Proceedings of the ASME 2023
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC/CIE2023
August 20-23, 2023, Boston, Massachusetts

DETC2023-113755

COMPARATIVE STUDY OF APPROACHES FOR AN ONTOLOGY OF DIGITAL ARTIFACTS

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ABSTRACT

Modern business, engineering, and manufacturing are supported by many software tools. Those tools not only help create new products for customers but also enable delivering them in increasingly shorter time periods. To achieve both, the ability to transfer, exchange, integrate, and analyze digital data among supply chain participants with diverse software tools is needed. Creating that ability, however, requires a higher level of interoperability with support from semantics tools, such as knowledge graphs and ontologies. As many engineering and business tasks involve digital communication, it is important to develop ontologies for digital artifacts of various fidelity levels and various scopes of the product life cycle to enable the required interoperability. There are ontologies associated with the various stages of the product life cycle. Those ontologies have various fidelity levels that correspond to specific lifecycle stages and that enable the required interoperability within those stages, with very few enabling interoperability between the stages.

To address those ontology needs, the Industrial Ontology Foundry (IOF) has released the first version of its Core ontology. The Core provides a basis to represent information about some digital objects such as plan specification as well as physical objects such as occurrence of a process (that may or may not be proceeding according to the plan). While that is the case, there is still a need for the IOF Core to provide further guidance on how they should be related and how to scale to various types of digital and physical objects.

To address the issues of relations between physical and digital objects, this paper provides an overview of approaches from recent literature and efforts by the authors and collaborators. It then illustrates in more detail four approaches that are more aligned with the Basic Formal Ontology (BFO), on which the IOF Core is based. General and use case specific requirements are used to arrive at our initial observations. Finally, we discuss a plan for further analysis.

Keywords: digital twin, digital thread, industrial ontology, digital artifacts

1. INTRODUCTION

Ontologies can be used for organizing knowledge and providing a common language for communication between different types of information, between different software systems and different manufacturing domains. On of those types is a digital artifact, which is a digital object that sui related to its future or current physical counterpart. Ontologies can explicate the relationships between different types of digital objects and their properties, on one side and their physical counterparts, on the other side. Ontologies make these relations more easily searched and compared.

The study of digital artifacts, based on ontologies has become increasingly important for three emerging reasons. The first is the exponential growth of digital data. The second is the emergence of digital twins. The third is a new requirement for building a full, digital thread of both the product and process lifecycles. Because of these reasons, there are already several approaches for ontological representations in the domain of digital artifacts. In this comparative study, we review and compare ontological approaches based on several criteria, including ontology quality, scalability, and applicability. While the work is still in the early stage, we believe that it would be fruitful to share with the research community to garner more attention to this important problem. The future aim is to use the results from this study as the foundation for new types of ontology-based standards.

2. REQUIREMENTS

In order to be able to compare various approaches to the above identified problem, two sets of requirements will be used to characterize each approach. The first are general requirements, which include quality characteristics of any ontology of digital artifacts. The second are use case requirements, which refer to a set of competency questions that the ontology must be able to answer.

2.1 General requirements

The following general requirements are proposed: scalability, number of constructs, efficiency, compliance and digitization.

- Scalability (i.e., extensibility) to unknown/new types of digital and physical artifacts, e.g., considering differing product lifecycles in various industries. For example, in agricultural industry there are notions of as-planted, as-applied, and as-harvested unfamiliar to notions in traditional manufacturing such as as-designed and as-manufactured.
- Number of constructs (classes, relations, and individuals) required
- Information retrieval efficiency
- IOF/BFO (Basic Formal Ontology) compliance
- Digital twin modeling for a product/process/system

Scalability refers to how many different classes or relations need to be added when introducing a new type of digital artifacts, e.g., we talk about design, about requirements, plan, and predictive model.

Number of constructs required for representing a new digital refers to the number of classes, relations, and individuals in one specific model type such as dimensions, designs, parts, components, tolerances, part-of relations, roles, capabilities, etc.

Information retrieval efficiency refers to how fast competency questions can be answered from a real case of knowledge graph and more importantly how it scales – linearly, polynomially, or exponentially as the number of objects grows.

IOF/BFO compliance means adherence to realist ontology principles [1] of BFO, which is the top-level ontology of the IOF Core ontology.

Modeling the characteristics of a digital artifact considers how the ontology may address the requirements to support digital twin use cases which can be generalized according to three cases with varying complexities, namely digital model, digital shadow, and digital twin [2]. Also, varying levels of details of each individual digital artifact should be considered, for example, 3D models, static simulations, and dynamic simulations. The scope is another dimension in considering digital artifacts, cases such as a product digital twin, a process digital twin, and a system digital twin need to be considered.

2.2 Use Case Requirements

Use case requirements are based on our collaborations with industry partners in discrete and biopharmaceutical manufacturing. In those collaborations, it is typical to observe the need to trace and compare the digital artifacts such as requirement, designs, and plans, with the actual as-manufactured, as-executed, as-tested, physical counterparts both from the material and process perspectives. Some of the common competency questions are:

1. What is the structure of a designed artifact versus the structure of its physical counterpart (e.g., which parts it MUST/SHOULD/MAY have versus which parts a manufactured artifact has)?
2. What are the specified process settings in the plan versus the actual settings, which are based on the measured values?
3. Which participants are prescribed to participate in a process according to a process plan vs the participants in the actual occurrence of the process?
4. Which attributes (e.g., capability) MUST an equipment in a process have according to a plan and what is the equipment and its respective attributes that are used in the actual process?
5. How do designs (in terms of components and their attributes) change from one version of the artifact to another version - artifact design v_1 vs artifact design v_2?
6. How do we compare the artifact's design to artifact's requirements, to artifact's simulated model, or to its physically manufactured artifact?
7. How do we compare the prescribed process plan versus the actual, executed process plan? Of particular importance is to understand the structure of optional steps in the plan and which of them occurred in the physical process.

This list is by no means complete, as more questions may surface when more use cases are considered. Many of them refer to physical objects, but question 7 refers to physical processes. For example, digital processes have not been included in our consideration in this paper. They will be considered in our future works.

3. PREVIOUS WORK

Using ontologies to establish digital artifacts and their physical counterparts has attracted a lot of research attention in recent years. Ontologies not only provide more precise semantic definitions of terms in the increasingly complex digital engineering domain, but they also provide a way to represent knowledge and data in a structured and, more importantly, readily connected manner. These ontologies will give scientists and engineers access to the knowledge they need to execute planning and manufacturing tasks.

3.1 OntoSTEP

The International Organization for Standardization (ISO) has developed a comprehensive international standard called **STEP** which stands for "**ST**andard for the **E**xchange of **P**roduct model data" known as ISO 10303 [3]. STEP is intended to provide a common language for representing product data throughout the entire product lifecycle, from conceptual design to disposal. It covers a wide range of product-related data, including geometry, attributes, relationships, tolerances, manufacturing processes, and more [4]. The standard enables product data to be exchanged easily, consistently, and error-free between different software systems used by different organizations. STEP represents and exchanges the information about the objects and their relationship in schemas using EXPRESS, a modeling language [5,6].

The National Institute of Standards and Technology (NIST) developed *OntoSTEP* as part of its efforts to introduce more formal semantics and reasoning capability to the use of the STEP standard [7]. OntoSTEP is a translation of EXPRESS schema into the Web Ontology Language (OWL). Subsequent work in [8] demonstrated OWL as a linked data facility to link OntoSTEP OWL geometric data with non-geometric design data from tools such as the Unified Modeling Language (UML).

One of the key features of OntoSTEP is its ability to represent different versions [7] of the same digital artifact. This is important in engineering and manufacturing, where multiple versions of a product may be created over time. OntoSTEP provides a way to track those version changes to the product data. However, there is no explicit provision in OntoSTEP to represent and link data about physical parts with their design counterparts.

3.2 CCO and MRO Ontologies

Common Core Ontology (CCO) was developed to support the representation of common concepts and relationships across different domains [9]. The Common Core Ontology is designed to be modular and extensible, allowing the addition of new concepts and relationships as needed.

The Modal Relation Ontology (MRO) is a method within CCO. It allows for the representation of situations that are specified, such as an action outlined in a plan or a functionality specified in the design of an artifact, but do not currently exist or may never come to realization [10].

The motivation behind developing this ontology can be explained through an example. Not all plans happen exactly as they were originally intended, and this necessitates a differentiation between two events: the intended events and the actual events. Similarly, not all (digital) artifacts are materialized as they were designed. Because of this, the relationships between a designed artifact and the actual artifact are complicated. First, the actual artifact may not be functioning as intended. Second, the ideal functioning of the artifact might not be possible to implement. In essence, it is often important to distinguish between the execution of a plan and the plan itself.

Overall, the MRO provides a means of distinguishing between the actual and the ideal states of manufactured parts. Parts may be prescribed, but may not necessarily exist. This situation, thereby, requires facilitating a more nuanced representation of information. MRO can be tailored to the user's needs, allowing for precise modeling of prototypical artifacts and any artifacts built according to the same specifications. MRO facilitates the integration of data about planned events, artifact specifications, and performance characteristics of hypothetical entities in a robust manner.

3.3 Other Approaches Related to Digital Artifacts

Baker states that artifacts are objects created by humans for specific purposes, which are based on the functions and the intentions of their creators [11]. The digital artifacts can be thought of as digital replicas of real-world, physical objects. But artifacts also have a kind of identity that is tied to those specific purposes. In terms of digital artifacts, they pose challenges to traditional ontological frameworks, since they are ontologically ambivalent [12]. This ambivalence exists becuase digital artifacts are created through complex technological processes that involve both physical and non-physical components, such as algorithms and software code that can be just ideas or ones written on a piece of paper. As a result, digital artifacts have a hybrid ontological status that makes them difficult to classify and analyze.

Ontology visualization techniques are examples of such a hybrid status. Dudáš et al. stated that ontologies are formal representations of knowledge that can be used for knowledge management, information retrieval, and semantic web applications. Visualization can help users understand and explore the structure and content of ontologies and can support various tasks such as ontology development, evaluation, and alignment [13]. There are various visualization methods, including tree-based, graph-based, 3D representations, interactive, and matrix-based techniques.

Katifori et al. highlighted some of the challenges in ontology visualization, such as the need to balance complexity and readability, the need to support interactive exploration, and the need to provide visualizations that are accessible to different groups of users [14]. Other challenges of designing effective visualizations for ontologies include dealing with substantial amounts of data and ensuring that the visualizations are intuitive and easy to understand. As Lanzenberger et al. emphasized, the reason for incorporating visualizations into ontology tools to help users navigate and make sense of complex, digital knowledge structures [15].

4. REPRESENTING DIGITAL ARTIFACTS

Based on the initial sections, the extended literature review, and the authors experience in working within IOF, we have identified four, BFO-compliant, candidate approaches for representing digital artifacts. In this section we will illustrate each based on the same, simplified, engineering-design task. Those approaches are a) modal relations ontology (MRO) Approach, b) Information Content Entity (ICE) approach, c) Representation/Specification approach, and d) Counterpart relation approach. All of them have been reported in the literature (we will provide references in each subsection) and all have been used in different manufacturing domains. In each approach, we will demonstrate how the relationships between the digital and physical artifacts are represented as the semantics needed for the following engineering task: "*There is a need to* *design and produce a jet engine that will have a compressor as its part, and it will be able to produce a minimal thrust of 700 kN*". This simple example provides sufficient elements to compare the approaches.

In the following subsections, representation of the use case in all four approaches is explained. It is recommended to read the paper and the pictures with colors, as we have color-coded the classes and instances. BFO classes are shown in magenta, IOF classes are shown in cyan, while use case specific classes are shown in light green and yellow. Instances are shown consistently in all approaches, such that instances of ICEs are green circles, instances of physical artifacts are in pink, and instances of qualities are in blue. The legends are shown in the figure of the first example. All relations are labeled, except *is-a* and *instance-of*, which are shown with different line styles – coarse and fine dotted line – respectively.

4.1 MRO Approach

The Modal Relation Ontology (MRO) approach was conceived as part of the CCO effort [9]. As noted, MRO provides a way of representing future states that currently do not exist yet or may never exist. Examples of such future states include an action prescribed by a plan or some functionality prescribed by an artifact's design specification. The need to distinguish physical artifacts from their prescriptions was recognized in work by Rudnicki et al [10]. They argued that numerous benefits could be obtained from being able to compare data about actual instances with the data about plans and specifications for those instances in the context of mission planning, sensor assignments, and asset tracking in the military domain.

To achieve those benefits, the MRO approach proposed to use two namespaces for relations, CCO and MRO. The approach is facilitated by BFO 2.0, which modularized basic relations into a separate ontology module called Relation Ontology or RO[1]. The MRO ontology is essentially a copy of the RO ontology but uses a different namespace, here designated as the MRO namespace. All definitions and axioms from the original including the domain and range of the relations are preserved. Jensen et al. demonstrated how such an approach can be used to model planned and actual entities. For actual entities, both material artifacts and processes, CCO relations are used, while for planned or future entities (material artifacts and processes), MRO relations are used. An illustration of the approach is shown in FIGURE 1 from [10] where both real sensor (xyz_201) and desired sensor (xyz_101) are instances of Sensor class, but with different relations to the sensor model instance (xyz_102) which is information about the sensor, real sensor using *cco:prescribes* and the desired sensor using *mro:prescribes*. Similarly, the *mro:has function* and *mro:realized by* go on and add more information about the desired characteristics of the sensor.

For our jet-engine use case, this approach produces the knowledge graph shown in FIGURE 2[2]. This figure also shows higher level classes from BFO and IOF utilized in the use case. It shows that the representation of our use case follows the parallel relations of two namespaces, CCO and MRO as prescribed by this approach. The following observations are made from this approach:

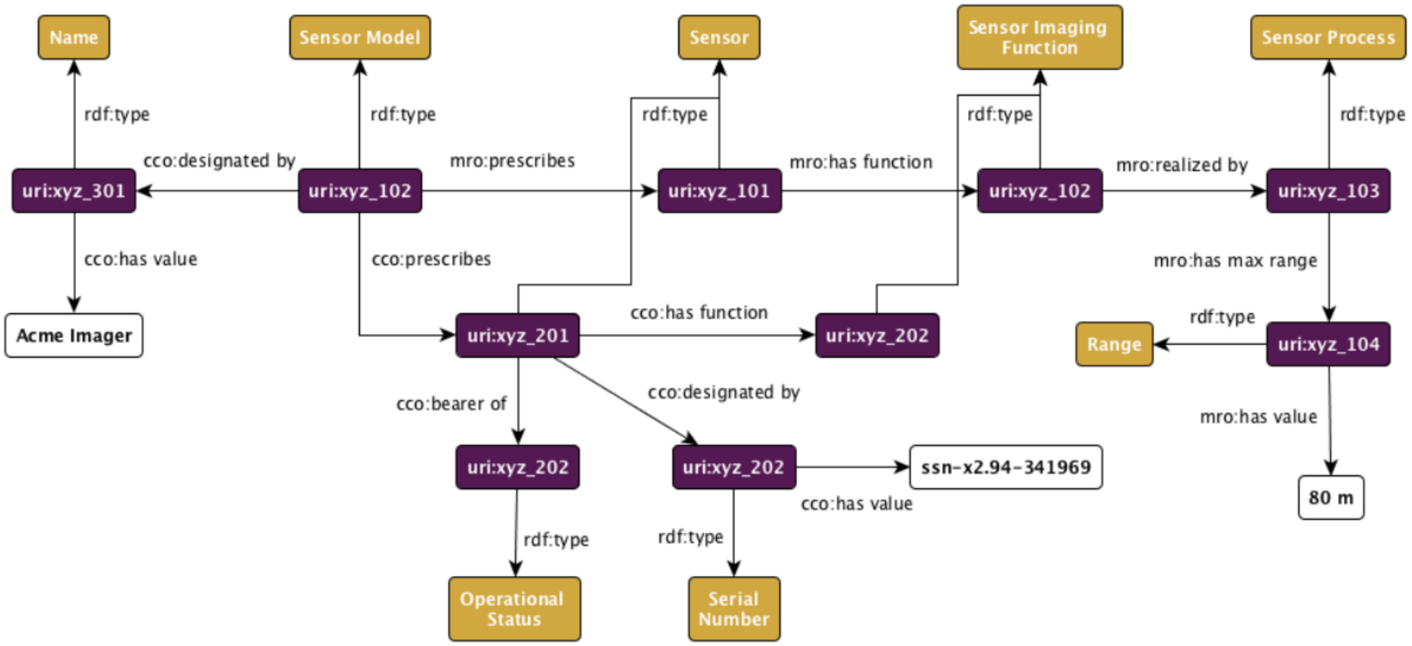

FIGURE 1: USE OF REAL RELATIONS AND MODAL RELATIONS (FROM [8])

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[1] Note, that this is not the case for the newest BFO 2020 version.

[2] Note that the BFO hierarchy is abbreviated in subsequent figures.

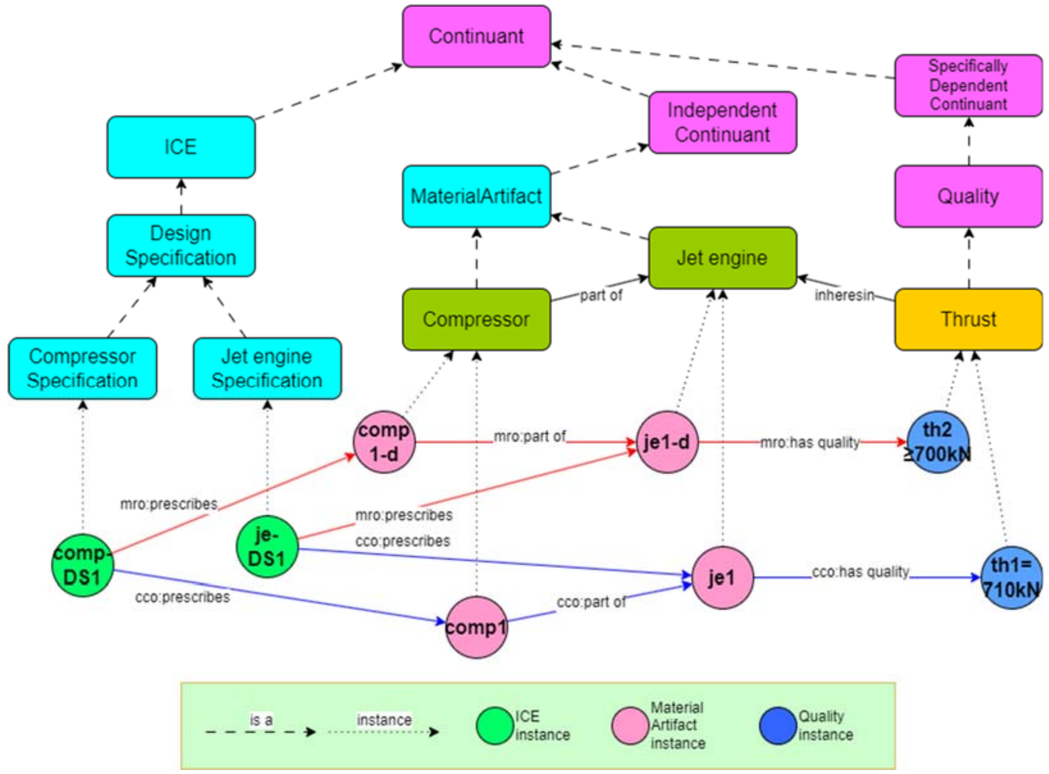

FIGURE 2: REPRESENTATION OF JET ENGINE REQUIREMENTS AND DESIGN USING THE MRO APPROACH

1. Digital counterparts of physical entities (for both materials and processes) are instances of ontology classes that represent physical entities, but they use different relations.
2. There is no differentiation at the class/universal level between the digital and the physical counterparts.
3. There is no explicit, ontological connection between the same relations from each of those two namespaces.
4. The is no clear designation of what kinds of models the MRO namespace represents, e.g., a requirement, a design, or a simulation model. Therefore, it is not clear how to represent these additional kinds of digital counterparts – should specific classes be defined for them, should additional namespaces be defined for them, or both? Having no classes for these different models would render the ontology deficient of their semantic definitions.

Unfortunately, having no classes for these different, new, or additional information models, renders the current ontologies deficient in their semantic definitions. Moreover, while the initial production of MRO relations was simple, their maintenance or extensions still requires significant work. Initial MRO relations have a replica of domain and range from their original relations, but any changes and updates are not linked automatically. Humans must help link them.

4.2 ICE Approach

The ICE approach is based on a strict decoupling between the physical entities and their digital counterparts. Such a decoupling can happen because digital artifacts are represented using **only** specific subclasses of the *IOF Information Content Entity* (ICE) class. This means that an individual level ICE can only reference physical entities that already exist and can only reference the entities that might exist in the future by referring to their universals using class axioms. Any potential interrelations of different attributes, structures and precedence associated with the future physical entities can thus just be captured through the combination of 1) relations of the corresponding ICEs and 2) relations based on related universal axioms.

The resulting representation of our jet engine use case using this approach is shown in Figure 3 bellow; and the following observations are noted:

1. There is a clear separation between digital and physical world as the digital world is completely constrained to ICE.
2. New properties need NOT be added to capture the relation between the digital and physical world as prior to physical world creation all properties point to universals.
3. Differences between existing plans and their current respective physical entities (e.g., a planned vs. actual participant in the process between the planned and realized) can only be understood through analyzing the future physical process as opposed to having an incomplete understanding from the ICE level due to a limited set of relations between ICEs.
4. It is difficult to translate the impact of, and especially connections between, the physical world changes and their intended meaning to the digital world. In the example given

above, the relation between jet engine specification and its quality specification is captured through the *has prescribed quality specification* relation as opposed to the physical world *has quality* relation. It should be noted that it is possible to extend *has continuant part* with properties such as *has prescribed quality specification* to increase the clarity of the intent of relation. However, such an approach implies that 1) all the physical relationships need to be "copied over" to the ICE and 2) that their hierarchy and inheritance in the digital world will potentially differ as opposed to the "physical world" (e.g., *has prescribed quality specification* is a subproperty of *has continuant part* as opposed to *specifically depends on* in the physical domain). In other words, the number of properties will increase by N, whereby N is the number of properties that exist for relations between physical world entities.

5. To address this difficulty, we need to introduce new properties for linking and comparing between different types of specifications of products and processes (e.g., artifact as designed vs artifact as required)
6. By pointing to a universal, the approach requires the introduction of a new class that accounts for the specifics of each product or process created or the axiom that points to a universal need to be complemented with additional information (e.g., if a requirement specification points to a Jet Engine version X there must either be a) Universal Jet Engine Version X or b) the axiom must state the version, e.g., *prescribes some (Jet Engine and 'has version' X).*
7. Unfortunately, reasoning cannot fully be applied to expressions pointing to a universal. For example, an IOF Core property chain states that if an 'occurrent part of' a 'process' x 'has participant' y then x also 'has participant' y. If a prescription points to a universal and states the following axiom *prescribes some (process and has occurrent part some (has participant some entity))*, the reasoner can't infer that the process also 'has participant' some entity. In other words, every type (Universal) related knowledge MUST be explicitly asserted.

4.3 Representation/Specification (R/S) Approach

The R/S approach is based on the BFO's realistic stance on ontologies. That stance assumes that we can represent only physical (real) entities (objects and/or processes) in the *Independent Continuant* or *Occurrent* branch. Therefore, any results from either engineering design task or the process planning task must be represented by various ICEs. While ICE definition is not part of the BFO 2020 specification, it has been developed as part of CCO (see [9]) and has been ported into IOF Core specification. Moreover, ICE is a subclass of BFO *Generically Dependent Continuant*, where the entities depend on some other independent entities for their existence.

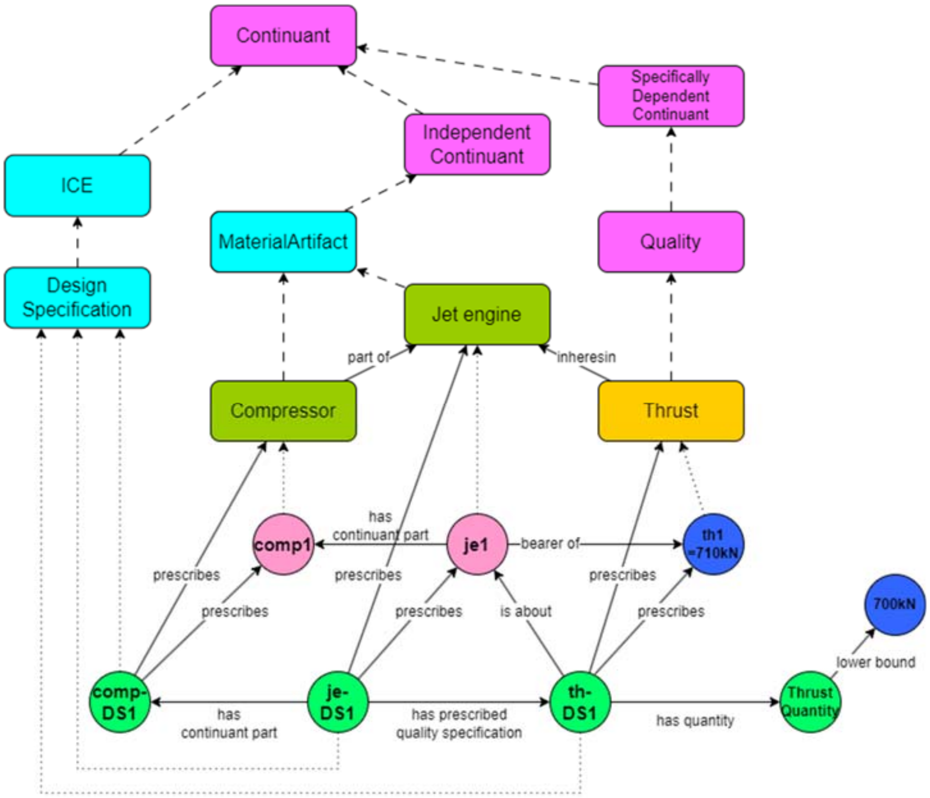

FIGURE 3: REPRESENTATION OF JET ENGINE REQUIREMENTS AND DESIGN USING THE ICE APPROACH

The illustration provided here for this approach is based on [16]. Product design is assumed to be a list of specifications that will guide physical product and its associated manufacturing processes. The members of the list include attributes of the product (such as size, or dimensions), how it will perform in its usage (e.g. car speed, or engine temperature, and similar), and what will (should) happen to a product at its end-of-life (e.g. recycle, or reuse). This approach uses two concepts, representation and specification as shown in FIGURE 4. Based on those concepts, the formalization of our use case statement in this approach is shown in FIGURE 5. This approach differs from ICE approach by representing related specifications in another ICE, called MapICE, which gives the two specifications specific roles. This approach requires several more instances of various classes to represent our use case. The following observations are noted:

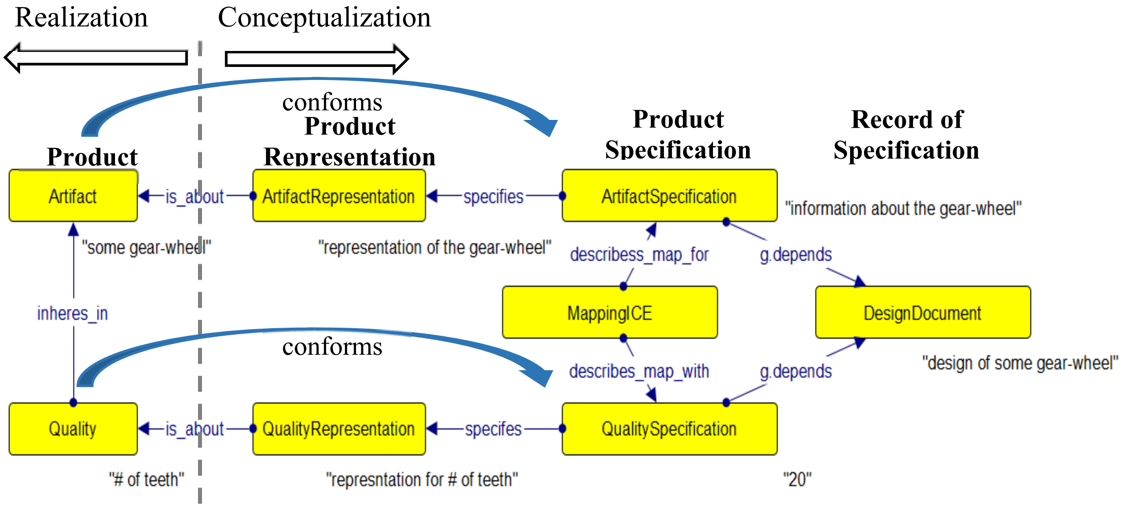

FIGURE 4: RELATIONS BETWEEN REALIZATION AND CONCEPTUALIZATION OF PRODUCTS (from [14])

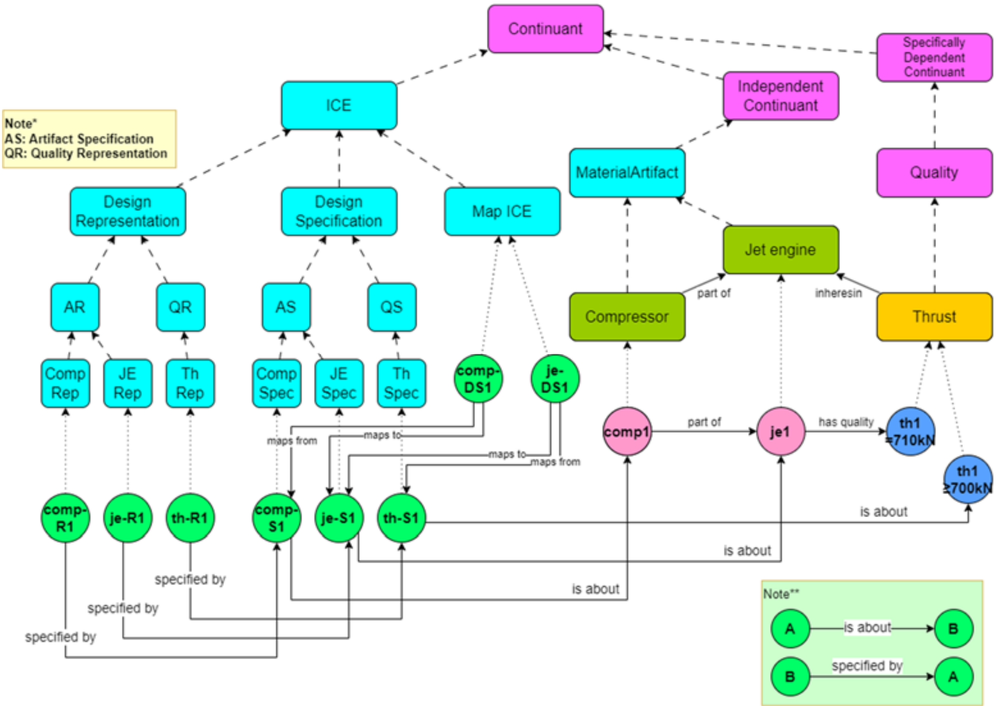

FIGURE 5: REPRESENTATION OF JET ENGINE REQUIREMENTS AND DESIGN USING THE R/S APPROACH

1. The designer’s intentions **must** be represented in a more explicit form than other approaches, because it includes considerations of the design process, design intent, and mental representation of design.

   It is straightforward to relate several versions of the same design using the MapICE entity
2. The R/S approach introduces many more classes, relations, and instances, as visible from the use case figure.
3. Like the ICE approach, this approach loses the semantics of various relations between the physical artifacts and their qualities, especially when digital versions of both are exclusively represented with ICEs.
4. The use of MapICE resembles the relational database approach and it uses a concept from software as a replacement for relations between different classes or instances.

4.4. Counterpart Relation (CR) Approach

This approach was proposed in a recent paper [17]. It is based on the understanding that a product life-cycle contains several phases: requirement, design, planning, manufacturing, usage, and end-of-life-disposal or recycling (see [18]). It is important to emphasize that engineering work is mainly done at the beginning of life, but it has to project product usage and (potentially) recycling. Also, using modern computer technologies, digital artifacts across all stages, are usually created before the actual, physical, manufacturing and inspection phases begin.

This CR approach utilizes a concept called ‘product possibilities’ and modal relations among them to represent the first three, projected, phases, in addition to final physical artifacts as shown in FIGURE 6. It is well known that most of engineering design, manufacturing planning, and scheduling activities are performed and completed well before the physical artifacts are manufactured and begin their use.

To complete those activities, each of those three phases must be evaluated against objectives, digitally. Evaluations can be based on many criteria including time, cost, and performance.

Designer and planner consider those designs and plans as first class artifacts, for example, designers talk in terms of them being artifacts, and not information. In our CR example, the designer and planner my use a sentence “My engine has a thrust of 720 kN” even after they just finish drawing or a CAD model of such engine and perform static calculation or dynamic simulation of the engine performance. Based on those premises, in this approach requirement, design, and plan virtual artifacts are connected to physical artifacts using their respective *corresponds* relations such as *req-corresponds* and *des-corresponds*. They are related to ICEs using respective *prescribes* relations such as *req-prescribes*, *des-prescribes*, and *plan-prescribes*, which are subrelations of the generic ‘prescribes’ relation. Application of this approach to our use case statement is shown in FIGURE 7. Observations for this approach are the followings:

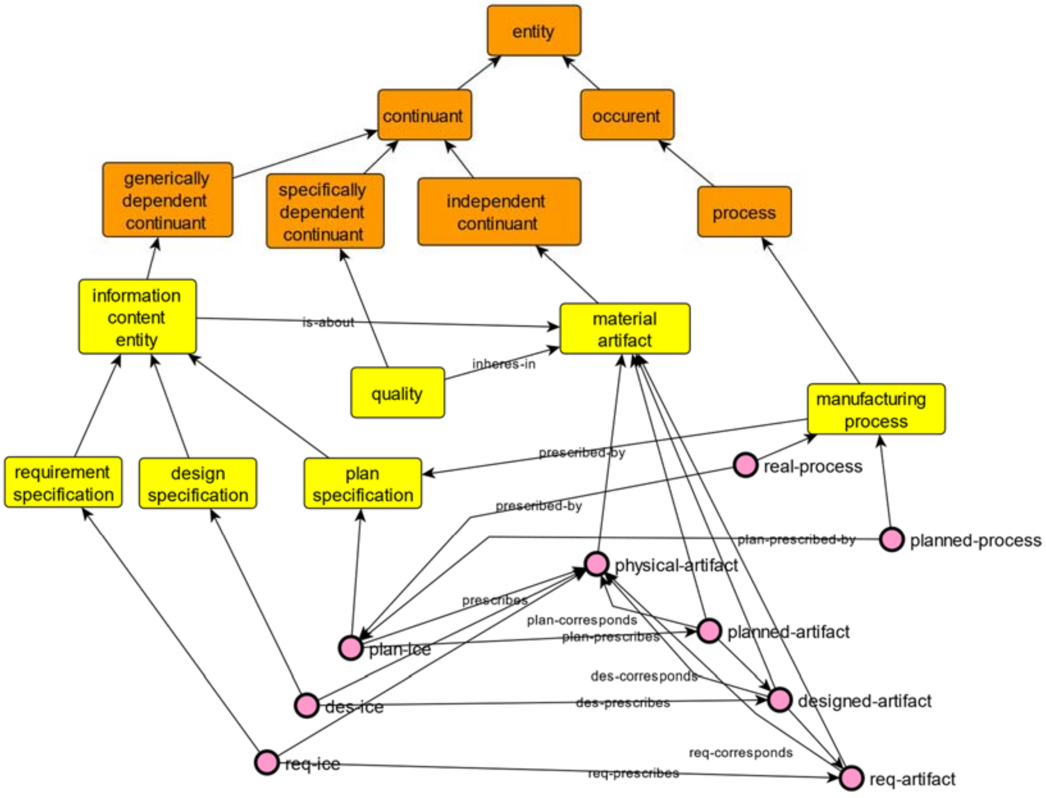

FIGURE 6 CONNECTING ICE-S WITH ARTIFACTS USING SUBCLASSES OF *PRESCRIBES* RELATIONS (from [15])

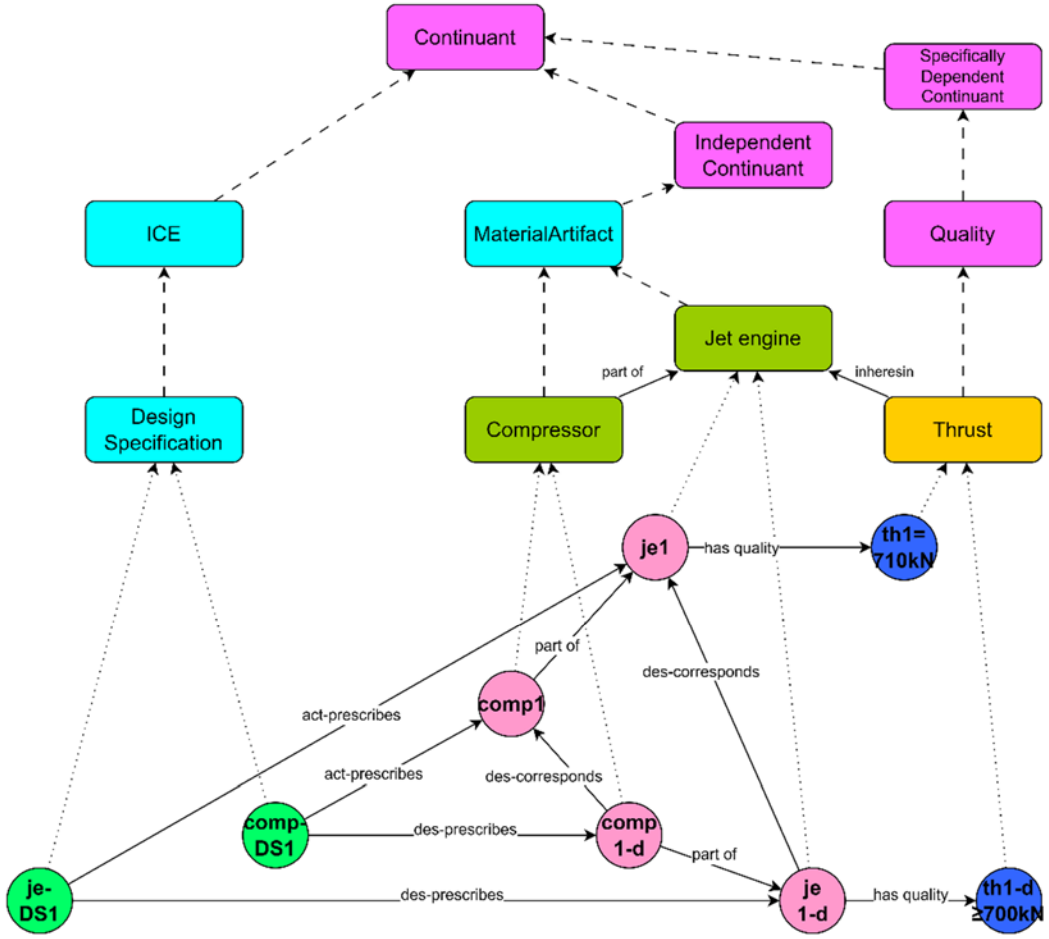

FIGURE 7: REPRESENTATION OF JET ENGINE REQUIREMENTS AND DESIGN USING THE CR APPROACH

1. This approach, as shown in the example, corresponds to natural language used by engineers and designers. They do not talk in terms of information about quality, but actual quality, for example, “my engine has a thrust of 710 kN”, and not “engine information has thrust information of 710 kN”.
2. This approach requires far fewer classes and entities than the previous two approaches (comparing their figures).
3. By deriving subrelations for each stage of product development and its uses, this approach benefits from BFO/IOF semantics of relations with necessary extensions given to enable proper and simple semantic reasoning about digital artifacts.
4. The approach explicitly connects digital and physical artifacts, by connecting them to the single ICE that prescribes both.
5. This approach can be used to compare attributes of digital, designed or planned artifacts with their physical counterparts, because the same relations are used for expressing attributes of both digital artifact and physical artifact.
6. This approach requires a new ontology of digital and physical artifacts to clearly establish which instances of a given class are physical artifacts today and which artifacts correspond to future or virtual physical artifacts.

4.5 Summary

Based on the initial results of our four approaches, it was concluded that more tests were necessary. Among other observations on these approaches, key differentiations between them are summarized as shown in TABLE 1 using two criteria: a) digital artifact class, and b) development level. More detailed summary will be given in a future extended version of the paper.

TABLE 1: GROUPING OF FOUR APPROACHES

		Digital Artifact class	
		ICE	Physical Artifact
Development level	Concept	ICE Approach	MRO Approach
	Details	Rep/Spec Approach	Counterpart Approach

The digital artifact class criterion separates ICE and Rep/Spec approaches from the other two because they use ICEs to represent digital artifacts, while the other two assert them as physical artifacts or both. From observations for all approaches, it seems that MRO and Counterpart approaches provide for more efficient representation and reasoning in industrial applications.

Development level criterion separates Rep/Spec and Counterpart approaches from the other two approaches since they provide more detailed treatment of various types of digital artifacts (e.g., design, requirement, plan). Nevertheless, further tests and analyses will be needed to determine the most appropriate one.

5. CONCLUSION

The paper presented a preliminary evaluation and discussion of four approaches for representing various kinds of digital artifacts and relating them to their corresponding real artifacts. We established requirements for using each of the four approaches and used a simplified engineering task to implement each approach. For each approach and each task, observations were noted based on those established requirements. The reported work is an initial phase of a project. Currently, ontology files for those approaches are being implemented within BFO/IOF framework in order to evaluate them on more comprehensive cases. Further works will expand on other types of digital artifacts and other manufacturing sectors such as biomanufacturing.

DISCLAIMER AND ACKNOWLEDGEMENTS

The work described in this paper was funded in part by NIST through Ohio University cooperation agreement #70NANB22H155. Certain commercial software products are identified in this paper. These products were used only for demonstration purposes. This use does not imply approval or endorsement by NIST, nor does it imply these products are necessarily the best available for the purpose.

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