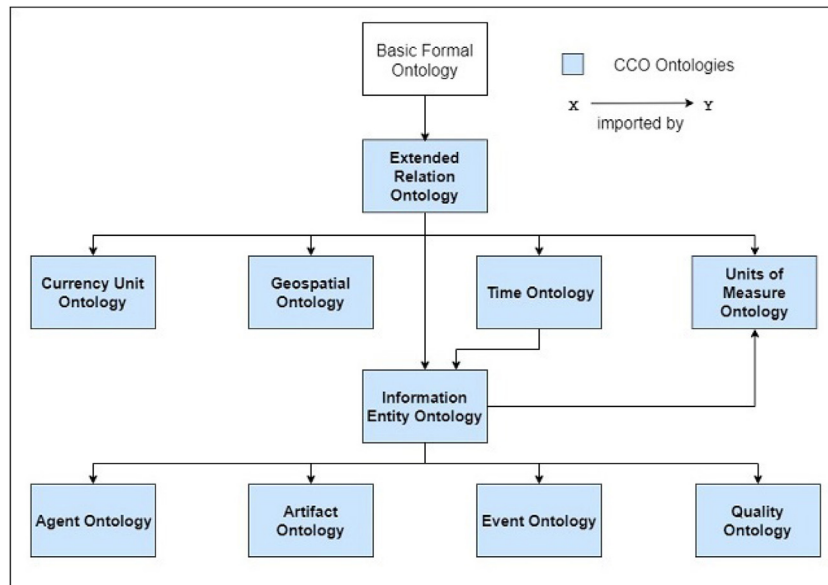


Fig. 3. The Common Core Ontology import structure [37].

- 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) 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.
- 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.
- 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 measuring various attributes of entities.

Fig. 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.

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 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 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:

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

Fig. 4 shows the CHAMP ontologies and their import structure.

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 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. Fig. 5 shows the framework for the AMO development.

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.

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

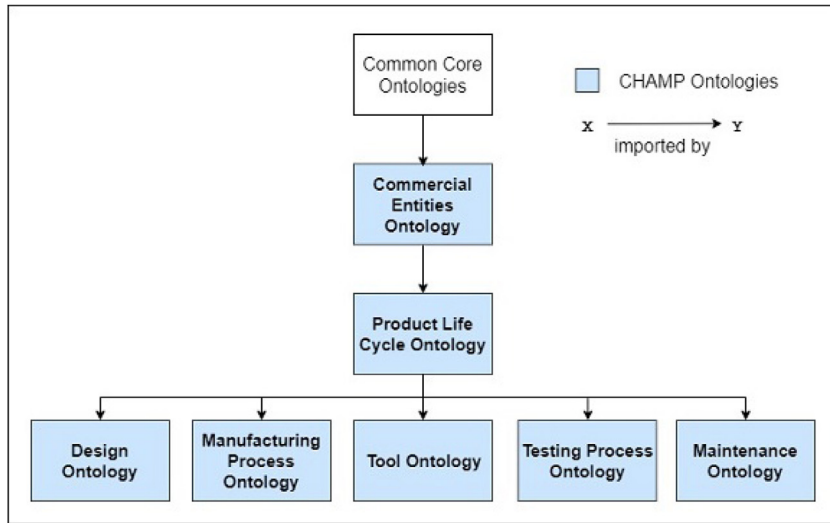


Fig. 4. The CHAMP Ontologies.

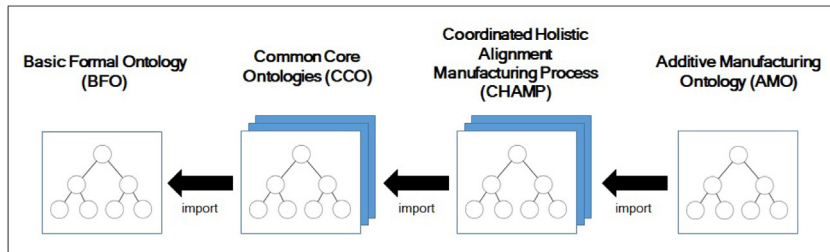


Fig. 5. An overview of AMO development.

3. Setting the process parameters;
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 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*
3. AMO: *ActOfCADModelDevelopment*
4. AMO: *ActOfDataTransformation*
5. Design Ontology: *ActOfManufacturingRequirementIdentification*
6. Manufacturing Process Ontology: *ActOfAdditiveManufacturing*
7. AMO: *ActOfSupportRemoval*
8. AMO: *ActOfPostProcessing*

As can be seen, some of these classes are imported from the Design Ontology and the Manufacturing Process Ontology. Fig. 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, 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.

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. Fig. 7 shows the example of some *ActOfSupportRemoval* that has *process_part* an *ActOfMaterialRemoval* and an *ActOfPostProcessing* that has an *ActOfAbrading* and an *ActOfJoining* as process parts.

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 BFO: *object*, *flat 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 in the AMO. These resources are:

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

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 Fig. 8. Meanwhile, *3DPrintingMachine*, *PrintedObject*, and *FinishedObject* are types of *object* in BFO [43]. *PrintedObject* and *FinishedObject* are defined classes with definitions as follows:

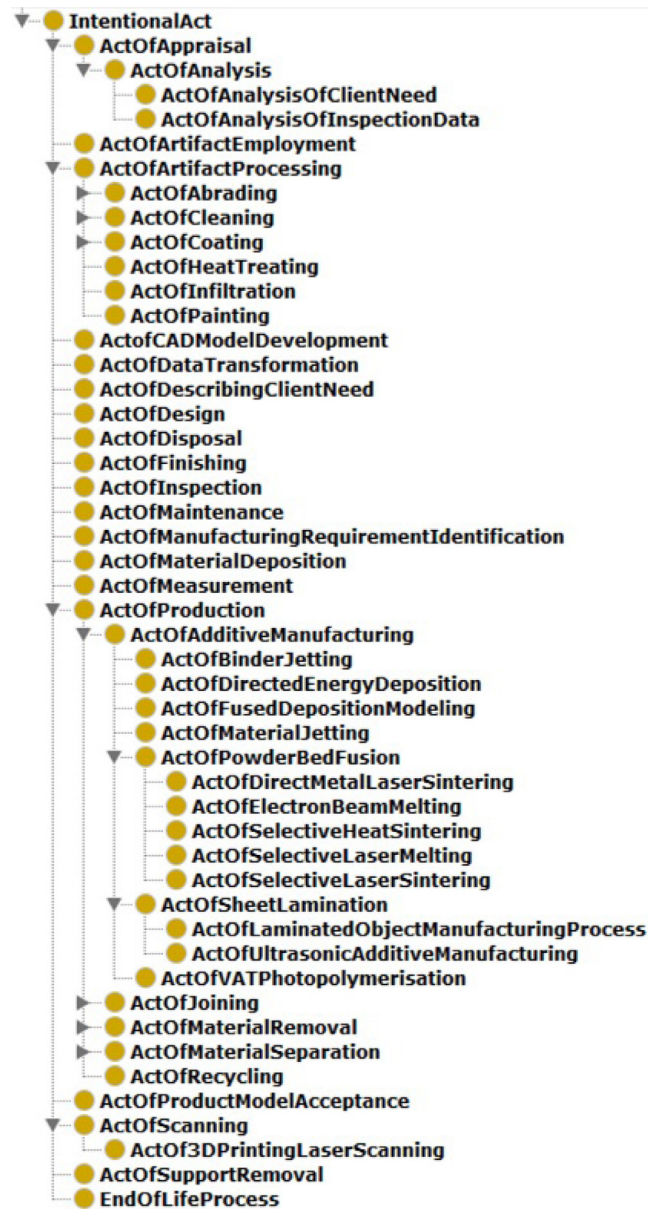


Fig. 6. Process classes in AMO.

- *PrintedObject* is an object that is and 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 Dependent Continuant* that generically depends on some *Information Bearing Entity* and stands in the relation of *aboutness* to some entity⁴". 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 a series of classes of information that either prescribe, designate, or describe various AMO processes and resources. These are displayed in Fig. 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 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, in a particular environment, using a set of

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

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

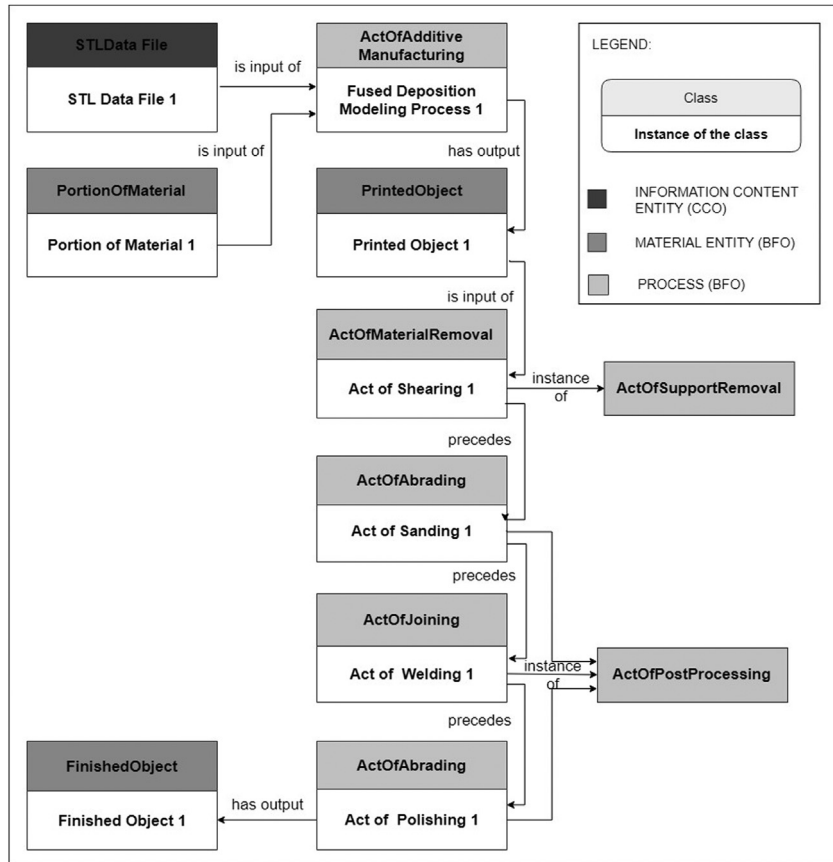


Fig. 7. Example for process parts of Act of Support Removal and Act of Post Processing.

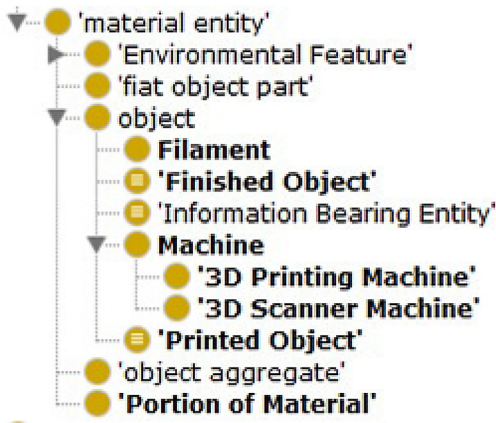


Fig. 8. Material Entity classes in AMO.

primitive components, satisfying a set of requirements, subject to constraints.

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

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

Fig. 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.

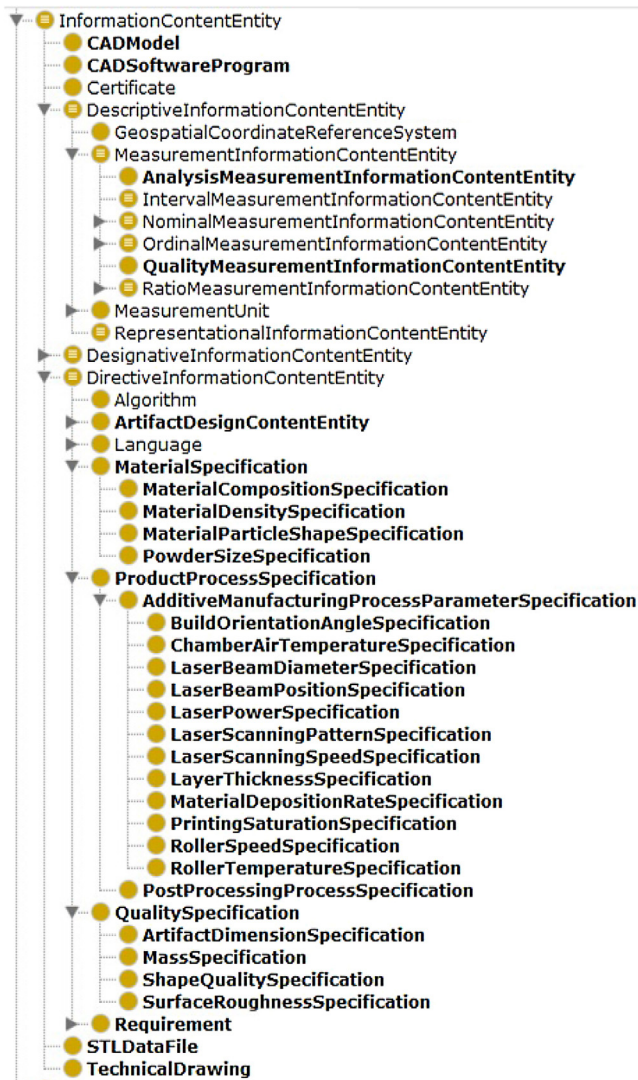


Fig. 9. Information Content Entity classes in AMO.

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 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.

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 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 Ontology (AMDO) and is depicted in Fig. 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.

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 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].

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

For the testing purposes of AMDO, we populated all data from Tables 2 and 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:

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?

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 subject-predicate-object. For each queries, following are the namespace and its 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#
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/
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#

```

Query 1: Identifying 3D printers used in the study.
The SPARQL Query for this question is as follow:

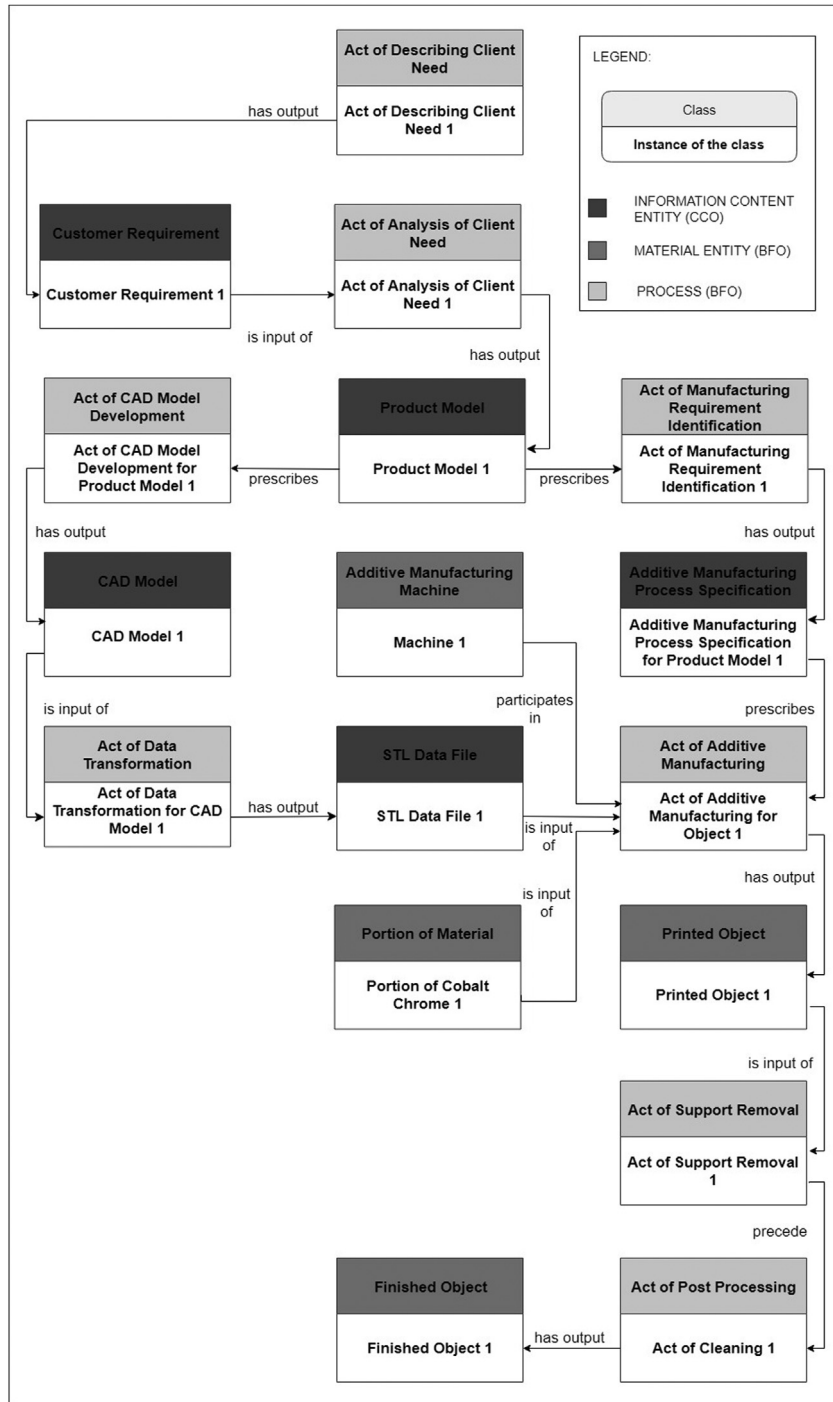


Fig. 10. An overview of AMO entities and relations.

```
SELECT ?Machine
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 input and low selectivity and does not assume any hierarchy information or inference. Fig. 12 shows the result of this query.

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

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 Query for this question is as follows:

```
SELECT ?Machine ?Material ?LayerThickness ?MeasurementUnit
WHERE {
  ?a rdf:type amos:ActOfVATPhotopolymerisation.
```

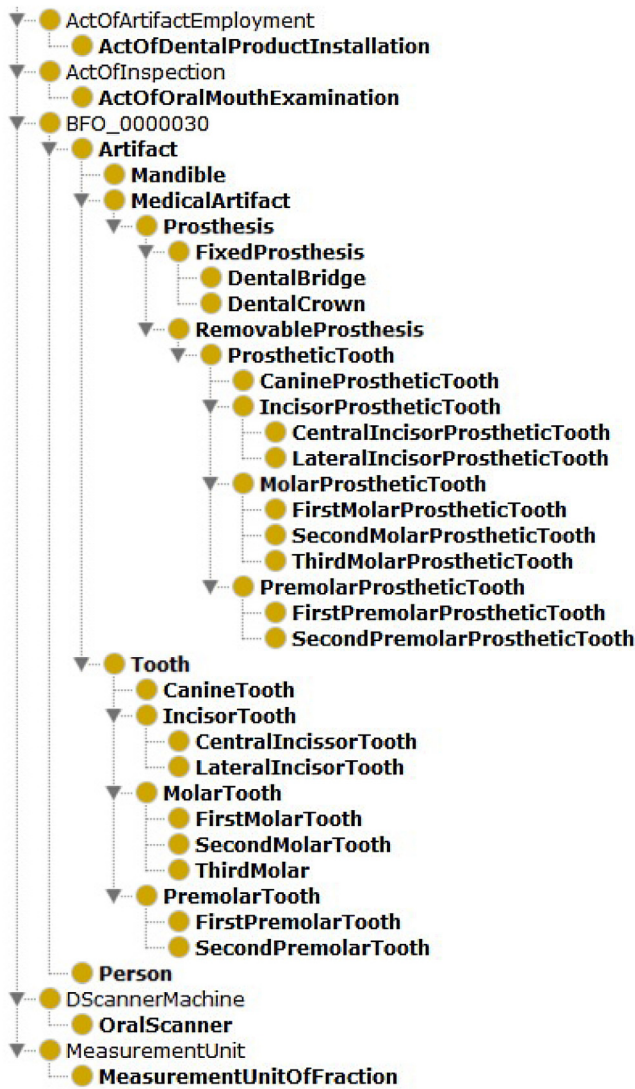


Fig. 11. Active classes in AMDO.

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

```
?Machine ros:agent_in ?a.
?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.
?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 }
```

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. Fig. 13 shows the result of this query.

Query 3: Identifying volume differences of the printed tooth with the uses of 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 shown in Fig. 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 follows:

```
SELECT ?Machine ?ProstheticTooth ?ProstheticToothVolume ?VolumeDifferencePercentage
WHERE {
?a rdf:type amos:ActOfMaterialJetting.
?Machine ros:agent_in ?a.
?Machine rdf:type amos:3DPrintingMachine.
?ProstheticTooth ccos:is_output_of ?a.
?ProstheticTooth rdf:type amdo:PremolarProstheticTooth.
?ProstheticTooth ccos:bearer_of ?d.
?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.
?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.
?h ccos:inheres_in ?i.
?i rdf:type ccos:InformationBearingEntity.
?i ccos:has_decimal_value ?VolumeDifferencePercentage }
```

Fig. 15 shows the result of this query.

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 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 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 concerning persons and organizations, roles of persons (for instance dental technician, patient), measurement units, and cost factors. Thus, the functionality of AMDO can be extended to cope with a digital record or a patient's 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.

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

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%)

Machine
ObjetEden2501
ObjetConnex3501
SLA1
UPPlus2

Fig. 12. Query 1 result.

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'

Fig. 13. Query 2 result.

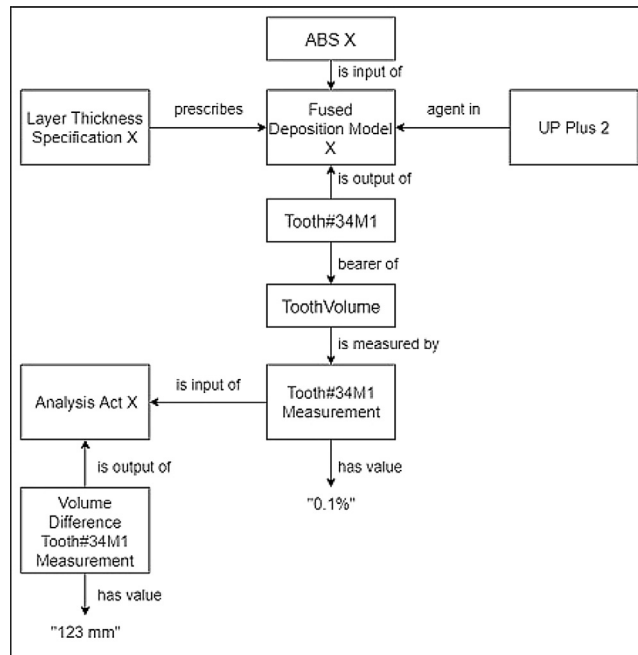


Fig. 14. Instances in AMDO.

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

Fig. 15. Query 3 result.

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 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.

As the manufacturing industry is evolving rapidly and becoming more competitive, 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 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 imports the whole of the CCO, as well as BFO.

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