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Preface

This volume contains the papers presented at FOMI 2014: Sixth Workshop on Foundational Ontologies Meet Industry held on September 22nd, 2014 in Rio de Janeiro, Brazil. FOMI is an international forum where academic researchers and industrial practitioners meet to analyse and discuss application issues related to methods, theories, tools and applications based on formal ontologies.

This volume contains seven peer reviewed articles that were presented at the workshop. In addition, the workshop featured an invited talk by Mara Abel on the use of ontologies in the petroleum industry and a panel discussion.

We thank the authors for their submissions and the program committee for their hard work.

September 2014

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Representing Organizational Structures in an Enterprise Architecture Language

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Abstract

Enterprise Architecture (EA) promotes the establishment of a holistic view of the structure and way of working of an organization. One of the aspects covered in EA is associated with the organization's "active structure", which concerns "who" undertakes organizational activities. Several approaches have been proposed in order to provide a means for representing enterprise architectures, among which the ArchiMate, an EA modeling language. In this paper, we present a semantic analysis of the fragment of the ArchiMate metamodel related with the representation of active structure. In addition, we present a proposal to extend the metamodel based on a well-founded ontology for the organizational domain. Our objective is to enrich the language with important capabilities to represent organizational structures using a principled ontology-based approach.

Introduction

Enterprise Architecture (EA) promotes the establishment of a holistic view of the organization in order to provide organizations with the ability to understand its structure and way of working. As defined in [1], the description of an EA usually "takes the form of a comprehensive set of cohesive models that describe the structure and functions of an enterprise". The majority of EA frameworks considers an organization as a system whose elements include: (i) organizational activities structured in business processes and services; (ii) information systems supporting organizational activities; (iii) underlying information technology (IT) infrastructures, and (iv) organizational structures (organizational actors, roles and organizational units).

This last domain of elements is also called "active structure" [2] and concerns "who" undertakes organizational activities. Active structure focuses on the business agents that perform tasks and seek to achieve goals, encompassing the definition of business roles, authority relationships, communication lines, work groups, etc. The relevance of organizational structure is clear from a management perspective in that it defines authority and responsibility relations between the various elements of an enterprise. Further, from the perspective of enterprise information systems, organizational actors can be considered as system owners, system maintainers, system users or simply system stakeholders in general, affecting the usage and evolution of such systems [3]. Our ultimate goal is to produce EA models that represent organizational reality faithfully and thus serve for the purposes of EA documentation, analysis and communication.

In this paper, we are particularly interested in the modeling of the active structure domain in the widely employed EA modeling language ArchiMate [2]. A strength of this language is the broad coverage of a wide number of aspects of EA, and the possibility to describe relations between the various aspects. Nevertheless, the emphasis on providing an overview of relations seem to have led to a less sophisticated treatment of some aspects, and that includes the active

structure domain. As a consequence, some shortcomings have been identified by the ontology community [4][5], such as limitations on its conceptual coverage and lack of clear real-world semantics for some of its constructs. The limitations in the coverage of concepts affect the language's ability to represent important organizational phenomena (affecting expressiveness, or what is called "completeness" in [6]). The absence of a well-defined real-world semantics opens space for interpretations not originally intended by a language user, resulting in ambiguous and inaccurate representations and ultimately in problems of communication between users.

Our primary goal is to address these limitations by proposing means to represent more sophisticated organizational structures in ArchiMate. We address this task with a principled approach. We first define a reference ontology for the active structure domain. Our objective for this reference ontology is to focus on core aspects of this domain in accordance with dominant themes in the management literature. Having this reference ontology enables us to analyze the capacity of ArchiMate to represent information about the active structure domain. We point out the problems and their consequences for the generation of high-quality EA models. Finally, we present a proposal to extend the language metamodel to address the identified issues and contribute to the increase of the expressiveness and clarity of the language.

This paper is structured as follows: Section 1 reviews basic organizational concepts in order to set minimum requirements for the representation of the active structure of organizations. Section 2 introduces the OntoUML Org Ontology (O3). Section 3 introduces ArchiMate active structure constructs briefly. Section 4 the analysis and revision of ArchiMate using the notions of O3. Section 5 discusses related work. Finally, Section 6 presents our conclusions.

1 Basic Notions in the Organizational Literature

In the organizational literature, some basic organizational notions are frequently referred to in order to characterize organizations. In this section, we discuss these notions, as they form basic requirements of expressiveness of organizational structure. We do not aim at exhausting all relevant aspects concerning organizational structure. We focus on three dominant themes in the management literature: (i) division of labor, (ii) social relations and (iii) types of structuring units.

1.1 Division of Labor

We, as human beings, have limitations on processing information and on accomplishing tasks [7]. Division of labor manages our human limitations and coordinates us to achieve organizational goals. Fayol defined in [8] that the division of labor aims to produce more and better, with the same effort, in addition to reducing the number of objectives upon which the attention and effort should be applied.

In a top-down view, organizations can be considered as systems composed of subsystems, each of which can be nested into subsystems recursively [9]. Division of labor consists in the top-down view of dividing an overarching organizational mission into specialized goals or tasks allocated to distinct well-defined units of work in order to increase efficiency. The creation of working groups aggregating individuals with heterogeneous skills that pursue a common purpose represents the definition of these subsystems (which we will call here Organizational Units). In a bottom-up view, "we are confronted by the task of analyzing everything that has to be done and determining in what grouping it can be placed […] Workers may be easily combined in a single aggregate and supervised together" [10].

The division of labor in its highest degree of specialization is represented by defining "positions". At this level of granularity, the tasks are distributed among the various positions as official duties. This infers a clear division of labor between positions, as defined in [11]. Positions also allow the formalization of the organization based on descriptions of duties, rights, requirements and social relations assigned to reusable organizational roles and not directly on the actors who play them.

1.2 Social Relations

Within the universe of a formal organization, social relations of power and communication are of great relevance. Concerning power relations, [8] defines that authority is the right to command and the power to be obeyed. Without authority, i.e., without explicit formal organization in upper and lower positions, where the superiors have more power than the lower, the organization ceases to be a coordinated entity [12][1]. Apart from power relations, communication relations allow the definition of interactions between business actors without requiring the establishment of relations of authority. The existence of a relationship of authority between organizational actors implies the existence of a relationship of communication between them, but the contrary is not always true.

[1] This reveals our interest specifically in organizations that are, to a certain extent, hierarchical

1.3 Types of Structuring Units

The working groups that compose organizations have different natures. Different structuring principles (functional, line-staff, divisional, matrix and flat organizations) lead to different types of structuring units like departments, divisions, line units, staff units, teams and task forces.

In organizations structured following the line-staff model, one of the main distinctions is between line and staff units. The line units comprise the functional organization and represent the specialization of division of labor in functional/production units following different criteria of aggregation of individuals. The line units can relate through relationships of authority and are composed of other line units [13]. In contrast, staff units are units without administrative authority, who have the responsibility of advising the production units to perform actions and do not have full responsibility for the execution of tasks [14]. The "staff authority is subordinate to line authority, and they tend to identify line with managers or administrators and staff with experts and specialists" [14].

Other types of working groups present in organizations that adopt the matrix model are the teams and task forces [15], which are units with dual authority relationship, where the relationship of power is balanced between formal authority and technical authority [15]. Teams and task forces aggregate employees belonging to different departments/divisions/line units and can have limited lifetime. In addition, these types of structuring units put together in a single unit the authority and information necessary for performing tasks [15]. The main difference between teams and task forces lies in the fact that task forces are used to solve temporary problems, while teams are used to solve recurring problems [15].

2 The Reference Domain Ontology

The basis of the semantic analysis of ArchiMate performed in this paper is a reference domain ontology which we call OntoUML Org Ontology (O3). It covers the organizational domain, focusing on the themes discussed in the previous section. In order to represent this reference ontology, we employ OntoUML, a UML profile that incorporates the foundational distinctions of the Unified Foundational Ontology (UFO) using UML stereotypes. Thus, our domain ontology employs and specializes the more general domain-independent notions of objects, types, events, social entities, etc. (A brief description of the required UFO concepts is given below in sections 2.1 and 2.2. See [6] and [16] for thorough presentations.) Our choice for UFO is based on the key role it has played in previous efforts in domain ontology engineering [16], harmonization of semantic models [17][18] and evaluation and revision of enterprise languages [3][19]. By specializing UFO, O3 provides an ontologically well-grounded view that covers the basic notions of the organizational domain.

2.1 Basic Entities

We start with the basic distinction in UFO between Individuals and Universals. Individuals are entities that exist in reality instantiating one or more universals and possessing a unique identity. Universals (more specifically *first-order* universals) are patterns of features that can be realized in a number of individuals. Roughly speaking, individuals can be viewed as elements and first-order universals as their types.

Substantials are individuals that do not need others individuals to exist, i.e., are existentially independent (e.g., a car, an apple, Bill Gates). Moments are particularized properties inherent to an individual and are existentially dependent on the individuals on which they inhere. Moments can be intrinsic or relational. Intrinsic moments apply to a single subject (e.g., an apple's color, someone's headache). Relational moments are called relators and depend on various relata (e.g., an employment contract relating an employee and an employer, a marriage contract between husband and wife) [6].

The stereotypes in OntoUML correspond to ontological distinctions for universals of UFO, enabling us to use class diagrams to represent ontologies that employ the distinctions of UFO. For instance, a class stereotyped as <<category>> represents a rigid concept, i.e., a class that applies necessarily to its instances (throughout their entire existence). A class stereotyped as <<kind>> also represents a rigid concept but one that supplies a principle of identity to its instances (e.g., Person). A class stereotyped as <<role>> (or <<role mixin>>), in turn, is an anti-rigid concept, applying contingently to its instances (e.g., a Person is only an Employee contingently and can cease to play that role and still exist). A role is also relational dependent, i.e., it defines contingent properties exhibited by an entity in the scope of a relationship (when an individual instantiates a role universal, it is thus connected to at least one other individual through a relator).

2.2 Intentional and Social Aspects

UFO includes a social layer that specializes its core with distinctions to account for intentionality and social reality [16]. An important distinction in this layer is that between agentive and non-agentive objects. Agentive objects (agents) can perform actions and have mental/intentional moments (intentions, desires and beliefs). Agents are differentiated in

physical agents (e.g., a person) and social agents (e.g., an organization). Objects are passive entities that can be used, consumed, destructed, modified and created by agents. Objects are partitioned into physical objects (e.g., a computer, a pen) and social objects (e.g., a piece of legislation, a language).

Normative descriptions are social objects that define rules/norms recognized by agents. Normative descriptions can define nominal universals, such as social objects (e.g., the crown of the King of Spain) and social roles (e.g., IT Analyst, surgeon).

2.3 OntoUML Org Ontology (O3)

O3 has been defined by extending the social concepts of UFO, such as social role, social agent and physical agent. In this paper we present fragments of O3 focusing on the concepts required for the purpose of this paper, namely, the analysis and revision of the ArchiMate active structure elements. We discuss the ontology following two points of view: (i) organizational structure (section 2.3.1) and (ii) roles (section 2.3.2).

2.3.1 Organizational Structure

Figure 1 presents the fragment of O3 related with the organizational structure concepts. The top-most concept is organization, specializing the UFO notion of Social Agent. As defined in [12], organizations are (artificial) social units built with the explicit intention of pursuing specific goals. In another definition, organizations are defined as "collectivities that have been established for the pursuit of relatively specific objectives on a more or less continuous basis" [20]. Human resources are among the major means used by organizations to achieve its goals [12]. In healthy organizations, the organizational goals are assimilated by its human resources in combination with its personal goals. Organizations include corporations, armies, hospitals and churches, but exclude tribes, ethnic groups, families and groups of friends. Organizations are characterized by division of labor, presence of one or more power centers that control the combined efforts of the organization and coordinate activities to achieve goals. Members of an organization can be replaced or relocated to other functions without the organization ceasing to exist. An organization may be structured into other social agents that together contribute to the operation or behavior of the whole, defining thus what is called a functional complex in [6]. (See [19] for a discussion on the whole-part relation of UFO applied at the organizational context.)

We specialize organizations into formal organizations and organizational units. Formal organizations are formally recognized by the external environment. Their creation is determined by normative descriptions or speech acts which are recognized by the normative context in which formal organizations exist. Examples of formal organization include Microsoft Inc., the UK Government and the Fed. University of Espírito Santo.

Organizational units are those organizations that are only recognized in the internal context of a formal organization and represent the working groups of a formal organization. An organizational unit can be a structural unit or a missionary unit. Structural units are closely related to functional structure of the organization, including line units and staff units. A line unit has authority relationships with other line units (upper or lower). Such relationships result in a hierarchy of authority. Furthermore, it may be composed of other line units, resulting in a relationship of authority (represented by the relationship "manages") between parts. The justification for the structuring of line units through two distinct relationships (whole-part and authority) lies in the fact that the whole-part relationship (in the organizational domain) naturally implies power, but power does not imply a whole-part relation. Examples of line unit include a Marketing Department, a Board of Directors and a Sales Division. As seen in Section 1, a staff unit is a "counselor" unit, which has no administrative authority, thus it is not part of line hierarchy composed by line units. Although they have no line authority, staff units relate to line units through the relation "staff of", which determines the line unit to which a staff unit responds. Examples of staff unit: a Group of Financial Advisors and an Internal Audit Group. Missionary units represent teams and task forces related to the matrix structure of the formal organization, such as a project group and a task force to deliver a product to the market in the schedule. A feature of this type of work group is the aggregation of actors belonging to different line units. Examples of missionary unit include an ERP Project Team, an Audit Committee and a Financial Task Force.

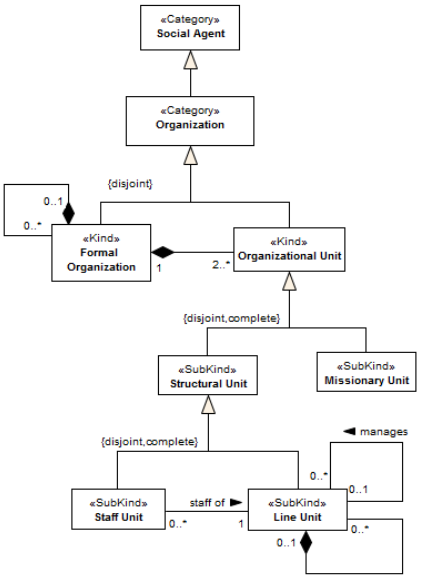

Figure 1: Fragment of OntoUML Org Ontology related with organizational structure.

2.3.2 Organizational Roles

Figure 2 presents the concepts related with the agents that compose the organization and the types of roles they may play. We are concerned in this fragment with the roles persons play, first of all as a member of a formal organization (formal organization member), and then when they are given more specific places in the power structure, either in a structural (line or staff) unit (structural unit member) or in missionary units (missionary unit member). (For the sake of brevity the diagram omits the <<relator>> classes that connect the individuals playing the roles and the formal organization, structural and missionary units.) Note that in order to play a particular role in an organizational unit, a person needs to be a formal organization member first.

In the scope of each organization, different specializations of these more general roles are required. For example, in a university, employee types such as "Professor" and "Secretary" become relevant, while in a hospital employee types such as "Doctor" and "Nurse" may be defined. Therefore, O3 includes the second-order notions of employee type and other business roles. They are to be instantiated in particular settings creating thus specific roles. The instances of employee type specialize formal organization member, and the instances of business role specialize either structural unit member or missionary unit member. We represent them by following UML's "powertype" representation pattern with the second-order concept stereotyped <<hou>> (for higher-order universal), highlighted in gray. Specific employee types define the set of roles (business roles) that a typified employee can occupy in the organization (see "cover" relationship). Business roles defines more specific capabilities, duties and prerogatives possibly in the scope of organizational units. An employee allocated to a structural unit plays a structural business role; employees assigned to missionary units play missionary business roles. Authority relations between these types of business roles can be define through the relationships "is superior to".

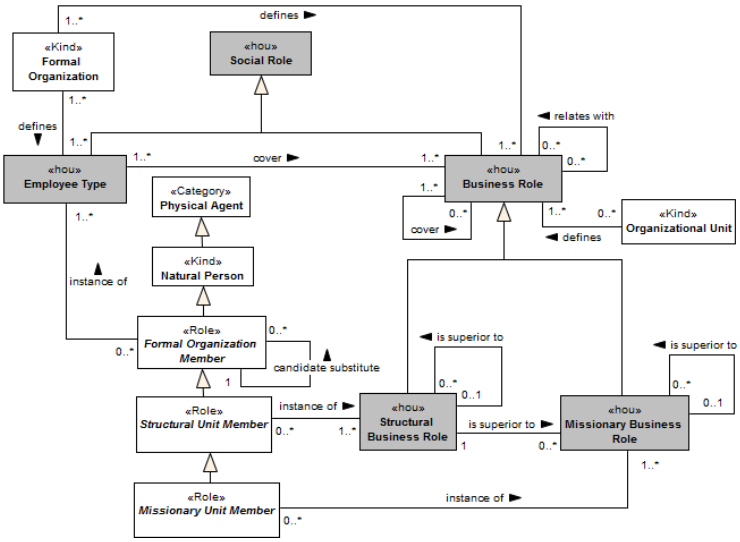

Figure 2: Fragment of OntoUML Org Ontology related with organizational roles.

3 An Overview of Active Structure in ArchiMate

For the purposes of this paper, we focus on the active structure aspects of ArchiMate's business layer, whose abstract syntax metamodel is presented in Figure 3.

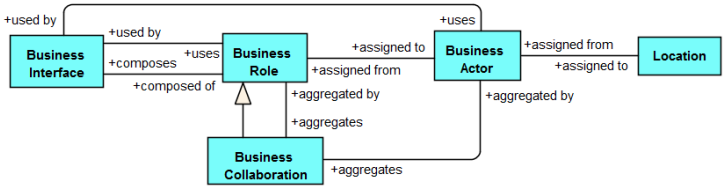

Figure 3: ArchiMate metamodel fragment and relations between active structure elements. Adapted from [2].

In the ArchiMate specification, a *Business Actor* is defined as "an organizational entity that is capable of performing behavior" [2]. It can represent an individual entity or a group entity, as a department, for example. Examples of *Business Actors* are: "John", "Customer" and "Marketing Department". A *Business Role* is the "responsibility for performing specific behavior, to which an actor can be assigned" [2]. Examples of Business Role include "Project Manager", "Secretary" and "Sales Consultant". In ArchiMate, a *Business Role* can be assigned to a *Business Actor* through a relation called "assignment". The *Business Collaboration* construct represents the interactions between two or more *Business Roles*. The *Business Collaboration* does not have an official status within the organization and can be temporary [2]. An example of *Business Collaboration* is a "Supply Chain" collaboration performed between two organizations, which one plays the role of "Customer", and the other plays the role of "Supplier". A *Business Interface* exposes the functionality of a business service to *Business Roles* and *Business Actors*, or expects functionality from other business services. The exposed interface is a channel that provides means to interaction, e.g., "Internet", "Mail", "Telephone" and "Care Unit". Finally, *Location*, in the scope of Business Active Structure, allows the definition of the distribution of the *Business Actors*. A *Location* "is defined as a conceptual point or extent in space" [2]. (In addition to the relations shown in Figure 3, all elements in ArchiMate can be related with other elements of the same type through the generic relations of composition, aggregation, association and specialization.)

Figure 4a presents an example of an ArchiMate model concerning business active structure. In this example, two *Business Actors* ("Insurance Department" and "Customer"), play the *Business Roles* of "Insurance Seller" and

"Insurance Buyer", and interact through a telephone interface. Figure 4b presents an example of nested business actors, representing a composition or aggregation of actors in ArchiMate.

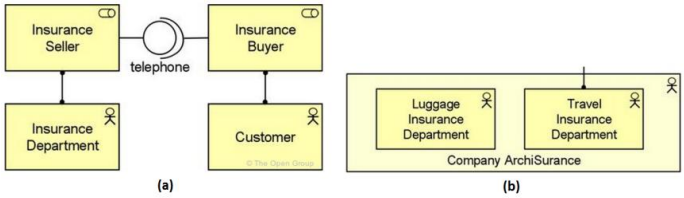

Figure 4: Examples of ArchiMate model with active structure elements [2].

4 ArchiMate Analysis and Revision

Using O3 as a semantic background, and based on the ArchiMate specification and official examples, a number of observations can be made with respect to the expressiveness of ArchiMate in the specification of organizational structures. First of all, we can note that the *Business Actor* construct is used indistinctively to model both social agents and natural persons. Absence of such distinction prevents the specification from elaborating on rules for the language's syntax, e.g., aggregation (a whole-part relation) may be used inadvertedly by language users to relate business actors representing natural persons (e.g., Mary as part of John).

Another point of attention identified is related with the inability to indicate that a business role is pertinent to an organizational unit. Despite the absence of such possibility in the current version of ArchiMate, this type of relationship was possible in earlier versions, as explained in [5]. In addition, it is not possible to represent the relation between staff units and line units, a basic notion of organization charts.

There is further no explicit construct for representing missionary units. Although there is a *business collaboration* construct, it is unclear whether *business collaboration* results in the definition of a new social agent. Finally, observing the ArchiMate metamodel (Figure 3), *business collaboration* seems to hide several problems: we can see that *business collaboration* can aggregate *business actors* without the intermediary of roles. Moreover, because it is a *business role*, *business collaboration* inherits all relationships of the *business role* construct, thus, an actor can "play" a collaboration. These situations defy a clear interpretation of the business collaboration construct as is.

Considering these shortcomings, we propose a revision of the metamodel, as shown in Figure 5. Classes marked with darker colours represents constructs added.

The constructs *natural person*, *organizational unit*, *formal organization*, *staff unit*, *line unit*, *missionary unit* and *employee type* of the revised metamodel have a direct mapping to the corresponding O3 concepts. The *business actor* construct is partitioned in three sub-categories: *formal organization*, *organizational unit* and *natural person*. The specialization of *business actor* comes in response to the overload of constructors present in the original meta-model.

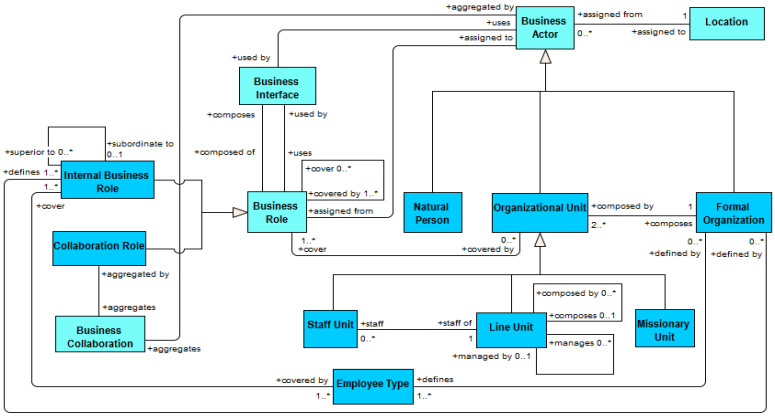

Figure 5: Extended metamodel of ArchiMate.

Besides the constructs added to the metamodel, we have added or removed some of the relationships between the constructs of the original metamodel. We modify extensively the *business role* construct, including a different proposal of semantic interpretation, which eliminates the semantic overload existing between a role in an internal context (played by an employee) and a role in an interaction context, e.g., between a supplier and an organization. In the revised metamodel the *business role* construct is thus specialized into: *internal business role* and *collaboration role*.

An *internal business role* defines more specifically than *employee type* the capabilities, duties and privileges of an employee who plays a certain role. Moreover, while it is a member of the organization, an agent can play different *internal business roles* (both at the same time, as well as switching between different roles). The *internal business role* construct also limits the range of business roles that a member of the organization that plays a certain *Business Role* can claim (through the "cover" relationship). This situation is common in matrix organizations where an employee can play a *business role* in a department and a different *business role* in a project. A b*usiness role* is defined in the context of a *formal organization*.

Collaboration roles represent roles played in recurrent interactions outside and inside the organization. It is defined in the context of the *business collaboration* construct, being part of the definition of a collaboration. The *collaboration role* is more flexible than *internal business role*, admitting that an external actor (physical or social) may play the *collaboration role*, while only members of the organization can play *internal business roles*. In the revised metamodel, the *business collaboration* construct is also not a specialization of *business role*. We made this change in response to the semantic problems that arise from relationships that were inherited from business role in the original metamodel but that cannot be applied meaningfully to collaborations.

5 Related Work

The organizational structure domain has been the focus of a number of ontologies since the end of the 90s. The Enterprise Ontology EO, e.g., includes a fragment that addresses the organization structure domain [21]. It is described in natural language and is based on formalized meta-ontology, with good coverage of concepts related to organization structure. Differently from O3, it makes no distinction between staff, line and missionary units. EO also includes a direct relationship between a “person” and an “organisation unit” (“working for”), without the intermediary of roles or positions they play in the scope of an “organizational unit”. In case a person plays multiple roles its not possible to define which role is played in the context of each “organisation unit”. The organization ontology for the TOVE enterprise model [22] chooses for a fixed structure with three levels: organization, division and sub-division. It has a notion of team that is independent of these levels of decomposition. It does not distinguish staff and line units as well as the different categories of roles individuals may play. Roles are also not related to organization units (only indirectly through authority). The Organizational Structure Ontology of the SUPER project (OSO) [23] is aimed at providing organizational context for the execution of business processes. Differently from O3, OSO is not specified using a well-defined language and is not based on a foundational ontology. Further, it does not include some important distinctions in O3 (line vs. staff units, different sorts of roles). The W3C Org Ontology [24] concerns the description of organizational structure for Semantic Web applications. It is defined in OWL and, given its focus on Semantic Web data, it is less suitable for meaning negotiation, which is required in our intended application (semantic analysis and language revision). It does not make fine distinctions in the sorts of roles that can be played in an organization as well as the different kinds of organizational units (staff, line, missionary). The W3C Org Ontology is further not grounded in a foundational ontology. Finally, E-OPL [25] aims to provide a basis for an enterprise pattern language whose fragments can be selected flexibly. It is grounded in UFO and is defined using OntoUML, however it does not cover missionary and staff units, which is important to the representation of organograms in EA descriptions. We intend to add patterns to E-OPL that reflects the distinctions in O3 as part of our future work.

In a broader scope, some approaches aim to provide languages for representation of EA aspects in general, including the organizational structure aspects. UPDM [26], e.g., is a profile for DoDAF and MODAF frameworks focused on representation of EA aspects in UML, including active structure elements. It is grounded on the IDEAS foundational ontology. UPDM lacks expressivity, since it does not differentiate types of organizational units and types of business roles. It could also have been the subject of our analysis (along with other EA modelling techniques beyond ArchiMate).

The use of reference ontologies for evaluating and revising enterprise modeling languages have been shown to be promising, as observed in [4][5][3][19]. The efforts most closely related to this work include: a semantic analysis of another fragment of ArchiMate (more specifically the motivational layer [4]); a semantic analysis of the notion of role in ArchiMate and other EA description techniques [5]; and an analysis and revision of the ARIS capabilities for organizational structure modeling [3]. Here we address a different language (or language portion) and we use more specialized domain concepts (with domain distinctions that complement general UFO notions).

6 Final Considerations

This work demonstrates the application of an organizational ontology in the semantic analysis and improvement of a modeling language and is part of a research for defining a well-founded ontology for the organizational domain. The organizational domain ontology presented covers the basic aspects discussed in the organizational literature, such as division of labor, social relations and classification of structuring units. We have intentionally left out in the current version aspects related to skills, resource allocation, business interaction and communication relations.

The use of the well-founded OntoUML profile for modeling O3 leverages the conceptual distinctions in UFO as well as the tool support already developed for OntoUML. Future work in the development of O3 include employing the OntoUML tools for formal verification of the model (guaranteeing that the models are compliant with UFO axioms), validation of the model via visual simulation (relying on an OntoUML infrastructure developed on top of the Alloy Analyzer) as well as the systematic implementation of O3 in computational level languages such as OWL.

The analysis using O3 has revealed predominant themes of the literature on organizational structure – those that have influenced the design of the O3 – have been left out of the range of expressions of ArchiMate. We have proposed a revised metamodel that address the identified shortcomings, enabling a more sophisticated representation of organizational structures in the language. We have strived to maintain the alignment of the introduced revisions with the original metamodel in order to favor the acceptance by prospective users. Thus many of the additions are in fact specializations of the existing constructs of the language. Further investigation is required in order to propose graphical conventions to represent the abstract syntax elements identified here.

6.1.1 Acknowledments

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ISA-88 Formalization. A Step Towards its Integration with the ISA-95 Standard

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Abstract.

ANSI/ISA-88 and ANSI/ISA-95 are two well accepted standards in the industrial domain that provide a set of models considered as best engineering practices for industrial information systems in charge of manufacturing execution and business logistics. The main goal of ANSI/ISA-88 is the control of batch processes, whereas the one of the ANSI/ISA-95 standard is the development of an automated interface between enterprise and control systems. In consequence, both standards should interoperate. However, there are gaps and overlappings between their corresponding terminologies. Moreover, there are additional problems, such as semantic inconsistencies within each of the standards, as well as the use of an informal graphical representations in one of the ANSI/ISA-88 models. This work presents an ontological approach that aims at formalizing the ISA-88 standard as a first step towards its integration with a formal representation of the ANSI/ISA-95 one. Additionally, methodological aspects of the ontology development process are presented.

1 Introduction

Industrial organizations address their planning activities within the context of the enterprise hierarchical planning pyramid. This pyramid (see Figure 1) includes activities performed at different time frames, handles information having distinct granularities, and involves scheduling interplaying with the Production Planning and Control (PPC) and Plant Control (PC) functions. The difficulties associated with these interactions were pointed out almost a decade ago [Sho02] and this topic has recently gained renewed attention. To tackle the integration of PPC and scheduling, researchers have proposed various solution strategies [Mar09]. In addition, a few authors have pointed out the requirements that apply to the data exchange in order to support such integration [Kre06]. Similarly, regarding integration between scheduling and plant control, researchers have started to draw the attention to data exchange problems [Mun10], [Har09]. Moreover, the standards ANSI/ISA-88 [Ans10] and ANSI/ISA-95 [Ans00] (referred as ISA-88 and ISA-95 for simplicity reasons) have been developed to tackle issues related to planning, scheduling and control activities and data. Whereas both standards address the exchange of data between the scheduling function and its immediate upper and lower levels in the planning pyramid, a more comprehensive approach is required to address integration problems, since this matter entails much more than data exchange.

The aforementioned problems are related with semantic issues, which constitute challenges that should be addressed to reach a semantic integration of enterprise applications. For example, the *batch* concept has three definitions in ISA-88. This term is used as an abstract contraction of the words "the production of a batch"[Ans10]. Therefore, according to the context, batch means both the material made by and during the process and also an entity that represents the production of that material. In a similar way, the terms *procedure* and *recipe component* have different meanings within the ISA-88 standard. The opposite situation, more than one term to represent a given concept, also occurs between the ISA-88 and ISA-95 standards. Both use different terms to define concepts such as "amount of material", "equipment", "group of products scheduled to be manufactured" and "how to make a product". Moreover, ISA-88 lacks a formalism to represent the procedural part of a recipe, since it employs an informal graphical model

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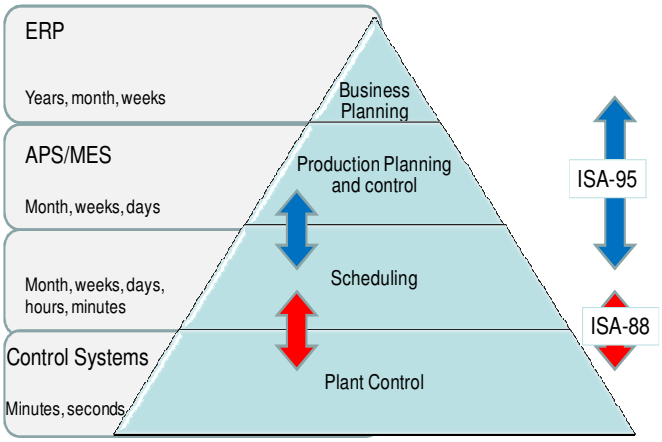

Figure 1. Scheduling function in the enterprise hierarchical planning pyramid

To overcome these semantic challenges, this work proposes the formalization of the ISA-88 [Ans10] standard as a first step towards its semantic integration with the ISA-95 [Ans00] one. This article is organized as follows: section 2 briefly introduces the ISA-88 standard. Section 3 presents general methodological considerations for the development of the proposal, describes the main concepts of the ontology and its application to a case study. Conclusions and future work are drawn in Section 4.

2 ISA-88 standard

The ISA-88 standard originally addressed batch process control issues, and was later extended to tackle discrete manufacturing and continuous processes. It organizes knowledge along three different perspectives: the physical model, the process model, and the procedural control one. All these representations are hierarchical ones.

The *physical model* hierarchically organizes the enterprise into sites, areas, process cells, units, as well as equipment and control modules. The three higher levels are more precisely defined in the ISA-95 standard, as they are often beyond the scope of batch control. The criteria for establishing these boundaries are not well defined neither in the ISA-88 nor in the ISA-95 standard. The *process model* is a multi-level hierarchical model for the high level representation of a batch process, and it is the basis for defining equipment independent recipe procedures. The ISA-88 standard divides a batch process hierarchically into process stages, process operations and, finally, process actions. The *procedural control model* is a hierarchical representation that depicts the orchestration of procedural elements to carry out process oriented tasks.

According to ISA-88 a recipe provides the necessary set of information that uniquely defines the production requirements for a specific product. Recipes are defined at different abstraction levels: General, Site, Master and Control. Distinct recipes (at the same abstraction level) may exist for different sets of raw materials that can be used to manufacture the same product. This work focuses on the Master and Control recipes since they are the ones that take part on integration issues. A Master recipe includes cell specific information, which is based upon equipment types and classes. Finally, the Control recipe is obtained from the Master one by incorporating batch specific information, such as batch size, the allocation of process equipment, and the definition of quantities of raw materials by scaling the recipe parameters according to the adopted batch size. Thus, the master recipe acts as a template for the derivation of control recipes. Typically, the information comprised in a recipe includes: (i) the header, with the recipe ID, version, status, date, etc., (ii) the formula, containing process inputs (data about the materials, energy and other resources that are required), expected outputs (products, by-products and waste products), and process parameters (temperatures, flowrates, processing times, etc.), (iii) equipment requirements, (iv) the recipe procedure, which defines the sequential and parallel actions needed to produce a batch of a certain product, and (v) safety and compliance information.

The recipe procedure, which is the core part of a recipe, can be hierarchically decomposed into recipe unit procedures, recipe operations and recipe phases, which define the procedural control model. Each unit procedure consists of an ordered set of operations, which consist of an ordered set of phases. The ISA-88 standard proposes a graphical model, referred as the Procedure Function Chart (PFC), in order to represent the recipe procedure for both, the Master recipe and the Control one. Although there are several accepted ontologies for process representation, like PSL (Process Specification Language) [ISO04], the model included in the standard is one adopted by batch

industries for the specification of their production processes. Therefore, in this article a formalization of PFC is done. A PFC is defined by a set of symbols representing recipe procedural elements, begin and end points, resource allocations, synchronization elements, recipe transitions and directed links, as well as selection and simultaneous sequences. Figure 2 illustrates the PFC of a recipe for Mint Swirled Toothpaste production and partial details of the low level PFC associated with this recipe [Par00]. According to the control model of ISA-88, the recipe of a Mint Swirled toothpaste batch is related to a procedure called *Mint Swirled Toothpaste Production* in the example. Figure 2 shows three encapsulated unit procedures, which correspond to the production of mint and gel toothpaste and the mixing of both components. Figure 2 also shows the details of the *Make Gel Toothpaste* unit procedure, which encapsulates a sequence of three operations: *Add Ingredients, React* and *Prepare to Transfer*. The first operation combines various ingredients to form a new intermediate material. The second one mixes, heats, and then cools the new mixture to create toothpaste. Finally, the last operation gets the vessel ready to transfer its contents to the blender/extruder unit. The last two operations are linked by an explicit transition, which implies that the condition *Approved by lab* has to be satisfied before the *Prepare to Transfer* step operation starts.

An expansion of the *Add Ingredients* operation is included in the right part of Figure 2. Five phases are comprised in this operation. Each phase performs a unique and independent function. The phase *Add Water* precedes the following three parallel phases: *Add Filler*, *Add Flavorings* and *Add Stabilizers*. The three phases have to be completed before the *Add Sodium Fluoride* phase starts. The two pairs of horizontal lines represent the begin and end of the parallel sequence.

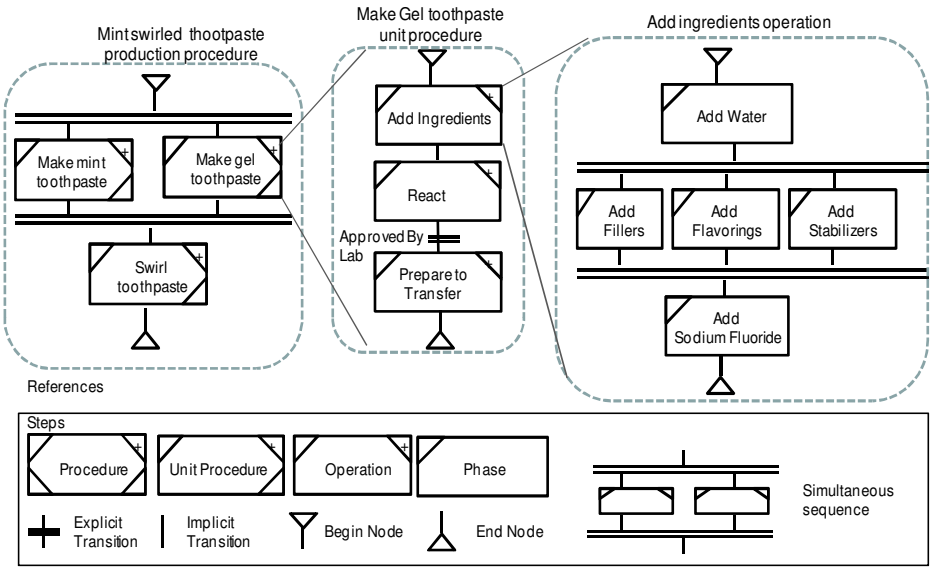

Figure 2. PFC example

As it can be seen in Figure 2 any procedural element above the level of a phase may represent an encapsulation of other procedural elements pertaining to the subsequent lower level in the procedural control hierarchy. Moreover, the level of the control model to which a step belongs, is represented by 1 to 4 diagonal lines located at the corners of the step rectangle. Therefore, the different types of steps are identifiable only by a person that analyzes the diagram. Only such person is capable of detecting which steps (unit procedures, operations, phases) are executed in parallel, which is the predecessor or the successor of a given step, or which are alternative steps. In consequence, the relation between a procedural element and the components that it encapsulates is not understandable without a human eye. Therefore, the implicit nature of this graphical representation makes it impossible for a computer to infer knowledge from it. In addition, the graphical representation of a PFC lacks the capacity to automatically validate the correctness of a diagram. The formalization of the PFC that is presented in this work helps to overcome this drawback.

3 ISA-88 Formalization. A First Step towards its Integration with ISA-95

In order to deal with the semantic challenges introduced in section 1, this work proposes a formalization of the ISA-88 and ISA-95 standards by defining an ontology per each standard and then an ontology to integrate them. This approach avoids defining just one big ontology, which would be very complex and rigid, by sticking to a "divide and conquer" strategy.

The development of each ontology has been carried out separately. The formalization of ISA-88 has been done first because it is the one that has the major semantic inconsistencies in its term definitions. The models proposed within ISA-88 are taken into account to divide the proposed ontology into small ontology modules. The same approach was considered in the formalization of the other standard. Due to space limitations, only a part of the formalization of the ISA-88 ontology is presented in this paper. In particular, the main concepts involved in its Procedural Control Module, which is the one of the most advanced modules in this project's implementation, are introduced in the following paragraphs.

For the development of the Procedure Control ontology, an ad-hoc methodology based on well accepted principles has been proposed. It has the following four stages:

- Requirements specification: identifies the scope and purpose of the ontology.
- Conceptualization stage: organizes and converts an informally perceived view of the domain into a semi-formal specification using UML diagrams.
- Implementation stage: codifies the ontology using a formal language.
- Evaluation stage: allows making a technical judgment of the ontology quality and usefulness with respect to the requirements specification, competency questions and/or the real world.

It should be mentioned that these stages were not truly sequential; indeed, any ontology development is an iterative and incremental process. If some need/weakness was detected during the execution of a given stage, it was possible to return to any of the previous ones to make modifications and/or refinements. Moreover, as it is proposed by Ontology Summit 2013 Communiqué [Neu13], some evaluation activities have been done in all the stages of the proposed development process. Some highlights of these methodological stages are given in the remaining of this section.

3.1 Requirement Specification

Competency questions, which were proposed by Uschold and Gruninger [Usc96] in their methodology, helped at this stage to identify the requirements. The gathered competency questions were classified in groups related to the levels defined in the control model. A small sample of the competency questions that were stated, are the following:

- Which are the procedural elements associated with a given Master Recipe?
- Which are the conditions that should be fulfilled to start a given Operation?
- Which are the operations comprised in a given Unit Procedure?
- Which are the phases that need the conclusion of a given phase P in order to start their execution?
- Which phases are executed in parallel with a given phase P?

3.2 Conceptualization

The second main step in the development process required the identification and capture of the domain concepts and their relationships, trying to fulfill the previous requirements. To support this activity, UML (Unified Modelling Language) [OMG13] was adopted. In addition to class diagrams, constraints about the objects in the model and invariants on classes have been added using OCL (Object Constraint Language) [OMG14]. The complete results of this stage are not described due to lack of space. However, a partial model will be described in this section.

As it was mentioned in Section 1.1, the ISA-88 procedural control model describes recipe procedures. Therefore, the main concepts in the corresponding ontology are related to recipes and their components. Figure 3 introduces the main concepts associated with recipe definition.

The *RecipeEntity* is the combination of a *ProceduralElement* with associated recipe information, which includes a *Header*, *EquipmentRequirements* and a *Formula*.

Each *Recipe Entity* is built up of lower-level recipe entities. But these levels should be hierarchically organized according the procedural control model. Therefore, the concepts *ProcedureRecipeEntity*, *UnitProcedureRecipeEntity*, *OperationRecipeEntity* and *PhaseRecipeEntity* have been added to the ontology in order to represent recipe entities at *Procedure*, *UnitProcedure*, *Operation* and *Phase* Level respectively. Eq. 1 shows how the instances of *ProcedureRecipeEntity* are inferred. Similar expression have been defined to compute recipe entities at the other levels. In addition, to guarantee consistency in this hierarchy, constraints on the *composedOf* relationship have been added to the proposed ontology. All *RecipeEntities,* except the ones at *Phase* level, which does not have components, should include *composedOf* recipe entities belonging to the immediate lower level. Eq. 2 states this constraint for the *ProcedureRecipeEntity*.

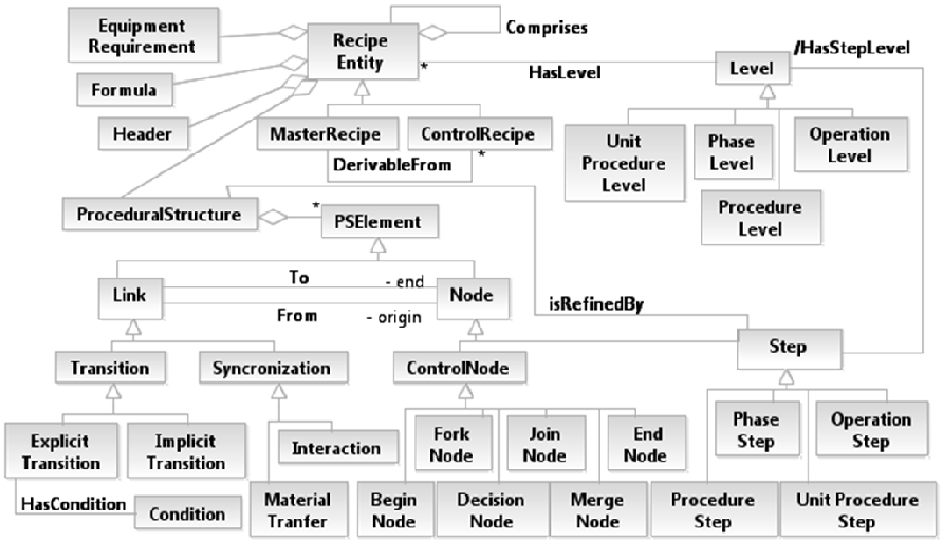

Figure 3. Recipe entity and its procedural structure definition

```
context ProcedureRecipeEntity::allInstances():Set(ProcedureRecipeEntity)                    (1)
body: RecipeEntity.allInstances()->Select(r| r.level.oclIstypeOf(ProcedureLevel))
context ProcedureRecipeEntity inv ProcedureComposedOfUnitProcedure:                         (2)
self.component->forall(r:RecipeEntity | r.oclIsTypeOf(UnitProcedureRecipeEntity))
```

A *Recipe* is a *RecipeEntity*, which is defined at the highest level of the procedural control model. In particular, a *MasterRecipe* is a *RecipeEntity* at the *ProcedureLevel,* which is the highest one (Eq. 3). Similarly, a *ControlRecipe* is also a *RecipeEntity* that is derivable from a *MasterRecipe*.

```
context MasterRecipe::allInstances():Set(MasterRecipe)                                      (3)
body: RecipeEntity.allInstances()->Select(r:RecipeEntity|
r.level.oclIstypeOf(ProcedureLevel))
```

Figure 3 also shows the relation of a recipe entity with its components: *Header*, *EquipmentRequirement*, *ProceduralStructure* and *Formula*. As it was indicated in Section 2, ISA-88 suggests the use of Procedural Function Charts (PFC) to describe the procedural structure of a recipe. The proposed ontology formalizes the elements that this type of diagram includes. A *ProceduralStructure* is a set of procedgural elements (*PSElement* in Figure 3) that depicts the procedural logic for all levels of the recipe: recipe procedure, recipe unit procedure, and recipe operation.

A Procedural Element may be a *Link* or a *Node*. A *Node* is a procedural element that represents an action (procedure, unit procedure, operation or phase) or a symbol that controls the transition between steps. A *Link* defines a relation between two nodes. Different types of links and nodes are defined in order to formalize all PFC symbols. Some of the proposed links and nodes are shown in Table 1.

Valid diagrams have to follow consistent rules for threads of execution. The formalization of the procedural structure allows the definition of constraints that helps building valid procedural structures. For example, the specialization of the *Step* concept to represent steps at different levels of the Procedural Control Model allows defining restrictions that avoid the construction of a PFC in which *UnitProcedures*, *Operations* or *Phases* could be mingled in the same diagram. For lack of space, the restriction are not shown in this article.

Table 1: Different types of links and nodes

Type of Link	
Transition	A direct link between nodes.
Implicit Transition	A transition whose only condition is that the directly preceding step has to finish its execution.
Explicit Transition	A transition having a condition that has to evaluate to true in order to activate the following step in the transition.
Synchronization	A link that relates recipe elements among which there is a certain form of synchronization.
Material Transfer	A link that represents material transfer from a step to another one.
Interaction	A kind of synchronization that does not involve movement of material.
Type of Node	
Step	A node that represents a recipe procedural element: procedure recipe entity, unit procedure recipe entity, operation recipe entity or phase recipe entity. According to the level of the procedure control model associated to the PFC in which the step is defined, this concept can be specialized in *ProcedureStep*, *UnitProcedureStep*, *OperationStep*, and *PhaseStep*.
Control Node	A node that controls de intended thread of execution of the recipe procedural elements.
Begin Node	A node that identifies the start of each procedural structure and/or each subordinate structure.
End Node	A node that indicates the end of a procedural structure and/or a subordinate structure.
Fork Node	A node that defines the start of independent threads of execution of certain recipe elements, which are executed in parallel.
Join Node	A node that indicates the end of independent threads of execution.
Decision Node	A node that specifies the beginning of alternative threads of execution.
Merge Node	A node that shows the joining of alternative threads of execution.

3.3 Implementation and Evaluation

The main goal of the ontology implementation activity is to create a computable model deployed in an ontology language from the conceptual model created during the conceptualization phase. Based on its ample acceptance, the OWL 2 language [14], developed by the W3C (World Wide Web Consortium), was chosen to implement the ontology and the Protegé 4.3 editor has been selected to support the ontology development and implementation.

The development process has been guided by the principles of coherence, conciseness, intelligibility, adaptability, minimal ontological commitment and efficiency. Some of these principles are conflicting among themselves. Due to such incompatibilities, a suitable balance between the clashing principles was sought. Nowadays it is widely accepted that there is a lack of a formal methodology that considers all these criteria, which could be applied to evaluate domain ontologies. According to Gómez-Pérez [Gom96] , the ontology evaluation phase comprises three aspects: (i) ontology validation, (ii) ontology verification, and (iii) ontology assessment. Validation and verification activities are associated with a technical judgment of the content of the ontology with respect to a frame of reference, which can be requirement specifications, competency questions, or the real world. In turn, assessment focuses on judging the ontology content from the user's point of view. The results of using the proposed ontology in the development of different types of applications in various contexts are required to be analyzed in order to assess the ontology.

Although there is no formal methodology that considers all the aforementioned evaluation criteria, many authors have reached an agreement on assessment needs during all the ontology lifecycle stages [Neu13]. Having them in mind, partial evaluation through competency questions has been done during the implementation phase. To do so,

the ontology has been applied to represent recipe information of several literature case studies [Hai11] [Fis90], including the PFC that is shown in Figure 2 [Par00]. In particular, the results of executing some of the competency questions of this case study are introduced in Table 2. For the sake of simplicity, prefixes are omitted in Table 2. While the namespace corresponding to the proposed ontology is represented with the p0 prefix, the *rdf* one identifies the namespace of the RDF (Resource Description Framework) language.

The formal competency question in the first row of the table asks about explicit transition links (?lk rdf:type p0:ExplicitTransition) having a condition (?lk p0:HasCondition ?cnd.) that points to a step (?lk p0:To ?stp.) at the operation level (?stp p0:HasStepLevel p0:Operation.) and, from this set of links, the query filters the operation step *Prepare2TransferStep* (**FILTER** (?stp = p0:Prepare2TransferStep). The execution of this SPARQL query gives as a result the *ApprovedByLab* condition which according to the PFC shown in Figure 2 is necessary to be fulfilled in order to start the mentioned operation.

The second SPARQL query in Table 2 selects all the recipe entities (?rcp rdf:type p0:RecipeEntity.) at the *UnitProcedure* level (?rcp p0:HasLevel p0:UnitProcedure.) whose procedural structure has some step as element (?rcp p0:HasProceduralSTR ?up,
?up p0:HasElement ?op and ?op rdf:type p0:Step triples). From this set of results, the query filters the unit procedure that is of interest to the competency question (FILTER (?rcp = p0:MakeGelRcp)).

The third question searches whether there is a phase that needs the end of the *AddWater* phase to start its execution. This query is more complex because it should consider different situations in which the mentioned phase is located in the PFC: (i) before a *DecisionNode*; (ii) before a *ForkNode*; (iii) in a simple sequence, (iv) after a *JoinNode*; or (v) after a *MergeNode*.

Table 2. SPARQL queries used to formalize some competency questions

Informal CQ	SPARQL query	Results
Which are the conditions that should be fulfilled to start the *Prepare2Transer* operation?	**SELECT** ?cnd **WHERE** {?lk rdf:type p0:ExplicitTransition. ?lk p0:HasCondition ?cnd. ?lk p0:To ?stp. ?stp p0:HasStepLevel p0:Operation. **FILTER** (?stp = p0:Prepare2TransferStep)}	|cnd| SampleAprovedByLab
Which phases are executed in parallel with the *AddFillers* phase?	**SELECT** ?ph **WHERE** { ?frk rdf:type p0:ForkNode. ?lk p0:From ?frk. ?lk p0:To ?ph. ?ph rdf:type p0:Step. ?lk2 p0:From ?frk. ?lk2 p0:To p0:AddFillersStep. **FILTER** (?ph != p0:AddFillersStep) }	|ph| AddFlavoringStep AddStabilizersStep
Which are the operations comprised in the *MakeGelToothpaste* UnitProcedure?	**SELECT** ?op **WHERE** { ?rcp rdf:type p0:RecipeEntity. ?rcp p0:HasLevel p0:UnitProcedure. ?rcp p0:HasProceduralSTR ?up. ?up p0:HasElement ?op. ?op rdf:type p0:Step. **FILTER** (?rcp = p0:MakeGelRcp)}	|op| AddIngredientStep ReactStep Prepare2TransferStep
Which are the phases that need the conclusion of *AddWater* phase in order to start their execution?	**SELECT** ?op2 **WHERE** { {?lk p0:From ?op. ?lk p0:To ?cnd. ?cnd rdf:type p0:DecisionNode. ?lk2 p0:From ?cnd. ?lk2 p0:To ?op2. ?op2 rdf:type p0:Step. **FILTER** (?op = p0:AddWaterStep) } **UNION** { ?lk p0:From ?op. ?lk p0:To ?cnd. ?cnd rdf:type p0:ForkNode. ?lk2 p0:From ?cnd. ?lk2 p0:To ?op2. ?op2 rdf:type p0:Step. **FILTER** (?op= p0:AddWaterStep) } **UNION** { ?op2 rdf:type p0:Step. ?op rdf:type p0:Step. ?lk p0:To ?op2. ?lk p0:From ?op. ?op2 rdf:type p0:Step **FILTER** (?op = p0:AddWaterStep)} **UNION** { ?lk p0:From ?op. ?lk p0:To ?cnd. ?cnd rdf:type p0:JoinNode. ?lk2 p0:From ?cnd. ?lk2 p0:To ?op2. ?op rdf:type p0:Step. **FILTER** (?op = p0:AddWaterStep)} **UNION** { ?lk p0:From ?op. ?lk p0:To ?cnd. ?cnd rdf:type p0:MergeNode. ?lk2 p0:From ?cnd. ?lk2 p0:To ?op2. ?op rdf:type p0:Step **FILTER** (?op = p0:AddWaterStep)} }	|op2| AddFlavoringsStep AddFillersStep AddStabilizersStep

The last question presented in Table 2 looks for phases that should be executed in parallel with the *AddFillers* one. In order to do that, the query searches if there is any step that follows the *ForkNode* to which the *AddFillers*

phase is linked to. If the mentioned phase does not follow a *ForkNode*, the query gives an empty result because *AddFillers* is not in a parallel sequence.

The implementation of several cases studies, as well as the formalization and execution of the whole set of competency questions have allowed the identification of missing concepts and properties that have to be added to the ontology. Among others, these concepts are related to the detailed description of equipment units and their relations to recipes and the different levels of the procedural control model.

4 Conclusions and Future Work

This contribution describes an ontology based approach that can play a central role in solving nowadays integration problems that appear in the enterprise hierarchical planning pyramid when adopting the ISA-88 and ISA-99 standards. The definition of three ontologies is suggested: one per each standard formalization and another ontology to integrate the previous ones. In particular, the article focuses on the formalization of PFCs, the graphical representation of the recipe procedures proposed by ISA-88. Since knowledge is explicitly and formally expressed, the ontology supports inference processes and an analysis of the construction of valid PFCs. In addition, some methodological aspects of the proposed ontology development process are also shown.

It is necessary to perform more activities to evaluate and validate the proposed formalization. In parallel with these tasks, the formalization of ISA-95 and the definition of the integration ontology are being carried out.

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Improving Ontology Service-Driven Entity Disambiguation

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Abstract.
One of the long-standing challenges in natural language processing is uniquely identifying entities in text, which when performed accurately and with formal ontologies, supports efforts such as semantic search and question-answering. With the recent proliferation of comprehensive, formalized sources of knowledge (e.g., DBpedia, Freebase, OBO Foundry ontologies) and advancements in supportive Semantic Web technologies and services, leveraging such resources to address the entity disambiguation problem in the industry setting as "off the shelf" within natural language processing pipelines becomes a more viable proposition. In this paper, we evaluate this viability by building and evaluating an entity disambiguation pipeline founded on publicly available ontology services, namely those provided by the NCBO BioPortal. We chose BioPortal due to its current use as an ontology repository and provider of ontological services for the biomedical informatics community. To consider its usage outside the biomedical domain, and given our immediate project goal for facilitating semantic search over Earth science datasets for the DataONE project, we focus on the disambiguation of geographic entities. For this work, we leverage NCBO's Term service in conjunction with NCBO's entity disambiguation service, the Annotator, to demonstrate an enhancement of the Annotator service, through application of a vector space model representation of ontological entities and relationships to drive scoring improvements. This work ultimately provides a methodology and pipeline for improving publicly available ontology service-based entity disambiguation, demonstrated through an enhanced version of the NCBO Annotator service for geographic named entity disambiguation.

Keywords. entity disambiguation, ontology, geospatial

Introduction

One of the long-standing challenges in natural language processing is uniquely identifying entities in text, which when performed accurately and with formal ontologies, supports efforts such as semantic search and question-answering. Semantic search would greatly facilitate our project, the Data Observation Network for Earth (DataONE), as it is aimed at limiting the excessive time and effort spent to discover, acquire, interpret, and use related data for biological, ecological, environmental and Earth science data.[1]

[1] http://dataone.org

The DataONE metadata catalog is composed of content uploaded by participating research institutions, that includes a *keywords* field populated by data managers, where these keywords and keyword-"worthy" terms in the scientific abstracts are not yet linked to domain knowledge in a formal way to aid discovery, besides what exist as disparate controlled vocabularies. Clearly here, the use of publicly available formal ontologies to disambiguate terms of relevance for search provides advanced capabilities for precise search and a "free extension" to their existing vocabularies that does not require manual development.

With the recent proliferation of comprehensive, formalized sources of knowledge (e.g., DBpedia,[2] Freebase,[3] OBO Foundry ontologies[4]) and advancements in supportive Semantic Web technologies and services, leveraging these resources to address the entity disambiguation problem in the industry setting as "off the shelf" within natural language processing pipelines becomes a more viable proposition. In this paper, we evaluate this viability by building and evaluating a novel entity disambiguation pipeline founded on publicly available ontology services, namely those provided by the NCBO BioPortal. We chose BioPortal due to its central role as a ontology repository and provider of ontological services for a given community, that being biomedical informatics. To consider its usage outside the biomedical domain, and given our immediate project goal for facilitating semantic search over Earth science datasets for the DataONE project, we focus on the disambiguation of geographic entities, using the Gazetteer Ontology (GAZ).

In this work, we use NCBO's Term service in unison with NCBO's own entity disambiguation service, the NCBO Annotator, to demonstrate an enhancement over the Annotator service, using a vector space representation of ontological entities and relationships to drive scoring improvements. Fittingly then, we evaluate our results against the NCBO Annotator, and apply the TopN scoring method, since both systems are suited to provide inputs to a semi-automated semantic-mapping workbench environment. Ultimately, this work evaluates whether our techniques improve on TopN mapping accuracy of the Annotator service, including if introducing all domain-level relationships into the vector space provides additional discriminatory power over just those relationships considered "broader", while at the same time provides insights into the process of using and augmenting publicly available ontology-service driven web services for entity disambiguation.

Our overall approach extracts named entity labels from natural language text, and where applicable, maps each to a resource of an ontology that best represents and disambiguates its meaning. The set of entities that can be disambiguated within our pipeline is flexible, to disambiguate what in the formal ontology community is referred to as particulars or concepts (or types), and what in the Web Ontology Language (OWL) considers individuals or classes,[5] that the Semantic Web community at large via the Resource Description Framework (RDF) refers to simply as resources.[6] Thus we describe our pipeline at the abstraction of "resource", and where appropriate for its current application we describe how it functions for geographic named entities disambiguation. In the following sections we describe related work, background on the topic-based vector

[2] http://dbpedia.org/
[3] http://www.freebase.com/
[4] http://www.obofoundry.org/
[5] http://www.w3.org/TR/owl-ref/
[6] http://www.w3.org/TR/1999/REC-rdf-syntax-19990222/

space model algorithm we apply, and our methodology and pipeline that utilizes these algorithms and services. In Section 4 we evaluate results using the TopN scoring metric, comparing against the existing annotation service using an initial, hand-curated gold standard. In Section 5 we present qualitative findings that resulted from application of our the pipeline, and in sections 6 and 7 we discuss future work and conclusions.

1. Background on eTVSM

In this section we formally present the definition and implementation of an eTVSM model [10][5]. An eTVSM formalizes how resources represent named entity labels by first including a TVSM of the ontology, and then representing entity labels within the TVSM based on links between named entity labels and resources. The first step in building an eTVSM is to encode a graph representation of resources connected through a given set of relationships into resource vectors that compose a TVSM. This graph representation is based on candidate resources and their related resources. (We consider candidate resources those resources which are discovered by initial lexical matching and potentially represent to what a named entity label refers.) For each resource, we consider $P(r,k)$ to be the power set of all resources at distance k from resource r. We construct a resource vector $\vec{r}$ as follows:

$$\vec{t} = \left\langle \sum_{k=0}^{\beta} \sum_{r_1 \in P(r,k)} \alpha^k, \ldots, \sum_{k=0}^{\beta} \sum_{r_n \in P(r,k)} \alpha^k \right\rangle, \vec{r} = \frac{1}{\|\vec{t}\|}\vec{t} \tag{1}$$

Each resource in the graph representation of an ontology is assigned an index from 1 to n, which means that each resource vector has size n and there are n resource vectors. The vector for resource n is calculated by assigning an exponentially declining weight to connected resources and summing the total weights for each resource. For example, resource i is assigned a weight of 1, all resources one node away from i adds a weight of 0.5, resources two nodes away from i add a weight of 0.25, etc. The sum of the weights are normalized. In this way we assign a resource vector to each candidate resource. The constant α is an exponential decay which is used to determine how important resources are distant from the candidate. [5] experiments with different decay values and identify .9 as being optimal for the DBpedia Ontology; in our work we apply an exponential decay constant of .5 and leave this analysis for future work. The constant β is used to limit the distance between resources that we wish to consider; in our case β is 5.

Next, an interpretation vector is constructed from an interpretation, i, which is a unique mapping of a named entity label to a resource, which we multiply by an ambiguity weight:

$$\vec{i} = \vec{r}\, g(i) \tag{2}$$

In order to reduce the effects of ambiguous mappings (i.e., which map labels to multiple resources), we weigh each interpretation vector by an ambiguity weight $g(i)$, defined as:

$$g(i) = \frac{1}{|j : j \in I(k), k \in K(i)|} \tag{3}$$

The ambiguity weight $g(i)$ forces labels which are mapped to many resources to have less weight toward disambiguating other named entity labels. Here, $K(i)$ is the set of all labels for interpretation i, and $I(K)$ is the set of all interpretations derived from label k. We represent the document as the collection of all resource mappings by summing the weighted interpretation vectors:

$$\vec{t}_d = \sum_{i \in I} w_{d,i} \vec{i} \tag{4}$$

Each interpretation vector is weighted by multiplying the frequency at which the named entity label for interpretation i is found in the extracted named entities from document d. The cosine similarity metric is used to compare individual interpretation vectors for the document against the document vector, $\vec{t}_d$. Incorrect interpretations will not significantly affect the document vector and result in a low cosine similarity score, whereas interpretations that are more similar to other interpretations will result in a higher cosine similarity.

2. Pipeline

We apply a three-phase pipeline for executing our entity disambiguation approach, including NER, resource mapping, and eTVSM scoring. We describe each phase as a black-box system, with inputs and outputs which link the phases together. Our overall pipeline takes as input an unstructured text document in the form of a science publication abstract from DataONE outputs a ranked list of candidate resources.

The *NER phase* of our pipeline extracts named entities embedded in unstructured text using the Natural Language Tool Kit (NLTK) [11]. This phase serves the sole purpose of generating a set of labels to be processed for resource mapping in the next phase. The NLTK software library contains NER algorithms that extract named entity labels from unstructured text. It applies a series of tokenizers to parse sentences into terms, and using part-of-speech tagging generates parse trees as input to supervised learning algorithms for named entity detection. The unstructured text which is passed through the NER phase of our pipeline outputs a list of named entity labels for each given document.

The *resource-mapping phase* of our pipeline processes a list of named entity labels and returns a set of named entity label to resource mappings and an ontology portion (i.e., a set of statements) describing each matched resource. In the context of geospatial named entity recognition, there are multiple resources which are referred to by the same preferred label annotation. For example, in the United States, the city of Springfield can refer to greater than 40 different cities located in multiple states. Also some states, such as Wisconsin, have multiple cities named Springfield. Therefore, the purpose of the resource-mapping phase is to map each named entity label to those resources which define a unique instance of that particular location with that name. For every named entity label extracted from the NER phase, we query the NCBO Annotator Service for a list of candidates, that is, resources which could potentially define that particular named entity within an ontology.

Next, we obtain statements about the resources, including annotations as well as object property and subclass statements, using the NCBO Term Service, by supplying a

resource URI and ontology identifier as parameters to the service.[7] The object property and subclass-based statements are filtered according to a preselected set of properties, where the objects of these statement are recursively submitted to the Term Service. In this way, we perform a breadth-first search along a set of properties until the final resource in the path is reached. This phase concludes when the statements are collected for each candidate resource.

The *eTVSM scoring phase* scores each entity label-to-resource mapping in a given document by first generating a TVSM of the obtained ontology graph, and then encoding the resource mappings into an eTVSM. We use the cosine similarity metric to determine how strongly one candidate resource is related to all candidate resources for a given document [5]. Given an eTVSM that encodes each mapping of a named entity label to candidate resources into a vector space, closely related candidate resources will have higher scores than those than are more indirectly related or not related at all to other candidate resources. Ultimately, the eTVSM scoring phase provides a quantitative measure for how strongly a resource disambiguates a named entity label.

3. Evaluation

In this section we introduce a small hand-annotated dataset which we use as a gold standard for comparing our result against the existing NCBO Annotator Service. We score output from the NCBO Annotator Service and from our pipeline using the TopN scoring metric. We demonstrate how our approach contributes an enhancement to the NCBO Annotator Service for geographic named entity disambiguation using the eTVSM algorithm. The process for which we created our gold standard is described below.

First, we selected scientific paper abstracts by processing each abstract through our pipeline and selecting those which have at least one named entity label that has greater than 10 candidate concept mappings. This decision was due to a lack of preexisting gold standard data and our desire to disambiguate highly ambiguous named entity labels. For each named entity label we hand-annotated it with a concept in the Gazetteer Ontology which correctly identifies it. The result is 24 unique named entities labels, which were extracted using the NER phase of our pipeline. For these 24 named entity labels, there are 18 unique candidate concepts contained in the GAZ ontology, which we discovered by querying the annotator service with our named entity labels. The remaining six named entity labels were either too generic for us to assign a unique concept, or the correct concepts are not contained in the most current version of GAZ; in order to get a meaningful comparison of our pipeline against the NCBO Annotator Service we excluded these six labels for our evaluation. The 18 named entity labels were hand-mapped to concepts in GAZ, composing our gold standard dataset which we use in our evaluation.

In the setting of a semantic-mapping workbench, when a prospective curator inspects the list of candidate concepts for a set of named entities extracted from a document, the most accurate or correct concept will ideally appear at or near the top of a ranked list of candidate concepts. In fact, the Annotator website presents candidate concepts in this ranked manner. To be fair, there are just two levels of ranking produced by the Annotator

[7] We describe the atoms of the ontology portion extraction in terms of statements, to maintain our abstraction at the level of resources. In the case of named entity disambiguation these statements are a mix of assertions and axioms, and in the case of conceptual entities these statements are primarily axioms.

service, determined by whether a match was made on the preferred or alternate term, while our approach uses a much more granular similarity score metric. Still, we evaluate our augmented version of the annotator alongside the publicly available Annotator Service in order to demonstrate improvement upon the existing service. Therefore we evaluate the two approaches using the position of the correct concept returned in a ranked list of concept-mapping scores. To do this, we use the TopN scoring metric [12,5]:

$$TopN = \frac{\sum_{j=1}^{N} \alpha_c^{k_j}}{\sum_{i=1}^{N} \alpha_c^{i}} \tag{5}$$

where N is the number of named entity labels which are mapped to a concept in the gold standard. k_j is the position of concept j in the returned concepts from the Annotator Service. α_c is an exponential decay coefficient used for penalizing concepts that appear later in the list. A score of 1 is realized for a document if for all named entity labels, the top scoring candidate concept corresponds to the gold standard's concept for that document. Note that since we only consider concepts that are in our gold standard, and by definition, are returned by the Annotator Service, the TopN score can never have a value of 0. However, if all the correct concepts for each entity are returned at the bottom of the list, the TopN score will be significantly small. We chose a value of 0.8 for our constant α_c, so, for example, the position of the correct concept will contribute 0.1 to the score if it appears in the tenth position [5].

For the evaluation of our pipeline, we construct our vector space using two methods. The first construction uses *located_in*, while the second uses all (13) relationships contained in the GAZ ontology. This comparison provides some evidence that including relationships beyond those considered generalizations improves scoring. Table 1[8][9] shows the comparison between the NCBO Annotator Service and our pipeline as constructed using the two methods. These results demonstrate that the application of the eTVSM-scoring phase outperforms the Annotator Service for disambiguating geographic named entities. The results demonstrate that a quantitative approach for disambiguation which measures and ranks the strength of each concept mapping outperforms an approach which relies on simple lexical matching.

4. Qualitative Findings

In this section we present some qualitative insights of applying our pipeline to a sample scientific publication abstract. Figure 1[10] shows a graph output of our pipeline as applied to a sample scientific abstract. In this run we included all geographic relationships from GAZ during the concept-mapping phase.

We confirmed that our ontology-based resource mapping approach successfully down ranks irrelevant resources and thus outperforms purely lexical-based resource map-

[8] A version of this paper with figures included is available at http://tw.rpi.edu/web/doc/ImprovingOntologyServiceDrivenEntityDisambiguation/.

[9] https://www.flickr.com/photos/127739444@N02/15066654769/

[10] https://www.flickr.com/photos/127739444@N02/15230553716/

pings. For instance, where only lexical matching algorithms are used (e..g., the current Annotator Service), the entity label 'Oregon' receives equal ranking for "State of Oregon (GAZ:00002515)" as resources "Oregon (GAZ:22225751)" and "Oregon (GAZ:00084619)" (cities in Michigan and Illinois). Our approach leverages fine-grained geographic relationships and considers relationships with other mapped named entities mentioned in the same abstract (e.g., Deer Creek, Josephine County), so that the similarity score of the mismatches for 'Oregon' is significantly lower than the correct one.

We also identified improvements to the scoring of correct resources after applying additional relationships in the resource-mapping phase of our pipeline, beyond those considered generalizations (e.g., *located_in*). For example, for the abstract of the fourth study of our gold standard, the named entity label 'Cumberland River' was mapped to three distinct candidates. When only the *located_in* relationship is applied, the two incorrect resources received a score while the correct resource (GAZ:00150754) did not (see left side of Table 2[11]); however, when applying all geographic relationships, the correct resource accurately received the highest score. This is due to relationships to other resources, via the inclusion of additional kinds of geographic relationships, that have been mapped to other named entity labels extracted from the abstract (shown in Figure 2[12]).

Finally, we learned that our pipeline improves the quality of ontologies available through Bioportal, by facilitating curators in the process of identifying and reporting existing gaps. For example, in an abstract that mentions the Deer Creek Field Station and Educational Center of the state of Oregon, the named entity label 'Deer Creek' returned 29 unique resources labeled as 'Deer Creek', none of which were the correct one. We informed the GAZ team, who quickly created the resource and appropriate statements, increasing coverage of the ontology. Figure 1 illustrates the results of the pipeline after the newly added resource "Deer Creek (GAZ:00633440)" was included, which became the highest ranking candidate resource for 'Deer Creek' due to relationships to "Josephine County" and "State of Oregon".

5. Related Work

In this section we discuss recent work that applies ontologies to the named entity recognition (NER) problem, including that which the current work uses and builds upon: the NCBO Annotator and enhanced topic-based vector space modeling (eTVSM). Researchers at the BBC experimented with eTVSMs [10] to automatically apply editor tags to archived radio programs for use in a manual curation environment [5]. Concepts contained in the DBpedia ontology were represented in a topic-based vector space model (TVSM), a model constructed by creating vectors for each concept that include those concepts related by SKOS *broader*[13]. The eTVSM was built by linking text transcribed from radio programs to concepts in the DBpedia Ontology,[14] scoring each link using the relationships between concepts that were encoded in the TVSM. Links that were closely related scored higher, while incorrect links which were not as closely related scored lower. Our work reuses the same underlying theory for using a vector space model for

[11] https://www.flickr.com/photos/127739444@N02/15066727059/
[12] https://www.flickr.com/photos/127739444@N02/15253595325/
[13] http://www.w3.org/2004/02/skos/
[14] http://wiki.dbpedia.org/Ontology

disambiguation, and additionally explores the benefits of using relationships more explicit than *broader*, to take advantage of knowledge beyond that found in a generalization hierarchy, formalized by expert curators.

The NCBO BioPortal project supports efforts to linking unstructured text to ontologies through publicly accessible services for leveraging community based ontologies [2]. The NCBO Annotator Service matches inputted text to ontological terms contained in community-developed ontologies by applying a lexical string matching algorithm to a lexicon based on preferred and synonym labels [3,4].[15] By default, the Annotator Service is configured to consider all ontologies published through BioPortal, however there is a parameter for restricting it to a set of target ontologies. [3] highlights the additional need for enhancing the service by developing components that use the knowledge in ontologies to recognize relationships between concepts, which is a focus of this paper. The service returns a list of candidate concepts from the selected ontologies and provides a score for each candidate concept based on whether the concept was matched on preferred label or synonym. Our approach builds on this service and ultimately creates an enhanced version of it that quantitatively measures how suitable each candidate concept represents a named entity. Further, our approach and pipeline starts by recognizing tokens in the text, while the Annotator spots named entities using terms from the target ontologies and supporting lexicons. Therefore with our approach a curator is more easily able to find and report gaps in the existing ontologies in a semantic-mapping workbench setting, since extracted token are immediately available for inspection. We describe how we practically applied this mechanism in Section 3.

Aside from the BBC and NCBO efforts, there exists extensive previous research in the area of entity disambiguation leveraging ontology or more generally, linked data sources. Alexopoulos et al. [6] propose a disambiguation framework that utilizes DBPedia to detect intended meaning of named entities (e.g., soccer clubs, organizations) in unstructured text, using an algorithm similar to [10]. Kleb et al. [8] focus on disambiguation using spreading activation on an RDFS-based ontologies. Mendes et al. [9] provides disambiguation and mapping to DBpedia URIs, within DBpedia Spotlight. Hoffart [7] applies a novel collective disambiguation strategy using a new form of coherence graph using DBpedia and Yago. There are also many off-the-shelf concept extraction tools available: Open Calais,[16] Zemanta,[17] Alchemy API[18]); all of these approaches identify entities and generate URIs for them through disambiguation.

Our work differs from these in that we focus on the practicality of using NCBO Bioportal and its APIs as an "off the shelf" resource for applying eTVSM for semantic disambiguation within an NLP pipeline. BioPortal is of particular interest because the ontologies registered with it include many that are developed by expert curators. The benefit of our approach is that the more explicit relationships and to what resources they relate are used for disambiguation and subsequently for fine-grained semantic search capabilities. What results from our work is an enhanced version of the NCBO Annotator for geographic entity disambiguation. Due to the Annotator's wide usage, it provides immediate utility to the community upon release.

[15] http://bioportal.bioontology.org/annotator
[16] http://www.opencalais.com/
[17] http://www.zemanta.com/
[18] http://www.alchemyapi.com/

6. Future Work

In future work, we will expand our gold standard to help determine if they further validate our results. Since it is a time-intensive process, we will seek external resources for performing the work, such as Mechanical Turk.[19] We will also leverage such resources for tagging corpora for geographic named entities, which can be used for statistically training the NLP tokenizer that we employ in the pipeline.

Our methodology and pipeline lays a foundation for widening its use to conceptual entities and other types of named entities. Therefore, in future work we will evaluate how well, in practice, that our results are generalizable for disambiguating concepts and named entities for other domains, such as biomedical. On the side of named entities, one requirement is to request the NCBO to add additional ontologies that are specific to individuals, similar to the crowdsourced content available via Dbpedia.

For concept-based disambiguation, we lose the immediate benefit of the NLTK named entity recognizer, but which is mitigated when corpora tagging is carried out for the concept domain of interest, via Mechanical Turk or use of some other resources (e.g. PubMed). While there exists a wide range of biomedical ontologies available that cover similar sets of concepts, we will incorporate and test publicly available mappings between NCBO-registered ontologies, though performing the mapping task itself falls out of our scope. For the ontology extraction task of the resource-mapping phase, the mechanism for obtaining axioms at the class level instead of assertions at the instance level remains the same via the NCBO Term service.

In cases where concept mappings are not available, selecting the ontology to use that provides the best coverage and overall representation becomes more critical, as the eTVSM approach requires the selection of one ontology. This selection should be an automated process, as within the context of an annotation software tool for semi-automated mapping, it reduces burden on the annotator, enabling them to focus on finding the most accurate concept match in a ranked list of candidates. Therefore, in future work we will leverage a domain classifier for selecting the most suitable ontology for disambiguation.

To further support annotation software tools that leverage our pipeline, we will make modifications to capture the statements in RDF and/or OWL for ease of rendering in graph form; currently we are applying the XML-based results from the NCBO services in a non-RDF graph representation for processing into the vector models. We anticipate that, generally, the graph representations (as shown in Figure 1), when presented, will provide a curator context and visual justification of the ranking scores. Finally, at the time of this writing the NCBO ontology service for the version of BioPortal being used is deprecated, therefore we are working to port our code to leverage the latest version prior to making it publicly available.

7. Conclusions

To help address the challenge of using publicly available ontology services for entity disambiguation, in this paper we 1) provide an enhanced version of the NCBO Annotator service for geographic named entity through novel application of vector space model-based disambiguation in concert with existing NCBO Term and Annotator services; 2)

[19] https://www.mturk.com/

demonstrate that using the available fine-grained relationships in an expert-curated ontology improves disambiguation; and 3) provide insights into the process of using publicly available ontology-service driven web services and expert-curated domain ontologies for entity disambiguation and organically improving upon those services.

In support of future semantic mapping workbench applications, this approach provides a ranked list of results using quantitative scoring methods to disambiguate named entities. In Section 4 we evaluated the performance of our pipeline against the Annotator Service using the TopN scoring metric and demonstrated how in the context of a manual curation workbench, our pipeline provides benefit by reducing the time a curator would spend looking for the concept that correctly matched an extracted named entity label. To further demonstrate its value as an enhanced version of the NCBO BioPortal Annotator Service, in Section 5 we presented some insights resulting from the pipeline being applied to Earth and environmental science abstracts, leveraging domain-level relationships available in GAZ to power the disambiguation process.

Our approach also helps aid curators to create gold standard datasets as training data for performing entity disambiguation using statistical machine learning methods. For curators who manage metadata like those within the DataONE project, the output from our pipeline could be added as metadata, improving metadata quality by showing how named entities in the text are related, which can we used to enhance search capabilities. Our approach provides benefits over using methods that do not rely on ontologies for the disambiguation task, or when ontologies with minimal semantics (e.g., *broader* relationship in SKOS) are used, as subsequent search interface capabilities will have better precision.

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Towards an Ontological Grounding of IFC

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Abstract

The Industry Foundation Classes (IFC) is a standard providing an open vendor-independent file format and data model for data interoperability and exchange for Architecture/Engineering/Construction and Facility Management. Some works in the literature addressed the conversion of the standard to the Web Ontology Language, but there is still need of an in depth ontological analysis of its constructs. With this work we start such an analysis focusing on the IFC type/occurrence distinction. The goal is to increase the correct understanding and use of the standard while ensuring logical coherence, ontological soundness and conceptual clarity.

1 Introduction

Information and Communication Technologies (ICT) play a central role in supporting various engineering tasks in the field of manufacturing, building and construction industry. Nevertheless, the use of heterogeneous application tools supporting industrial activities, the lack of a common conceptualisation of the terms used by various actors across different communities, and the lack of formal representations threaten the quality of process and product modelling as well as the effective sharing of data between the stakeholders [25, 30]. In this paper, we focus on the Industry Foundation Classes (IFC) [6], an information modelling standard supported by several Computer Aided Design (CAD) systems. According to the U.S. National Building Information Modeling Standard [17], IFC is the most mature and widespread schema for the building industry.

In order to overcome some drawbacks related to the native language specification of IFC, namely EXPRESS, and benefit from the use of Semantic Web based approaches and technologies, different communities have been working on the conversion of the standard into the Web Ontology Language (OWL) [33]. Nevertheless, the development of IFC-like ontologies has not yet delved into the ontological grounding of the standard, its assumptions and rules that are not always explicitly formalized (e.g. the distinction and relation between type and occurrence entities; the inheritance and overriding of property sets). A simple conversion of IFC into OWL is not enough because ontologies should attempt at making explicit the implicit ontological commitments and conceptualisations of the world laying behind information systems terminologies. When concepts used for knowledge representation and data sharing are not analysed and clearly defined, the different information systems using

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them cannot be rigorously (thus reliably) aligned for automated information sharing and exploitation. Indeed, a rigorous ontological perspective, as suggested modern theories of Ontology Engineering [9, 10, 34, 5, 23], is crucial to take full advantage of modern ontological tools.

We focus hereby on the IFC type/occurrence distinction, which plays an important role in the standard, aiming at exploiting the re-use of data and minimising the replication of information. Thus it is important to correctly understand to what types and occurrences refer, especially if one aims at developing IFC-driven ontology-based applications. In the next section we introduce IFC and its general structure; Section 3 presents the state of the art about the conversion of IFC into OWL; Section 4 analyses the IFC type/occurrence distinction, from both a terminological and ontological perspective. We conclude with some remarks about future work.

2 Industry Foundation Classes

The Industry Foundation Classes (IFC) is a standard providing an open vendor-independent file format and data model for data interoperability and exchange for Architecture/Engineering/Construction and Facility Management (AEC/FM). It is released by buildingSMART International and its current release (IFC 4) is registered as ISO 16739. IFC supports interoperability across different applications used to design, construct and operate construction facilities by capturing information about all aspects of a building throughout its lifecycle [14, 30, 2, 21].

The IFC data model is defined in the EXPRESS modelling language, the dedicated formal language developed within the ISO 10303 STEP standard [11]. The current IFC release is built on a modular structure that distinguishes among four conceptual layers, which are tailored in turn in different schemas (aka modules):

- Resource layer: it specifies classes that do not stand in taxonomical relationships with classes defined in the other layers, but they can be rather recalled by means of specific relationships. For example, it includes amongst its schemas the `IfcGeometryResource`, which contains entities needed to define geometric representations (e.g. `IfcCartesianPoint`, `IfcPlacement`, `IfcSurface`). In this way, a product (as a physical object) - defined in the Core Layer (see below) as a `IfcProduct` - can be characterised by a specific placement by the `ObjectPlacement` attribute that points to `IfcPlacement`;

- Core layer: it contains the most general concepts of the IFC data model. Its purpose is to provide the main backbone concepts and relationships of the IFC data model. It thus supports interoperability among the IFC layers and compatibility with the various IFC releases. The Core layer comprises two main schemas:

  1. *IfcKernel*, which collects the most general concepts of the standard like `IfcRoot`, `IfcObjectDefinition`, `IfcProcess`, `IfcContext`;
  2. *IfcCoreExtension*, which is further subdivided into three modules: *IfcControlExtension*, *IfcProcessExtension* and *IfcProductExtension*. These specialise the *IfcKernel* with AEC/FM concepts. In particular, the *IfcControlExtension* contains entities for control objects like `IfcPerformanceHistory` and `IfcControl`; the *IfcProcessExtension* specifies entities for the representation of process-like entities, e.g. `IfcEvent`, `IfcProcedure`, `IfcTask`; the *IfcProductExtension* contributes to the specialisation of entities related to product modelling like `IfcElement`, `IfcElementAssembly`, `IfcGrid`;

- Interoperability layer: it contains concepts, defined in the Domain layer (see below), shared by multiple domains and used for inter-domain exchange and sharing of construction information. Amongst its schemas, it includes the *IfcSharedBuildingElements* and the *IfcSharedFacilitiesElements*. The former specialises the *IfcProductExtension* (Core) schema by classes used for representing building structures. Amongst its entities, it includes `IfcChimney`, `IfcDoor`, `IfcRamp`. The latter provides a set of entities concerning facilities management. Some of them specialise the *IfcProductExtension* schema (e.g. `IfcFurniture`, `IfcFurnitureType`), while others are attached directly under the *IfcKernel* (e.g. `IfcInventory`, `IfcOccupant`);

- Domain layer: it contains the most specific concepts of IFC. The Domain layer organises concepts according to industry disciplines and amongst its schemas it includes the *IfcArchitectureDomain* and the *IfcBuildingControlsDomain*. The former defines concepts used in architecture, like `IfcDoorStyle`, `IfcWindowStyle`, `IfcWindowPanelProperties`, among others. The latter supports the modelling of building automation, control, instrumentation and alarm. Amongst its entities, it includes `IfcActuator`, `IfcAlarm` and `IfcSensor`.

The modular architecture operates on a so-called *gravity principle*: at any layer, an entity may refer only to an entity at the same or lower layer [21]. For instance, entities at the Core layer may refer to other Core classes, as well as to Resource layer classes, but cannot refer to entities within the Interoperability or Domain layers. The same principle applies also within the Core layer, in the sense that *IfcKernel* entities cannot refer to *IfcCoreExtensions*, while the reverse is allowed.

The concepts of IFC, modelled in EXPRESS by the **ENTITY** construct, are organised into taxonomies via the supertype/subtype partial ordering relation. For instance, `IfcProcess` is the supertype of `IfcEvent`, `IfcProcedure` and `IfcTask`. Some concepts (e.g. `IfcProcess`) are declared to be *abstract*, in the sense that they can only be instantiated through their subtypes. Inheritance is allowed along the hierarchy, so that subtypes inherit those attributes defined at the level of the supertypes. For example, Fig.1 shows the EXPRESS specification of `IfcProduct`. This is modelled by **ENTITY** and stands for the abstract super-type of different classes, which are mutually disjoint (the construct **ONEOF** specifies the disjointness). The relationship **SUBTYPE OF** states that `IfcProduct` is subsumed under `IfcObject`. *ObjectPlacement*, *Representation* and *ReferencedBy* are attributes, while **WHERE** is a rule specifying a certain condition.

EXPRESS Specification:

```
ENTITY IfcProduct
 ABSTRACT SUPERTYPE OF(ONEOF(IfcAnnotation, IfcElement, IfcGrid, IfcPort, IfcProxy,
 IfcSpatialElement, IfcStructuralActivity, IfcStructuralItem))
 SUBTYPE OF IfcObject;
  ObjectPlacement     :OPTIONAL IfcObjectPlacement;
  Representation      :OPTIONAL IfcProductRepresentation;
 INVERSE
  ReferencedBy        :SET OF IfcRelAssignsToProduct FOR RelatingProduct;
 WHERE
  PlacementForShapeRepresentation:(EXISTS(Representation) AND EXISTS(ObjectPlacement)) OR
                                  (EXISTS(Representation) AND (SIZEOF(QUERY(temp <*
                                  Representation.Representations |
                                  'IFCREPRESENTATIONRESOURCE.IFCSHAPEREPRESENTATION' IN
                                  TYPEOF(temp))) = 0)) OR (NOT(EXISTS(Representation)));
END_ENTITY;
```

Figure 1: `IfcProduct` in EXPRESS, from [6]

3 Owl-izing IFC

IFC supports data exchange among Building Information Modeling (BIM) applications [30]. Nevertheless, different communities have explored its conversion into the Web Ontology Language (OWL) [33] to overcome drawbacks due to some limitations of EXPRESS, and to benefit from the exploitation of Semantic Web technologies for the management of BIM data [18].

Beetz and colleagues [3, 4], as well as Krima et al. [1], draw attention to the EXPRESS lack of formal semantics, so that a logic-based language as OWL is preferable for the definition of axiomatic theories aimed at supporting knowledge representation and data sharing. Additionally, Beetz et al. [4] stress that the popularity of EXPRESS among the engineering community is very limited, apart from the STEP initiative, so that the reuse of existing ontologies or tools for interoperability is often inhibited, especially those related to the Semantic Web initiative. In the paper, the authors explore a semiautomatic method for lifting EXPRESS schemas onto OWL files.

Schevers et al. [24] as well as Zhang et al [35], argue that the conversion of IFC into OWL facilitates the linkage between different IFC models and databases, apart from enabling the exploitation of Semantic Web technologies for building information models. Katranuschkov and colleagues [13] develop an ontology framework aimed at supporting data modelling and data sharing in civil engineering by reusing the IFC data model. However, differently from other approaches, their library of ontologies is developed as an XML Schema. Pauwels and colleagues [18, 19] present a conversion service of the XML-based schema into OWL ontologies in order to represent building information through the enriched RDF graphs, which can be used with reasoning engines [19]. Following the Linked Data approach, the authors stress the advantages of a semantic rule checking environment for the AEC domain [18].

Terkaj et al. [27] propose a modular OWL ontology for virtual factory modelling and data sharing between heterogeneous and geographically distributed software tools. The main structure of the ontology, called Virtual Factory Data Model (VFDM), is based on IFC and the conversion of the standard from EXPRESS to OWL mainly follows the pattern proposed in [3, 4]. The VFDM models the main building blocks of manufacturing

systems and their inter-relations, namely, products to be manufactured, manufacturing processes, manufacturing resources and the factory building. The ontology is used as a key enabler inside an integration framework [31] to interoperate different software applications by developing ontology-based plugins for both commercial (e.g. Arena by Rockwell Automation [28], Plant Simulation by Siemens PLM [12]) and non-commercial (e.g. GIOVE Virtual Factory [32], OntoGUI [29]) software tools, aiming at realising an integrated software platform that can support the design and management of a factory along its lifecycle phases [7]. The VFDM shows how an OWL version of IFC can be more easily extended and integrated with other ontologies to represent specific knowledge domains (e.g. factory sustainability [26, 8] and ambient assisted living [22]).

4 Types and occurrences in IFC

As it stands today, IFC is a data model that relies on human interpretation, in the sense that the meanings of its modelling elements are not constrained by means of formal semantics. As discussed in the previous section, semantic considerations lead to look for a formalization of IFC in some formal language, primarily OWL, which is frequently used for computational reasons (which we do not discuss in this paper). However, if the change of language helps to improve some aspects of the standard (e.g. making explicit semantics), it does not *per se* lead to the clarification of the ontological coherence laying behind IFC. For this reason, the use of ontological analysis can help to highlight possible drawbacks in the standard and in the conversion patterns used to build IFC-driven ontological systems.

There are different ways to analyse a standard from the ontological viewpoint. The aim of this section is to verify whether the main distinctions on which IFC relies are well defined and understood. In this initial work, we focus on the distinction between IFC modelling elements named 'type' and 'occurrence' aiming at clarifying what they amount to in ontological terms. The IFC conceptual schema applies this distinction to several modelling constructs, e.g. `IfcObject` and `IfcTypeObject`; `IfcProduct` and `IfcTypeProduct`. Types and occurrences are linked through the (objectified) relationship `IfcRelDefinesByType`, as showed in Fig.2. We want to understand what kind of entities are involved in the distinction, how they are classified, and what kind of relationships hold between them. The investigation aims at reducing the risk of an erroneous implementation of the standard in languages such as OWL by clarifying the notions and how they should be used for modelling purposes.

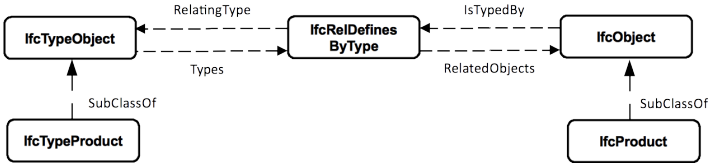

Figure 2: IfcObject and IfcTypeObject with the subclasses IfcTypeProduct and IfcProduct

Let us consider a paradigmatic case: `IfcTypeProduct` vs. `IfcProduct`. As anticipated in Section 2, `IfcProduct` is a subclass of `IfcObject`, while `IfcTypeProduct` is a subclass of `IfcTypeObject` (see Figures 1 and 2). According to the IFC documentation: "The `IfcProduct` is an abstract representation of any object that relates to a geometric or spatial context. Subtypes of `IfcProduct` usually hold a shape representation and an object placement within the project structure. [...] Any instance of `IfcProduct` defines a particular occurrence of a product[...]" ([6], section 5.1.3.10). Therefore, from the definition, `IfcProduct` is a class because it has (a) subtypes (thus structured in a hierarchy) and (b) instances.

The construct `IfcTypeProduct` is defined in the following way: "`IfcTypeProduct` defines a type definition of a product without being already inserted into a project structure (without having a placement), and not being included in the geometric representation context of the project. It is used to define a product specification, that is, the specific product information that is common to all occurrences of that product type" ([6], sect. 5.1.3.49). Although some terms are left unspecified, e.g. project structure, it seems clear that the `IfcTypeProduct` construct represents a class as well. In particular, an instance of `IfcTypeProduct` refers to a set of product specifications, i.e., properties that can be common a set of instances of `IfcProduct`.

The terms *instance* and *class* are commonly used with a variety of meanings in the literature, thus we need to make their interpretation precise. The main distinction between a class and an instance is that the former is a collection of entities (its members), whereas the latter is not[1]: a class is said to *have instances*, whereas an

[1]We do not distinguish classes from sets and call instance any member of a class which is not a class itself.

instance itself cannot instantiate. For example, a particular automobile produced by FIAT, call it `FIAT500#001`, is an instance of the class FIAT_CAR, and the distinction between the class and the instance relies on the way they are related to the expression *being* FIAT_CAR: we say that any instance of the class satisfies the expression and that the class is characterised by such an expression. More specifically, *being* FIAT_CAR is a property used to *talk about* instances: some instances are cars produced by FIAT, while others, e.g. a product manufactured by Microsoft as well as the Everest mountain, are not. Properties help to discriminate entities because they allow to state which entities are distinct and why. To be an instance of the class FIAT_CAR is thus equivalent to satisfy the property *being* FIAT_CAR, which is a shortcut for a conjunction of several more specific properties regarding the engine size, the chassis model, the chassis colour, among others. This complex property is known, in logical and ontological terms, as the *intension* of the class, while the collection of the entities satisfying the property is called the *extension* of the class. The difference between intensionality and extensionality plays a relevant role in ontological engineering, because it allows understanding whether a class is bound or not to the particulars it talks about [9].

Following the distinction between extensionality and intensionality, IFC occurrences can be understood as extensional classes, whose intensional properties can be also defined by the properties associated with the types. The type-ocurrence dichotomy can be further discussed by referring to Fig. 3. Recall that IFC, being formalized in EXPRESS, explicitly models the upper side of the schema only (`IfcTypeObject`, `IfcObject` and `RelDefByType`), while the boxes in the middle and lower side (`TypeTruck`, `IC_FIAT_500`, `id1`, `OccTruck`, `Fiat500#001`, among others) are here included to help in the interpretation.

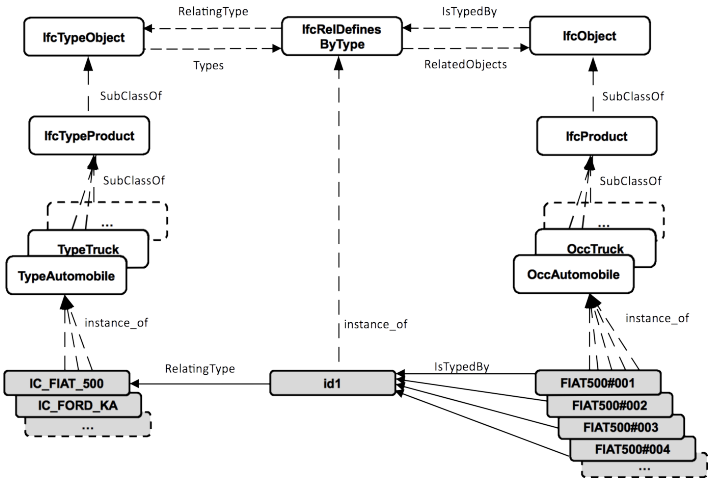

Figure 3: Example of IFC type/occurrence

The relationship of instantiation holding between classes and their corresponding members is labeled `instance_of` in Fig. 3. `RelatingType` and `IsTypedBy` are (non-objectified) relationships holding between the represented modelling constructs at both the class and the instance levels. The bottom-right elements (e.g. `Fiat500#001`) of the figure are instances representing particular objects, e.g. a particular car that someone owns and drives. This object is characterised by a conjunction of properties (like *having chassis model*, *having chassis color*, *having engine size*) that provide the identity criterion for belonging to the class *OccAutomobile*. The object `FIAT500#001` and the class *OccAutomobile* are thus connected by the instantiation relationship. Moreover, the qualifications of these properties (i.e. values and ranges like chassis model $\#F22$, chassis color $\#red3F$ and engine size 1200) are used as the criterion to link an instance (`FIAT500#001`) with its corresponding type (`IC_FIAT_500`), belonging to a type class (*TypeAutomobile*).

The class *OccAutomobile* is associated to a unique subclass of `IfcTypeObject`, namely *TypeAutomobile*. This relationship is at the intensional level, in the sense that it relies on the properties characterizing *OccAutomobile* and does not depend on its instances (whether they exist or else). We have seen some examples of these properties: *having chassis model*, *having chassis colour* and *having engine size*. *TypeAutomobile* thus refers to the collection of some common properties that characterize *OccAutomobile* but, generally speaking, not on their values. We

call the relationship between the type and occurrence elements, i.e. the classes on the top of Fig. 3, *typization* since it allows to associate to each homogeneous collection of instances in the right hand-side of the diagram a single general description, i.e. a set of properties in terms of which it is meaningful to consider a comparison of instances[2].

Finally, an instance of *TypeAutomobile*, that is, an element in the bottom-left of Fig. 3, is associated with a collection of these very properties with specified values and ranges: in our example, *having chassis model* $\#F22$, *having chassis colour* $\#red3F$, *having engine size* 1200 and the like. We call this object `IC_FIAT_500`. In ontological terms, `IC_FIAT_500` is called an information object. Also, we could call the relationship between the collection of qualified properties `IC_FIAT_500` and the instance(s) `FIAT500#001` that satisfies them a *realization* since the object `FIAT500#001` manifests all the properties given by the information object `IC_FIAT_500` with the requested qualifications. This relationship differs from that between the class *TypeAutomobile* and the class *OccAutomobile*: the first (realization) is between instances and says that an entity satisfies a set of properties with given values; the latter (typization) is between classes and associates the class corresponding to a set of properties (a type) to the occurrence class whose members must satisfy those properties for some admissible value. Note that a realization does not need to be a physical entity; it may very well be a virtual element.

Currently, it is a matter of ambiguity whether an occurrence instance represents in IFC a physical entity (e.g. the car owned by someone), or a virtual representation in an information system. In our experience we note that IFC practitioners adopt both readings depending on their application tasks. Note however that physical and virtual entities have different ontological properties: on the one side, the former has e.g. a spatiotemporal location according to which it can be classified as a *physical object* in a formal ontology framework like the one proposed by the DOLCE foundational ontology [15]; on the other side, the latter lacks spatial location in the former sense and is classified in DOLCE as an *abstract object* when it also lacks temporal location (in a common sense perspective that is usually associated with physical objects); or as a *concept* when existing in time, for example in the form of a description. Since physical, abstract and conceptual elements are distinguished by distinct properties, an ontology artefact requires to clearly separate them. Note also that the identification of classes at the virtual (abstract) and the physical levels plays a relevant role in data sharing, communication and verification since it determines which data are affected by time and in which way. Consider a scenario in which a practitioner develops an ontology-based instance model (A-Box) with an occurrence instance o_1, which is a virtual entity. When a user accesses the ontology, s/he would not be able to properly interpret o_1 as a virtual entity unless this is somehow modelled in the system by specific formal constraints. An explicit specification of the ontological kind of entity that is represented (virtual or physical) could enhance the reliability of the information sources that use the standard.

5 Conclusion and further discussion

Current attempts towards the OWL formalization of IFC have not been systematically supported by the ontological analysis of its terminology and modelling constructs. While bringing the benefits of formal semantics into IFC, OWL-ized IFC ontologies do not clarify the meanings of its modelling elements. Indeed, choosing how to interpret IFC notions relies on the users' knowledge of the standard and their application needs, issues that threaten automated interoperability between IFC models developed by different communities. Our approach differs from the state of the art (Section 3), because it proposes a reading of the standard aimed at increasing its ontological soundness and conceptual clarity. The performed ontological analysis explains the type/occurrence modelling pattern in terms of the difference between descriptions (i.e., information entities) within the type hierarchy, and their realizations within the occurrence hierarchy, where realizations might be both physical and virtual elements in the system.

The distinction between IFC types and occurrence classes should not be confused with the distinction between meta-classes and classes [16]. Briefly said, meta-classes and classes differ on the abstraction level: the meta-class has the class as an instance. Yet, if a class instantiates a meta-class, then the meta-class should be associated with a collection of the properties that are *necessary* for a class to be classified as an instance. According to our analysis, *TypeAutomobile* is related to *OccAutomobile* via properties like *having chassis model*, *having chassis colour* and *having engine size*. However, these properties do not necessarily have to be linked to the properties of the class *OccAutomobile* for two reasons. First, IFC allows that some properties associated with types can be overridden [6], thus they are not treated as *necessary* properties. Second, analogous to the example

[2]Ontologically speaking, we could say that IFC is a contextual modelling framework since the notion of 'homogeneous instances' depends on the user or the application task. This observation is crucial for a suitable choice of the classes to consider in the diagram.

of `IfcBuilding` [6], which does not need to have specified `IfcBuildingType`, it is possible to have an instance of class *OccAutomobile* and directly characterize it with as many properties as possible (i.e. chassis et al.) without linking it to any instance of class *TypeAutomobile*. This example, together with the possibility to override some properties associated with the types, demonstrate that the standard currently does not treat the IFC types as meta-classes of the occurrence classes. Accordingly, the `Instance_of` relationship does not apply to types and classes of occurrences in IFC.

The difference between IFC type and occurrence classes may remind the materialization modelling pattern [20]. Materialization is a binary relationship holding between abstract and concrete entities, e.g. between the abstract `CarModel` and the concrete `Car`, where the former is a class of properties, and the latter is a class of particular automobiles defined by the class of properties. Concrete classes are said to materialise abstract ones; e.g. one could say that John's and Mary's Fiat500s materialize the same Fiat500 model, although they are two different particular cars. However, the abstract-concrete pairs, and thus the materialization relationships, are ambiguously defined: firstly, materialization holds that one and the same thing can be both concrete and abstract [20] while ontological theories force to distinguish them as different kinds [15]. Secondly, the semantics of the materialization relationship is defined through the instantiation and generalization/specialization relationships (together with a metaclass/class correspondence), but generalization and abstraction are quite different operators, similarly for specialization and concretization. It remains unclear how abstract and concrete entities are related by these operators. The study of materialization might enlighten the IFC type/occurrence dichotomy; nevertheless, this can be assessed only once the semantics of materialization has become conceptually transparent and (possibly) formally represented.

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Ontologies in Enterprise Applications: Dimensional Comparison

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Abstract

Many important categories of applications such as information integration, data analytics, and personal assistance require access to a general store of knowledge. The usefulness of such a store depends not only on its factual content, but also on its conceptual framework, or ontology. Ontologies vary markedly in their characteristics, and the value of an ontology varies according to the purpose for which it will be used. Thus, selecting one or more ontologies suitable for an application can be challenging. We have created a set of dimensions to consider when making this selection. Although these dimensions are motivated by the needs of conversational assistance applications, they can benefit the development of a wide variety of enterprise applications. We applied these dimensions to four large, general-purpose ontologies—Cyc, Freebase, SUMO, and YAGO—and made qualitative comparisons between them.

General-purpose ontologies are playing an increasingly central role in many important categories of applications such as information integration, distributed knowledge management, data analytics, and personal assistance. These ontologies aim to provide a framework for better organization and access of data, effective information and knowledge sharing, reliable information exchange, and improved coordination between distinct organizations or among members of the same organization. Consequently, companies face an increasing need to be able to choose the most suitable ontologies for their applications. This paper addresses that need.

We aim to provide an evaluative framework that may be applied to assess the usefulness of an ontology for any particular commercial application. Specifically, we set out to define the *dimensions* under which ontologies can be compared, and focus on those dimensions that assess *terminological knowledge* (definitions of concepts and their properties and relationships), not *assertional knowledge* (instances of concepts and facts about them). This focus is warranted because treatments of terminological knowledge are often overshadowed by assertional knowledge, or overlooked altogether. We believe our dimensions can provide an evaluative framework for comparing the strengths and weaknesses of different ontologies, which may prove useful for others investigating a robust use of semantic knowledge.

Our dimensions have resulted from our investigation of different ontologies suitable for conversational systems, as described in Kaplan's "Beyond the GUI: It's Time for a Conversational User Interface" [6], and are exemplified by our end-to-end speech-driven *second screen* application for television program discovery, described in [14]. Despite our focus application, we believe that our dimensions and our preliminary results from applying them should be applicable to a wide variety of companies that need to make the best choice for their applications.

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This is because of the extremely broad range of requirements of conversational systems. A conversational system is more than just speech recognition and synthesized speech; it must combine these voice technologies with natural-language understanding of the intention behind those spoken words. The intelligence comes from contextual awareness (who said what, when and where), perceptive listening (automatically waking up when you speak), and artificial intelligence *reasoning*. Moreover, a conversational system needs to be capable of question answering, intent recognition, semantic database integration, proactive behavior and even social intelligence.

Much work has been done in comparing and evaluating ontologies, especially devising quantitative metrics for ontologies using OWL as their representation language [13, 3, 12]. [13] characterizes most prior work as focusing on the mere structural aspects of an ontology and not considering the *semantics* of the ontology. Our paper shares the goal of semantic focus, but because our scope is more general in the kinds of languages we want to compare (i.e.not only OWL-based) it is less formal, and we actually apply our evaluation strategy to four ontologies. The goals and motivations of [10] are similar to ours, they provide a broad overview and discussion of issues in ontology evaluation, and approaches that may be used. While [10] touches on some of the same dimensions that we identify, it does not propose a specific set of dimensions that make up an evaluative framework. Since its focus is on approaches and specific evaluations from the life sciences literature, it does not give a comparative evaluation of specific ontologies as we have done. Similarly, we share with the work on OntoQA [12] the goal of general-purpose ontologies, the idea that one should have independent metrics for schemas, knowledge bases (KBs) and classes, but we concentrate efforts on qualitative dimensions for the schemas, while they concentrate on a specific system to measure OWL-based ontologies.

We subjected four general-purpose ontologies to our dimension-based comparison: ResearchCyc [8], Freebase [2],[1] SUMO [9], and YAGO [11, 5]. Resource constraints limited the number to four. Our analysis, and the numbers we report, are for these systems as they existed in early 2014. We chose these particular four systems because they are among the most prominent large, general-purpose, broad-coverage ontologies. They also take quite different approaches to modelling the world. Cyc is a long-standing project to assemble a comprehensive ontology and knowledge base of everyday common sense knowledge, with the goal of enabling AI applications to perform human-like reasoning. The Suggested Upper Merged Ontology (SUMO) and its domain ontologies form a large formal, open-source ontology with significant numbers of definitional axioms and rules. YAGO is a knowledge base developed at the Max Planck Institute for Computer Science in Saarbrücken, automatically extracted from Wikipedia, WordNet and other sources. Freebase is a large collaborative knowledge base consisting of metadata composed mainly by its community members. It is an online collection of structured data harvested from many sources, including individual 'wiki' contributions. Freebase aims to create a global resource which allows people (and machines) to access common information more effectively. Google's Knowledge Graph is powered, in part, by Freebase.

We also looked at the DBpedia [7] ontology and schema.org, http://schema.org, two other efforts that might be considered to be general-purpose ontologies. However, both of these were immediately seen to be unsuitable for our needs, as they are both comparatively small and inexpressive. As well, the meaning of constructs in schema.org is very hard to determine. This is not to say that the data available from DBpedia or the data described by schema.org markup would not be valuable, just that their ontologies are too limited to form the background ontology necessary for general conversational systems.

We first discuss the dimensions of comparison that we found useful when comparing the ontological schemas exemplified by the four chosen knowledge repositories. How the four compared in each one of these dimensions forms the basis for the matrix shown in table 1. We then discuss the main points or lessons learned from these one-by-one comparisons.

1 Ontology Evaluation Dimensions

Most knowledge repositories consist of three main components that are of interest to real-world applications: the ontology (i.e., schema, axioms, etc.), the representation language, and the data (i.e., instances of entity types in the ontology). These components are equally important, but our focus in this paper is on the ontology, which

- provides a scaffolding to organize data of interest to an application, and

[1] After we did our comparison, Google announced that Freebase will be discontinued in mid-2015, and that Google will provide a tool to help users add Freebase content to Wikidata (http://www.wikidata.org). We hope that users will transition most Freebase content to Wikidata and that the ontology supporting Wikidata will also grow into a general-purpose ontology on par with the ontologies in SUMO and ResearchCyc.

- supports the inferences over the data required by the application.

We propose ten dimensions for evaluating the utility of an ontology with respect to the above roles. These dimensions are inspired by those from data quality [1], but have been modified (and extended) for ontologies. We intend for these dimensions to provide a common yardstick for comparison across the ontologies of different knowledge repositories.

Domain Breadth: What is the breadth of domains covered by the ontology? For example, does the ontology cover a single domain such as geography or multiple domains ranging from entertainment to pathology? Broad domain breadth is important for applications that need to support a wide range of domains, such as virtual assistants.

Axiomatic Depth: Is the ontology complete in terms of the entity types, relations, and axioms for each domain covered? Axiomatic depth is orthogonal to *domain breath*, and is important for applications that focus on specialized domains such as healthcare, finance, etc.

Accuracy: How accurately do the entity types, relations, and axioms in the ontology reflect the real-world objects and domains they represent? Accuracy directly impacts the organizational quality of the data used by an application and the validity of any inferences over the data.

Consistency: Are there contradictions or incompatibilities in the ontology, e.g. contradicting axioms, incompatible generalizations, etc. If so, then how pervasive are these contradictions and incompatibilities? Like *accuracy*, consistency impacts data organization and inference validity. We note that it is impractical to expect a large ontology to have no inconsistency. Hence, this dimension is not intended to be binary. Instead, the intent is to provide a measure on the degree of consistency observed.

Integrity: Are the basic relations and axioms (e.g., generalization, instance, disjointness, selectional restrictions, etc.) present in the ontology? Have they been codified, or are they captured only in documentation and comments? Integrity is critical in enabling many common types of inference (e.g. subsumption, constraint violation, etc.) required by real-world applications, and can be viewed as *axiomatic depth* applied to the basic relations and axioms of an ontology.

Uniformity: Are the entity types and relations in the ontology used in a uniform manner? Do these uses conform with the semantics of the types and relations? Uniformity reduces the likelihood of modeling errors and hence the organizational quality of the data. Uniformity also improves the maintainability of an ontology and hence the maintainability of applications that use the ontology.

Redundancy: Are there redundancies in the ontology? For example, an ontology may have multiple entity types and relations for representing time, or generalizations that share similarities as well as differences. Redundancy is orthogonal to *uniformity*, and hence increases the difficulty in maintaining and using the ontology. Moreover, redundancy can result in unanticipated inference behaviors or invalid inference results.

Granularity: How granular are the entity types and relations in the ontology? An ontology that is too coarse (e.g. every type is a specialization of *Thing*) is not ideal. Neither is an ontology that is too fine-grained, e.g. an ontology with types like *Person-from-California*, a subclass of *Person*. Ontologies that are too coarse or fine-grained are difficult to extend, and hence less desirable for applications requiring additional customization.

Timeliness: How frequently is the ontology updated to reflect changes in the real-world objects and domains it represents? For example, how much time typically elapses for a pathology ontology to be updated when a new virus is discovered? Timeliness can be viewed as *accuracy* over time, and is important for applications that operate in dynamic domains.

Stability: How frequently is the ontology changed to fix mistakes, re-organized for efficiency purposes, etc? Stability directly impacts the maintainability of the applications that use the ontology.

2 Comparison Between Ontologies

We applied the dimensions outlined above to the ontologies (i.e. schemata) of four well-known knowledge repositories (i.e., YAGO, SUMO, Freebase, and ResearchCyc) as part of a preliminary comparison. We emphasize that our comparison focuses on the *ontologies* of the selected knowledge repositories, not the data or representation languages. Table 1 shows the qualitative findings that we observed from this comparison. Additional qualitative observations and remarks along the most salient dimensions for each ontology can be found in their respective subsections below.

We note that the findings presented are not based on a formal, rigorous evaluation and should be treated as qualitative observations suitable for high-level guidance. Thus, given the preliminary nature of our work, additional effort is needed such as providing more quantitative characterizations of the ratings for each dimension.

In addition, we deliberately have chosen not to prioritize these dimensions. The relative weights given to the dimensions should be established in the context of a particular application.

	YAGO	SUMO	Freebase	ResearchCyc
Domain Breadth	excellent	good	good	excellent
Axiomatic Depth	weak	average+	average	excellent
Accuracy	good	good+	good	excellent
Consistency	good	excellent	average+	good+
Integrity	weak	good	week	good+
Uniformity	good	excellent	average	excellent
Redundancy	average	excellent	weak	excellent
Granularity	poor	average+	average	good
Timeliness	weak	weak	average+	average
Stability	weak	good	average	good

Table 1: Qualitative findings from applying the dimensions outlined in the previous section.

2.1 The ResearchCyc ontology

Work on Cyc began in 1984 with the original goal of ontologizing human common sense reasoning and has continued until the present day. Currently, the Cycorp website claims adoption of Cyc-based products by a major database company, a Fortune 100 investment bank, and an oil company, among others.

Our focus, ResearchCyc (RCyc; in particular, CycL Version 10.148440, KB 7164), is one of three main offerings. The other two are OpenCyc (an Apache-licensed free version with almost all of the defining axioms removed) and EnterpriseCyc (a business-focused version). Cyc's *microtheories* are one of the means by which assertions are contextualized. A given microtheory may contain assertions made from a particular point of view or belief system or topic area. In addition a microtheory may define the time range of the assertions contained.

As seen in the table above, RCyc's greatest strengths evaluation were in **accuracy**, **domain breadth**, and **axiomatic depth**. Since we started use of RCyc in the conversational prototype [14] in the Spring of 2013, we have collectively looked at thousands of assertions and have only found between 5 and 10 factually incorrect sentences. That said, these assertions were safely encapsulated in crowdsourced microtheory and thus not subject to the typical level of review by Cycorp's professional ontologists. **Domain breadth** was deemed high because of the broad range of content and the raw numbers. In terms of "raw numbers", there is a large number of classes (52K, contrasted with Freebase's 25K types) and predicates (26K). Breadth is high, for example because there are 366 instances of #$GeneralMicrotheory (against a background of all 21K Microtheories) contrasted with 40 domain ontologies listed on the SUMO website. Additionally, there are not only content areas from business and economics, sciences, arts, etc., there is also a meta-knowledge ontology that enables expressing facts about provenance, reflection, and database integration. **Axiomatic depth** is high because RCyc has more definitional axioms than any of the sources we have looked at.

Timeliness was one of RCyc's weaker areas. Unlike the vast army of volunteers that a resource like Freebase has, the RCyc Ontology gets updated depending on what contracts Cycorp has. **Granularity** was also a relative weakness largely due to the relatively large number of predicates with highly specifc meaning or non-obvious distinctions. In **stability** the RCyc is tied with SUMO for first place. Nonetheless it is another relative weakness. RCyc is under active development. New terms are added regularly, and sometimes existing term names are changed.

2.2 The Freebase Ontology

Freebase [2] is a large-scale knowledge graph of topics and relations organized around a schema that provides typing (approx. 25K types), domain and range constraints, etc.

We observed that the Freebase ontology (which we will refer to as just Freebase for brevity) is strongest along the dimensions of **domain breadth** and **accuracy**. Freebase covers a wide variety of domains ranging from popular culture (e.g. movies, music, etc.) to the sciences (e.g. physics, geology, etc.). Its breadth is nearly comparable to the other ontologies examined, but many concepts that are types in the other ontologies examined are instances in Freebase. For example, specializations of profession (e.g., lawyer and doctor) and organism (e.g., dog and cat) are all instances in Freebase, not types.

We note that the instance-level data in Freebase (although outside the scope of this comparison) is more comprehensive than the other systems examined. Freebase has over 40 million topics (i.e. entities), and over 2 billion triples, corresponding to semantic relationships between these topics. This is an important consideration if the target application has significant data requirements.

Moreover, most types (and their properties) in Freebase accurately reflect the real-world objects they represent. We reached this observation by examining different types, their properties, and the expected values of these properties across multiple domains such as entertainment, biology, etc. We note that our observations on accuracy are on the schema only, not the data.

On the other hand, we observed that Freebase is weakest along the dimensions of **integrity** and **redundancy**. Although Freebase has generalization and type relations, they are largely absent. For example, Freebase does not have a unified type hierarchy like Cyc, SUMO, and YAGO. Instead, generalization relations only exist between select types, via the *included_types* relation, resulting in noticeable gaps in Freebase's type hierarchy. Similarly, an instance in Freebase can have multiple, incompatible types (e.g. an instance can be of type person and book subject). However, Freebase lacks sufficient disjointness constraints to prevent these integrity issues.

Freebase also has significant redundancies. For example, the *instance* relation in Freebase is used to assert that an instance X is of type Y. However, in the biology domain, the *organisms_of_this_type* relation is also used to capture the same relationship. Similarly, the profession domain uses the *specialization_of* relation to encode that one profession is a subclass of another. However, the biology domain uses the *higher_classification* relation to encode the same relationship between organism classifications. These redundancies cause significant overhead in using, extending, and reasoning with the ontology.

2.3 SUMO

The Suggested Upper Merged Ontology (SUMO) [9], http://www.ontologyportal.org/, together with its domain ontologies, form a large formal ontology licensed under several open-source licenses. As its name suggests, SUMO itself is an upper ontology with broad coverage of various categories including time and space, measures, sets, and classes. SUMO also includes a mid-level ontology (MILO) that expands the upper ontology into general groupings of domains. SUMO comes with a set of domain ontologies covering a variety of domains including political regions, people, and transportation. Domain ontologies are mostly contributed, but there is a vetting process for domain ontologies.

SUMO is written in a variant of KIF [4], which makes SUMO quasi-higher order. SUMO ontologies provide not just domain hierarchies, but also have a rich axiomatization of the domains. SUMO has tools to extract standard first-order logic and OWL from SUMO ontologies. SUMO has over 25,000 terms (including classes and properties) if the domain ontologies are included. However, this is a slightly inflated number, since some of these terms are nationalities and regions.

The upper and middle levels of SUMO provide excellent **breadth** for high-level organization of knowledge. At first glance the domain ontologies provide reasonable **depth** in their domains, but there are quite a few holes on closer investigation. For example, movies and tv shows are only lightly covered. There is the class MotionPicture for representing the class of all physical objects that have motion picture content (e.g. my DVD copy of "Gone with the Wind") but no class for representing instances of the conceptual creative works, e.g., "Gone With the Wind" itself. As well, there are only a limited number of domain ontologies, so many areas are only covered by the upper and middle levels of SUMO.

The upper and mid-level ontologies have been carefully vetted, and we have not found any problems with **accuracy**. The domain ontologies are less well vetted, but neither have we found any problems in them. SUMO has been machine-validated, meaning that there are no discoverable **inconsistencies** in its ontologies, nor classes that are necessarily empty.

The upper and mid-level ontologies are well-**integrated** and well-axiomatized, forming an excellent, **uniform** basis for the domain ontologies. The domain ontologies themselves are somewhat varied, but are generally well-axiomatized.

The upper and mid-level ontologies are parsimonious, with no observed problematic **redundancies**. The domain ontologies are well-separated, with no observable redundancies betwen them. The upper and mid-level ontologies take a middle, reasonable road on **granularity**. The domain ontologies are a bit mixed, with some providing only a coarse specification for their domain.

There is an update mechanism but it largely depends on submissions, and there is not that much use of SUMO, leading to questions of how **timely** updates are generated and applied to SUMO. There is a vetting

mechanism for all updates to the ontology, leading to good **stability**. However, there is not a full formal process for checking that updates are reasonable.

In summary, SUMO and its domain ontologies form a good, well-axiomatized broad-coverage ontology. We were most impressed with the care that has gone into the upper and mid levels of SUMO, which provides an excellent scaffolding for general organization of knowledge. However, SUMO is much less useful at lower levels. There are not that many domains covered and even those that are covered are not always covered in sufficient detail for use as a core domain in a system.

2.4 The YAGO Ontology

YAGO, of which YAGO2s is the current release, is derived from Wikipedia, WordNet, and GeoNames. It is a huge semantic knowledge base in terms of the numbers of classes, entities, and facts, but defines a relatively small number of properties — about 100 properties for facts extracted from Wikipedia, a small number for capturing temporal and geospatial data, and several for capturing contextual (provenance) information. Roughly speaking, the upper level classes of YAGO correspond to synsets from WordNet, and the lower level classes correspond to Wikipedia categories. As of March 2011, YAGO had 292,070 classes based on Wikipedia categories, 68,446 classes based on WordNet synsets, 642 GeoNames-based classes, and 53 of its own classes. (These statistics refer to the YAGO release available at that time.)

For our purposes, the characteristics of YAGO are dependent on the nature of its three sources, and the limited ontological structuring provided by those three sources. YAGO naturally ranks high on **domain breadth**, due to the encyclopedic breadth of both Wikipedia and WordNet. It ranks high on **accuracy**, **consistency**, and **uniformity**, partly because of the high quality of those sources, and partly because of the high quality of its approach to data extraction. However, these high rankings are also partly due to the simplicity of what YAGO tries to express. In other words, because the bulk of the YAGO ontology is the class taxonomy, along with the small number of properties mentioned above, there aren't too many opportunities for mistakes along these three dimensions.

At the same time, this limited expressiveness of the ontology is reflected in a low score on the dimensions of **axiomatic depth** and **integrity**. The Wikipedia categories are often idiosyncratic, e.g., "Catalan handball clubs" and "Hotels established in 1806". Except for the taxonomic relations that YAGO determines for them, they are not axiomatized (that is, they have no properties directly associated with them). Although it is true that such categories carry information understandable by a human reader, that information is not accessible to a computational system without the creation of additional axioms. This could involve a large effort in manual annotation and/or further research on algorithms for extracting meaning from Wikipedia text. WordNet is not well structured for reasoning purposes, and has only minimal axiomatization. (Furthermore, some WordNet properties, such as meronym and holonym, are not present in YAGO.)

YAGO's ratings on **granularity** and **redundancy** are also directly related to the nature of its sources. For our purposes, **granularity** is particularly problematic. With over 360,000 concepts, there is a great deal of clutter; that is, concepts that are unlikely to be directly employed, such as the Wikipedia categories mentioned above.. In addition, most instances in YAGO have many types — some corresponding to Wikipedia categories and others corresponding to WordNet senses — and there appears to be no robust automated way to identify the most useful type(s) for the kinds of use cases we have in mind.

Finally, YAGO's low ratings on **timeliness** and **stability** are simply due to the small number of releases since its inception, the possibility of non-incremental exploration of future directions, and its status as an academic research effort with only a small community of contributors.

3 Analysis

The four ontologies we examined fall into two camps. The Freebase and YAGO ontologies are relatively inexpressive, containing little more than generalization relationships and role typing. The Cyc ontology and SUMO are much richer, with disjointness and many other axioms that define the concepts and relationships in the ontologies.

Of course, if you don't care too much about this extra information, or cannot utilize it, the added computational costs in working with expressive ontologies may be daunting. For example, if you are concerned with simple access to information (i.e., your application performs retrievals over data), then you probably only need simple typing, and the Freebase ontology would be a reasonable choice, particularly as Freebase contains a large amount

of data. In this scenario, the Freebase ontology's issues with redundancy, integrity, and uniformity become less critical, because you are only returning retrievals for further analysis by humans, or for import into some other ontological framework. However, even in this scenario you can run into difficulties; for example, the two different relationships for birth date in Freebase—one for persons and one for non-human animals—makes even simple information access more difficult, showcasing a problem caused by Freebase's lack of uniformity. YAGO can be similarly used as a simple information source, but is less versatile in that, although it covers many domains, its ontology says very little about each of them (that is, it defines a much smaller number of properties).

However, if you need to perform reasoning over information, such as we envision in a conversational system to implement general user requests in terms of a knowledge repository, then the extra organizational power of Cyc and SUMO is extremely useful. Along with this extra power, Cyc and SUMO are better in terms of accuracy, consistency, and integrity, all important in a reasoning setting because incorrect information is magnified during reasoning. Between SUMO and Cyc, we prefer the Cyc ontology because it covers more domains and provides a more complete organization of many of these domains.

In some sense, any large system is going to have to interact with several ontological setups, as it will be pulling information from several sources, and the different sources are very likely to have different organizations of their information. This again argues for a powerful ontological system, one that can axiomatize the relationships between its organization and the organization of the other ontology.

On a final note, different ontologies, and data sources, come with different licenses. The licenses of some of the freely-available ontologies may cause problems in an industrial setting and these need to be considered separately.

4 Conclusion

We have defined 10 dimensions for use in evaluating general-purpose ontologies, and applied them in a qualitative, informal comparison of four such ontologies – SUMO and the ontologies associated with ResearchCyc, Freebase, and YAGO. We have discussed these particular ontologies so as to illustrate how the dimensions may be used in studying a broad range of ontologies. Because ontologies are so varied in their underlying philosophy, formalisms, and approach, we believe these dimensions provide a structure that can facilitate the selection of ontologies for many different kinds of enterprise applications.

As stated in Section 2, these results do not constitute a formal, rigorous evaluation. This should be addressed in the future by a statistically-meaningful evaluation of ontology content.

Our dimensions currently do not cover connections between an ontology and the the natural language expressions that may be used to organize, search or populate it. This is a drawback of our comparison, as ontologies such as SUMO have a full mapping from WordNet synsets to SUMO concepts, which is beneficial in practice. Moreover, Cyc and Yago also have similar mappings. Additional investigation is required to assess their strengths and weaknesses.

This refinement will also enable us to extend our work to comparing lexical ontologies. Clearly some of the concerns are similar, in that lexical ontologies can be domain-specific or aim for the whole language; lexical ontologies can pay attention to their consistency or not, etc. We hope that this broadening of the investigation may prove that our findings are robust. We also hope to help any application developer in need of guidance when it comes to the many choices offered by Linguistic Linked Open Data (http://linguistics.okfn.org/resources/llod/).

Another direction we would like to take this work is to multilingual ontologies. Many complain about the fact that hand-curated knowledge repositories can be fragile, as they represent some individual (or group of individuals) conceptualization of the world, with their social and cultural biases. If our ontologies can be automatically created in many languages in parallel, some of this criticism is curtailed. There are already some attempts at such multilingual ontologies (for example UWN, Menta, BabelNet and UBY) and presumably our dimensional criteria and/or a suitable modification will allow us to compare those.

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Towards Ontological Support for Principle Solutions in Mechanical Engineering

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Abstract

The engineering design process follows a series of standardized stages of development, which have many aspects in common with software engineering. Among these stages, the principle solution can be regarded as an analogue of the design specification, fixing as it does the way the final product works. It is usually constructed as an abstract sketch (hand-drawn or constructed with a CAD system) where the functional parts of the product are identified, and geometric and topological constraints are formulated. Here, we outline a semantic approach where the principle solution is annotated with ontological assertions, thus making the intended requirements explicit and available for further machine processing; this includes the automated detection of design errors in the final CAD model, making additional use of a background ontology of engineering knowledge. We embed this approach into a document-oriented engineering design process, in which the background ontology and semantic annotations in the documents are exploited to trace parts and requirements through the design process and across different applications.

1 Introduction

Much like software engineering design (in an ideal world), design processes in mechanical engineering proceed in multiple stages successively refining abstract requirements into a final solution. This process of *systematic engineering design* is standardized in models that bear substantial resemblance to the V-model, such as the German VDI 2221 [**?**]. However, only the last stage in this process, corresponding to the actual implementation in software engineering, has well-developed tool support, in the shape of CAD systems that serve to document the final design. Other stages of the design process are typically documented in natural language, diagrams, or drawings. There is little or no support available for interconnecting the various stages of the design, let alone verifying that decisions made in one stage are actually implemented in the next stage.

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Here, we embark on a program to fill this gap, focusing for a start on the last step in the development process, in which we are given a *principle solution* and need to implement this solution in the final design, a CAD model. The principle solution fixes important design decisions in particular regarding physical layout, materials, and connections but does not normally carry a commitment to a fully concrete physical shape. It is typically represented by a comparatively simple drawing, produced using plain graphics programs (e.g. within standard presentation tools) or even by hand. As such, it has a number of interesting features regarding the way it does, and also does not, convey certain information. The basic issue is that while one does necessarily indicate only one concrete shape in the drawing, not all aspects and details of this sketch are actually meant to be reflected in the final design. Some of this is obvious; e.g. it is clear that slight crinkles in a hand drawing are not intended to become dents in the final product, and to some (possibly lesser) degree it is also clear that not everything that is represented as a straight line or a rectangle in a simple sketch will necessarily be realized by the same simple geometry in the actual design. Other aspects are less straightforward; e.g. symmetries in the drawing such as parallelism of lines or equal lengths of certain parts, right angles, and even the spatial arrangement and ordering of certain components may constitute integral parts of the principle solution or mere accidents of the sketch. Other aspects of the design may be indicated by standard graphical symbolism; e.g. crosses often represent bolts. To aid human understanding of the principle solution, it is typically accompanied by a natural-language explanation that (hopefully) clears up most of the ambiguities; other aspects of the design are understandable only in the context of sufficient implicit knowledge, i.e. based on the experience of the design engineer.

The approach we propose in order to strengthen and explicate the links between the stages of the design process is, then, to integrate the documents associated to each stage into a unified document-oriented engineering design process using a shared background ontology. This ontology should be strong enough to not only record mere hierarchical terminologies but also, in our concrete scenario of principle solutions, to capture as far as possible the qualitative design intentions reflected in the principle sketch as well as the requisite engineering knowledge necessary for its understanding. (It might be fruitful to combine this approach with work on sketch maps in GIS [**?**] in order to distinguish between intended and contingent parts of the sketch automatically.) Such an ontology will in particular support the tracing of concepts and requirements throughout the development process; we shall moreover demonstrate on an example how it enables actual *verification* of a final design against constraints indicated in the principle solution.

Technically, we realize this approach by means of a modular semantic middleware architecture, the *Multi-Application Semantic Alliance Framework* (MASally), which connects a system of knowledge management web services to standard applications – in particular document players and CAD systems – via a network of thin API handlers that essentially make the framework parametric in the choice of CAD system. Background knowledge and design intentions are represented in a modular ontology that provides material for user assistance and forms the basis for the verification of design constraints. The formalized engineering knowledge required for the latter task is managed within the heterogeneous logical framework provided by the *Heterogeneous tool set* Hets [**?**], with the *Web Ontology Language (OWL)* [**?**] playing the role of the primary representation logic for the sake of its good computational properties. Sources of ontological knowledge include, besides manually extracted knowledge on engineering and basic geometry, semantic annotations of the principle sketch and the extraction of assertional knowledge from a CAD model. We illustrate our framework by means of an example where we verify aspects of the design of an assembly crane against the principle solution.

2 A Document-Oriented Process with Background Knowledge

We recall the stages of the *engineering design process* according to VDI 2221 [**?**].

S1 Problem: a concise formulation of the purpose of the product to be designed.

S2 Requirements List: a list of explicitly named properties of the envisioned product. It is developed in cooperation between designer and client and corresponds to the user specification document in the V-model.

S3 Functional Structure: a document that identifies the functional components of the envisioned product and puts them into relation with each other.

S4 Principle Solution: an abstract sketch capturing the most important aspects of the design.

S5 Embodiment Design: a CAD design that specifies the geometry of the final product.

S6 Documentation: accompanies all steps of the design process.

An approach to vertical semantic integration of this process is outlined in [**?**]. In this paper we concentrate on step **S4**, as it offers the most obvious handles for adding value using semantic services, and also discuss in more detail the structure of the ontology that drives them.

2.1 Principle Solutions

According to Pahl and Beitz [**?**], one can develop a principle solution for a product by combining working principles that correspond to the sub-functions identified in the function structure of the product. The search for applicable working principles and their ensuing combination in the principle solution is essential for the product development. For example, the manufacturing costs are determined to a large extent by these decisions. However, a combination of working principles cannot be fully evaluated until it is turned into a suitable representation. At this highly creative stage of the design process, the engineer does not want to consider the formalities inherent to a full-fledged CAD system. For this reason, probably the most common representations of principle solutions in mechanical engineering are old-fashioned hand-drawn sketches. Developing the principle solution mainly involves the selection of materials, a rough dimensional layout, and other technological issues. The design engineer can refer to various support tools in the search for working principles, such as the design catalogues of Roth [**?**] and Koller [**?**]. The degree of detail of a sketch varies between the two main levels of the design: while at the assembly level, the focus is mainly on the topology of the product, to ensure compatibility of the principles to be combined, at the level of parts and sub-assemblies more attention is given to the actual shape of the product to be developed. In the following, we discuss an example of a representation of a principle solution.

2.2 Case Study: An Assembly Crane

Our main case study concerns an assembly crane for lifting heavy machine components in workshops. This example has been used in a practical design assignment for engineering students at FAU Erlangen-Nürnberg in the winter term of 2012. In this design exercise, students were given a principle solution (Figures 1 and 2) along with some requirements (e.g. specified maximum power consumption, maximum torque, and maximum weight) and were asked to design an embodiment. Thus we have realistic documents for phases **S4** and **S5** of a representative and non-trivial design task to study.

The assembly crane to be designed can be divided into modules performing various functions. The modules are indicated by numbers in the figure: the main frame with a vertical beam, a cantilever, and parallel horizontal base profiles (1); and a lifting system, consisting of an electrically powered winch unit (2), connected via a cable (3), which is guided via deflection rollers, to a crane hook (4). This allows lifting, lowering and holding the machine components to be assembled. The requirements of the crane, which have been defined in a previous step, concern the material to be used (standard steel profiles for high strength and stiffness), the topology (the legs of the crane must be parallel, the vertical and the horizontal cantilever are perpendicular, the motor (2) must not be attached to the frame within the crane's working space), dimensions (maximum total height, minimum space between base profiles, minimum cantilever length) and manufacturing process constraints (weldment of main frame profiles and bolt connection of winch unit and main frame).

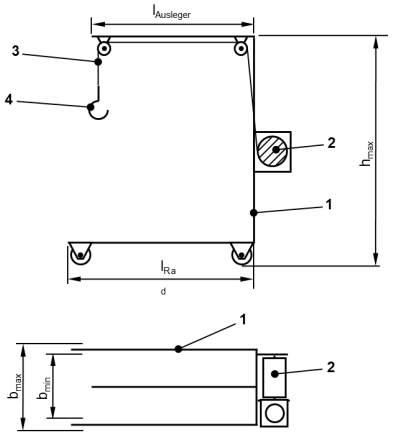


Figure 1: Principle Solution: Assembly Crane

Figure 2 details the principle solution of the winch unit: It consists of a drum (6a), which is welded (generally, the requirement of a weldment is indicated by a folded arrow) between two side plates (6b). In order to ensure correct reeling of the cable, the drum is thread-structured (6). The main shaft (7) is driven by an electric worm-geared flange motor (5) that is connected to the winch frame (11) via blind-hole bolts (indicated by crosses in the sketch). In order to decelerate the winch, to hold the load, and to allow emergency stops, a lamella disk break (9) is installed; it is connected to the main shaft by a suitable shaft-hub connection (10) that can withstand sudden increases in torque (e.g. due to emergency stops). An arrangement of locating and non-locating bearings (8) supports the main shaft. The ball bearings have to be arranged in such a way that axial forces are kept from

the motor. The winch frame is realized as a stiff, yet weight-minimized, welded assembly, made of steel and is connected to the main frame of the crane with through-hole bolts.

3 Semantic Support for a Document-Oriented Engineering Design Process

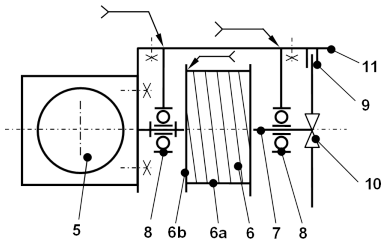


Figure 2: Principle Solution for the Winch Unit.

Every step of the engineering design process results in particular documents, e.g. text documents for **S1** to **S3** and **S6**, an image for **S4** (hand-drawn or produced in a simple graphics program), and a CAD assembly in **S5**. One of our goals is to integrate these into a document-oriented engineering design process, using semantic technologies.

3.1 A Semantic Annotation System

We build on the MASally architecture presented in [**?**] (under the name FFCad, considerably extended here to embrace document-oriented design processes), which assumes that the background knowledge shared by the manufacturer, design engineer, and the clients is reified into a flexiformal ontology (the cloud in Figure 3) and that the documents are linked into that ontology via a *semantic illustration mapping* (depicted by dashed arrows in Figure 3) from fragments or objects in the documents to concepts in the ontology (dotted circles), which may themselves be interconnected by ontology relations (solid arrows). The ontology itself is a federation of ontology modules describing different aspects of the engineering domain that are interconnected by meaning-preserving interpretations (see Section 4 for details). In the case of principle solutions, for instance, the semantic illustration mapping is currently generated from manual annotations of parts of the drawing with ontological concepts; to which degree annotations can be inferred by interpreting graphical jargon is the subject of further investigation.

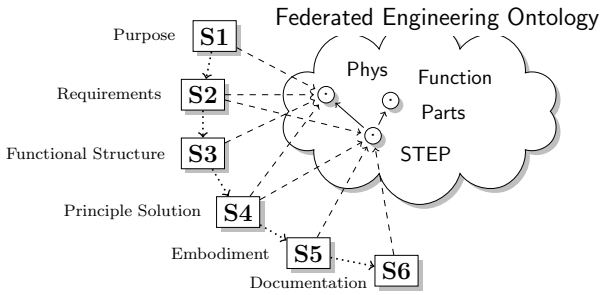


Figure 3: An Ontology-Supported Document-Oriented Design Process

In addition to the ontology links, we assume that the documents themselves are semantically linked via relations (the dotted arrows between the **S***i*) that model the process of goal refinement in the development process. These two primary relations are augmented with fine-grained annotations about document status, versioning, authorship, etc. Note that our approach crucially extends metadata-based approaches in that the annotations and relations point to document fragments – e.g. text fragments down to single symbols in formulae, regions in sketches, or shapes/sub-assemblies in CAD objects. All of these explicit annotations in the documents are the basis for semantic services that can be integrated into the documents (and their player applications) via the MASally framework, which we describe next.

3.2 Semantic Services via the MASally System

The Multi-Application Semantic Alliance Framework (MASally) is a semantic middleware that allows embedding semantic interactions into (semantically preloaded) documents. The aim of the system is to support the ever more complex workflows of product developers with their knowledge intensive tasks that so far only other humans have been able to perform without forcing them to leave their accustomed tool chain.

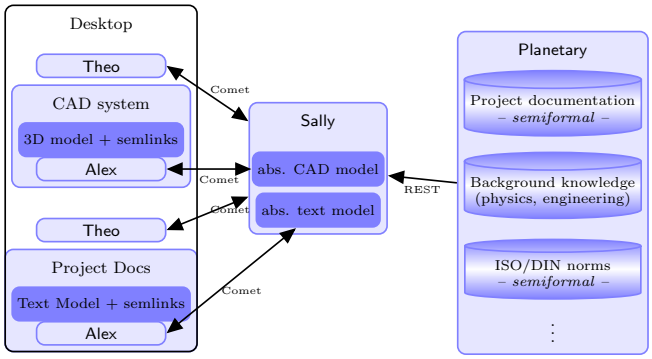


Figure 4: The MASally Architecture

The MASally system is realized as

- a set of semiformal knowledge management web services (comprised together with their knowledge sources under the heading Planetary on the right of Figure 4);
- a central interaction manager (Sally, the *semantic ally*) that coordinates the provisioning and choreographing of semantic services with the user actions in the various applications of her design process;
- and per application involved (we show a CAD system and a document viewer for **S4**/**S5** in Figure 4)
  - a thin API handler Alex that invades the application and relates its internal data model to the abstract, application-independent, content-oriented document model in Sally;
  - an instance of the application-independent display manager Theo, which super-imposes interaction and notification windows from Sally over the application window, creating the impression the semantic services come from the application itself.

This software and information architecture is engineered to share semantic technologies across as many applications as possible, minimizing the application-specific parts. The latter are encapsulated in the Alexes, which only have to relate user events to Sally, highlight fragments of semantic objects, handle the storage of semantic annotations in the documents, and export semantically relevant object properties to Sally. In particular, the Theos are completely system-independent. In our experience developing an Alex for an open-API application is a matter of less than a month for an experienced programmer; see [**?**] for details on the MASally architecture.

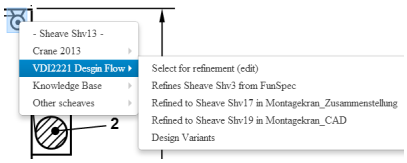


Figure 5: Navigating the Refinement Relation

As a use case, let us consider the following situation. The design engineer is working on the principle solution from Figure 1 – a sketch realized as a vector image, displayed in an (in this case browser-based) image viewer. The user clicked on a detail of the sketch and received a (Theo-provided) menu that

1. identifies the object as 'Sheave S13' (the image is extended with an image map, which allows linking the region 'S13' with the concept of a 'sheave' in the ontology); further information about the object can be obtained by clicking on this menu item;
2. gives access to the project configuration that identifies the other documents in the current design;
3. gives access to the design refinement relation between the project documents: here, the object S13 is construed as a design refinement of the requirement S3 in the principle solution and has been further refined into objects S17 and S19 in the CAD assembly and the manufacturing plans generated from it;
4. allows direct interaction with the ontology (e.g. by definition lookup; see Figure 6, here triggered from the CAD system for variety);
5. gives shortcuts for navigation to the other sheaves in the current project.

Generally, the MASally system supports generic help system functionalities (definition lookup, exploration of the concept space, or semantic navigation: lookup of concrete CAD objects from explanations) and allows focus-

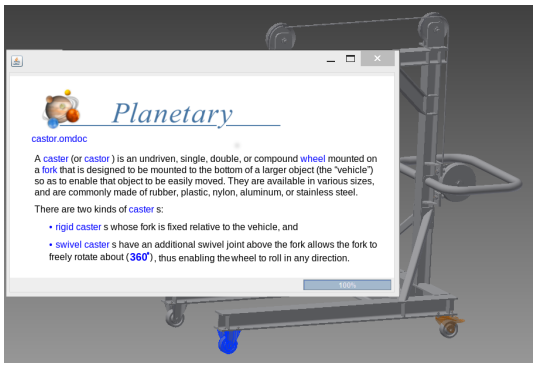


Figure 6: Definition Lookup

preserving task switching (see [?] for a discussion). All we need for this are annotations of the VDI2221 relations, ontology links and of course the ontology itself, which we will discuss next.

4 The Federated Engineering Ontology

We proceed to discuss the design of the ontology that acts as the central repository of background knowledge. It serves as a synchronization point for semantic services, as a store for the properties of and relations between domain objects, and as a repository of help texts for the MASally system. As it has to cover quite disparate aspects of the respective engineering domain at different levels of formality, it is unrealistic to expect a homogeneous ontology in a single representation regime. Instead, we utilize the heterogeneous OMDoc/MMT framework [?, ?] that allows representing and interrelating ontology modules via meaning-preserving interpretations (i.e. theory morphisms). In particular, OMDoc/MMT supports the notion of meta-theories so that we can have ontology modules represented in OWL2 alongside modules written in first-order logic, as well as informal modules given in natural language. The OMDoc/MMT meta-morphisms relate all of these and moderate a joint frame of reference. Reasoning support is provided by the verification environment of the Heterogeneous Tool Set Hets [?], a proof management tool that interfaces state-of-the-art reasoners for logical languages. Hets mirrors the heterogeneity of the representation framework: new logics, logic translations or concrete syntaxes of languages can be plugged in without having to modify the heterogeneous and the deductive components of Hets. In our verification of design constraints, we employ, within OMDoc/MMT/Hets, the Distributed Ontology, Modeling and Specification Language DOL [?, ?] that provides specific support for heterogeneity in ontologies.

4.1 A Verification Methodology

We propose a general methodology for the verification of qualitative properties of CAD assemblies against principle solutions. While the checking of explicit *quantitative* constraints in principle solutions is supported by a number of research tools (e.g. the ProKon system [?]; in fact, some CAD systems themselves include constraint languages such as CATIA Knowledge Expert, which however are not typically interrelated with explicit principle solutions), there is to our knowledge currently no support for checking *qualitative* requirements given by the principle solution.

Example 4.1. In our case study introduced in Section 2.2, commonly encountered violations (in realizations produced by engineering students) of qualitative requirements in the principle solution were the following:

- the horizontal base profiles of the frame were not parallel;
- the types of weldments used did not ensure high stiffness and the local weldment area was not designed properly (e.g. missing ribs or stiffenings);
- the ball bearings were arranged in such a way that the non-locating bearing was closer to the motor, and thus the axial forces were transmitted into the motor.

We are going to use the requirement that the legs of the frame should be parallel as a running example throughout the rest of the section. It is clear that the other examples can be treated similarly.

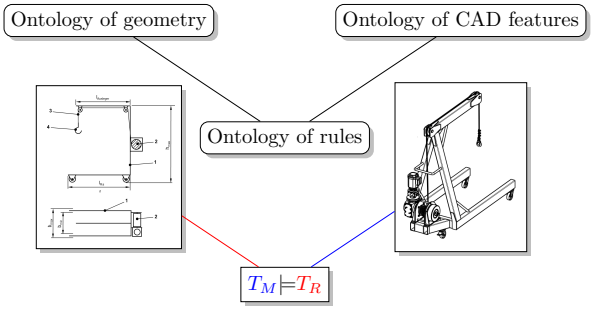


Figure 7: Verification of qualitative properties of CAD designs.

The first step is to provide a formal terminology for expressing the qualitative properties that a CAD design should fulfill. Since we are at the stage **S5** of the engineering design process, we have to collect requirements from all previous stages, in particular **S1** - explicit requirements - and **S4** - further restrictions on the acceptable designs introduced by the principle solution. Here, we concentrate on geometric properties of physical objects and therefore we tackle this goal by developing an ontology of geometric shapes. We then need to have means to formally describe the aspects of a CAD design that are relevant for the properties that we want to verify. Since we want to verify geometric properties, we are going to make use of an ontology of CAD features. We then need to formulate general rules regarding geometric properties of objects constructed by repeated applications of CAD features. This gives us a new ontology, of rules relating geometric properties and CAD features.

We now come to the task of verification of a concrete CAD design against the requirements captured by a given principle solution. In a first step, we generate a representation of the requirements as an ABox T_R over the ontology of rules, in a way that will be explained below. The next step is to generate a representation of the CAD design as another ABox T_M over the same ontology of rules, and then to make use of the rules to formally verify that T_M logically implies T_R. This process is illustrated in Figure 7.

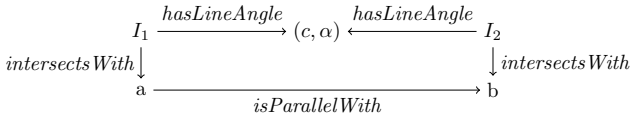
4.2 Ontology of Shapes

We begin setting up our verification framework by developing an ontology of abstract geometric objects, with their shapes and properties. The shape of a geometric object would seem to be a well-understood concept; however, the task of formalizing the semantics of shapes and reasoning about them is difficult to achieve in a comprehensive way. For a broader discussion, including some attempts to develop ontologies of geometric shapes, see, e.g., the proceedings of the Shapes workshop [**?**].

Our ontology, inspired by CYC [**?**], concentrates on geometric primitives of interest for CAD design . The central concept is that of *PhysicalObject*, which may be of an unspecified shape or can have a 2-dimensional or 3-dimensional shape. The object and data properties of the ontology are either parameters of the geometric shapes (e.g. diameter of a circle, or length of the sides of a square) or general geometric properties, like symmetric 2D- and 3D-objects and parallel lines.

Example 4.2. We present the fragment of the ontology[1] of shapes that is relevant for asserting that two objects are parallel, a DOL specification that extends our OWL formalization of geometry with the axiom that two coplanar lines are parallel if the angles of their intersections with a third line are equal. Since the intersection of two lines is a three-place relation, the two intersecting lines and the angle between them, we use reification to represent it as a concept *Intersection*, together with a role *intersectsWith* that links to the first constituent line, a class *LineAngle* for pairs of lines with angles (with associated projection roles) and a role *hasLineAngle* that links to the pair of the second line of an intersection and the angle between the two lines:

[1]The ontology modules relevant for the running example are available at `http://ontohub.org/fois-ontology-competition/FormalCAD/`.



We denote the inverses of *hasLineAngle* and *intersectsWith* with *lineAngleOf* and *hasIntersection*, respectively. Since OWL does not support intersection of roles, the property will be expressed as a SWRL rule, that we write here informally to save space:

`isCoplanar(?a, ?b)` $\wedge$ `hasIntersection(?a, ?i1)` $\wedge$ `hasLineAngle(?i1, ?la)` $\wedge$ `lineAngleOf(?la, ?i2)` $\wedge$ `intersectsWith(?i2, ?b)` $\Rightarrow$ `isParallelWith(?a, ?b)`

4.3 Ontology of CAD Features

Inspired by [**?**], our ontology of features contains information about the geometry and topology of CAD parts. It describes assemblies and their parts, feature constructors and transformers, 2D sketches and their primitives, and constraints (cf. Example 4.3).

Example 4.3. We present a fragment of the ontology of features that is relevant for verifying that two objects are parallel. We have a concept of *3DPart* of an assembly and each part has been constructed in a 3D space which has 3 axes of reference. We record this by an object property *hasAxis*, with the inverse *isAxisOf*. Furthermore, 3D parts can be *constrained* at the assembly level. The constraint of interest for us is an angle constraint that specifies the angle formed between two axes, two edges or two faces of two chosen parts. Since this is again a relation with three arguments, we use reification, in a similar way as in Example 4.2, that is, we have a class *AngleConstraint* and three roles, *firstConstrainedLine* and *secondConstrainedLine* giving the two lines that are constrained and *constrainedAngle* giving the specified angle.

In a similar way, a *Mate* constraint determines that the two axes are in the same plane.

4.4 Ontology of rules

The next step is to relate via rules the concrete designs using feature transformers and constructors, given as elements of the ontology of features, to the abstract shapes in the ontology of geometry. It is worth mentioning that the rules can be themselves subject to verification (a proof of concept was given in [**?**]). The advantage of our approach is that the task of verifying the rules, which can be quite complex, is separated from the task of checking correctness of individual CAD designs, which makes use of the rules.

Example 4.4. The DOL *alignment* below states that each part is a physical object and that lines and angles in the same ontologies are equivalent (we elide namespaces).

alignment BASE : FEATURES **to** SHAPES =
Line = *Line*, *Angle* = *Angle*, *3DPart* < *PhysicalObject*

The outcome is that we can use DOL *combinations* to put together the two ontologies while taking into account the semantic relations given by the alignment. We further state that an angle constraint in an assembly gives rise to an intersection between the constrained lines and that two parts of an assembly are parallel if their axes are parallel. We use Manchester syntax for OWL, with **o** denoting role composition.

ontology RULES = **combine** BASE **then**
ObjectProperty: *intersOfAngleConstraint*
Domain: *AngleConstraint* **Range:** *Intersection*
ObjectProperty: *isParallelWith*
SubPropertyChain: *hasAxis* **o** *isParallelWith* **o** *isAxisOf*
ObjectProperty: *firstConstrainedLine*
SubPropertyChain: *intersOfAngleConstraint* **o** *intersectsWith*
ObjectProperty: *secondConstrainedLine*
SubPropertyChain: *intersOfAngleConstraint* **o** *hasLineAngle* **o** *lineOfLineAngle*
ObjectProperty: *constrainedAngle*
SubPropertyChain: *intersOfAngleConstraint* **o** *hasLineAngle* **o** *angleOfLineAngle*

Similarly, we have a rule saying that two objects that are in planes constrained using *Mate* are coplanar.

4.5 Generating the ABoxes and proving correctness

The principle solution is available as an image file, together with a text document that records additional requirements introduced in the principle solution, thus further restricting the acceptable realizations of the design. Each part of the sketch has been identified as a functional part of the principle solution and given a name; this yields the required individual names for our ABox. The assertions regarding the individuals thus obtained are added as semantic annotations to the text that accompanies the image (Figure 8).

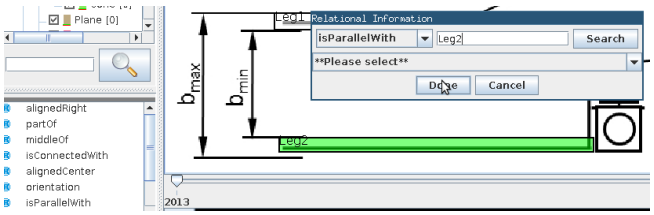


Figure 8: Making assertions regarding individuals explicit using AKTiveMedia [**?**]

Example 4.5. The following ABox expresses that the parts identified as *leg1* and *leg2* of the principle solution should be parallel:

ontology PrincipleSolution = Rules **then**
Individual: *Leg2* **Individual:** *Leg1* **Facts:** *isParallelWith Leg2*
...

The ABox of the CAD design is generated from its history of construction, using the Alex for CAD. The following part of this ABox expresses that the two legs of the crane have been explicitly constrained to be perpendicular to the main frame and coplanar in the CAD model:

ontology CADModel = Rules **then**
Individual: *a1* **Types:** *Line* **Individual:** *a2* **Types:** *Line* **Individual:** *a3* **Types:** *Line*
Individual: *craneLeg1* **Types:** *3DPart* **Facts:** *hasAxis a1*
Individual: *craneLeg2* **Types:** *3DPart* **Facts:** *hasAxis a2*
Individual: *frameBase* **Types:** *3DPart* **Facts:** *hasAxis a3*
Individual: *alpha* **Types:** *Angle* **Facts:** *valueOf 90*
Individual: *ac1* **Types:** *AngleConstraint*
Facts: *firstConstrainedLine a1*, *secondConstrainedLine a3*,*constrainedAngle alpha*
Individual: *ac2* **Types:** *AngleConstraint*
Facts: *firstConstrainedLine a2*, *secondConstrainedLine a3*, *constrainedAngle alpha*
...

Following Figure 7, we have to show that all models of the ABox generated from the CAD design are models of the ABox generated from the principle solution. DOL uses *interpretations* to express this; e.g., checking that the two legs of the crane are parallel amounts to checking correctness of the DOL interpretation

interpretation VERIF :PrincipleSolution **to** CADModel =
Leg1 $\mapsto$ *craneLeg1*, *Leg2* $\mapsto$ *craneLeg2*

using one of the provers interfaced by Hets, e.g. the Pellet reasoner for OWL [**?**]; as expected, the reasoner makes short work of this.

5 Related Work

In previous work [**?**], we have developed an export function from SolidWorks that generates from the internal representation of a CAD design a description of its construction in a variant of higher-order logic. One can

then relate this construction to abstract geometric shapes and prove this relation to be correct using a higher-order proof assistant. In the context of the methodology introduced in Section 4.1, each such relation between the construction and its abstract geometric counterpart gives rise to a formally verified rule in the ontology. At the informal level, we have moreover developed a semantic help system for CAD objects based on the Semantic Alliance Framework [**?**], and have illustrated the use of this information for semantically supported task switching [**?**]. Our methods should be seen as distinct from the use of ontologies in workflow management and web service composition, as, e.g., in the Taverna system [**?**], in that we aim to semanticize the actual content of documents.

Several ontologies of features have been developed, with the typical application scenario being interoperability and data interchange between CAD systems, rather than verification of qualitative properties of CAD assemblies. E.g., OntoSTEP [**?**] enriches the semantics of CAD objects represented in the system-independent ISO-standard interchange format STEP. Our heterogeneous approach allows integrating OntoSTEP (or any other ontology of features) into our federated engineering ontology and relating it to our ontology of features, without having to modify our verification methodology.

Various approaches have been explored to integrate semantics into the engineering design process. E.g., *features* as used in *feature technology* [**?**] aggregate geometric objects and semantics. Different types of features are defined (eg. form features, semantic features, application features, compound features), depending strongly on the technical domain and the product life-cycle phase in which features are used. We expect features to play a role in further semanticizing step S5 (embodiment, Section 2) in future work.

As mentioned in Section 2.1, the most common representations of principle solutions in mechanical engineering are probably hand-drawn sketches. One alternative approach is the Contact-and-Channel Model (CCM) [**?**]. The basic idea is that every technical system can be represented as a system of *working surface pairs* and *channel and support structures*. In our case study, an example of a working surface pair would be the shaft-hub connection between the winch main shaft and the lamella disk break, and the main shaft, where the break torque of the disk break is *channeled* to the winch drum in order to stop the cable, would be a channel and support structure. Approaches of this kind, in combination with ontological models of function (e.g. [**?**]; see also the survey by Erden et al. [**?**]), are candidates for integration with our ontological process model in future extensions covering the step from the function structure to the principle solution.

6 Conclusions

We have described a framework for semantic support in engineering design processes, focusing on the step from the principle solution to the embodiment, i.e. the CAD model. We base our framework on a flexiformal background ontology that combines informal and semiformal parts serving informational purposes with formalized qualitative engineering knowledge and formal semantic annotation of principle sketches. The latter serve to separate contingencies of the sketch from its intended information content, and enable *automated* verification of the CAD model against aspects of the principle solution. We combine this approach with a document-oriented process that relies on the background ontology for tracking the identity of parts through the design process and across different applications, which are accessed in a unified manner within the MASally framework.

As a proof of concept, we have illustrated our approach on the partial verification of a CAD model of an assembly crane against the principle solution, showing in particular that the ability to draw logical inferences is important when verifying qualitative constraints. This allowed the system to, e.g., accept two parts as satisfying a parallelism constraint formulated in the principle solution although the CAD model did not mention such a constraint, which instead had to be inferred from other constraints in the model.

We currently use OWL as the logical core of our verification framework, representing the requisite background knowledge in a TBox and generating ABoxes from the principle sketch and the CAD model. Our approach is based on heterogeneous principles, through use of the Heterogeneous Tool Set Hets and the Distributed Ontology, Modeling and Specification Language DOL [**?**, **?**]. It is thus easily possible to go beyond the expressivity boundaries of OWL where necessary, e.g. by moving some parts of (!) the ontology into first-order logic or, more conservatively, by using rule-based extensions of OWL such as SWRL [**?**] — this will increase the complexity of reasoning but the Hets system will localize this effect to those parts of the ontology that actually need the higher expressive power. Use of SWRL will in particular increase the capabilities of the system w.r.t. arithmetic reasoning.

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