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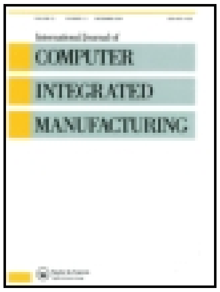

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Boonserm Kulvatunyou [a], Nenad Ivezic [a], Yunsu Lee [a] & Junho Shin [a]
[a] Systems Integration Division, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 20899, USA
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An analysis of OWL-based semantic mediation approaches to enhance manufacturing service capability models

Boonserm Kulvatunyou*, Nenad Ivezic, Yunsu Lee and Junho Shin

Systems Integration Division, National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899, USA

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The exchange of accurate, computer-interpretable information is critical in today's dynamic supply chains in which manufacturers come and go as needed. This exchange begins when manufacturers, who hope to join the supply chain, provide the OEM (original equipment manufacturer) with information regarding their production capabilities. These capabilities are represented electronically in what are called manufacturing service capability (MSC) models. These models are frequently proprietary, which makes them difficult to access, and imprecise, which makes them difficult to use. Web Ontology Language (OWL) is a powerful language for capturing the semantics of such models. OWL can enhance both precision and accessibility, but it requires semantic mediation to resolve semantic conflicts and more importantly to enhance model semantics. Semantic-mediation approaches can generally be classified into two approaches mapping-based and reference-ontology-based. This paper characterises and compares the two approaches. Characterisation is based on examples of proprietary MSC models and by deployment criteria including mediation quality, scalability, evolution, and knowledge organisation. Comparison is based on the behaviours and trade-offs of the two approaches in the context of these deployment criteria. The paper also provides a decision-making template associated with these criteria. Finally, the paper uses this template to show under what conditions each mediation technique is preferred.

Keywords: OWL; semantic mediation; semantic enhancement; semantic enrichment; characterisation; manufacturing service; service-oriented manufacturing; dynamic supply chain

1. Introduction

A significant opportunity to advance the performance of contract manufacturing supply chains lies in the manufacturing supplier sourcing processes (Chiang, Kocabasoglu-Hillmer, and Suresh 2012; Lio and Hong 2010). OEMs use these processes to assess the manufacturing capabilities of available suppliers and, subsequently, to select specific suppliers for inclusion into the supply chain. To enable the supply chain optimisation, suppliers must provide OEMs with easily accessible and highly accurate information about their manufacturing capabilities (Kulvatunyou et al. 2005). Presently, the sourcing process has been traditionally manual based on incomplete information either from a limited number of local suppliers or from previous members of the supply chain.

Increasingly, suppliers have opportunities to share their manufacturing capabilities electronically using various Web technologies and information sharing portals. Sharing could be facilitated using what are called manufacturing service capability (MSC) models. These models capture and represent capabilities, in computer-interpretable data formats, as manufacturing services provided by the suppliers (see Figure 1). For example, process capability may be represented from the process or equipment perspective; material capability may be represented using a taxonomy of material types and/or by composition of substances. Service description model may be a taxonomy and/or a combination of other capability models.

Commonly used MSC models are accessible through information sharing portals owned and managed by suppliers or a number of commercial e-marketplaces (e.g., mfg.com, thomasnet.com). This means that current models are proprietary, making information sharing very difficult. In addition, these models use a number of ad hoc, informal, representation schemes ranging from pure textual and graphical descriptions of products and processes to catalogues of, literally thousands of, manufacturing service categories. These service categories are constructed from mixtures of terms from taxonomies describing manufacturing processes, material, equipment, industry, and more. Example service categories are CNC Machining, Wood CNC Machining, CNC Machining for Aerospace, and Ultra Precision 5-axis CNC Machining. GoodRelation[1] is another commonly used MSC model to describe product offering. It provides schemas and an ontology model to describe products and services. However, the model tends to be somewhat generic and provide little specific semantics and terminologies related to the product and service characteristics. In summary, manufacturing capability information captured by commonly used service models are proprietary and contain inadequate

*Corresponding author. Email: serm@nist.gov

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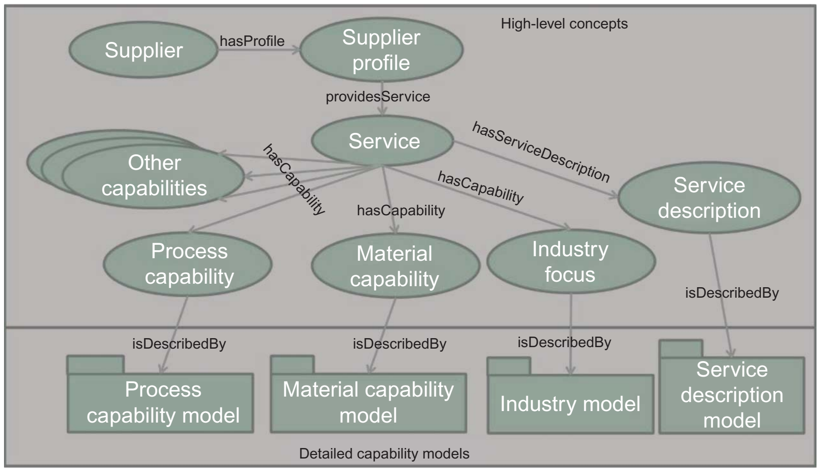

Figure 1. Conceptual model of manufacturing service capability model.

computer-interpretable data. This results in very limited sharing of manufacturing capabilities between OEMs and contract manufacturers.

OWL, the Web Ontology Language, has the potential to address both the precision and accessibility limitations described above (W3C 2009a). In particular, the use of OWL description logic (OWL-DL) and semantic mediation has proven successful in other areas. For example, Bicer et al. (2005) demonstrated OWL-DL based semantic mediation in the health-care domain, while Ye et al. (2007), Yarimagan et al. (2009), and Vujasinovic et al. (2009) demonstrated the applications in the supply chain domain. Together, OWL DL and semantic mediation can enhance proprietary manufacturing service models to obtain higher semantic precision and improved accessibility and interoperability. There are two commonly used OWL-DL-based, semantic-mediation approaches: the mapping-based approach and the reference-ontology-based approach (Vetere and Lenzerini 2005; Hameed et al. 2004). In this paper, we describe our research efforts to characterise and compare these two approaches. Using a single manufacturing capability example, deep-hole drilling, we characterise and compare the two approaches using four criteria: mediation quality, scalability, evolution, and knowledge organisation.

The rest of the paper is structured as follows. First, we provide background related to the semantic-mediation objectives to enhance semantic precision and accessibility of proprietary MSC information. Within that context other semantic works are discussed and compared with the OWL-based semantic mediation. Subsequently, the two OWL-based semantic-mediation approaches are described. Then, we provide a deployment analysis of the two alternative approaches using a simplified running example that contains common issues found in MSC models used in today's commercial supplier information sharing portals. In the following section on related technologies, technologies that are related to the deployment of the OWL-based semantic mediation are discussed. Finally, conclusions and our future plans are provided.

2. Semantic mediation

2.1. Background

The main objective of semantic mediation is to obtain higher semantic precision and accessibility across proprietary MSC manufacturing service models. This is achieved via semantic mapping which shall achieve two objectives including introduction of shared semantics into the proprietary models and resolution of semantic conflicts between them.

Introduction of shared semantics is accomplished by establishing axiomatic relationships between concepts across proprietary models. In Section 2.3, we describe two alternative approaches where relationships are established either with concepts in another proprietary model or with concepts in a reference ontology. These axiomatic relationships enable inheritance of shared semantics from the other model.

Resolution of semantic conflicts is accomplished by meeting functional requirements, which can be described with respect to types of semantic conflicts. According to Park and Ram (2004), semantic conflicts, at the high level, can be classified into data-level conflicts and schema-level conflicts. However, when the semantic-mediation framework relies upon a formal logic system such as OWL DL, logical conflict is yet another type of conflict.

Data-level conflicts are differences in data domains caused by the multiple representations and interpretations of similar data. Data-level conflicts include *data-representation* conflicts, *data-unit* conflicts, and *data-precision* conflicts. Data-representation conflicts occur when the semantically same values are represented differently; e.g., `05/08/2012` vs. `May-08-2012`. The data-unit conflicts occur when the same quantities are represented with

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differing units; e.g., '2 inches' vs. '5 centimetres'. Data-precision conflicts occur when different scaling is used; e.g., the continuous scale (0, 100) vs. a discrete scale (low, medium, high). Typically, data-level conflicts are more easily resolved than schema-level conflicts.

Schema-level conflicts are characterised by differences in logical structures and/or inconsistencies in the metadata between models of the same domain. The schema-level conflicts include *model coverage conflicts*, *naming conflicts*, *entity-identifier conflicts*, *schema-isomorphism conflicts*, *scope conflicts*, *aggregation conflicts*, and *schematic discrepancies* (Sheth and Kashyab 1992; Visser et al. 1997). Model coverage conflicts generally occur when two models have differing extents of knowledge of the same domain, e.g., when one model has certain concepts disjoint from all concepts in the other model. Naming conflicts occur when two semantically equivalent concepts are named differently (synonyms); or, when two semantically different concepts are named the same (homonyms). Entity-identifier conflicts occur when differing keys are used for same instances of the same concept in differing data sources. Isomorphism conflicts occur when two semantically equivalent concepts are modelled with differing set of attributes, differing number of attributes, or differing set of axioms (i.e., differing semantic precision); e.g., `Supplier(ID, GeneralPhone, SupportPhone)` and `Supplier(ID, Phone)`. Scope conflicts occur when concepts subsume or overlap one another; e.g., `CNCMachine(ID, Name)` subsumes `MillingMachine(ID, Name)`. Aggregation conflicts occur when a property of a concept is an aggregation of properties from multiple instances of another concept. For example, the `MonthlyProduction(ID, Month, Year, ItemID, Quantity)` is an aggregation of the `DailyProduction(ID, Date, Item, Quantity)`. The schematic discrepancies occur when concepts are modelled using differing constructs – table/class name, attribute name, and attribute value.

Logical conflict means that there is a logical contradiction in the models under consideration. In other words, there is an interpretation that is true in one model but false in another model. For example, if there are statements in one model saying 'Company X is a Customer' and 'Company X is a Supplier' and there is a statement in another model saying 'A Company cannot be both Customer and Supplier' (i.e., Customer and Supplier are disjoint), then there is a logical contradiction between the two models when the Company, Customer, Supplier concepts in one model are linked/mapped to those in the other model.

2.2. Semantic mediation technologies

Today's popular technologies to semantic mediation rely on procedural transformation languages such as XSL transformation language (XSLT) (W3C 1999) or XML Query Language (XQuery) (W3C 2010). These languages are relatively easy to use and are computationally efficient; however, the resulting code is sensitive to the structure of the source and target schemas, which are typically large and aggregated. Execution can also become computationally expensive when the source and target data-structure definitions are large and when multiple transformation hops are necessary (because logical transitivity cannot be exploited). In addition, procedural-transformation approaches are not easily integrated with underlying domain knowledge; hence, introduction of the shared semantics for the purpose of semantic enhancement is not always straightforward using these types of approaches.

There are a number of non-procedural semantic-mediation technologies. However, they focus only on information integration and do not consider semantic enhancement. In other words, they enhance accessibility but not semantic precision. These technologies rely on various architectures, languages, formalisms, and techniques. Below we review technologies we have found to be comprehensively documented and applicable to the MSC type of information (e.g., systems that mediate only taxonomy or lexical relationships are excluded).

MAFRA (Maedche et al. 2002) and RDFT (Omelayenko and Fensel 2001) use RDF (Resource Description Framework, W3C 2004a) to uniformly represent data from proprietary sources in the semantic mediation. MAFRA uses the notion of semantic bridge and its own mapping language to provide declarative relations between concepts; while RDFT uses XSLT. It turned out that XSLT did not work well to translate data in RDF representation, because XSLT is designed to work with a tree-based data structure while RDF is a graph-based data structure. Similar to MAFRA and RDFT, MedMaker (Papakonstaninou et al. 1996) uses its Object Exchange Message as a common data representation and its Mediator Specification Language (MSL) to map data. OntoMerge (Dou et al. 2002) uses its language call Web-PDDL, which is a type of first-order logic to represent data and mapping. InfoMaster (Genesereth et al. 1997) similarly uses a first-order logic language called KIF. OBSERVER (Mena et al. 2000) and MOMIS (Bergamaschi et al. 1999 and Bergamaschi et al. 2001) are distributed ontology querying environments. These environments rely on query rewriting techniques and varying languages based on descriptive logic to capture ontology and mapping. OBSERVER uses the ontology language called CLASSIC and relies on pairwise mapping between source ontologies. MOMIS uses the language called ODL_{I3} and relies on mapping between each source ontology and the merged ontology, which is created from merging of source ontologies. None of these systems uses semantically rich ontology as the basis for semantic mediation. Only CREAM (Park and Ram 2004), which suggested an agent-based framework and its own knowledge representation, uses simple ontology to help resolve data-level conflicts. Other systems only use ontology language

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either as uniform data representation from heterogeneous sources and/or as an interlingua that captures commonalised data structure and vocabulary with little axiomatised definitions. Sciorer, Siegel, and Rosenthal (1994) suggested a framework where source data are first semantically enriched with contextual information to give complete semantics before semantic mediation. In that framework, each piece of data is enriched with contextual information that becomes an information unit called *Semantic Value*. Semantic Value is represented in LISP. Of all the systems, only OntoMerge relies on logical inference to mediate information. Although some other systems use rule-based languages, they seem to use them primarily for data translation rather than knowledge inference. An additional drawback to these systems (except those ones that use RDF and XSLT) are that they use languages that are not broadly used, lack of commercial support, and not internet-enabled. OWL is a broadly used language with commercial tools support. It is also internet-enabled and multi-lingual, which lend itself better for information sharing across enterprises. Although OWL-DL is less expressive than first-order logic, it has a built-in mechanism for semantic inheritance and enhancement.

2.3. OWL-based semantic mediation approaches

Semantic-mediation approaches studied in this paper are based on OWL and its description logic (DL) semantics. OWL is an internet-aware ontology/logical language. Its underlying syntax is based on the RDF (Resource Description Framework, W3C 2004a), which provides the framework and mechanism to uniquely identify and link information across information sources. OWL has three semantic tiers including OWL-Lite, OWL-DL, and OWL-Full. While OWL-Full is the most powerful to express semantics, it does not guarantee finite computational time. For this reason, we consider only OWL-DL in our semantic-mediation approaches.

OWL-DL has features that make it attractive as a language for semantic mediation. It is not a procedural language and, hence, semantic mediation/mapping statements are scalable – they can be specified independent of messages or object structures. For example, the same concept (data structure) used in multiple other concepts or messages requires separate sets of mapping statements using such a procedural approach like XSLT. In case of OWL-DL, mapping statements for the concept are specified once regardless of where the concept is used. In addition, unlike first-order logic languages, OWL-DL models are akin to object-oriented modelling languages making it easier to understand and use. Being a logic-based language, several built-in logical semantics are available such as transitivity, equivalence, inverse, and subclass/inheritance relationships. These can make OWL-based mediation more scalable and easier to maintain. More importantly for our purposes, such built-in semantics also lend themselves well to semantic enhancement. That is, whenever a semantically poor concept A is linked by a single equivalent assertion to a semantically rich concept B, A will be inherently enhanced by the semantics of B.

Another OWL feature that lends itself well to semantic enhancement is the Open World Assumption (OWA) in its underlying description logic. The essence of OWA is that nothing is assumed unless otherwise stated. That is, OWA-compliant OWL reasoners will not raise a logical conflict flag when a necessary condition is not met. Consequently, such necessary condition (i.e., such semantics) will be inherited rather than cause rejection, unless there is an explicit statement/axiom expressing that such condition can never be met. Take the following as an example. Assume a reference ontology defines the Service concept as things that have one or more relationships to the Process concept. A proprietary model on the other hand defines its Service concept as things that have one or more relationships to the Equipment concept. Let's assume that the proprietary model has some instances of its Service asserted which have some relationships to instances of the Equipment concept. When the shared Service concept in the reference ontology is introduced/linked to the Service concept in the proprietary model by asserting the equivalence between the two concepts, OWL reasoner will not raise a logical conflict simply because the instances of the Service concept in the proprietary model do not have any relationship to the Process concept (the necessary condition). On the other hand, the Service concept and its instances in the proprietary model have been enhanced by the semantics of the Service concept in the reference ontology. In particular, the Service concept is now defined as things that have some relationships to the Equipment concept or things that have some relationships to the Process concept. In other words, if a query asks for things that have some relationships to the Process concept, instances of the Service concept in the proprietary model will be returned despite the fact that they do not yet have relationship to any Process concept (because the inherited definition from the reference ontology says that they have and the OWA assumes that they have not yet been asserted).

In that vein, we analyse how the various types of semantic conflicts discussed earlier can be resolved (or in some cases, dissolved) in OWL-based semantic mediation. It should be noted, however, that the focus of this paper is the analysis of two general approaches that use OWL in semantic mediations. It is out of the scope of this paper to provide details regarding how each of the conflicts can/should be resolved. The specific solutions depend on specific data values, query requirements, and performance requirements.

At the schema level, the model coverage and isomorphism conflicts become infused when concepts and individuals are linked through resolutions of other conflicts. In other words, concepts and properties that do not

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exist in one model become part of the other model. The scope conflict can be resolved with the OWL subclass or equivalent class axioms along other operators (e.g., union and intersection) and a new class expressing the overlapping conditions. The aggregation conflicts can be resolved in a similar way with additional algebraic equations. The use of OWL rule language extensions may be necessary to provide sufficient constructs for expressions in the algebraic equations. Examples of available rule language extensions that have commercial supports are the Semantic Web Rule Language (SWRL) (W3C 2004b) and SPARQL Inference Notation (SPIN) (W3C 2011). The naming and identification conflicts are resolvable via the OWL class/property equivalence and the same individual axioms. Lastly, the schematic discrepancies are resolvable using the combination of the class/property equivalence axiom and operators using the notion of mapping class. The mapping class has multiple equivalence axioms each of which defines the class using each of the differing schemes. We describe this mapping class technique in more detail in Section 3. In the 'Related technologies' section (Section 4), we describe another emerging approach called canonicalisation, which preprocesses proprietary models using pattern-based transformation. The approach can efficiently circumvent several types of conflicts, simplify mapping and its maintenances, and increase the computational performances.

At the data level, the data-representation conflicts are largely resolved by the use of standard XML Schema Datatypes (W3C 2004c) to express data. Different representations supported by the standard are understood by OWL compliant reasoners. The type of data-representation conflicts that are intertwined with the schema-level conflicts will, however, need to rely on OWL rule language extensions or the canonicalisation described above to tokenise the value. This occurs, for example, when a single string-based data in one model is mapped to two or more structured properties in another model, e.g., part size capability = '3 to 5' in one model vs. part size capability min = '3' and part size capability max = '5' in another model. The data-precision conflicts are typically partially resolvable. That is, it is precisely translatable from higher precision value to lower precision value while the reverse is an imprecise translation. The mapping class technique mentioned earlier can provide the links between the high and low precision values. The data-unit conflicts can be resolved by using the QUDT (Quantities, Units, Dimensions Data Types) ontology (Hodgson and Keller 2011). The QUDT ontology provides a common and extensible framework to specify in OWL the data that is a measurement quantity. Once measurement data in proprietary models are expressed using QUDT, they can be mediated with the help of unit conversion functions defined in SPIN. Allemang and Hendler (2011) describe how to use QUDT and how to define associated SPIN conversion function for semantic mediation in Chapter 11 of their book.

Execution time for logic-based systems is typically longer than the procedural ones. This is due to their non-procedural nature and the need to address global effects of logical statements. Nevertheless, OWL-based mediation can be attractive in environments where transformations occur neither frequently nor in real-time. The manufacturing supplier sourcing is one such environment.

Next, we describe the two alternative OWL-based semantic-mediation approaches, namely mapping-based approach and reference-ontology-based approach. Both approaches rely on logical mappings and description logic semantics of OWL.

2.3.1. *Mapping-based approach*

In the mapping-based approach, mapping ontologies are created between participating proprietary models where the logical transitivity of mapping statements is exploited to enable mediation among the proprietary models. The mapping-based approach is defined in Definition 1 below.

> ***Definition 1:*** Mapping-based approach is a 2-tuple $\Phi = \{\Gamma, M\}$ where
>
> - Γ is a union of proprietary models participating in the semantic mediation, given by $\Gamma = \bigcup \gamma_i$ where:
>   - The proprietary model γ_i is an ontology consisting of a set of DL statements,
>   - $i \in \{1,2,3,...,n\}$, where n is the number of participating proprietary models;
> - M is a set of mapping ontologies forming a complete mapping chain between all γ_i's, and given by $M = \{\mu_{(i,j)}\}$ where:
>   - $\mu_{(i,j)}$ is a set of two-way DL mapping statements between γ_i and γ_j, $i \neq j, \mu_{(i,j)} = \mu_{(j,i)}$, and
>   - $(n-1) \leq |M| \leq n(n-1)/2$

For example, suppose there are three proprietary models $-\gamma_1, \gamma_2, \gamma_3$. That is $i\{1,2,3\}$. Then possible M sets include the following:

$$M_1 = \{\mu_{(1,2)}, \mu_{(1,3)}\},\ M_2 = \{\mu_{(1,2)}, \mu_{(2,3)}\},$$

$$M_3 = \{\mu_{(1,3)}, \mu_{(2,3)}\},\ M4 = \{\mu_{(1,2)}, \mu_{(2,3)}, \mu_{(1,3)}\}$$

Because each $\mu_{(i,j)}$ is a two-way mapping ontology, which takes part in a mapping chain, the mediation can occur from any source ontology γ_i and target ontology γ_j without the need for a common/reference ontology. Section 3.1 will demonstrate this.

2.3.2. *Reference-ontology-based approach*

In the reference-ontology-based approach, a reference ontology is created to mediate between dissimilar proprietary models. The reference ontology is a conceptual superset of the union of all γ_i's. Mapping ontologies are then defined between each γ_i and the reference ontology. The reference-ontology-based approach is defined by Definition 2 below. Note that in this approach, M' also forms a mapping chain via the linkages between each proprietary ontology γ_i and the reference ontology, $\sum$.

In the reference-ontology-based approach, the reference ontology acts as interlingua among proprietary models as well as a source of semantics to enrich the proprietary models. A number of researchers have proposed methods for creating such a reference ontology. In particular, Ameri and Dutta (2006) have defined an OWL-based manufacturing service ontology using the manufacturing-process-oriented view; and Jang et al. (2008) have defined an OWL-based manufacturing service ontology using the machining-feature-oriented view. Alternatively, MSC can also be defined using the resource-oriented view such as that defined by Vichare et al. (2008). Defining a reference manufacturing service model, which necessarily covers broad manufacturing domain, is beyond the scope of this paper. The authors are working with a standard consortium to begin such work. In addition to the aforementioned works, other existing research works and standards need to be taken into consideration in developing such reference model. In the machining area alone, these can include ISO 14649 (STEP-NC) which has standardised machining feature, ISO 15331 which includes a standard for representing machining resources, ISO 13399 which includes a standard for representing cutting tool information, ASME B5.59-2 which is an informal standard for describing the performance and capabilities of a milling and turning machines, and Ameri and Summers (2008) which provides an ontology for representation of fixture design knowledge. Therefore, for illustration purposes, we have used a simplified manufacturing-process-oriented model similar to that created by Ameri and Dutta in this paper.

2.3.3. *Ontology mapping*

In order to introduce shared semantics in either of the two OWL-based semantic-mediation approaches, mapping ontologies must be developed. In addition, one way to create the reference ontology is by performing ontology merge among the proprietary models. Ontology matching technologies can assist in both of these processes. Integrating ontology matching technologies into these processes is beyond the scope of this paper yet should be considered in future works. This section provides overview of recent developments in ontology matching.

Early works in ontology matching approaches includes PROMPT (Noy and Musen 2003) and Chimaera (McGuiness et al. 2000). PROMPT has been integrated into the popular OWL development environment, namely Protégé (BMIR 2011). Our evaluation of PROMPT in Protégé 4.1 indicates limitations when dealing with schema-level conflicts, particularly the schematic discrepancies.

<u>*Definition 2:*</u> Reference-ontology-based approach is a 3-tuple $\chi = \{\Gamma, \Sigma, M'\}$ where

- Γ is defined as in Definition 1;
- Σ is a reference ontology where $\Sigma \supseteq_c \Gamma$, and $\supseteq_c$ is conceptual (logical) superset. $\Sigma \supseteq_c \Gamma$ means that every statement entailed in Γ can be entailed by Σ. The concepts in Γ may be modeled differently in Σ, however;
- M' is a set of mapping ontologies between each γ_i and Σ, and given by $M' = \{\mu_{(i,\Sigma)}\}$, where
    - $\mu_{(i,\Sigma)}$ is a set of two-way DL mapping statements between γ_i and Σ,
    - $|M'| = n$

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Ontology matching has become a discipline due to the Ontology Alignment Evaluation Initiative (OAEI) which has organised ontology matching tests since 2004 according to the OAEI website.[2] Shvaiko and Euzenat (2012), which is one of the most recent ontology matching surveys, summarised the evolution, improvement, limitation, and future direction of ontology matching technologies over the last decade. The report points out that ontology matching technologies do not deal with schematic discrepancies. In particular, all tools provide only the equivalence relationship within the matching correspondence except one tool which provides one additional subclass relationship. These tools match only entities of same types – class-to-class and property-to-property. Mapping between different entity types is still an open issue. None of the tools provide correspondence using expression, e.g., a concept is equivalence to an intersection of other two concepts, although some tools provide n:m correspondences. Shvaiko and Euzenat (2012) survey only covers evaluation results up until 2010 and three data set. However, our investigation of the 2012 result on one of the data sets called Conference[3] has indicated the same characteristics. For these reasons,[4] the process to develop the mapping ontologies and the process to merge ontologies are expected to be largely manual even though ontology matching technologies can provide assistance.

3. Deployment analysis

In this section, we show how to deploy the two OWL-based semantic-mediation approaches on a specific manufacturing capability, deep-hole drilling. First, we describe the different MSC model representations of deep-hole drilling from three, commercial, information-sharing portals – Portal-A, Portal-B, and Portal-C. These MSC models exhibit different conceptualisations, data structures, and model coverage. Then, we describe the specific semantic-mediation goals through query requirements, which are used to attest that the semantic mediation enhances semantics and reconciles differences found in these models. Deployment of each of the semantic-mediation approaches is then illustrated and verified against these goals.

To use the various portals, suppliers must declare their specific manufacturing capabilities by associating them to categories of manufacturing services. This means that all manufacturing capabilities, or services, within the same category share common semantics. Each portal employs its own taxonomies to define those semantics. Suppliers can provide additional details about their manufacturing capabilities that are outside those taxonomies. Each portal defines the kinds of information it will accept about those capabilities. Some allow only structured information about the manufacturing capabilities; others allow only freeform text or combination of structured information and freeform text. Only structured information is relevant to the semantic mediation in this paper.

In our two approaches to semantic mediation, the first step is to encode the proprietary MSC models using OWL-DL (W3C 2009a). Since these models are captured originally in a number of different data stores with differing schemes, the encoding will be based primarily on their syntax. The result of this encoding is called *OWL-encoded proprietary MSC model*. This means that there will likely be heterogeneous OWL representations of similar concepts. The intention is to show that the semantic mediation can reconcile such heterogeneity.

In the three commercial supplier portals that we have investigated, suppliers register to a subcategory; unfortunately, they are not registered to the parent category automatically. Suppliers must deliberately perform this registration. The first step of encoding in OWL DL results in automatic registration to parent categories. This happens because the OWL subclass relation used to encode the subcategory relationship entails this. Therefore, the semantics of proprietary MSC models have been enhanced in the first step of our semantic-mediation approaches.

Note that in the rest of the paper, the *OWL-encoded proprietary MSC model* at a particular supplier portal will be referred to as a *proprietary model* for brevity. In this paper, we will illustrate portal content, which has already been encoded in OWL DL. Tools that assist in the transformation of proprietary MSC model into OWL are discussed in Section 4. In the subsequent sections, when necessary, we will use the prefixes '`pa:`', '`pb:`', and '`pc:`' to denote terms from Portal-A, Portal-B, and Portal-C, respectively.

Portal-A model

Figure 2 below depicts a portion of the hierarchy of manufacturing service categories present in Portal-A. It represents a taxonomy that suppliers use for declaring their manufacturing capabilities. In the figure, the arrow lines represent the subcategory relationships. These are encoded with classes in OWL DL as shown in Table 1. Manchester OWL style syntax (W3C 2009b) is used throughout the paper for expressing axioms. Table 2 summarises the OWL properties, and Table 3 summarises the individuals (i.e., class instances). The two tables represent suppliers' manufacturing capabilities in Portal-A. Notice in Table 3 that suppliers in Portal-A declare their manufacturing capabilities by making associations *from instances of the respective manufacturing service category classes to the instance of the* `Supplier` class via the `hasSupportingSupplier` property. Other portals use differing approaches.

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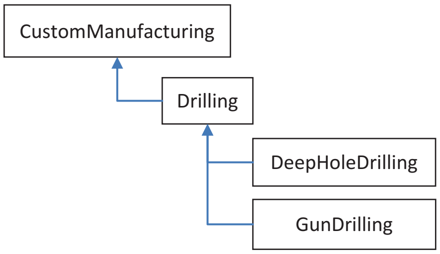

Figure 2. Portal-A's taxonomy of manufacturing capability categories related to deep-hole drilling.

Table 1. Portal-A classes and axioms.

Class	Necessary Conditions
CustomManufacturing	SubClassOf: hasSupportingSupplier min 0 Supplier
Drilling	SubClassOf: CustomManufacturing
DeepHoleDrilling	SubClassOf: Drilling
GunDrilling	SubClassOf: Drilling
Supplier	

Portal-B model

Portal-B has a simple taxonomy related to the deep-hole drilling. This is illustrated in Figure 3 and is encoded as the OWL subclass relationship in Table 4. Notice that its deep-hole drilling category is a direct subcategory of the machining category, not the drilling category like in Portal-A. In addition, there is no gun drilling category. Tables 5 and 6 summarise properties and individuals, respectively. They represent suppliers' manufacturing capabilities in Portal-B. Note, as depicted in Table 6, suppliers in Portal-B declare their manufacturing capabilities using a relation that is conceptually the same as that used in Portal-A but a different property name, `hasSupplier`.

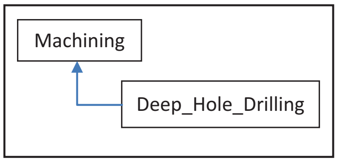

Figure 3. Portal-B's taxonomy of manufacturing capability categories related to deep-hole drilling.

Gun drilling is generally known as the process which produces a deep hole like the gun barrel. Therefore, it is a kind of deep-hole drilling. Portal-B's description of the deep-hole drilling service category also indicates the same semantics. Portal-A however does not relate its `pa:DeepHoleDrilling` category to its `pa:GunDrilling` category. Hence, suppliers registered to `pa:GunDrilling` are not retrieved when searching by `pa:DeepHoleDrilling` category. The semantic-mediation behaviour shall enable gun drilling suppliers to be retrievable under the deep-hole drilling category (a semantic enhancement). In addition, since `pb:Deep_Hole_Drilling` is semantically equivalent to `pa:DeepHoleDrilling`, semantic mediation should be able to entail suppliers registered to `pa:DeepHoleDrilling` or `pa:GunDrilling` to also be registered to `pb:Deep_Hole_Drilling` (a model coverage, scope, and naming conflicts resolution). This shall be the case even though Portal-B does not possess the `pa:GunDrilling` concept. This semantic mediation will be demonstrated in Section 2.

Table 4. Portal-B classes and axioms.

Class	Necessary Conditions
Machining	SubClassOf: hasSupplier some Supplier
Deep_Hole_Drilling	SubClassOf: Machining
Supplier	

Table 2. Portal-A properties.

Property	Type	Range
hasSupportingSupplier	Object	Supplier

Table 5. Portal-B properties.

Property	Type	Range
hasSupplier	Object	Supplier

Table 3. Portal-A individuals.

Individual ID	Type(Class)	hasSupportingSupplier Property Value
Supplier_1	Supplier	
Supplier_2	Supplier	
DeepHoleDrilling_1	DeepHoleDrilling	Supplier_1
GunDrilling_1	GunDrilling	Supplier_2

Table 6. Portal-B individuals.

Instance ID	Type(Class)	hasSupplier Property Value
Supplier_3	Supplier	
Deep_Hole_Drilling_1	DeepHoleDrilling	Supplier_3

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Portal-C model

The Portal-C model has two noted differences from the previous two models. First, it does not model the deep-hole drilling as a category. It, however, models a generic CNC machining category where concepts related to deep-hole drilling (and other processes) are features of that category. These concepts are translated to classes and instances in OWL as shown in Table 7. The `CNCMachining` class is defined as an enumerated class whose members are manufacturing process capabilities.[5] The column labelled 'N&S Conditions' in Table 7 describes the necessary and sufficient conditions associated with the classes. In OWL, class enumerates its members using an N&S condition.

The other noted difference is that suppliers declare their manufacturing capabilities using an inverse relation relative to Portal-A and Portal-B; Portal-A and B use relationships where 'capability is provided by supplier' whereas the Portal-C uses a relationship where 'supplier has capability'. This is shown in Table 8 and the last two rows of Table 9.

The two noted differences above fall into the category of schematic discrepancies. Another category of semantic issue across the three portals is the naming conflict where the same concepts are labelled with different terms such as `pc:DeepHoleDrilling` and `pb:Deep_Hole_Drilling`. Our method of semantic mediation resolves both of these categories of semantic issues.

Semantic mediation goals

The goals of semantic mediation are to resolve semantic issues described in the portal models. More specifically, semantic mediation shall resolve the naming conflicts, model coverage, scope, and schematic discrepancies across the portals. Additionally, within each specific portal, the semantic mediation shall disambiguate and relate the semantics of their service categories. That is, the semantic mediation enriches the MSC models and service categories in particular.

These goals are demonstrated using queries. These queries identify suppliers by relying on mediation to match the query condition within and across the three portals semantically. Queries are composed of terms native to any one of the portals without borrowing terms from other portals. Specifically, the four queries below, seeking suppliers supporting drilling or deep-hole drilling, are performed. The desired outcome is that `Supplier_1` to `Supplier_4` shall be retrieved but not `Supplier_5`. This is because `Supplier_1` to `Supplier_4` directly or indirectly indicate that they have drilling and deep-hole drilling capabilities but `Supplier_5` does not.

`Q1`: Identify suppliers having drilling capability using only Portal-A terms, including `pa:Supplier`, `pa:Drilling`, and `pa:hasSupportingSupplier`.

`Q2`: Identify suppliers having deep-hole drilling capability using only Portal-A terms, including `pa:Supplier`, `pa:DeepHoleDrilling`, and `pa:hasSupportingSupplier`.

`Q3`: Identify suppliers having deep-hole drilling capability using only Portal-B terms, including `pb:Supplier`, `pb:Deep_Hole_Drilling`, and `pb:hasSupplier`.

`Q4`: Identify suppliers having deep-hole drilling capability using only Portal-C terms, including

Table 8. Portal-C properties.

Property	Type	Range
hasCNCMachiningCapability	Object	owl:Thing

Table 7. Portal-C classes and axioms (note that N&S is short for Necessary and Sufficient Condition).

Class	Necessary Conditions	N&S Conditions
CNCMachining		EquivalentTo: {DeepHoleDrilling, Turning}
Supplier	SubClassOf: pc:hasCNCMachiningCapability min 0 pc:CNCMachining	

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Table 9. Portal-C individuals.

Individual ID	Type(Class)	hasCNCMachiningCapability Property Value	Different Individuals
DeepHoleDrilling	CNCMachining		Turning
Turning	CNCMachining		DeepHoleDrilling
Supplier_4	Supplier	DeepHoleDrilling	
Supplier_5	Supplier	Turning	

pc:Supplier, pc:hasCNCMachiningCapability, and pc:DeepHoleDrilling.

3.1. Mapping-based approach deployment

In this section, we describe the mapping-based approach. First, we describe its deployment approach. Then, we formulate mapping ontologies and finally discuss the semantic-mediation results.

To deploy the mapping-based approach to semantic mediation, we created a mediating model (Φ) that is a union of all the proprietary models and mapping ontologies from the three portals. We use the Pellet OWL DL reasoner (Clark and Parsia 2012) to perform inferences over Φ and used the Manchester OWL DL Query Protégé plugin to determine if the mediation goals Q1–Q4 were met.

Q1 to Q4 are represented in the OWL DL query (W3C 2009b) as follows:

Q1: pa:Supplier and inverse pa:hasSupportingSupplier some pa:Drilling

Q2: pa:Supplier and inverse pa:hasSupportingSupplier some pa:DeepHoleDrilling.

Q3: pb:Supplier and inverse pb:hasSupplier some pb:Deep_Hole_Drilling.
Q4: pc:Supplier and pc:hasCNCMachiningCapability value pc:DeepHoleDrilling

Based on rough matching between concepts across the three portals shown in Table 10, the mapping ontology sets M_1 and M_2 have the same number of matches while M_3 has the least number of matches. In this illustration we use the mapping ontology set $M = \{\mu_{(1,2)}, \mu_{(2,3)}\}$.[6] That is, Portal-A model is paired with Portal-B model, and Portal-B model is paired with Portal-C model to create a complete mapping chain. The mapping ontologies, $\mu_{(1,2)}$ and $\mu_{(2,3)}$, consist of the axioms illustrated in Table 11. It should be noted that because OWL entities (classes, properties, individuals) in those three proprietary models are translated from terms that have no formal semantics, we imparted our reference-ontology semantics on those entities with exact maps, as shown in the mapping table.

It should be noted also that the axiom A4 is not a mapping axiom because it contains only the terms from Portal-A. It is rather a semantic enrichment axiom to the Portal-A model that eliminates a specific semantic ambiguity. The best placement of the axiom A4 is in the Portal-A model itself so that it is always available when there is a need to perform the reasoning with the Portal-A model. However, this is not an issue in our deployment since reasoning is always performed over the mediating model, Φ, that is a union of all the ontologies.

DL Query evaluation of Q1, Q2, and Q3 over inferred Φ in the semantic mediation returns Supplier_1 to Supplier_4 as required in the mediation goals. However, this is not the case for Q4. Only Supplier_4 is returned. This is because the deep-hole drilling concept is modelled as an instance in the Portal-C terminology space (See Table 9); consequently, it cannot be accurately mapped to the class-level concepts defined in Portal-B (or Portal-A). The best possible mapping is represented by B3, which states that, the pc:DeepHoleDrilling instance-level concept is an instance of the pb:Deep_Hole_Drilling class-level concept. It is not possible in Portal-C terminology to refer to suppliers who have the pc:hasCNCMachiningCapability property with *some* instance values that are members of a class

Table 10. Ontology mapping set evaluation using concepts matching across portals.

Portal-A Term	Portal-B Term	Portal-C Term
CustomManufacturing		
	Machining	CNCMachining
Drilling		
DeepHoleDrilling	Deep_Hole_Drilling	DeepHoleDrilling
GunDrilling		
		Turning
Evaluation Summary	$[\mu_{(1,2)}] = 1$, $[\mu_{(2,3)}] = 2$, $[\mu_{(1,3)}] = 1$; $M_1 = \{\mu_{(1,2)}, \mu_{(2,3)}\}$, $M_2 = \{\mu_{(1,3)}, \mu_{(2,3)}\}$, $M_3 = \{\mu_{(1,2)}, \mu_{(1,3)}\}$; $[M_1] = 3$, $[M_2] = 3$, $[M_3] = 2$; Where $[\mu_{(i,j)}]$ and $[M_n]$ are total number of matching concepts in the mapping ontology $\mu_{(i,j)}$ and in the mapping ontology set M_n, respectively.	

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Table 11. Mapping ontology between Portal-A and Portal-B models ($\mu_{(1,2)}$) and between Portal-B and Portal-C models ($\mu_{(2,3)}$).

Mapping Ontology	Axiom ID	Axioms in Manchester OWL Syntax
µ(1,2)	A1	Class: pb:Supplier EquivalentTo: pa:Supplier
	A2	Class: pb:Deep_Hole_Drilling EquivalentTo: pa:DeepHoleDrilling
	A3	ObjectProperty: pb:hasSupplier EquivalentTo: pa:hasSupportingSupplier
	A4	Class: pa:GunDrilling SubClassOf: pa:DeepHoleDrilling
µ(2,3)	B1	Class: pc:Supplier EquivalentTo: pb:Supplier
	B2	ObjectProperty: pc:hasCNCMachiningCapability InverseOf: pb:hasSupplier
	B3	Individual: pc:DeepHoleDrilling Types: pb:Deep_Hole_Drilling

equivalent to pb:Deep_Hole_Drilling class. That class does not exist in Portal-C.

Below we discuss alternatives to enable the Q4.

Alternative 1 – instance-level mapping workaround

A workaround to the Q4 problem is to add instance-level mappings to $\mu_{(1,2)}$ and $\mu_{(2,3)}$. Table 12 shows these additional mappings. With all these mapping axioms added, Q4 will return Supplier_1 to Supplier_4. However, there are two issues with this workaround.

(1) The mappings are inaccurate. The axiom A6 is the most problematic among the three. Gun drilling is a kind of deep-hole drilling, not identical with it. However, suppliers registered only to the gun drilling (specifically, Supplier_2) will not be returned without A6. A5 and B4 are also not accurate mappings because pa:DeepHoleDrilling_1 and pb:Deep_Hole_Drilling_1 are in principle just two of the many possible instances of pa:DeepHoleDrilling and pb:Deep_Hole_Drilling. Undesirable results might occur particularly when these instances had capability details/attributes. That is, mapped instances are stated to be the same but they have different property values.

(2) The mapping and mediation are not scalable. The reason is that every time instances of the pa:DeepHoleDrilling or pb:Deep_Hole_Drilling get added or deleted, the mapping has to change.

Alternative 2 – use SWRL rule

An alternative to the previous workaround is to use a rule encoded in SWRL (W3C 2004b). SWRL is designed to work with OWL. This rule (see below) enables Q4 without sacrificing semantics. With the Pellet DL reasoner, Q4 successfully returns Supplier_1 to Supplier_4 instances. This rule states that any Portal-B suppliers that provide any Portal-B deep-hole drilling (class) also provide the Portal-C deep-hole drilling (instance). Notice that only one rule, which states the relationship between the Portal-B and Portal-C terminologies, is needed. This rule also entails the Portal-A terminology because of other Portal-A and Portal-B mapping axioms and the integrated mediating model deployment making all axioms available in one place. The caveat to this alternative solution is that DL reasoners have limited support for SWRL rules due to a decidability issue (W3C 2004b).

```
pb:Deep_Hole_Drilling(?dhd), pb:hasSupplier(?dhd,?s), pb:Supplier(?s)
->pc:hasCNCMachiningCapability(?s, pc:DeepHoleDrilling)
```

Alternative 3 – use mapping class

We define *Mapping class* to bridge differing views of a particular concept. A mapping class is an OWL defined class with multiple necessary and sufficient (N&S) conditions (see Table 13). Each condition (an axiom) references terms from a single portals. Because multiple N&S conditions are interpreted as disjunctively

Table 12. Additional mapping axioms to Table10 for instance-level mapping workaround.

Mapping Ontology	Axiom ID	Axioms in Manchester OWL Syntax
$\mu_{(1,2)}$	A5	Individual: pb:Deep_Hole_Drilling_1 SameAs: pa:DeepHoleDrilling_1
	A6	Individual: pb:Deep_Hole_Drilling_1 SameAs: pa:GunDrilling_1
$\mu_{(2,3)}$	B4	Individual: pc:DeepHoleDrilling SameAs: pb:Deep_Hole_Drilling_1

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Table 13. Additional axioms to Table 10 for the mapping class.

Mapping Ontology	Axiom ID	Axioms in Manchester OWL Syntax
$\mu_{(2,3)}$	B5	`Class: DeepHoleDrillingSupplier EquivalentTo: pb:Supplier and (inverse (pb:hasSupplier) some pb: Deep_Hole_Drilling)`
	B6	`Class: DeepHoleDrillingSupplier EquivalentTo: pc:Supplier and (pc:hasCNCMachiningCapability value pc: DeepHoleDrilling)`

related, they give the reasoner the ability to relate views in different models as represented in each condition.

Table 13 shows the mapping class `DeepHoleDrillingSupplier` added to $\mu_{(2,3)}$ of our running example. The axioms `B5` and `B6` are the N&S conditions. With these mapping class conditions, `Q4` successfully returns `Supplier_1` to `Supplier_4`. This is because the `DeepHoleDrillingSupplier` is defined with the deep-hole drilling concept in both the class view in `B5` and instance view in `B6`. In addition, the object of the EquivalentTo predicate in `B6` is exactly the same as the query condition in `Q4`. Hence, the reasoner returns all (inferred) members of the `DeepHoleDrillingSupplier`. Notice that although the class DeepHoleDrillingSupplier is a new term, this term does not appear in `Q4;` consequently, our mediation requirement outlined in the semantic-mediation goals that the query uses only native and no alien terms is still satisfied.

In our running example, Alternative 3 is the most favourable among the three because decidability is ensured when only OWL DL axioms are used. In addition, the mapping axiom B3, which is just an approximate map, is not needed for the successful semantic mediation. The SWRL rule option in alternative 2 still requires the B3 mapping axiom (otherwise, additional rules would be needed). Because of that and the potential decidability issue, Alternative 2 is a secondary option that can be resorted if the OWL expression cannot resolve the semantic conflict. Both approaches do not sacrifice the semantics and mediation scalability that were a problem for the instance-level workaround. However, specific query requirements will need to be known in advance to construct appropriate mapping classes – in this case a supplier with specific manufacturing capability. If a query requirement is a facility with specific manufacturing capability then an additional mapping class or SWRL rule will be needed.

3.2. *Reference-ontology-based approach deployment*

In this section, we will first describe the reference ontology ($\sum$). Then, we describe the mapping ontologies between γ_1, γ_2, γ_3, and $\sum$ that make up the mapping ontology set M'. Finally, we discuss the semantic-mediation results of the reference-ontology-based approach. It should be noted that the deployment approach used in this approach is the same as that of the mapping-based approach. The prefix used with the reference ontology will be ‘`ro:`’.

The reference ontology is based on Manufacturing Service Description Language (MSDL) (Ameri and Dutta 2006). Figure 4 illustrates a taxonomy of the manufacturing service categories related to deep-hole drilling in the reference ontology. The taxonomy is encoded using OWL subclass relationships as shown in Table 14.

Table 14 summarises all the classes and associated axioms defined in $\sum$, while Table 15 summarises the properties. Notice that $\sum$ contains no individuals. For brevity, $\sum$ illustrated here does not satisfy the requirement that it is a conceptual superset of Γ. It however has sufficient concepts to mediate the target semantic issues across the three portals. This is validated by the successes of all the target queries.

We could have given the `ro:DeepDrilling` and `ro:GunDrilling` class N&S conditions. The `ro:DeepDrilling` could be defined as `ro:Drilling` that can produce a hole having a depth-to-diameter ratio greater than five (Bralla 1999). The `ro:GunDrilling` could be defined as ro:Deep Drilling that can produce a hole having a depth-to-diameter ratio of greater than 20 and that uses a specific set of cutting tools (UNISIG 2012). These definitions would make the reference ontology more semantically precise (i.e., semantically richer).

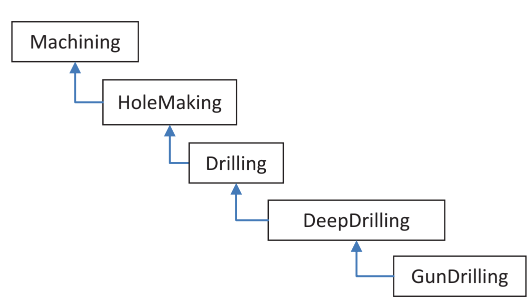

Figure 4. Taxonomy of manufacturing service categories related to deep-hole drilling in the reference ontology.

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Table 14. Reference ontology (∑) classes and axioms.

Class	Necessary Conditions
`Machining`	
`HoleMaking`	`SubClassOf: Machining`
`Drilling`	`SubClassOf: HoleMaking`
`DeepDrilling`	`SubClassOf: Drilling`
`GunDrilling`	`SubClassOf: DeepDrilling`
`Supplier`	`SubClassOf: Actor SubClassOf: ro:hasMachiningCapability min 0 ro:Machining`

Table 15. Reference ontology (∑) properties.

Property	Type	Range
`hasMachiningCapability`	`Object`	

This can be useful for mapping verification if participating proprietary models also have similar precision. Since the proprietary models in the three portals do not use any of these attributes, we did not include those definitions. Nevertheless, one necessary condition exists for each concept of the `ro:DeepDrilling` and `ro:GunDrilling` classes – (1) `ro:GunDrilling` is a subclass of `ro:DeepDrilling`, and (2) `ro:DeepDrilling` is a subclass of `ro:Drilling`. In other words, `ro:GunDrilling` is a specialised manufacturing capability of the `ro:DeepDrilling`; and `ro:DeepDrilling` in turn is a specialised manufacturing capability of `ro:Drilling`. Similar to the mapping-based approach, we imparted our reference ontology semantics on those classes in the proprietary models with exact maps because of the lack of formal semantics in the original proprietary models. Table 16[7] illustrates these mappings.

Similar to the mapping-based approach, we tested the semantic-mediation goals by first creating $\Phi' = \Gamma \cup M' \cup \sum$ and then running the Pellet DL reasoner over Φ'. The reasoner produces inferred Φ', on which `Q1` to `Q4` encoded in Section 3.1 are executed. The following observations are made:

(1) Similar to the mapping-based approach, `Q1`, `Q2`, and `Q3` but not `Q4` return the desired results.
(2) Mapping axioms specific to proprietary models can be replaced by statements maintained in the reference ontology. For example, axiom `A4` in Table 11 is entailed by a statement that `ro:GunDrilling` is a subclass of the `ro:DeepDrilling`. By just mapping `pa:GunDrilling` and `pa:DeepHoleDrilling` to those two respective classes, the two Portal-A classes have inherited subclass relationship and semantics from the reference ontology. Generally speaking, semantic enrichment in the reference-ontology-based approach is achieved by linking and inheriting semantics from the reference ontology.
(3) To enable `Q4`, the instance-level mapping workaround described in the mapping-based approach is not possible here because there are no instances in the reference ontology.

Table 16. Mapping ontologies between Portal-A, B, and C models and the reference ontology.

Mapping Ontology	Axiom ID	Axioms in Manchester OWL Syntax
$\mu_{(1,\sum)}$	X1	`Class: pa:Supplier EquivalentTo: ro:Supplier`
	X2	`Class: pa:DeepHoleDrilling EquivalentTo: ro:DeepDrilling`
	X3	`Class: pa:GunDrilling EquivalentTo: ro:GunDrilling`
	X4	`ObjectProperty: pa:hasSupportingSupplier InverseOf: ro:hasMachiningCapability`
$\mu_{(2,\sum)}$	Y1	`Class: pb:Supplier EquivalentTo: ro:Supplier`
	Y2	`Class: pb:Deep_Hole_Drilling EquivalentTo: ro:DeepDrilling`
	Y3	`ObjectProperty: pb:hasSupplier InverseOf: ro:hasMachiningCapability`
$\mu_{(3,\sum)}$	Z1	`Class: pc:Supplier EquivalentTo: ro:Supplier`
	Z2	`Individual: pc:DeepHoleDrilling Types: ro:DeepDrilling`
	Z3	`ObjectProperty: pc:hasCNCMachiningCapability EquivalentTo: ro:hasMachiningCapability`

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(4) The SWRL rule approach similar to Alternative 2 above can enable `Q4`. The SWRL rule below would need to be added.

```
ro:DeepDrilling(?dd), ro:Supplier
(?s), ro:hasMachiningCapability(?
s,?dd)
->pc:hasCNCMachiningCapability(?s,
pc:DeepHoleDrilling)
```

(5) The mapping-class approach similar to the Alternative 3 above can enable `Q4`. To do so, a mapping class `DeepDrillingSupplier` with an N&S condition is added to the reference ontology as shown in Table 17; and an additional mapping axiom is added to the Portal-C mapping as shown in Table 18. Notice that in this case, only one additional mapping axiom is needed in the Portal-C mapping, unlike the mapping-based approach that needs two. This is because the N&S condition of the `ro:DeepDrillingSupplier` in the reference ontology does the job of the other axiom. Also, other mapping classes such as `ro:GunDrillingSupplier` or `ro:DrillingSupplier` could be added to enable mediation of other queries.

Similar to the mapping-based approach, the mapping class approach is more favourable than using SWRL rules. The approximate mapping axiom `Z2` in Table 16 can also be removed once the mapping class is included.

3.3. Discussion

In this section, we characterise the mapping-based and the reference-ontology-based semantic-mediation approaches and discuss their behaviours with respect to the deployment criteria including mediation quality, scalability, evolution, and knowledge organisation. Finally, we provide a table summarising the behaviours as a quick reference when choosing between the two semantic-mediation approaches.

3.3.1. Mediation quality

In the case of mapping-based approach, it is important that the proprietary models γ_i and γ_j in each mapping pair in the set M are closely matched; otherwise, the mediation quality can degrade significantly. A modification to the running example illustrates this issue.

We add statements to Portal-C content as follows. Following the Portal-C design convention where processes are modelled as instances, we (1) add the `pc:GunDrilling` instance to the `pc:CNCMachining` class; (2) add `Supplier_6` as an instance of the `pc:Supplier` class; and (3) add an assertion that `Supplier_6` has CNC machining capability `pc:GunDrilling`. Table 19, Table 20, and Table 21 show Portal-C content after these additions. Table 22 shows the

Table 17. An additional mapping class to the reference ontology (∑) in Table 13.

Class	N&S Conditions
`DeepDrillingSupplier`	`EquivalentTo: ro:Supplier and (ro:hasMachiningCapability some ro:DeepDrilling)`

Table 18. An additional mapping axiom to the mapping ontology – $\mu_{(3, \sum)}$.

Mapping Ontology	Axiom ID	Axioms in Manchester OWL Syntax
$\mu_{(3, \sum)}$	`Z4`	`Class: ro:DeepDrillingSupplier EquivalentTo: pc:Supplier and (pc:hasCNCMachiningCapability value pc:DeepHoleDrilling)`

Table 19. Modified Portal-C classes and axioms.

Class	Necessary Conditions	N&S Conditions
`CNCMachining`		`EquivalentTo: {DeepHoleDrilling, GunDrilling, Turning}`
`Supplier`	`SubClassOf: hasCNCMachiningCapability only CNCMachining`	

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Table 20. Modified Portal-C properties.

Property	Type	Range
`hasCNCMachiningCapability`	`Object`	`owl:Thing`

modified $\mu_{(2,3)}$, while $\mu_{(1,2)}$ remains the same as in Table 11. The desired outcome of the semantic mediation is that querying for suppliers with gun drilling service using the Portal-A terminology, as shown in `Q5` below, returns `pa:Supplier_2` and `pc:Supplier_6`. However, this is not possible because there is a *semantic gap*. Specifically, there is no concept in Portal-B that corresponds to the `pa:GunDrilling` class-level concept in Portal-A and the new `pc:GunDrilling` instance-level concept in Portal-C (Figure 5 illustrates this gap[8]). The best possible map is to say that pc: GunDrilling is an instance of the `pb:Deep_Hole_Drilling` as shown in the new `B7` mapping axiom. Even with this mapping, `Q5` returns only `Supplier_2` and *not* `Supplier_6`. Using either of the techniques described in Section 3.1 will also not work. On the other hand, had the Portal-C model been paired with the Portal-A model as illustrated in Figure 6,[9] `Supplier_6` would have been returned (while other queries are still enabled).[10] This is because Portal-A model has the `pa:GunDrilling` class which is conceptually a match with the `pc:GunDrilling` instance and a mapping class could be used to resolve the modelling conflict. In the case of the reference-ontology-based approach, the choice of mapping pairs is not an issue because all mappings are performed against the reference ontology. If the reference ontology satisfies the conceptual superset condition where $\sum \supseteq_c \Gamma$, then there will be no semantic gap. It should be noted that the semantic-mediation quality discussion above is only from a single factor perspective. Other factors do affect the quality of the semantic mediation, such as the quality of the mapping ontology.

Table 21. Modified Portal-C individuals.

Individual ID	Type(Class)	hasCNCMachiningCapability Property Value	Different Individuals
`DeepHoleDrilling`	`CNCMachining`		`Turning, GunDrilling`
`Turning`	`CNCMachining`		`GunDrilling`
`GunDrilling`	`CNCMachining`		
`Supplier_4`	`Supplier`	`DeepHoleDrilling`	`Supplier_5,Supplier_6`
`Supplier_5`	`Supplier`	`Turning`	`Supplier_6`
`Supplier_6`	`Supplier`	`GunDrilling`	

Table 22. Mapping Ontology between Portal-B and modified Portal-C models ($\mu_{(2,3)}$).

Mapping ontology	Axiom ID	Axioms in Manchester OWL Syntax
$\mu_{(2,3)}$	B1	`Class: pc:Supplier` `EquivalentTo: pb:Supplier`
	B2	`ObjectProperty: pc:hasCNCMachiningCapability` `InverseOf: pb:has Supplier`
	B3	`Individual: pc:DeepHoleDrilling` `Types: pb:Deep_Hole_Drilling`
	B7	`Individual: pc:GunDrilling` `Types: pb:Deep_Hole_Drilling`

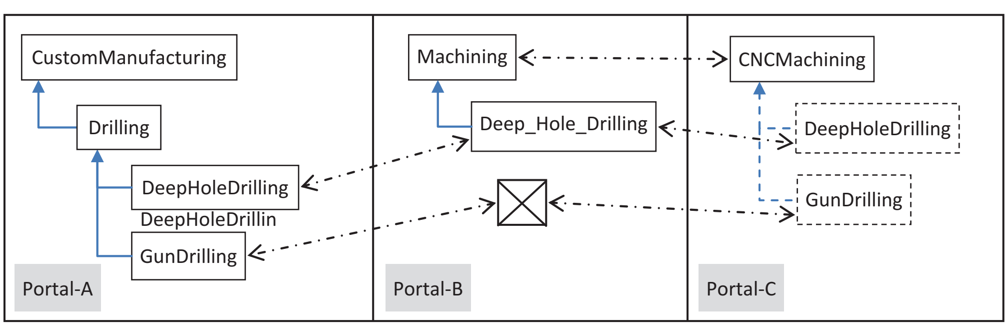

Figure 5. Mediation gaps.

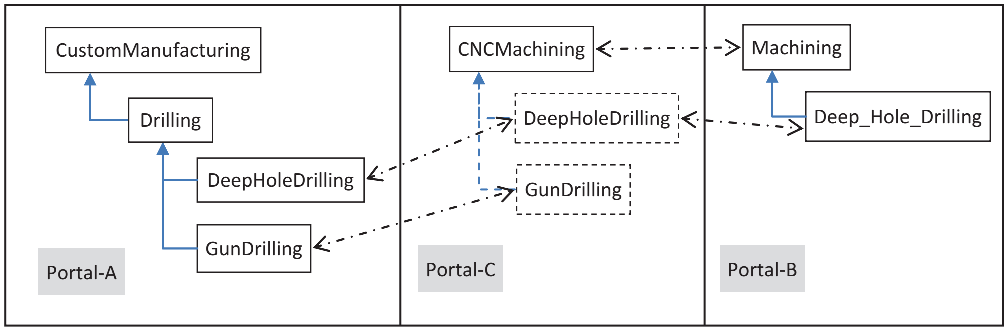

Figure 6. Mediation gaps elimination with different pairings.

In the case of the reference-ontology-based approach, the choice of mapping pairs is not an issue because all mappings are performed against the reference ontology. If the reference ontology satisfies the conceptual superset condition where $\sum \supseteq_c \Gamma$, then there will be no semantic gap. It should be noted that the semantic-mediation quality discussion above is only from a single factor perspective. Other factors do affect the quality of the semantic mediation, such as the quality of the mapping ontology.

```
Q5 = > pa:Supplier and inverse pa:
hasSupportingSupplier some
pa:GunDrilling
```

3.3.2. *Scalability*

As described in the previous section, the quality of the semantic mediation depends on the quality of the mapping set M for the mapping-based approach and the quality of the reference ontology in the case of the reference-ontology-based approach. In this section, we compare and discuss the scalability of these two approaches based on this mediation quality condition. To do this, we estimate levels of effort necessary to get the desired semantic-mediation quality for each approach.

For the mapping-based approach, we assume the concepts matching between all pairs of proprietary ontologies are necessary to choose the mapping ontology set M that gives good mediation quality.[11] Let $f(n)$ denote the effort required to define the concepts matching for n proprietary models where p is a constant representing the average effort required to produce one pair of matching. The function $f(n)$ is then represented by Equation (1) below:

$$f(n) = pC_2^n = p.n(n-1)/2 \qquad (1)$$

In the case of the reference-ontology-based approach, we assume that $\sum$ is created via a practical ontology merge procedure. We then compute the amount of effort based on that procedure. The diagram in Figure 7 illustrates the ontology merge procedure.[12]

Based on the procedure, mappings between γ_i's and $\sum_i$'s are performed $(n-1)$ times when there are n proprietary models. In practical terms, $\sum_n$ can change a lot from its initial state $\sum_1$; consequently, we assume that another round of mappings n times needs to be performed between γ_i's and $\sum$ for the semantic-mediation purpose (note that $\sum_n = \sum$). Assuming that γ_i's are in the same domain and consequently the size of $\sum_i$ as well as $\sum$ is not much larger than the largest γ_i; therefore, the average effort to map a pair of γ_i and $\sum_i$ is roughly the same effort as producing a mapping between a pair of γ_i's which is p. Let $g(n)$ denote the effort associated with the reference-ontology-based approach for n proprietary models. The function $g(n)$ is then represented by

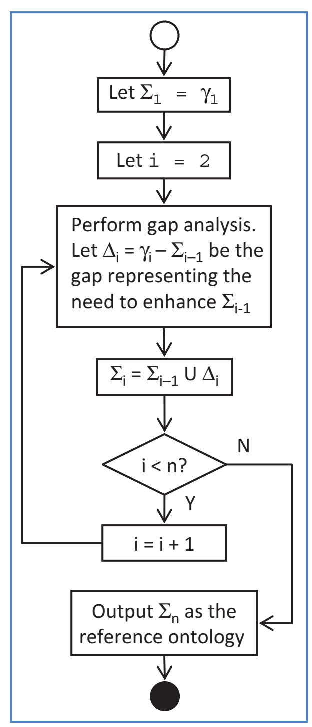

Figure 7. Ontology merge procedure to construct the reference ontology – $\sum$.

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Equation (2) below.

$$g(n) = p(2n - 1) \quad (2)$$

Equations (1) and (2) illustrate that the effort grows linearly with the number of proprietary models in the case of the reference-ontology-based approach, and quadratically in the case of the mapping-based approach. Mathematically, we have $f(n) = O(n^2)$ and $g(n) = O(n)$, which implies that there exists a constant n_0 such that $f(n) > g(n)$ for all $n > n_0$. In fact, the mapping-based approach requires less effort when $n < 5$, but as n grows, the effort surpasses that of reference-ontology-based approach and the gap becomes increasingly greater. This result makes practical sense since producing a reference ontology requires an effort that is beyond creating maps between proprietary models. Agreements on terms representing concepts and axiomatic knowledge about those concepts are necessary. In practice, the challenges of coming up with a reference ontology are not only technical but also 'political' – different organisations have different preferences to call the same concepts. The greater the number of parties involved, the greater the challenges. Therefore, when the number of proprietary ontologies is small, it may be better to use the mapping-based approach in which the effort is mostly technical. Other factors need to be taken into consideration, however. For example, if additional proprietary models are expected or existing proprietary models change frequently, the reference-ontology-based approach will likely be a better alternative. We discuss this in the next subsection in the topic of evolution.

3.3.3. *Evolution*

Even when the initial set of proprietary models is small, it may be better to use the reference-ontology-based approach if the number of models is expected to grow. This is because introducing another proprietary model typically means only one additional mapping is necessary when the reference ontology is available. With a small initial set of proprietary models, it also means fewer parties are involved in creating the reference ontology. In the case of the mapping-based approach, the set M may need to change when an additional proprietary model is introduced or when an existing proprietary model changes – particularly if M does not include all the mapping pairs. This is because a change to an existing proprietary model may require a different pairing that is a better match.

It should be noted that as the proprietary models evolve or the number of proprietary models grows, the reference ontology may also grow. This can make mapping to the reference ontology increasingly more difficult or more costly. Organisation, scoping (e.g., domain partitions), and maintenance of the reference ontology should be considered for the adoption of the reference-ontology-based approach.

3.3.4. *Knowledge organisation*

Additional domain knowledge not present in proprietary models is typically required for a successful semantic mediation. In our running example, for example, we added the subclass relationship between deep-hole drilling and gun drilling. Often, it will also be necessary to add domain independent knowledge such as unit transformations and time zone relationships. The mapping-based approach, depending on the deployment, may require that such additional knowledge be localised or distributable to each mapping ontology. On the contrary, the additional knowledge can be centralised in the reference ontology in the case of the reference-ontology-based approach. In this case, the mapping ontologies always have access to such knowledge because they are always paired with the reference ontology. As in our running example, the subclass relationship between deep-hole drilling and gun drilling concepts is centralised in the reference ontology. Therefore, reuse of the additional knowledge is easier in the case of the reference-ontology-based approach.

Modelling of general knowledge typically requires knowledge engineering and/or ontology engineering skills beyond basic terminology mappings. This is apparent even in the running example, in the definition of the mapping class. Local mappings are largely performed by domain experts who usually have limited knowledge engineering skills. The reference-ontology-based approach eliminates the need for the many engineers of proprietary models to independently specify general knowledge, since they are likely to perform in ways that are mutually incompatible. As we can see in the running example, a richer reference ontology somewhat simplifies the mapping ontologies. Participations of domain experts as well as knowledge engineers are typically required to produce a good reference ontology.

3.3.5. *Discussion summary*

Table 23 below summarises the behaviours for the two semantic-mediation approaches. The table provides a quick reference to selection criteria between the two approaches.

4. Related technologies

In this section, we discuss related works that complement the OWL-based semantic-mediation approaches. Like other logic-based information integrations, heterogeneous data syntaxes such as relational database (RDB) and XML need to be preprocessed for use by a logic-based system. In this paper, we assume that this preprocessing of data into OWL

Table 23. Mapping-based versus the reference-ontology-based semantic-mediation approaches behavioural summary.

Behavioural category	Mapping-based approach	Reference-ontology-based approach
Mediation quality	Need a suitable mapping ontology set M. $(n-1) \le |M| \le n(n-1)/2$	Need a sufficient reference ontology.
Scalability	The number of proprietary models (n) should be small, in principle less than five. Requires little to no upfront effort; however, adding a new proprietary model or changing existing ones can result in a significant maintenance effort.	More appropriate when the number of proprietary models (n) is five or more. Requires more upfront effort to define the reference ontology but more scalable when needing to add a new proprietary model or change the existing ones.
Evolution	Proprietary models should be relatively stable from both perspectives of content and the number of participants. Changes to a proprietary model may mean changes to the mapping ontology set M, hence requiring more maintenance effort.	Changes to existing proprietary models or addition of a participating model only impact the reference ontology and the mappings between the affected models and the reference ontology. They do not impact other mapping ontologies. Reference ontology, however, may keep growing, making the mapping increasingly more difficult.
Knowledge organisation	Additional domain specific or domain independent knowledge necessary for semantic mediation may need to be duplicated or distributed to each mapping ontology. Similarly, the knowledge engineering skills will need to be more accessible to experts for each mapping ontology.	Additional domain specific or domain independent knowledge necessary for semantic mediation can be centrally maintained within or in association with the reference ontology. Similarly, concentration of knowledge engineering skill will be more centralised.

representation has been done. Since we plan to address this step, we envision this preprocessing to be a two-step transformation including syntax transformation and canonicalisation.

In the syntax transformation step, heterogeneous syntaxes of data are transformed into a common syntax such as the RDF. RDF is a good candidate because it has both the syntax and model on which OWL is based. Support for this transformation is abundant. In particular, the W3C's Direct Mapping of Relational Data to RDF (W3C 2012a) and RDB-to-RDF Mapping Language (R2RML) (W3C 2012b) provide a standard-based framework for RDB-to-RDF transformation. There are a number of open source and commercial tools that implement and support such transformation (Satya et al. 2009). We have investigated the RDB-to-RDF mapping in one of the open source tools and found the approach to be promising.

The purpose of the canonicalisation step is to resolve structural heterogeneities that include schematic discrepancies (Krishnamurthy et al. 1991). Our hypothesis is that the structural heterogeneities can be resolved by changing the structure to follow OWL general ontology modelling conventions and domain specific modelling patterns. An example of a general ontology modelling convention is to model all concepts as classes. An example of domain specific modelling pattern is to model all geometric dimensional capabilities of manufacturing processes as a class instance with two properties – minimum size and maximum size. This would align the model more with the reference ontology, which follows the same pattern – hence making the mapping easier. Use of higher order languages (Krishnamurthy et al. 1991; Lakshmanan et al. 1997) and the notion of RDF-based semantic annotation based on reference or upper level ontology (Vujasinovic et al. 2009) can be the driver for indicating what must be canonicalised. In addition, works by Svab-Zamazal and his colleagues (Svab-Zamazal et al. 2009; Svab-Zamazal and Svatek 2011) on pattern-based ontology transformation provide the methodology and software platform to execute the canonicalisation.

As described earlier, the reference ontology is needed in the reference-ontology-based approach. Creation, architecture development, and management of the reference ontology are non-trivial tasks. Previous work related to the methodology to create unified database views, such as Navathe et al. (1986) and Hayne and Ram (1990), are relevant to the creation and evolution of the reference ontology. Ontology change management and evolution is a large research topic. Previous work in this area has been well-summarised in Flouris et al. (2008).

5. Conclusion and next steps

Our work is motivated by the need to improve precision and information sharing/access of MSC models. By doing so, we expect to increase the effectiveness of manufacturing sourcing and, ultimately, supply chain performance. We gave formal definitions of two approaches to semantic mediation that address the issues of semantic enhancement and semantic modelling conflicts using OWL DL language and its associated description logic reasoning. These approaches are the mapping-based approach and the reference-ontology-based approach. The precision

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and accessibility enhancement benefits of the two approaches could be exploited with little to no change to the existing proprietary MSC models. However, trade-offs exist between the two approaches. To that end, we have discussed criteria for considering deployments of the two approaches. The analysis shows that all-in-all the mapping-based approach is economical for small and relatively static set of MSC models. On the other hand, the reference-ontology-based approach requires more upfront effort yet can become more economical over larger and evolving set of MSC models.

In terms of the future works, our interests lie in the following three research areas. First, we intend to publish a companion paper that provide more deployment details with additional semantic mediation use cases that further validate the usefulness of OWL DL for the mediation of MSC models. Second, we will explore a semi-automated method based on the idea of canonicalisation discussed in the 'Related technologies' to decompose, simplify, and improve the mapping task. Third, we will explore a framework than enable synergies between the mapping-based and the reference-ontology-based approaches. The framework shall allow for a systematic transition from the mapping-based approach to the reference-ontology-based approach. For example, mapping ontologies created in the mapping-based approach can be reused for creating an initial reference ontology via the ontology merge procedure discussed in this paper; and a new set of mapping ontologies to the reference ontology can be automatically generated from the existing mapping ontologies.

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Disclaimer

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.

Notes

1. http://www.heppnetz.de/projects/goodrelations/
2. http://oaei.ontologymatching.org/
3. http://oaei.ontologymatching.org/2012/conference/eval.html. Conference is the most relevant data set from the semantic-mediation perspective because it is the only data set that includes ontologies using DL expressions beyond subclass relationships.
4. These reasons may be driven by the test cases and reference alignments/maps provided by OAEI. The reference alignments consist of only equivalences between same types of entity that do not use any OWL operator/expression.
5. Notice that because OWL does not use the Unique Name Assumption (UNA), the 'Different Individuals' column is added in the individuals table (Table 9) to state that members of the `CNCMachining` class are different (otherwise OWL reasoners can still conclude that they are the same yielding undesirable reasoning results).
6. Additional discussion about mapping ontology set selection is provided in the discussion in Section 3.3.
7. Other mapping axioms are possible; however, they are excluded from the table because they are unnecessary for achieving the semantic-mediation goals.
8. Solid arrows point from a subclass to a superclass. Dashed arrows point from an instance to a class to which it belongs. Solid boxes are classes. Dotted boxes are instances. Dash-dot arrows represent a mapping relationship.
9. If a concepts matching similar to Table 10 is constructed, the result will be $[M_1] = 3, [M_2] = 4, [M_3] = 3$. Clearly M_2 illustrated in this figure is a better mapping ontology set than M_1 illustrated in Figure 5.
10. Another alternative would be to include all the possible mapping pairs in M. This means more mapping work though.
11. The best possible mapping ontology set M is always to include mappings between all pairs when they are available. However, doing so means more mapping and maintenance works. In addition, further study on how this impacts the reasoning and mediation performance will be needed.
12. The purpose of the procedure is to illustrate how we arrive at g(n). The actual process of arriving at it may not follow this procedural flow (e.g., one may derive all Δ_i's first and simultaneously reconcile them with $\sum_1$). Either way g(n) is theoretically the same. A reference ontology created from merging proprietary model while can enhance access may not increase semantic precision. Additions of axiomatic definitions should be considered.

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