UNIVERSITY OF OREGON
APPLIED INFORMATION MANAGEMENT

Presented to the Interdisciplinary Studies Program:
Applied Information Management and the Graduate School of the University of Oregon
in partial fulfillment of the requirement for the degree of Master of Science

An Inventory of Semantic Models (Ontologies) for Use When Managing Enterprise Tacit Knowledge

CAPSTONE REPORT

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February 2010

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Abstract

Semantic web technologies provide flexible tools and approaches for modeling enterprise tacit knowledge. Literature published after 2000 identifies three primary types of ontologies: (a) upper level, describing general or common concepts, (b) mid level, extending upper level concepts to a domain space, and (c) lower level, or domain specific, that define the nuances to an organization or domain (Kiryakov, Simov, & Dimitrov, 2001). Tools and ontologies are cataloged in an inventory, including advantages and disadvantages.

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Introduction

Problem Area

The purpose of this study is to examine how ontologies are applied to tacit knowledge management and to assemble an inventory of models, tools, and approaches used to manage tacit knowledge. Choi, Edgington, Henso, Raghu, and Vinze (2004) note that "many organizations consider knowledge management as the key to sustained competitive advantage" (p.1). An enterprise knowledge management system is defined as a set of tools and technologies used to support "the exchange of problem domain-specific knowledge to inform decision activities" (Singh, Iyer, & Salam, 2003, p. 1). Small and Sage (2006) state that typically, an enterprise knowledge management system is "supported by a dedicated KM [knowledge management] staff who own the knowledge processes, templates, and technologies; and knowledge sponsors and integrators from the business units who "own" the knowledge content" (p. 156). Ontologies (structured representations of an area of knowledge) and the semantic web (a collection of standards, tools and formats for information representation and linking) are examples of templates and technologies which are used for (a) searching for information, (b) extracting information, (c) maintaining information, (d) discovering information through search and reasoning, and (e) viewing and communicating information (Antoniou & van Harmelen, 2004, p. 3).

Ontologies are formal descriptions of a domain area intended for sharing information and knowledge between applications (Noy, 2004). Furthermore, ontologies are used to create knowledge models that are critical to enterprise decision-making and retention of tacit knowledge in an organization (Han & Park, 2009). An enterprise "knowledge model" is defined as a mechanism for defining "business units, activities, resources needed, and more" in a reusable and machine-readable manner (Umar & Zordan, 2009). Knowledge models provide a "common understanding of the structure of information among people or software agents" (McGuinness & Noy, 2001, p. 1). Enterprise knowledge models are in current usage across government agencies and large enterprise environments such as Boeing, Chevron, and British Telecom (Feigenbaum, Herman, Hongsermeier, Neumann, & Stephens, 2007). The purpose of these ontologies is to assist in the "acquisition, representation and manipulation" of enterprise knowledge by ensuring that all participants in the process have a shared understanding of the relevant aspects of the enterprise (Han & Park, 2009).

In a 2001 Scientific American article, Berners-Lee, Hendler, and Lassila (2001) introduced to the mainstream public the concept of the "semantic web", defined as a collection of standards and approaches for bringing order and meaning to information on the Internet. Ontologies are a foundational component of the semantic web providing a framework for "standardization of concepts and relationships used to describe and represent an area of knowledge" (W3C Semantic Web FAQ, n.d.). Moreover, ontologies encapsulate rules or logic for automated inference and reasoning, making it possible for applications or software agents to discover relationships and meaning not explicitly defined in the data (Berners-Lee, et al., 2001).

The advent of World Wide Web Consortium (W3C) Semantic Web standards has fueled significant software development activity resulting in a number of commercial and open source software products that employ ontologies to support the codification of tacit knowledge in a reusable format. The key difference between the semantic web approach, which uses ontologies to represent the meaning of information, and other solutions is that users and application are not required to agree on a single set of data definitions (Berners-Lee, et al., 2001). Industry groups, including life sciences, pharmaceutical, oil and gas, and intelligence and defense, have formed working groups to share knowledge and develop templates for the application of semantic technologies in their industry (W3C, n.d.). These templates are the basis for creating "semantically-aware information systems to support diverse enterprise, government, and personal activities" (Denny, 2002, p.1). Examples of such systems include integration of ontology-driven tools for aircraft design, development of military course of action planning models, consumer telecom customer portals, and oil refinery lifecycle management models (Feigenbaum et al., 2007).

Purpose

Tacit knowledge—the thoughts and experiences of an expert performing a task—represents a valuable enterprise asset from which the organization can "draw greater productivity, create new value, and increase their competitiveness" (Antoniou & van Harmelen, 2004, p. 3). According to Kitamura and Mizoguchi (2003), ontologies provide the flexibility and representational richness required to meet the challenges of tacit knowledge management. Much of the ontology and semantic web development that has occurred over the last ten years focuses on the data integration and reasoning engines (Noy, 2004). However, in the realm of tacit knowledge, ontologies provide a way to structure historically unstructured, and poorly represented data, making accessible to people and applications. Berners-Lee, et al., (2001) address one of the fundamental problems afflicting tacit knowledge sharing stating that, "a small group can innovate rapidly and efficiently, but this produces a subculture whose concepts are not understood by others. Coordinating actions across a large group, however, is painfully slow and takes an enormous amount of communication" (p.43). The purpose of this study is to develop an inventory of tacit knowledge models, approaches, and tools, focusing on the most common methods for applying semantic technology to tacit knowledge management. This study examines literature primarily published after 2000 in the subject areas of (a) enterprise knowledge models (El-Diraby & Zhang, 2006), (b) semantic technologies applied to tacit knowledge management (Antoniou & van Harmelen, 2004), and (c) enterprise ontologies (Berners-Lee, et al., 2001).

Significance

Understanding the potential of ontologies and semantic technologies in the enterprise is important for information technology (IT) professionals striving to meet the challenges of the modern information glut (Stewart, 2008). Stewart (2008) asserts that worldwide enterprise data production exceeds 1,397 terabytes of digital information each year. Blumberg and Atre (2003) estimate that 85% of the information generated in the enterprise is comprised of unstructured information in the form of Microsoft Office documents, email, and other textual formats. Crompton (2008) confirms that managing these types of assets presents a large-scale problem for organizations. Furthermore, Jonas and Sokol (2009) contend that information cannot exist in isolation and needs systems that provide context and relationships to make individual data elements truly valuable.

This explosion of data and information comes at a time when large numbers of workers are preparing to retire thus risking the loss of tacit knowledge as people leave corporations (Toosi, 2005). DeLong (2004) points out that tacit knowledge is extremely hard to replace once it is lost. The loss of this type knowledge can be very costly and can result in significant time loss for organizations (DeLong, 2004). Choi et al. (2004) report that ontologies are a key component of capturing knowledge because they form the "basic structure or armature around which a knowledge base can be built" (p. 86).

Corporate memory and tacit knowledge are critical issues for many organizations where large swaths of the workforce, known as the baby boomers (people born between 1946 and 1964), are reaching retirement age (Toosi, 2005). Fidel and Liu (2007) report, "valuable institutional and operational knowledge are also lost when these knowledgeable individuals leave the organization" (p. 1).

Discoverability, or the ability for users and applications to find data (Stewart, 2008), and effective use of information assets—applying information to the benefit of the enterprise, are both knowledge management issues with far reaching social and financial impacts (Blumberg & Atre, 2003). Likewise, tacit knowledge, or "knowledge which is created in the mind of the individuals is generally of little value to an enterprise unless it is shared" (Sage & Small, 2006, p. 156). As noted by Stewart (2008), developing ontologies to represent a shared community consensus of tacit knowledge concepts and relationships is necessary to facilitate knowledge synthesis and sharing. Ontologies are particularly well suited to representing tacit knowledge because of their flexibility and rich representational qualities (Kitamura & Mizoguchi, 2003).

Outcome/Audience

The intent of this study is to develop an inventory of tacit knowledge models and approaches described in the academic and peer reviewed literature. The term inventory is used to describe a list of assets that are treated as products; in this case the products are reusable models. The inventory is designed for knowledge managers responsible for maintaining enterprise knowledge and the IT staff who are responsible for managing knowledge management systems (Sage & Small, 2006). The audience for this research spans both those responsible for building the IT systems for knowledge storage and retrieval and those responsible for creating and managing the ontologies used to describe information.

Information architects and managers are faced with massive increases in the amount of data that is being generated (Stewart, 2008). For example, Crompton (2008) estimates that Chevron Corporation generates 300 million new documents each year. Incumbent systems and technology are inadequate in the face of this onslaught, resulting in a large amount of enterprise tacit knowledge being lost or languishing in a state where discovery is impossible (Jonas & Sokol, 2009). Therefore, understanding emergent technology for tacit knowledge modeling is important to IT professionals facing these problems (Wierzbicki, 2007).

Delimitations

Timeframe. This study examines literature published after 2000. This timeframe covers the most relevant work in the area of ontologies and semantic web technology by encompassing the period of rapid emergence of this technology to present day developments (Feigenbaum, et al., 2007).

Types of sources. This study focuses primarily on works published in peer-reviewed journals, and papers presented at professional and academic conferences, the publications of professional organizations, and international standards bodies. These sources provide a broad range of both theoretical and applied research on the application of ontologies for tacit knowledge representation. Standards organizations like the W3C form an intersection of academic research and industry adoption for emerging technology that is reflected in a wealth of published papers and articles. Researchers and developers participating in technical standards development are an avenue for locating research not found through the primary search engine process described in the Report of Search Findings section.

Audience. This study is written for individuals and professionals tasked with the representation and management of tacit knowledge in an enterprise—people who face the challenge of turning tacit knowledge into a valuable asset to their respective organizations. This challenge requires a consideration of ontologies and knowledge models to meet the information demands of the next decade.

Focus. Ontologies are used broadly to codify information for purposes ranging from analysis and artificial intelligence to simple categorization, searching, and retrieval of information (Antoniou & van Harmelen, 2004, p. 3). This research focuses on tacit knowledge because it represents one of the most challenging areas for knowledge representation and one for which ontologies are well suited (Antoniou & van Harmelen, 2004).

Availability of Ontologies. Not all of the ontologies in the reviewed literature are published and available for use by others. Ontologies are frequently considered core intellectual property (IP) and therefore not published. The inventory in this research will include a selection of referenced ontologies and ontology-driven tacit knowledge management tools designed to orient IT managers to the available options for applying these technologies.

Non-Commercial Sources. This research focuses on ontologies and tools that are outside the commercial realm.

Preview of Data Analysis and Writing Plans

Data analysis plan. This research applies a conceptual literature analysis approach to the literature review, as described by Busch, De Maret, Flynn, Kellum, Le, Meyers, Saunders, White, and Palmquist (2005). Sources are evaluated for the occurrence of a set of specified terms within each work in order to identify the larger concepts of (a) enterprise knowledge models, (b) semantic technologies applied to tacit knowledge management, and (c) enterprise ontologies. The terms used in this analysis process are a pre-defined set of words derived from the search keywords and from the resultant literature sources. Using this set of terms, the eight-step process described by Busch et al. (2005) is applied to the literature analysis. Details are located in the Research Parameters section of the paper.

Writing plan. The study, designed as a literature review, evaluates, organizes, and identifies thematic patterns in the published literature (Leedy & Ormrod, 2001). Themes are identified in relation to an analysis of the core concepts that are revealed through the data analysis process. The final set of themes is used to frame the development of an inventory of commonly applied models, which includes an analysis of the trends and directions, and the advantages and disadvantages of enterprise tacit knowledge management using ontologies.

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Definitions

The following definitions provide a common context and frame of reference for this research. The purpose of these definitions is to ensure that the terms applied in this research are consistent with the meanings as they appear in the selected literature, and to make certain that technical terms and jargon are sufficiently defined for the needs of the stated audience.

Annotation. Semantic web annotations, made using components of an ontology, are a key method of capturing additional meaning from information by "formally identifying concepts and relations between concepts in documents" (Uren, Cimiano, Iria, Handschuh, Vargasvera, Motta, et al., 2006, p. 16)

Axiom. A rule or conditions in the form of restrictions to define classes in an ontology to allow computers to interpret natural language (Terziev, Kiryakov, & Manov, 2005).

Class. A key element of ontologies that are used to represent concepts or categories in an ontology (McGuinness & Noy, 2001).

Folksonomy. A social networking approach to tagging content and information from the bottom up rather than a top down imposed structure (Shirky, 2005).

Information Collaboration. The process of sharing knowledge and information for the purpose of jointly generating value for the enterprise (Blumberg & Atre, 2003).

Inventory. A collection or list of assets, in this case ontologies, that can be applied to tacit knowledge representation and management. A core concept of ontologies is their flexibility and reusability (Allemang & Hendler, 2008). The inventory of models, assembled in this research, is a set of models that can be used for tacit knowledge management.

Instance. Data elements that are represented by the ontology to form a knowledge base (McGuinness & Noy, 2001). Instances represent a specific individual or the manifestation of a concept. For example, an ontology with the concept of "Person" might have an instance "Bill Clinton".

Knowledge Management. The process of acquiring, accessing and modeling knowledge to maximize its value to the enterprise (Antoniou & van Harmelen, 2004).

Knowledge Model. A general representation of a knowledge area, not specific to any technology implementation, for "organizing knowledge for ease of learning by people or ease of programming in computers" (Sowa, 2005).

Knowledge. The state or asset that is achieved when "theory, information, and experience are integrated" (Sage & Small 2006, p. 2).

Ontology. A structured representation of an area of knowledge (Stewart, 2008). "An ontology defines a common vocabulary for researchers who need to share information in a domain. It includes machine-interpretable definitions of basic concepts in the domain and relations among them" (Stewart, 2008, p. 163).

Resource Description Framework (RDF). A World Wide Web Consortium standard syntax for representing "a term in a statement to an entity in the world that the term refers to" (Allemang & Hendler, 2008, p. 31). RDF data elements are expressed as the combination of a subject, predicate, and object; also known as a triple

Reasoner. Software that utilizes the axioms and logic defined in an ontology to infer meaning and assign classification for data in an automated fashion (Allemang & Hendler, 2008).

Semantic Web. A collection of standards, tools, and technologies for information representation for computers and humans (W3C, n.d.).

Tacit Knowledge. Small and Sage (2006) describe two types of knowledge: tacit and explicit. Small and Sage (2006) go on to state that:

> Explicit knowledge is knowledge that can be codified. It is more formal and systematic and is often found in books, enterprise repositories, databases, and computer programs. Tacit knowledge, which is highly personal, is difficult to articulate and is rooted primarily in our contextual experiences (Sage & Small, 2006, p. 3).

Note that for this research the primary focus is on enterprise knowledge in the heads of workers, and not the broader philosophical topic of tacit knowledge.

Taxonomy. A hierarchical system of classification used to organize information (Stewart, 2008).

Triple. A triple is the basic unit of information in the semantic web. A triple consists of a Subject, a Predicate, and an Object. These are combined to make descriptive assertions about concepts (Terziev, Kiryakov, & Manov, 2005).

Web Ontology Language (OWL). The web ontology language is a World Wide Web Consortium standard for modeling knowledge (Stewart, 2008). "OWL offers a wide variety of modeling capabilities for relating information in flexible and powerful ways" (Allemang & Hendler, 2008, p. 247).

Research Parameters

These research parameters define the scope and strategy applied to this literature review. The primary research questions are defined in this section in addition to the approach to searching for sources. Likewise, the evaluation criteria, the analysis plan, and writing plan are specified in this section.

Research Questions

Main question. Ontological models, as an approach for managing enterprise information, are already in active use in industries including pharmaceuticals, oil and gas, and intelligence and defense (Feigenbaum, et al., 2007). How are these technologies being applied and what are the most common models and approaches being used to represent tacit knowledge in the enterprise?

Sub-questions.

- What are the ways that semantics and ontology are applied to tacit knowledge representation? Antoniou and van Harmelen (2004) state that the standards have been developed to create ontologies to represent dynamic enterprise knowledge models.
- What types of models are in use? Finding the right information for decision-making is problematic in many organizations (Blumberg & Atre, 2003). Enterprise ontologies provide a structure for contextualizing information and making it easier to find (Stewart, 2008).
- What are the perceived advantages to using ontologies for tacit knowledge management? Jonas and Sokol (2009) conclude that knowledge models,

capable of representing how a data element relates to other data, are critical to capturing and contextualizing information and making it valuable to decision support.

Search Strategy Report

Search terms. The following terms and vocabularies are used to assess various sources and to find suitable material for the literature review. This list of terms is derived from high quality sources and tuned to improve result accuracy through iterative analysis of search results. The terms include:

- ontology
- knowledge model
- semantic technology
- knowledge models
- knowledge management

The following modifiers are in conjunction with these general terms to focus the search results:

- enterprise (used to modify all terms)
- tacit (used to modify the terms knowledge and models)

Report of Search Findings

Table 1 shows the results of various exploratory queries. The search sites and queries are expanded to find the best quality results in the peer-reviewed sources.

Search Site	Terms	Results	Quality
University of Oregon Libraries Worldwide http://uolibraries.worldcat.org/	Enterprise + ontology	1,123	Good
	tacit + knowledge model	1,335	Fair
	semantic technology	9,212	Fair (too broad)
	"knowledge model"	867	Fair
	knowledge management + tacit	1,263	Good
Google Scholar	Enterprise + ontology	102,000	Good
	tacit + knowledge model	129,000	Good
	semantic technology	854,000	Fair
	tacit + knowledge models	130,000	Good
	tacit + knowledge management	99,400	Fair
IEEE Digital Library	Enterprise + ontology	428	Fair
	tacit + knowledge model	5	Poor
	semantic technology	132	Good
	knowledge model	430	Good
	knowledge management + tacit	144	Good
Google	Enterprise + ontology	1,470,000	Fair
	tacit + knowledge model	5,560,000	Poor
	semantic technology	2,690,000	Fair
	tacit + knowledge models	3,660,000	Good
	tacit + knowledge management	632,000	Good
ACM Digital Library	Enterprise + ontology	1,326	Good
	tacit + knowledge	953	Good
	semantic technology	25,759	Fair (too

			broad)
	knowledge model	58,979	Good
	knowledge management +tacit	687	Good
EBESCO Academic Search	Enterprise + ontology	107	Good
	tacit + knowledge	736	Good
	semantic technology	2,169	Fair
	knowledge model	121	Good
	knowledge management +tacit	139	Good

Table 1 Search Results

Literature Resources. A large body of academic and international standards organization publications discussing the semantic web and ontologies is available. In general, the highest quality search results come from the Association for Computing Machinery (ACM) Digital Library, the Institute of Electrical and Electronics Engineers (IEEE) site, Springer Publications, and the EBESCO Academic Search site. These search sources are technology oriented and therefore eliminate many of the results for semantics that are more geared to the philosophical study of ontology. The bulk of the selected resources are published journal papers and conference submissions, however, books about the semantic web and knowledge modeling are also applied to this research.

Ontology Resources. Ontologies are generally published in XML syntax or other machine-readable formats. Ontologies included in the inventory assembled for this research come from a variety of search results and distribution websites including ontology exchanges such as SemWebCentral (SemWebCentral, 2009) and tool sites such as the Stanford University Protégé project (Protégé, 2009), and the Massachusetts Institute of Technology (MIT) SIMILE project.

Evaluation Criteria

Sources that meet the standards of authority, objectivity, quality, currency, and relevance are considered for this literature review research (Bell & Smith, 2009). Source authority is assessed by examining the author's identity, credentials, institution, and the publishing source of the article or paper. Objectivity is evaluated by looking at the goals of the author and the publication, checking for bias and affiliation, and ensuring that the work is well researched and citations are used. The relative quality of the source is evaluated by looking at the organization of the work and the completeness of the research. Currency is determined by the publication date and finding that it is in the defined period for this study. Relevance is determined by evaluating whether the work supports the defined topic—tacit knowledge ontologies. Each source is cataloged to indicate the element of the research question or sub-question it supports, and they are added to an electronic annotated bibliography document for tracking purposes.

Data Analysis Plan

The key evaluation methodology of a literature review is a conceptual analysis across a selected body of published works (Busch et al., 2005). The process of conceptual analysis, as described by Busch et al. (2005), requires the identification of a set of specific terms that are representative of the research question. These terms are used to analyze sources and determine occurrence, frequency, or both for the concepts in the literature. Likewise, a set of rules for handling generalization, implicit term meaning, and usage is developed to confirm that the content coding is applied in a consistent manner (Busch et al., 2005). This research focuses on identifying the occurrence of specific terms in the selected works and does not include a quantitative analysis based on term frequency. For analysis, the selected terms are described in an ontology that represents concepts as classes and the relationships between the classes to capture term generalization and groupings. These groupings are presented in Appendix A.

A preliminary set of coding terms, indicative of tacit knowledge management using ontologies, is derived from academic conference papers, the W3C Semantic Web site, and reports in peer-reviewed publications. These terms provide a representative view of the key considerations and dominant modeling approaches used in the management of tacit knowledge. The eight-step conceptual analysis process, described by Busch et al. (2005), is applied to evaluate, organize, and synthesize the selected literature (Leedy & Ormrod, 2005). The following eight analysis considerations are addressed to identify relevant themes in the literature:

1. ***Level of analysis.*** The level of term analysis includes both individual terms as well as groups of terms in the literature sources. Grouping terms supports the research focus on tacit knowledge and includes cataloging sets of words such as "tacit knowledge" and "knowledge management ontology" as well as single term variations of these concepts.
2. ***Number of concepts.*** The number of concepts used to analyze the literature is limited to a set of approximately six specific terms applied together and individually. These terms are:
    - Knowledge Discovery

- Knowledge Model
- Knowledge Management
- Knowledge Representation
- Tacit Knowledge
- Ontology

3. ***Coding approach.*** Existence of terms is coded for each document; the frequency of occurrences is not an analysis consideration.
4. ***Level of generalization.*** Term generalization is represented in the term ontology. The level of generalization in the analysis ontology allows for the equivalent treatment of similar terms such as "knowledge management", "knowledge modeling" and "knowledge engineering". Likewise, "semantic models", "ontologies", "ontological model" and "ontology" are similarly treated as the same for the purpose of coding literature sources.
5. ***Rules for content coding.*** The ontology of coding terms described above is used for data analysis and it establishes the rules for terms through the class and sub-class structures. Following this model ensures that classification of terms is applied consistently across the selected literature sources.
6. ***Irrelevant results***. Results that are irrelevant and inconsequential to the analysis are omitted.
7. ***Coding literature.*** The selected sources are encoded manually and with the assistance of semantic modeling tools and full text search that allow

the researcher to locate and extract the terms in the documents. The results of the document coding are recorded with indexes back to the source documents. The clustering of documents and concepts is presented in a semantic mind map format to illustrate the concentrations of concepts relative to the coded sources. This clustering is visualized using the Thetus Corporation Savanna semantic analysis tool. A report of the coding process is presented in Appendix A.

8. ***Results analysis.*** Analysis of the results ties the term presence results to the qualitative themes established in the research focus as described below in the Writing Plan.

Writing Plan

The nature of ontologies and knowledge management is that there is no single prescribed approach for developing ontologies (W3C, n.d.). However, there are patterns and methodologies that have been established to develop and manage knowledge in the enterprise using ontologies (Stewart, 2008). This writing plan presents these approaches and the dominant patterns such as upper level ontologies described in the literature. These patterns are derived from examination of the results of the data analysis process, and are presented in three key areas focus areas and are recorded in the following sections:

1. Tacit knowledge representation and management using ontologies.
    a. Upper, mid and lower level tacit knowledge models
    b. Approaches to tacit knowledge management using ontology.

2. Inventory of the dominant models and approaches
    a. Review of ontology use considerations.
3. Advantages and disadvantages.
    a. Disadvantages and barriers to adoption.
    b. Advantages of ontology for tacit knowledge management.

In summary, this writing plan encompasses the key considerations and information needed to understand the role of ontology in tacit knowledge representation and management.

Annotated Bibliography

The sources annotated here provide a view of the published resources considered to be key to address the stated research questions related to tacit knowledge. Each resource provides a facet of information presented in this study, relevant to tacit knowledge management and the use of ontologies.

Chen, A. N. K., & Edgington, T. M. (2005). Assessing value in organizational knowledge creation: Considerations for knowledge workers. *MIS Quarterly*, *29*(2), 279-309.

Abstract. To maintain competitive advantage, a firm's investment decisions related to knowledge creation are likely to be strategic in nature. However, strategic investments usually have an element of risk linked to uncertain and deferred investment benefits. To date, such investment decisions relating to knowledge workers have not been extensively researched. In this paper, we explore the following research question: How do we strategically assess knowledge creation over time giving consideration to complex decision criteria in order to improve organizational value? We develop a model based on economic and organization theory for assessing organizational value with regard to knowledge creation investments. Our model prototype provides managers with a learning tool relating to the timing and selection of knowledge creation investments. Our own use of the tool in simulation experiments yielded several insights, which suggest that the decisions typically made by managers may dilute

knowledge creation investments. Our results demonstrate that the organizational benefit of knowledge creation processes should be well aligned with near-term tasks. Under instances of high knowledge depreciation, however, it is unlikely that individual workers can optimize knowledge creation process decisions without organizational involvement in matching skills to task complexities. The organizational benefits of consistent and frequent knowledge creation process participation increase over time as the match of skills and task complexities improve.

Comments. This paper provides an in depth view of knowledge modeling and management. The authors go into detail on the considerations of knowledge value, depreciation and assert that knowledge creation is essential to business survival.

- Source Authority: Excellent. Both researchers are post-graduates in fields relevant to the subject.
- Objectivity: Excellent. No bias and a very scientific approach to quantifying the value of knowledge in the enterprise.
- Currency: Good. This study is dated 2005 and has very relevant topics for IT managers and knowledge curators.
- Relevance: Good for establishing significance, the authors are focused on assessing knowledge value and management for the enterprise. Not specific to ontology or semantic models.

- Application to this study: This paper addresses the question of significance of knowledge management and the value it has to the enterprise.

Cai, G. (2007). Contextualization of geospatial database semantics for human–GIS interaction. *GeoInformatica*, *11*(2), 217-237.

Abstract. Human interactions with geographical information are contextualized by problem-solving activities which endow meaning to geospatial data and processing. However, existing spatial data models have not taken this aspect of semantics into account. This paper extends spatial data semantics to include not only the contents and schemas, but also the contexts of their use. We specify such a semantic model in terms of three related components: activity-centric context representation, contextualized ontology space, and context mediated semantic exchange. Contextualization of spatial data semantics allows the same underlying data to take multiple semantic forms, and disambiguate spatial concepts based on localized contexts. We demonstrate how such a semantic model supports contextualized interpretation of vague spatial concepts during human–GIS interactions. We employ conversational dialogue as the mechanism to perform collaborative diagnosis of context and to coordinate sharing of meaning across agents and data sources.

Comments. Cai provides good examples of integrating ontologies with existing geographic information systems.

- Source Authority: Good. A known source of geospatially oriented information.
- Credentials: Good. Cai is a published researcher and associate professor at Penn State University.
- Objectivity: Good. Comes at ontology from the perspective of GIS but is balanced and realistic with his assessments.
- Currency: Good. This study is dated 2007.
- Relevance: Excellent. This paper speaks to the application of ontology in the context of geospatial data and knowledge management.
- Application to this study: This paper addresses the sub-question of how ontologies are applied to knowledge representation and enterprise data.

Cao, L. Liu, J. & Zhang, C. (2006). Ontology-based integration of business intelligence. *Web Intelligence & Agent Systems*, *4*(3), pp. 313-325.

Abstract. The integration of Business Intelligence (BI) has been taken by business decision-makers as an effective means to enhance enterprise "soft power" and added value in the reconstruction and revolution of traditional industries. The existing solutions based on structural integration are to pack together data warehouse (DW), OLAP, data mining (DM) and reporting systems from different vendors. BI system users are finally delivered a reporting system in which reports, data models, dimensions and measures are predefined by system designers. As a result of a survey in the US, 85% of DW projects based on the above solutions failed to meet their intended objectives. In this paper, we summarize our investigation on the integration of BI on the basis of semantic integration and structural interaction. Ontology-based integration of BI is discussed for semantic interoperability in integrating DW, OLAP and DM. A hybrid ontological structure is introduced which includes conceptual view, analytical view and physical view. These views are matched with user interfaces, DW and enterprise information systems, respectively. Relevant ontological engineering techniques are developed for ontology namespace, semantic relationships, and ontological transformation, mapping and query in this ontological space. The approach is promising for business-oriented, adaptive and automatic integration of BI in the real world. Operational decision-making experiments within a telecom company have demonstrated that a BI system utilizing the proposed approach is more flexible.

Comments. Article covers domain specific knowledge management area and covers knowledge representation and sharing.

- Source Authority: Good. Peer-reviewed publication.
- Credentials: All the authors come from mainstream universities and have multiple other relevant publications.
- Objectivity: Good. The authors support the study with over 25 citations.
- Currency: Good. Published in 2006.

- Relevance: Excellent. Provides examples of ontologies in use and contrasts theses ontologies with other business intelligence approaches.
- Application to this study: Provides ontologies for the inventory assembled in this research and addresses sub-questions dealing with business intelligence and decision support.

Choi, B., Edgington, T. M., Henson, K., Raghu, T., & Vinze, A. (2004). Adopting ontology to facilitate knowledge sharing. *Communications of the ACM*, *47*(11), 85-90.

Abstract. The article discusses Ontology-enabled knowledge management experiences derived from a domain ontology development project at Intel Corp. Knowledge management success is enhanced when applying a knowledge lens in an ontological manner. The concept of ontology is embraced by non-IS practitioners when the focus of the ontological development emphasizes content, independently of programmatic formalisms. Ontology development is enhanced by starting with a specific knowledge perspective, which we term the knowledge lens. From this knowledge lens, control vocabulary is extracted and, by adopting a top-down and bottom-up perspective, the conceptual model is developed by applying relationships, attributes and axioms. Knowledge management requires a continuous system of interaction and iteration with the knowledge owners to validate existing knowledge. Such iteration also allows for additional knowledge to be contributed as the knowledge lens becomes more apparent to all participants. The resulting ontology becomes useful as a foundation for inter-organizational communication and ontology expansion and also for training and intra-organizational value.

Comments. Provides an example of an applied ontology in an enterprise or agency domain space. Good for inventory of models and relevance.

- Source Authority: Excellent. The ACM publications are well respected in industry and academia and well reviewed by peer groups.
- Credentials: Excellent. This paper is written by a combination of authors from academia and enterprise. All the authors come from mainstream academic institutions or Intel Corporation.
- Objectivity: Excellent. The diversity of the authors across several institutions and the content of the work suggest no bias that would influence inclusion of this work.
- Currency: Good. This study is dated 2004, all the principles of ontology development and management have not changed significantly since publication.
- Relevance: Excellent. This paper speaks to the application of ontology in the context of knowledge management.
- Application to this study: This paper addresses the sub-question of how ontologies are applied to knowledge representation as well as

the primary question of applying semantic models to knowledge management.

El-Diraby, T. E., & Kashif, K. F. (2005). Distributed ontology architecture for knowledge management in highway construction. *Journal of Construction Engineering & Management*, *131*(5), 591-603.

Abstract. Recent Resource, Event, Agent (REA) research has focused on defining and theoretically justifying the ontology's contents. Here, we elaborate on more practical issues related to REA. First, we classify REA and its applications using ontology classification schemes and application frameworks. This analysis clarifies REA's application potential but also reveals weaknesses that may impede its operationalization. Next, we propose a new REA ontology specification that uses a Unified Modeling Language (UML) profile for graphically representing ontologies. This new specification is more complete and precise than previously available specifications, without compromising understandability. It can easily be transformed into a machine-readable representation for automatic processing, which is a prerequisite for the successful application of REA in business modeling, software engineering, knowledge representation, and interoperability creation. The paper ends with a proof of concept application in which a formal Ontology Web Language (OWL) specification of REA is fed into the Protégé knowledge representation tool and subsequently used for the development of an enterprise schema.

Comments. Provides an example of an applied ontology in an enterprise or agency domain space. Good for inventory of models and relevance.

- Source Authority: Good. Appears in a mainstream publication that is peer-reviewed.
- Credentials: Good. Authors all come from a major university and have other publications in peer-reviewed venues.
- Objectivity: Excellent. The authors discuss strengths and weaknesses of the ontological approach.
- Currency: Good. This study is dated 2008 and deals with current and relevant information.
- Relevance: Excellent. This paper is the product of applied research into ontology and knowledge representation in a specific domain.
- Application to this study: This paper addresses the sub-question of how ontologies are applied to knowledge representation and provides ontologies for inclusion in the ontology inventory developed through this research.

El-Diraby, T., & Zhang, J. (2006). A semantic framework to support corporate memory management in building construction. *Automation in Construction*, *15*(4), 504-521.

Abstract. Corporate memory tools represent one way organizations can document, retrieve and utilize best practice and lessons learned in enhancing their performance. Using semantic systems in building these tools (along with database and/or AI-based systems) allows for more efficient representation of tacit knowledge. Such systems are based on a common ontology of the subject domain, where entities (such as actors, processes and products) are interlinked to represent the essence of the knowledge in the domain. The paper presents a taxonomy for building construction. The taxonomy includes 6000 concepts and was developed using OWL. It maps to existing classification systems to assure better coverage. The taxonomy is the first attempt to present building construction knowledge in a semantic way. It also represents the foundations developing ontology-based corporate memory systems. To demonstrate the role and contribution of the proposed taxonomy a prototypical ontology for building construction was developed. Furthermore, a framework for agent-based system for supporting semi-automatic generation of reports such as lessons learned, work forms, and meeting agendas. Such agents allow organizations to capture and document its knowledge (in a taxonomy-complaint format) and to feed back post-project knowledge into new ones through access to lessons learned and through pre-defined meeting agendas. Access to these reports is done through semantic search according to the proposed taxonomy. Future research will develop a formal ontology and further develop the framework and implement it in actual organizations.

Comments. Second work form El-Diraby, has a good real world case study and deals specifically with tacit knowledge.

- Source Authority: Good. Appears in a mainstream publication that is peer-reviewed.
- Credentials: Good. Comes from the University of Toronto—well respected for engineering.
- Objectivity: Excellent. The authors discuss strengths and weaknesses of the ontological approach.
- Currency: Good. This study is dated 2005.
- Relevance: Excellent. This paper is the product of applied research into ontology and knowledge representation in a specific domain.
- Application to this study: This paper addresses the sub-question of how ontologies are applied to knowledge representation and provides ontologies for inclusion in the ontology inventory developed through this research.

Gruber, T. (2009). What is an ontology? *Encyclopedia of Database Systems*. Retrieved from http://tomgruber.org/writing/ontology-definition-2007.htm

Abstract. In the context of computer and information sciences, an ontology defines a set of representational primitives with which to model a domain of knowledge or discourse. The representational primitives are typically classes (or sets), attributes (or properties), and relationships (or relations among class members). The definitions of the representational primitives include information about their meaning and constraints on their logically consistent application. In the context of database systems, ontology can be viewed as a level of abstraction of data models, analogous to hierarchical and relational models, but intended for modeling knowledge about individuals, their attributes, and their relationships to other individuals. Ontologies are typically specified in languages that allow abstraction away from data structures and implementation strategies; in practice, the languages of ontologies are closer in expressive power to first-order logic than languages used to model databases. For this reason, ontologies are said to be at the "semantic" level, whereas database schema are models of data at the "logical" or "physical" level. Due to their independence from lower level data models, ontologies are used for integrating heterogeneous databases, enabling interoperability among disparate systems, and specifying interfaces to independent, knowledge-based services. In the technology stack of the Semantic Web standards, ontologies are called out as an explicit layer. There are now standard languages and a variety of commercial and open source tools for creating and working with ontologies.

Comments. Provides example of applied ontology for the inventory in a field that has led ontology application and semantic web adoption.

- Source Authority: Good. Gruber is a recognized figure in the semantics and ontologies community.
- Credentials: Excellent. Leading institution in the area of knowledge management and ontologies.
- Objectivity: Good. No indication of bias.

- Currency: Good. This article provides good context and base definition.
- Relevance: Good. Provides definitions of key concepts, however, this specific work does not cover any in great depth.
- Application to this study: Provides information on the specifics of ontologies and the technology that supports their use.

Jonas, J., & Sokol, L. (2009). Data finds data. Beautiful data. Sebastopol, CA: O'Reilly Media.

Abstract. An organization can only be as smart as the sum of its perceptions. These perceptions come in the form of observations—observations collected across the various enterprise systems, such as customer enrollment systems, financial accounting systems, and payroll systems. With each new transaction an organization learns something. It is at the moment something is learned that there exists an opportunity, in fact an obligation, to make some sense of what this new piece of data means and respond appropriately. For example, does the address change on the customer record now reveal that this customer is connected to one of your top 50 customers? If an organization cannot evaluate how new data points relate to its historical data holding in real time, the organization will miss opportunities for action.

Comments. This book chapter provides context and relevance on why models are needed to gain additional value and understanding from data.

- Source Authority: Excellent. O'Reily is a respected publisher of technical books and materials.
- Credentials: Good. Jonas is a recognized thought-leader in the area of modeling and knowledge extraction.
- Objectivity: Unknown. The authors do not appear to have any bias, however, the work is not supported with citations—the format of the publication is not oriented around citations.
- Currency: Excellent. Published in 2008.
- Relevance: Excellent. This paper provides supporting information and insight that is valuable for relevance and significance of this research.
- Application to this study: Jonas and Sokol provide insight in to the sub-question of what types of decisions can be made with ontological models and the advantages of a modeling approach.

Kim, H., Fillies, C., Smith, B., & Wikarski, D. (2002). Visualizing a dynamic knowledge map using semantic web technology. Engineering and deployment of cooperative information systems. EDCIS 2002 Lecture Note in Computer Science, pp. 130-140. Berlin: Springer.

Abstract. Visual knowledge maps are being used to improve the communication processes within global organizations. Knowledge maps are graphical presentations of ontological knowledge as well as of business processes. Especially for enterprises working in a multi-cultural space the explicit formalization of knowledge and business rules using graphical models seems to be a very promising approach in order to improve discussion and learning processes. Publishing and automatic inference or search techniques are becoming available due to the latest standards for Semantic Web worked out by W3C. This article gives an impression how to create end user interfaces for the ”Corporate Knowledge Base” using MS Office and Visio with the modeling tool SemTalk. Several problems on capturing and maintaining large-scale knowledge bases are discussed. Specific attention is given to the problem of weighting and association of information from orthogonal ontologies, which arises while using the same concepts in different graphical scenarios.

Comments. Deals specifically with the user experience and the tacit knowledge problem.

- Source Authority: Excellent. Published by Springer.
- Credentials: Good. All the authors come from universities around the world.
- Objectivity: Good. The authors support their work with citations from recognized sources
- Currency: Fair. Published in 2002.
- Relevance: Excellent. Provides examples of ontologies integrated into enterprise tools.
- Application to this study: Provides examples of how ontologies can be applied to existing tools in the workplace and capture tacit knowledge.

Kitamura, Y., & Mizoguchi, R. (2003). An ontological schema for sharing conceptual engineering knowledge. In: *Proceedings of the International Workshop on Semantic Web Foundations and Application Technologies* (pp. 25–28). Nara, Japan.

Abstract. In the engineering design, engineers have been suffering the difficulty in sharing conceptual engineering knowledge about functionality representing design rationales because of lack of rich common vocabulary for functionality. In order to promote sharing of such knowledge, we have developed an ontological framework for its modeling including layered ontologies, which provides rich concepts for describing consistent and reusable knowledge. This article summarizes the framework and the successful deployment in a company. In the context of the semantic web, our framework can be viewed as a metadata schema of documents about engineering devices. This article also discusses metadata from the viewpoint of functionality as a usage of our ontologies in the semantic web.

Comments. Kitamura and Mizoguchi provide an overview and details into the application of various ontologies in the area of engineering including a device ontology and models for mechanical systems.

- Source Authority: Excellent. Published in a mainstream conference proceeding.
- Credentials: Good. Both authors come from Osaka University.

- Objectivity: Good. The authors support their work with a large number of citations.
- Currency: Fair. Published in 2003.
- Relevance: Excellent. Provides examples of ontologies to represent knowledge in the context of engineering.
- Application to this study: Provides ontologies for the inventory assembled in this research and addresses sub-questions dealing with information contextualization.

Magro, D., & Goy, A. (2008). The business knowledge for customer relationship management: an ontological perspective. In *Proceedings of the first international workshop on Ontology-supported business intelligence* (pp. 1-6). Karlsruhe, Germany: ACM.

Abstract. This paper presents some results of an ongoing ontological analysis of the CRM field. In particular, it describes a fragment of O-CREAM, an ontology for CRM based on DOLCE and on other three DOLCE-based modules, i.e. DnS (for the representation of roles and for handling reification), OIO (for modeling information objects, the key concept for representing business knowledge), and OoP (whose notions are used to express the derivation of new business knowledge). Since the business knowledge plays a major role within CRM activities, a significant fragment of O-CREAM is devoted to the formal characterization of notions related to business knowledge; such a fragment is the focus of this paper.

Comments. This paper includes several good examples of models for the ontology inventory. Credible source from an institution that has done a lot of work in the domain area.

- Source Authority: Good. Peer-reviewed publication at a conference in a leading institution for semantics and ontology.
- Credentials: All the authors come from mainstream universities and have multiple other relevant publications.
- Objectivity: Good. The authors support their work with a large number of citations.
- Currency: Excellent. Published in 2008.
- Relevance: Excellent. Provides examples of ontologies applied to customer relationship management (CRM).
- Application to this study: This paper references several ontologies for the model inventory described in this research. Likewise the authors describe the type of CRM questions and decision making that can be supported through these models—a key sub-question for this study.

McGuinness, D. L., & Noy, N. F. (2001). Ontology development 101: A guide to creating your first ontology.

Abstract. Ontologies have become core components of many large applications yet the training material has not kept pace with the growing interest. This paper addresses the issues of why one would build an ontology and presents a methodology for creating ontologies based on declarative knowledge representation systems. It leverages the two authors experiences building and maintaining ontologies in a number of ontology environments including Protege-2000, Ontolingua, and Chimaera. It presents the methodology by example utilizing a tutorial wines knowledge base example. While it is aimed at users of frame-based systems, it can be useful for building ontologies in any object-centered system.

Comments. This resource provides excellent base information on model building and ontology. The paper comes from one of the most used open source projects for authoring OWL ontologies.

- Source Authority: Excellent. The Protégé project is a central project in the area of ontology authoring and development.
- Credentials: Excellent. McGuinness is the acting director of the Knowledge Systems, Artificial Intelligence Laboratory at Stanford University.
- Objectivity: Good. The authors are clearly predisposed to an ontology-based approach.
- Currency: Fair. Published in 2001, however, provides base concepts and definitions.
- Relevance: Good. Defines the premise and approach for model development.
- Application to this study: Addresses the area of model types and the perceived advantages of the ontology approach.

Nemrava, J., Kliegr, T., Svátek, V., Ralbovsky, M., Splichal, J., Vejlupek, T., et al. (2008). Semantic annotation and linking of competitive intelligence reports for business clusters. In *Proceedings of the first international workshop on ontology-supported business intelligence* (pp. 1-5). Karlsruhe, Germany: ACM New York.

Abstract. Competitive intelligence (CI) is a sub-discipline of business intelligence that supports the decision makers in understanding the competitive environment by means of textual reports prepared based on public resources. CI is particularly demanding in the context of larger business clusters. We report on a long-term project featuring large-scale manual semantic annotation of CI reports with respect to business clusters in several industries. The underlying ontologies are the result of collaborative editing by multiple student teams. The results of annotation are finally merged into CI maps that allow easy access to both the original documents and the knowledge structures.

Comments. Examples of semantic annotations relevant to tacit knowledge.

- Source Authority: Good. Peer-reviewed publication.
- Credentials: Good. Multiple publications.
- Objectivity: Good.
- Currency: Good. Published in 2008.
- Relevance: Good. Ontology development approach and advantages are discussed.
- Application to this study: Provides examples of annotation approaches.

Qin, J., & Paling, S. (2001). Converting a controlled vocabulary into an ontology: the case of GEM. *Information Research*, *6*(2).

Abstract. The prevalence of digital information raised issues regarding the suitability of conventional library tools for organizing information. The multi-dimensionality of digital resources requires a more versatile and flexible representation to accommodate intelligent information representation and retrieval. Ontologies are used as a solution to such issues in many application domains, mainly due to their ability explicitly to specify the semantics and relations and to express them in a computer understandable language. Conventional knowledge organization tools such as classifications and thesauri resemble ontologies in a way that they define concepts and relationships in a systematic manner, but they are less expressive than ontologies when it comes to machine language. This paper used the controlled vocabulary at the Gateway to Educational Materials (GEM) as an example to address the issues in representing digital resources. The theoretical and methodological framework in this paper serves as the rationale and guideline for converting the GEM controlled vocabulary into an ontology. Compared to the original semantic model of GEM controlled vocabulary, the major difference between the two models lies in the values added through deeper semantics in describing digital objects, both conceptually and relationally.

Comments. Specific information on the GEM ontology. Good for inventory information and inclusion for knowledge management approaches.

- Source Authority: Good. Peer-reviewed publication.

- Credentials: Good. Mainstream university and multiple publications.
- Objectivity: Good.
- Currency: Fair. Published in 2001.
- Relevance: Good. Ontology development approach and advantages are discussed.
- Application to this study: Provides inventory examples presented in the outcome of this study and addresses the question of the types of models in use.

Small, C., & Sage, A. (2006). *Knowledge management and knowledge sharing: A review*. Information Knowledge Systems Management 5 (2005/2006) 153–169 IOS Press.

Abstract. Knowledge Management is one of the major issues in the management of contemporary organizations and enterprises. A review of the knowledge management (KM) literature reveals many different definitions and perspectives on knowledge and knowledge management. Here, we provide an overview of some of this discourse along with descriptions of KM models and frameworks that can be used to guide KM initiatives. Knowledge sharing, critical to creation of knowledge and organizational performance, is often addressed under the umbrella of KM. We provide a survey of recent literature and progress in both of these areas.

Comments. Excellent literature review of related tools and approaches. MITRE is a well-respected research organization.

- Source Authority: Good. Peer-reviewed and industry tested.
- Credentials: Excellent. Mitre is a well respected organization.
- Objectivity: Good. Mitre exists to provide clear and unbiased advice to government organizations.
- Currency: Good. Published in 2006.
- Relevance: Good. Ontology development approach and advantages are discussed as well as the other publications on the topic.
- Application to this study: Provides inventory examples and addresses the question of the types of models in use.

Sowa, J. (2005). Knowledge soup. *Research Trends in Science, Technology and Mathematics Education* (pp.55-90). Mumbai: Homi Bhabha Centre.

Abstract. People have a natural desire to organize, classify, label, and define the things, events, and patterns of their daily lives. But their best-laid plans are overwhelmed by the inevitable change, growth, innovation, progress, evolution, diversity, and entropy. These rapid changes, which create difficulties for people, are far more disruptive for the fragile databases and knowledge bases in computer systems. The term *knowledge soup* better characterizes the fluid, dynamically changing nature of the information that people learn, reason about, act upon, and communicate. This article addresses the complexity of the knowledge soup, the problems it poses for computer systems, and the methods for managing it. The most important requirement for any intelligent system is flexibility in accommodating and making sense of the knowledge soup.

Comments.

- Source Authority: Good. Peer-reviewed publication.
- Credentials: Excellent. Sowa is a thought-leader and pioneer in the area of artificial intelligence and knowledge representation.
- Objectivity: Good.
- Currency: Good. Published in 2005.
- Relevance: Good background on the challenges of knowledge representation and semantics.
- Application to this study: Examples of the types of questions that can be answered and the models currently in use.

Umar, A., & Zordan, A. (2009). Enterprise ontologies for planning and integration of business: A pragmatic approach. *IEEE Transactions on Engineering Management*, *56*(2), 352-371.

Abstract. Enterprise ontologies (EOs), introduced in the mid 1990s, were expected to have a significant impact on enterprise computing, especially integration. However, despite a great deal of academic research on EOs, the actual use of EOs in real-life integration and planning projects is almost nonexistent. This paper describes an approach to build and use EOs for information system (IS) planning and integration projects with particular focus on

real-life eBusiness applications. The approach is based on firsthand practical insights gained through construction and use of an IS planning and integration environment that needs to capture business processes, enterprise applications, integration technologies, and computer-communication platforms. The planning model with the aforementioned information is based on an EO and is populated by a set of intelligent advisors while they guide the users through various stages of the planning process. This ontology has been used to support over 40 real-life business scenarios in the telecom, manufacturing, financial services, retail, healthcare, and insurance industries. The practical contribution of this paper is that it connects ontologies to the practice of IS planning and integration, links ontologies to decisions such as enterprise application selection, and provides tools for automatically creating and maintaining ontology repositories.

Comments. Provides an applied ontology example that has been used in several industries. Models for process and knowledge are described.

- Source Authority: Excellent. IEEE is a respected publisher.
- Credentials: Good. Mainstream university and multiple publications.
- Objectivity: Good.
- Currency: Excellent. Published in 2009.
- Relevance: Excellent. Ontology development approach and advantages are discussed.
- Application to this study: Provides inventory examples and addresses the core question of how models are being used.

Review of Literature

Tacit knowledge, or knowledge that is defined as the thoughts and experiences of an expert performing a task (Antoniou & van Harmelen, 2004), is viewed as an essential and valuable enterprise asset (Choi, et al., 2004). The value of tacit knowledge and the need to manage it effectively is fueled by the growing number of retirements among baby boomers. This trend emphasizes the need to capture the tacit knowledge that workers apply to their day-to-day activities (Toosi, 2005).

The management of this type of knowledge presents technical and process hurdles that require adopting new approaches and technologies. One of the primary challenges is that tacit knowledge, when captured at all, is often in free form or unstructured text rather than well formed database tables and rows. This lack of predictable structure makes query and retrieval difficult (Stewart, 2008). Nevertheless, the rewards for successful management of this type of information are substantial. Furthermore, the value of data to the enterprise increases exponentially if there is an awareness of how it relates to other data (Jonas & Sokol, 2008).

The purpose of this study is to present the critical considerations for tacit knowledge management in three sections: (a) a discussion of the application of ontologies to knowledge representation in the context of enterprise knowledge management approaches, including the types of ontologies that are employed in tacit knowledge representation, (b) an inventory of relevant models, described in the literature, that are currently used to manage tacit data in the enterprise, and (c) a summary of the reported advantages and disadvantages of ontologies for tacit knowledge management.

Uren, et al. (2006) point out that the market for managing enterprise knowledge, specifically unstructured text, is growing rapidly. The literature selected for review in this study examines solutions that focus on building models, either taxonomies or ontologies, to improve the manageability of unstructured text containing tacit knowledge. Feigenbaum et al. (2007) report substantial use of ontologies in large corporate knowledge management systems and explain that the semantic structure "permits workers in different organizations to use their own data language instead of trying to agree industry-wide on one rigid set" (p.93). This observation of the expressive and flexible nature of ontologies emerges as a dominant theme around the semantic web and ontology related literature reviewed in this study. When considered in the context of company mergers and acquisitions, where communities of experts are rolled up into a single organization, the potential of ontologies as a tool to manage knowledge and codify semantics is clear.

El-Diraby and Zhang (2006) examine the prospect of corporate knowledge management and conclude, "the true challenge in intensely competitive work environments is the representation of less tangible aspects of the organization, such as individual and group know-how, accumulated expertise, professional experience, and related heuristics" (p.505). Umar and Zordan (2009) offer a pragmatic approach to realizing the benefits of ontologies in the context of knowledge management and assert that ontologies are a valuable tool for enterprise information integration and services.

However, the bulk of the literature on the topic of ontologies and knowledge management focuses on using these technologies for application-to-application integration and automated reasoning, and less so on user defined tacit knowledge. Uren, et al. (2006) suggest that there is a need for better user interface and user interaction models to facilitate human participation in many applications. Jonas and Sokol (2008) discuss the concept of data sensors to capture data and observations—in the case of tacit knowledge, the human acts as the sensor.

Section One: Types of Ontologies Employed for Tacit Knowledge Representation in Support of Enterprise Tacit Knowledge Management Systems

The development of controlled vocabularies and taxonomies has been an enterprise knowledge management activity since the mid 1990s (Umar & Zordan, 2009), however, it was not until after 2001 that standards such as Resource Description Framework (RDF) and Web Ontology Language (OWL) were finalized by the W3C (W3C, n.d.). Development of ontologies often begins with creating enterprise taxonomies or controlled vocabularies to manage enterprise data and improve search and retrieval success (Stewart, 2008). Ontologies that are based on OWL extend the benefits of a well-designed taxonomy by providing a descriptive and a logical representation. The descriptive component of an ontology provides a human readable description of what something is, and what it means. McGuinness and Noy (2001) use the example of an ontology describing wines—this example ontology consists of classes or categories that describe wine types and wine makers. The names of the classes are defined using natural language making it possible for a user to discern meaning from the class hierarchy. The logic aspect of an OWL ontology makes it possible for software applications to draw inferences and find relationships across data described by the ontology. For example, classes in an ontology are further defined by axioms and semantic relationships that allow "natural language to be presented in an unambiguous form to computers" (El-Diraby & Kashif, 2005, p. 591). In the case of the wine ontology (McGuiness & Noy, 2001) the nature of a wine and relationships to other wines can be computed using the logic in the ontology. This is a very simple example of how classes and relationships are used to both classify and relate knowledge about a particular subject area. In practice, the level of inference and automated discovery supported by OWL is far broader, however, the basic concepts of description and logic are the same.

Representing tacit knowledge. There are several different approaches to developing the necessary classes, axioms and relationships needed to represent tacit knowledge. In fact, McGuinness and Noy (2001) go as far as to say that the same knowledge can be modeled many different ways and there is no definitive single answer for how a domain can be modeled. Choi et al. (2004) find that ontology development is similar to iterative software development, including a design phase, development phase, and an iterative feedback and refinement loop. The flexibility and desire for reuse in the ontology realm has spawned the formation of three primary types of ontologies, (a) upper level ontologies that describe general or common concepts, (b) mid level ontologies that extend or map to the upper level concepts to a domain space, and (c) lower level or domain specific ontologies that define the nuances to an organization or domain (Kiryakov, Simov, & Dimitrov 2001). Kiryakov et al. (2001) find that this structural pattern provides the most opportunity for reuse and sharing of ontologies at the upper level, and allows organizations to specialize only where necessary. Similarly, El-Diraby and Zhang (2006) describe the development of a tiered ontology approach to manage corporate memory in the field of construction management, beginning with a taxonomy of root concepts including: Project, Process, Product, Actor, and Resources. These concepts are a good example of a high level ontology; concepts can be subsequently refined and extended to represent more granular concepts, such as “activity-based estimation”, which are then mapped back up to the root concept of “Process” in the upper level model. Figure 1 shows different levels of ontologies and demonstrates that, as the level of generalization decreases and the ontology becomes more specific, the reusability of the model also decreases.

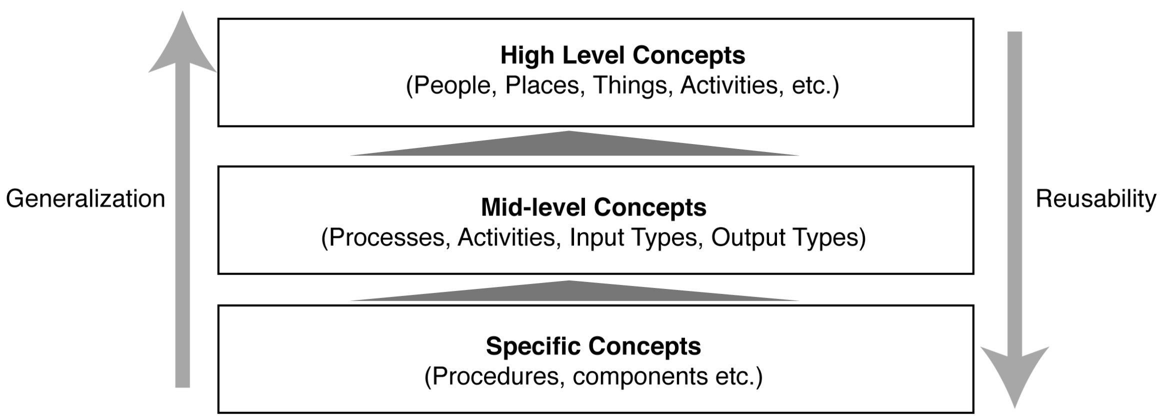

Figure 1. Levels of ontology from specific to general

The value of contextualization of information. Within the context of the development of a knowledge management system, Sage and Small (2005) find that tacit knowledge representations must take into consideration the dynamics of the organization in which the ontologies will be used. They note that tacit knowledge management has several dimensions that must be considered—the information must be contextualized in terms of intent, process, and expertise. Contextualization of information, or providing or the “viewpoint of the knower”, is an essential element of tacit knowledge management and ontologies provide the relationships and logic that can be used to assemble this context (El-Diraby & Zhang, 2006, p.505). Context, and understanding how information relates, is essential to modeling tacit knowledge because tacit knowledge deals with the thoughts and processes in the minds of experts.

Jonas and Sokol (2008) underscore this need for contextualization and understanding relationships in data, indicating that data becomes far more valuable when one understands relationships and context. They contend that context facilitates real-time evaluation of data for relevance and potential suitability of information to a problem or search query. Jonas and Sokol (2008) provide several examples of data relationships that allow the organizations to realize the existence of connections and take action based on these relationships. While many of these examples use automated correlation of information, the human element of understanding a relationship and annotating or amending the model to reflect tacit understanding follows the same path.

Contextualization is a theme that Small and Sage (2005) also explore in their review of knowledge management and knowledge sharing tools. Small and Sage (2005) present a model of data, information, knowledge, and wisdom, in which a contextual filter separates raw data from the information layer. Relating information and creating relationships across information points is one of the key components of an ontology making context an important aspect of the semantic web.

Managing tacit knowledge. Enterprise knowledge bases have traditionally been focused on content management of documents and data (Stewart, 2008), however the real challenge lies with the unstructured text and tacit knowledge (Uren, et al., 2006).

Advances in document repositories and document indexing make content management less of a challenge; the new frontier is to model and determine what the documents mean and how they relate to other knowledge in the enterprise. Choi et al. (2004) note that:

> Many organizations consider knowledge management as the key to sustained competitive advantage; however, they are often unsure how to best define the knowledge unit of interest, struggling to efficiently store relevant knowledge artifacts such that retrieval can be fast and relevant. Practical experience often takes a reactive and incremental approach: groups build reports and other documents and sometime later aggregate them into a file repository; the task of tagging documents for effective retrieval is often an afterthought (p. 85).

Without systems to effectively bridge the gap between the knowledge artifacts (e.g. documents, reports etc.) and the contextual knowledge in the heads of knowledge creators, the value of this information is jeopardized. As noted by Choi et al. (2004), understanding what constitutes a unit of knowledge for a given context is essential to developing a multidimensional knowledge base.

Moreover, Jonas and Sokol (2009) point out that many organizations struggle to manage thousands of databases and document repositories and understand how the content and meaning of the data relate to the goals and tasks of the enterprise. Ontologies provide a way to not only organize the data, but also to abstract the general concepts and relationships into reusable models that go beyond simple document indexing (McGuinness & Noy 2001). Kitamura and Mizoguchi (2004) support this point and state:

> An ontology, which is a system of fundamental concepts (i.e. a system of background knowledge of any knowledge base) explicates the conceptualization of the target world and provides us with a solid foundation on which we can build sharable knowledge bases for wider usability than that of a conventional knowledge base. Knowledge engineering has thus developed into ontological engineering (p. 329).

Section Two: Inventory of Models Currently Used to Manage Tacit Data

Pedrinaci et al. (2008) describe ontologies as a means of modeling the necessary information to solve knowledge intensive tasks in a domain independent manner. Modeling tacit knowledge involves the intersection of general concepts, process concepts, and very specific domain expertise concepts. In practice, ontologies can range from simple taxonomies or RDF descriptions, to more full-fledged conceptual models with classes, axioms, properties, and relationships. Table 2 shows an inventory of ontologies categorized by the domain of the ontology, the level of type, and the source or origination. This inventory is intended to provide a broad set of examples that span several domains and types of ontologies, and not an exhaustive list of all available ontologies.

The ontologies provided in this inventory fall across many domains and levels of ontology (Kiryakov et al., 2001). The inventory is not restricted to any specific ontology language such as OWL, however, to be included in the inventory, a model must have some axioms and relationships to distinguish it from simple taxonomies.

Name	Description	Type	Source
Upper Cyc Ontology	General Upper Ontology	Upper Level	http://www.cyc.com
FOAF	Social Networking and Collaboration	Mid-level	www.foaf-project.org/
SWEET	Environmental Modeling	Upper Level	http://www.planetont.org/
E-Cognos	Construction Management	Lower Level	http://i2c.engineering.utoronto.ca/I2C/Software.aspx
DBpedia	Cross-domain used to describe Wikipedia entries as RDF triples	Upper Level	http://wiki.dbpedia.org/Ontology
OntoWordNet	Collection of 60,000 general terms	Upper Level	http://www.loa-cnr.it/DOLCE.html
SUMO	General Upper Ontology	General	http://www.ontologyportal.org/
PROTON ontology	PROTON is a light-weight upper-level ontology	Upper Level	http://proton.semanticweb.org/
Open Calais	Ontology for entity extraction and tagging	Primarily Upper Level	http://www.opencalais.com/files/owl.opencalais-4.3a.xml
GoodRelations	GoodRelations is a	Domain	http://www.heppnetz.de/pr

	standardized vocabulary for product, price, and company data that can (1) be embedded into existing static and dynamic Web pages and that (2) can be processed by other computers.	ontology for online commerce	ojects/goodrelations/
RDFizer	Tools for converting various data formats into RDF.	Semantic Web Tool	http://simile.mit.edu/wiki/RDFizers
Semantic Bank	Semantic Bank is the server companion of Piggy Bank that lets you persist, share and publish data collected by individuals, groups or communities.	Semantic Web Tool	http://simile.mit.edu/wiki/Semantic_Bank
OWL Time	Ontology for representing temporal concepts.	Upper Level	http://www.w3.org/TR/owl-time/#examples
Mid-Level Ontology (MILO)	Midlevel general concepts.	Mid Level	http://sigmakee.cvs.sourceforge.net/*checkout*/sigm

			akee/KBs/Mid-level-ontology.kif
SIOC	SIOC (Semantically-Interlinked Online Communities) Core Ontology provides the main concepts and properties required to describe information from online communities (e.g., message boards, wikis, weblogs, etc.) on the Semantic Web.	Upper Level	http://rdfs.org/sioc/spec/
Linked Data	Linked Data is about using the Web to connect related data that wasn't previously linked, or using the Web to lower the barriers to linking data currently linked using other methods.	Tools and RDF Ontology	http://linkeddata.org/home

Table 2 Inventory of Tools and Ontologies

Ontologies referenced in the literature, in many cases, extend one of the upper level models described in this inventory. For example, Magro and Goy (2008) describe extending existing upper level ontologies to model a Customer Relationship Management (CRM) solution. Likewise, Qin and Paling (2001), describe extending known upper level models starting with a controlled vocabulary to create an ontology with relationships and axioms. Umar and Zordan (2009) review developing a set of enterprise ontologies in a real-world IT consulting environment with concepts ranging course grained to highly refined specific concepts. It should be noted that this inventory also includes ontology-based tools that are mentioned in the literature. While these are not standalone ontologies, they encapsulate examples and valuable concepts that are relevant to the stated audience for this research—IT professionals addressing tacit knowledge management.

The inventory includes ontologies at several different levels from broad upper level ontologies like the Suggested Upper Merged Ontology (SUMO) which covers high level concepts, to more specialized ontologies, such as SWEET, which is specific to the environmental modeling domain. SUMO is an upper level set of concepts and axioms designed to provide a basis for extension to other models. Figure 1 shows the basic structure of the SUMO ontology; what should be noted is the breadth of the concepts and their general applicability to almost any environment.

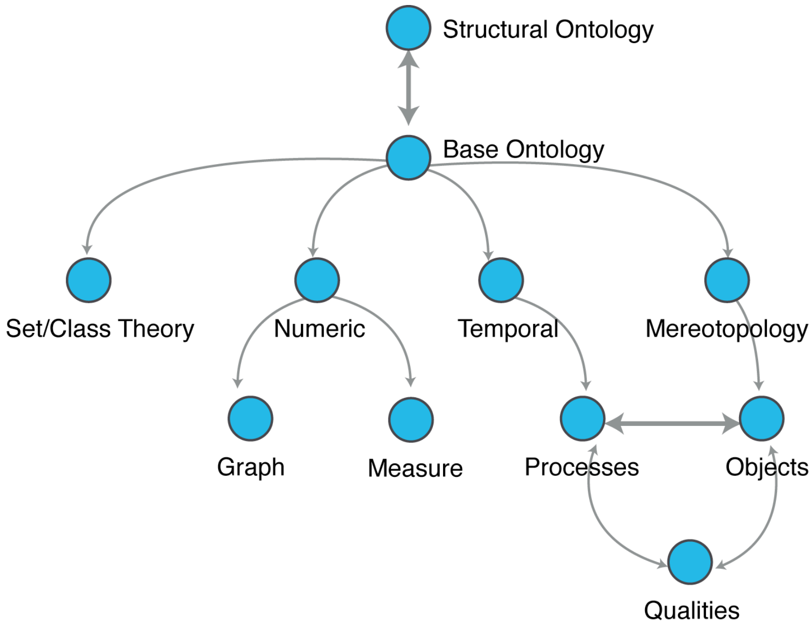

Figure 1. The SUMO ontology concept structure

The SUMO ontology can be contrasted with more specific domain or purpose oriented ontologies, such as the Friend of a Friend (FOAF) ontology, which is a simple structure for describing people, their contacts, publications, web identities, activities, and relationships. The FOAF ontology has much simpler and more tangible concepts and is specific to people and their social and professional networks. Figure 2 provides some examples of FOAF concepts.

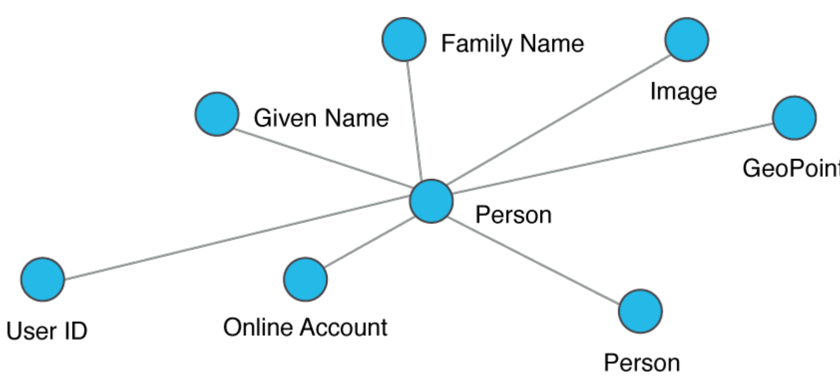

Figure 2. Example of a subset of the concepts in the FOAF ontology

Depending on the complexity of the environment, several interconnected ontologies should be employed to create an overall model. By using interconnected, separate ontologies, changes can be isolated and refinements can be more iterative. Kitamura and Mizoguchi (2003) describe an iterative approach to ontology development that allows for active refinement through use with subject matter experts, that incorporates a good feedback process. Likewise, large ontologies like Cyc or SUMO may be too complex for many environments. Lightweight upper level ontologies like PROTON offer a simple and powerful structure for modeling enterprise knowledge. PROTON is approachable with a core set of 300 classes and 100 properties (Terziev, Kiryakov, & Manov, 2005) that cover most of the general concepts.

Section Three: Advantages and Disadvantages of Ontologies for Tacit Knowledge Management

Most mainstream knowledge management systems focus on the realm of explicit knowledge and neglect capturing tacit knowledge (Small & Sage, 2005). The concept of knowledge management in itself is oriented to explicit rows and tables like those in a spreadsheet or relational database; however, tacit knowledge is more akin to a dynamic model than a static schema (Small & Sage, 2005). Ontologies unquestionably allow for the representation of richer models of the world and human generated knowledge than traditional data schemas (Terziev, Kiryakov, & Manov, 2005). Therefore, using an ontology, that expresses concepts and relationships, provides a viable representation for modeling higher-level meaning, context, and experience (Small & Sage, 2005). While

Jonas and Sokol (2008) do not point specifically to ontologies as the answer to relating data, they do refer to "semantically reconciled relationship aware directories" (p. 114), which is very much in line with using ontologies to map semantics and define or infer relationships across information sources.

Capturing tacit knowledge in a machine readable structure is essential to making this information really useful. Historically, a great deal of tacit knowledge has resided in unstructured text of various forms ranging from document files to comments fields in databases. Uren et al. (2006) conclude that "documents provide a rich resource describing what an organization knows and account for 80–85% of the information stored by many companies" (p.1). However documents are problematic when it comes to searching and applying meaning to their content. Numerous studies have been conducted showing the high cost to the enterprise of ineffective data search and retrieval systems (Stewart, 2008). These studies reveal that information is often not found or the process is intensely time consuming. Ontologies, when coupled with natural language processing, data analytics, and search tools, provide a mechanism for reconciling and mapping terms making it possible for software applications to accurately interpret this information. This capability is the first step to realizing the power of data related to other data that Jonas and Sokol (2009) and many others describe.

Disadvantages of ontology for tacit knowledge management. There are shortcomings of semantics and ontologies for knowledge management that surface in the literature. For example, Cai (2005) notes that there is vigorous debate over the ability of ontologies to represent tacit knowledge. Cai (2005) warns "the dictionary-like or modeltheoretic definitions of semantic concepts in an ontology fail to capture the tacit, experience-based, and context-adaptive nature of concept interpretation" (p.222). Uren et al. (2005) point out that capturing tacit knowledge in the form of human annotations is "prone to error and non-trivial annotations usually require domain expertise, diverting technical staff from other tasks" (p.3). The need for improved tools for ontology authoring (Stewart, 2008) and better manual data annotation tools (Uren et al., 2005) must be addressed to support ontology-based solutions. For tacit knowledge modeling to succeed in the enterprise there must be a user-centered solution for interacting with models—one which handles the complexities and adapts to the user workflow (Uren et al., 2005).

Ontology development can be a time consuming process with many opportunities to get bogged down and stalled (Umar & Zordan, 2009). Developing an exhaustive taxonomy or ontology can be a massive task; however, if the most important concepts are incorporated in the design phase, additional concepts can be added over time (El-Diraby & Zhang, 2006). The difficulties with ontology development are compounded by the lack of sufficient software tools to perform complex tasks such as ontology mapping and alignment (Nemrava et al., 2008).

Modeling knowledge in a way that is useful to humans and computers is not easy. Sowa (2005) points out that "in a few short years, children learn to associate linguistic patterns with background knowledge in ways that no computer can match" (p.16). Knowledge modeling efforts and ontologies often flounder in complexity. Hendler (2006) finds that a departure from the artificial intelligence mindset is necessary, stating that a little ontology goes a long way. Shirky (2005) takes this perspective a step further by asserting that centralized ontologies are not as effective as a collaborative tagging approach with less formal structure known as a folksonomy. Shirky (2005) also maintains that expert users and ontology managers are required for ontology-based classification systems to work, making them a tough proposition in most companies. However, Gruber (2007) contends that:

> The attack on "ontology" is really an attack on top down categorization as a way of finding and organizing information, and the praise for folksonomy is really the observation that we now have an entirely new source of data for finding and organizing information: user participation. For the task of finding information, taxonomies are too rigid and purely text-based search is too weak (p. 1).

The solution Gruber and others suggest is a hybrid approach that exploits the best aspects of a top down and bottom up classification approach (Gruber, 2007).

Advantages of ontology for tacit knowledge management. Distinguishing the processes of knowledge modeling from data and document management is critical to understanding the merits of ontologies for tacit knowledge management. Data management schemas are a reflection of what is in the repository and not a higher-level conceptualization that can be applied in different ways. One of the primary advantages of ontologies is that their structure is designed to convey context and meaning in a flexible and reusable manner (Gruber, 2009).

Likewise, an ontological approach facilitates the consideration of multiple points of view (Kitamura & Mizoguchi, 2004). This concept of a perspective or context is essential to interpreting tacit knowledge because it is these nuances that differentiate how information should be used and interpreted. Small and Sage (2005) discuss cultural influences that impact how knowledge management is approached—context is critical to understanding the subtleties of tacit knowledge and the culture in which it is applied. This context is expressed through ontological relationships between information and more dynamic concepts such as department and corporate level goals, relevance, desire, bias, mandates, and risks. Modeling these concepts allows organizations to conceptualize and relate information and data to their business imperatives (Small & Sage, 2005).

Gartner Research (2008) predicts that semantics and ontologies will be a major technology trend in the coming years. Already, many public Internet sites expose their data through a standard model for data interchange on the web, known as the resource description framework (RDF), which can be queried by users or automated agents. For example, the Wikipedia dataset can be accessed and consumed as RDF triples (i.e., a subject, a predicate, and an object). Other sites such as Linked Data (linkeddata.org) provide concrete examples of how to realize the semantic web vision and provide guidelines for exposing data and content in ways that it can be referenced in ontologies and related to other data. Figure 5 shows the Linked Data cloud that has been assembled across the Internet as of July, 2009 (Linked Data, n.d.).

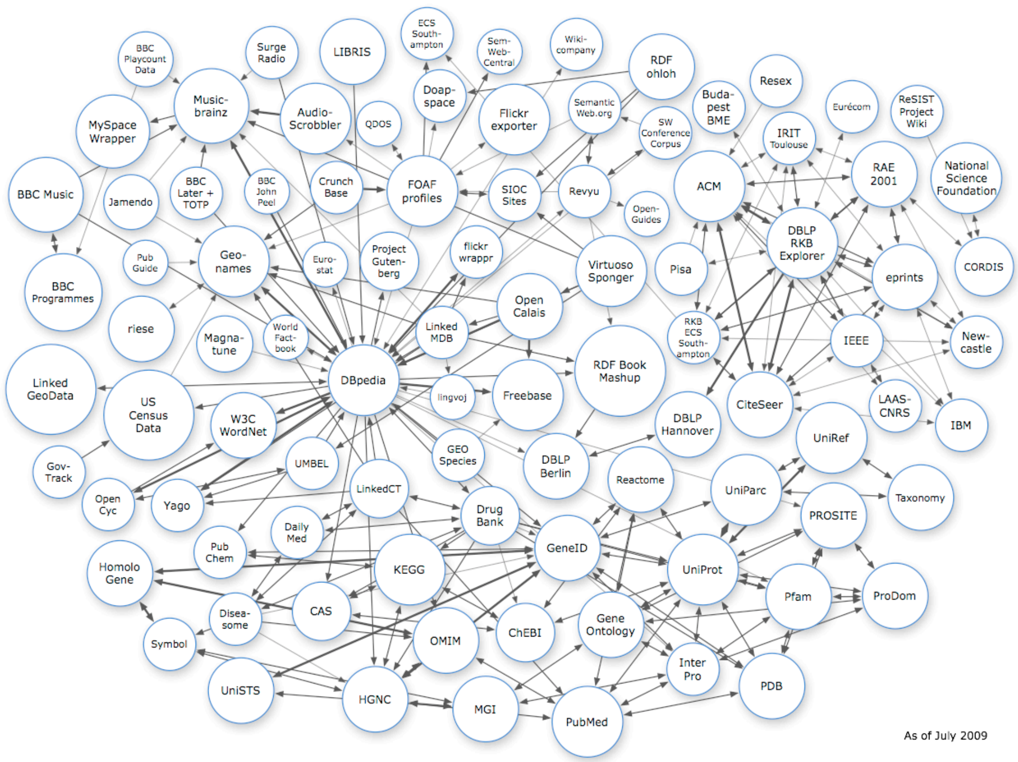

Figure 3. The datasets published in the Linking Open Data community project (Linked Data, n.d.)

While most of these sites are public or open data sets, this accomplishment shows the potential of the semantic web and ontologies to link together the thousands of databases and information sources that exist in an enterprise (Jonas & Sokol, 2009).

Conclusion

As the ability to share knowhow, context, user annotations, and intent with loosely structured information increases, tacit knowledge is unquestionably becoming a valuable facet of enterprise knowledge management. Recording and modeling tacit knowledge now represents a core business need, particularly as the digital data explosion and retirement wave intensifies. In response to these imperatives, the Semantic Web has continued to develop and evolve with the next generation of the OWL specification in review with the W3C (OWL 2, 2009). A large number of software companies have also emerged to serve the enterprise knowledge management and semantic web markets (Semantic Web Conference, 2009).

To answer the question of how ontologies are being applied in the enterprise to manage tacit knowledge, the broader information technology (IT) infrastructure must be considered. Ontologies comprise one part of a larger overall system and require other information management technologies to be put into operation to form a solution. On their own, these ontological models cannot do anything; they need integration with other technologies to be effective.

The literature reviewed in this study reflects the potential of ontologies and related semantic web technologies to handle aspects of the tacit knowledge management puzzle. Specifically, ontologies provide: (a) the ability to dynamically adapt to new information and concepts, (b) methods to relate disparate concepts and information elements, (c) reusable models that can be applied independent of the knowledge domain, and (d) machine readable structures for automated reasoning, inference, and retrieval of information (McGuinness, & Noy, 2001). These are all useful and powerful capabilities for managing tacit knowledge; case examples reported in this study reveal a number of applied real world projects. However, while in theory ontologies can be shared and published for broad reuse, there is not a great deal of evidence to suggest that this is happening in the commercial sector on a large scale. As soon as one diverges from the broad general concepts and descends into the realm of more specific models, it seems they are more closely tied to the application of proprietary information and seen as a potential competitive advantage. Moreover, because of the subjective nature of ontology development (McGuinness & Noy, 2001), in many cases the effort required to understand the ontology developer's approach and logic for their model is greater than simply developing the model from scratch. This dynamic suggests the need for better annotation and contextualization in the ontology structures—a need that is reflected in the next generation of the W3C OWL specification (OWL 2, 2009).

Literature reveals that many of the real world applications are built on top of published general concept or upper level ontologies. For example Magro and Goy (2008) discuss extending the Descriptive Ontology For Linguistic and Cognitive Engineering (DOLCE) to develop an ontology-driven Customer Relationship Management (CRM) application. Custom ontologies are often developed from the bottom up, derived from the data being used or mined from a corpus of text. These ontologies are generally rich in terms, however, they often lack properties and axioms to use them for inference or reasoning. Likewise, existing enterprise taxonomies or even database schemas are often the starting point for an ontology (Stewart, 2008), but unless additional properties, axioms, and relationships are added they are of limited use for automated information discovery and correlation tasks.

Modeling tacit knowledge is not easy; nevertheless it does not have to be an exhaustive undertaking. Hendler (2006) suggests starting small and simple may be a key to modeling success. McGuinness and Noy (2001) point out that the ontology creation process must focus on what is relevant to the questions being addressed in the knowledge management solution.

Developing an ontology and deploying a system is an iterative process (Umar & Zordan, 2009) that involves engaging subject matter experts and developing feedback mechanisms (Kitamura & Mizoguchi, 2004). The value of a pragmatic and iterative approach to knowledge management, as described by El-Diraby and Kashif (2005), is that complex processes and concepts can be linked together to give managers a more meaningful representation for decision-making. The key element to this approach is incorporating a feedback loop to understand how to improve the model fidelity—tacit knowledge is the core ingredient of this feedback loop.

When the ontology or collection of ontologies has been developed, the models are used for search and discovery (Stewart, 2008) and find non-obvious relationships that can inform people and applications decision-making processes (Jonas & Sokol, 2009). The development of knowledge bases is likewise an interactive process and the end product must provide users and software agents with the most current picture of what is known in the organization.

One of the greatest challenges with tacit knowledge management is how to incorporate the human factor. Very few of the solutions described in the literature touch on how the information is captured and the user interfaces for accomplishing this task.

Uren et al. (2006) state that user annotations are problematic because they are prone to error. This user interaction dimension of tacit knowledge collection, while not unique to ontologies, must be addressed for tacit knowledge management to flourish. The proliferation of tagging and easy to use public Internet sites for information management of pictures, documents, and messages (Shirky, 2005) suggests that these approaches may also be viable in the enterprise. Indeed, Gruber (2007) maintains that a hybrid approach of a structured ontology and more free-form tagging is viable and exploits the strengths of both techniques. The semantic web technologies, as described by Berners-Lee et al. (2001), have evolved a great deal and there are many commercial and open source examples of frameworks that employ this technology. Tacit knowledge ontologies have enormous potential, but in light of the ideas presented in this study, will always require a solution architecture and integration approach and an intuitive user interface to provide value to the enterprise.

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Appendix A

Data Analysis – Report of Coding Results

The process of term clustering analysis, as described in the Data Analysis Plan, is performed using the Thetus Publisher and Savanna analysis tools. Documents are ingested in the application, key terms are extracted, and full text searching is performed on the text. Figure 4 shows the extracted terms in the application.

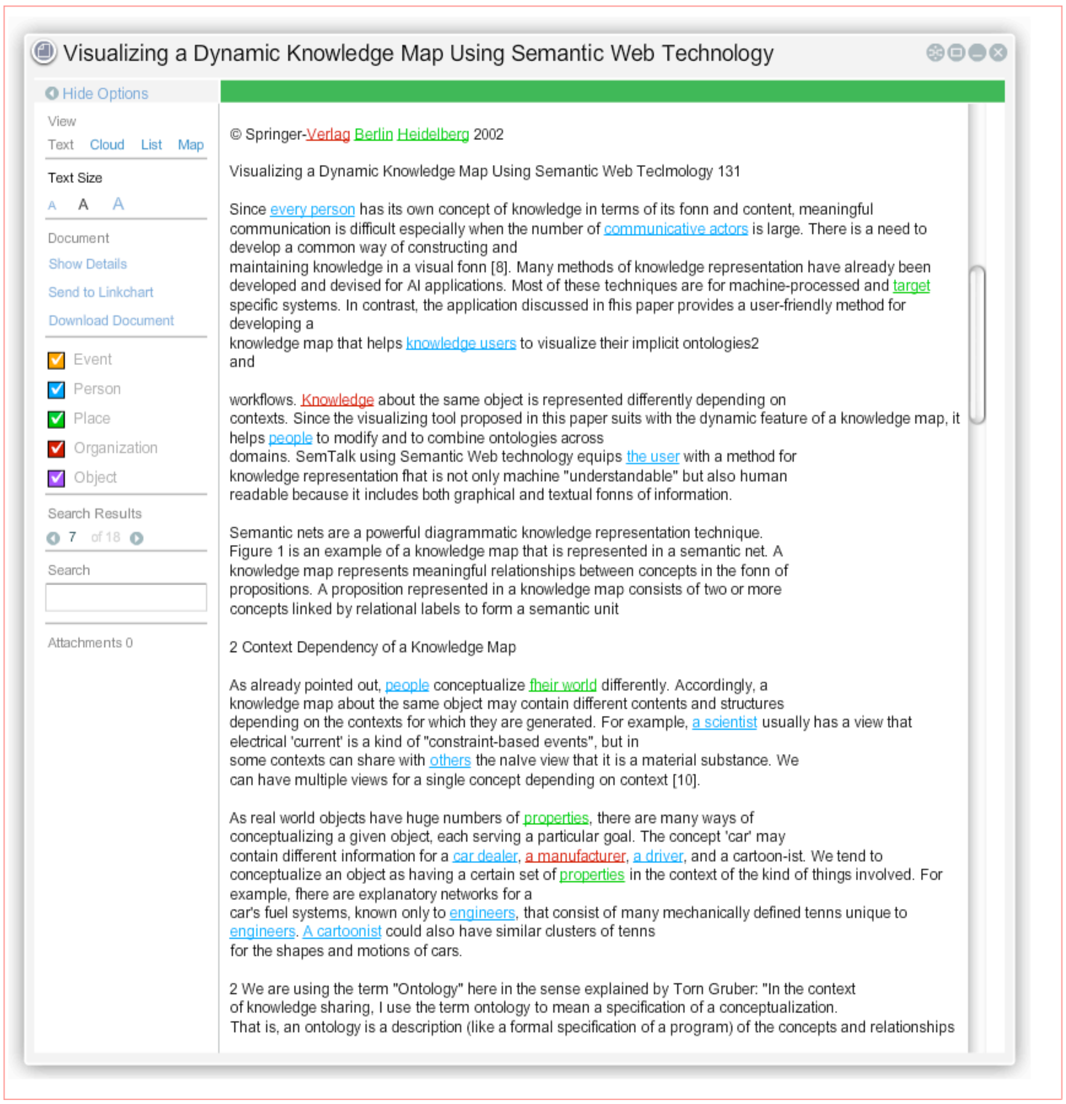

Figure 4. Indexed documents with extracted terms

Each of the specified analysis terms is represented in a simple ontology, and documents containing the terms are associated with concept clusters. Figure 5 presents the concept clusters and the associated sources for each of the data coding terms.

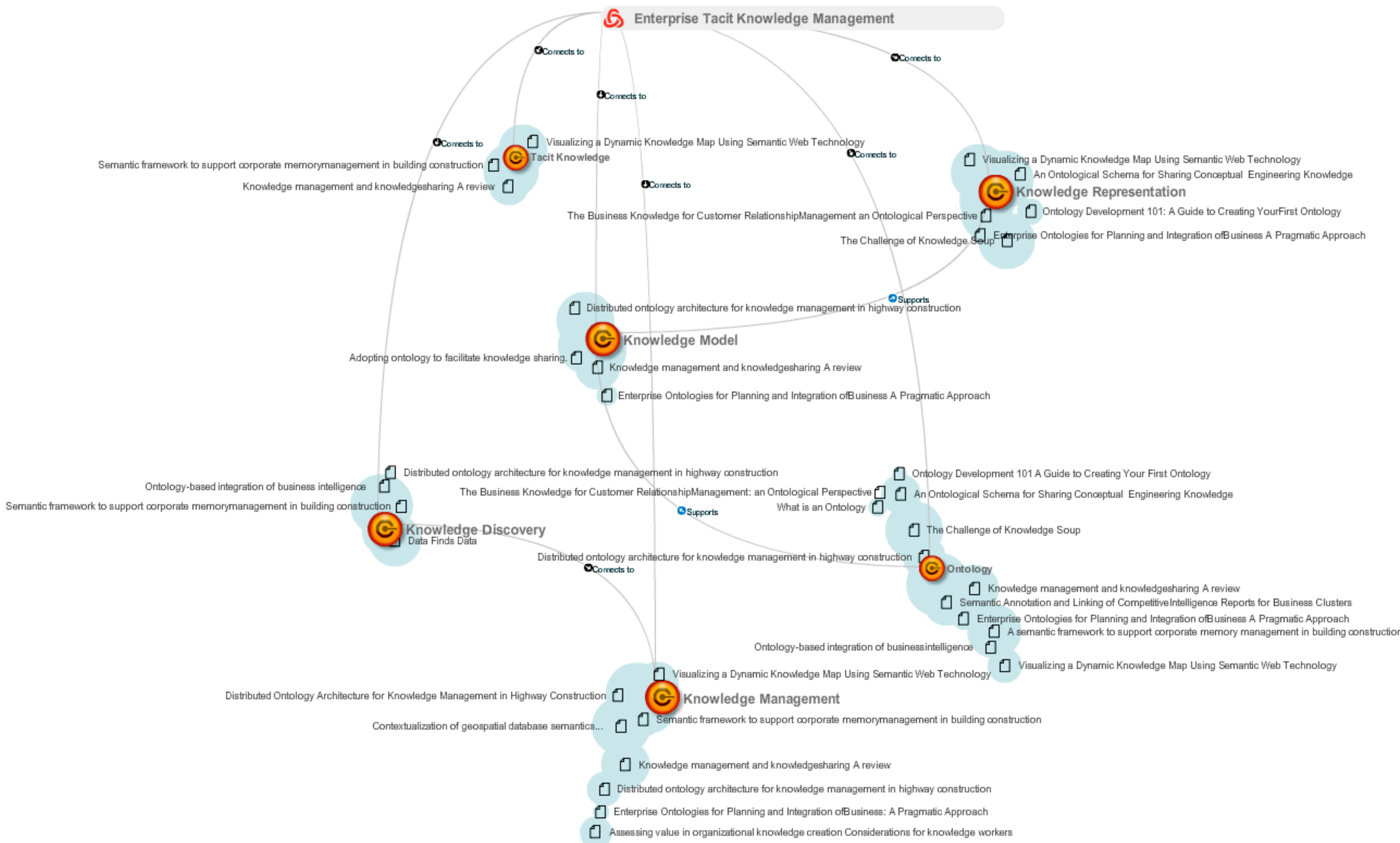

Figure 5. Concept clusters for coding terms in the literature sources

The relationships between the clusters are defined in an ontology. Likewise, the concept clusters are formed through semantic relationships between the articles and the concepts they reference. The model is used to perform inference-based queries to understand how the concepts and the associated documents are used to form knowledge about this domain. Tacit knowledge and observations are modeled in a similar fashion thereby relating the concept cluster to the documents, and to the research questions. Figure 6 shows the research questions with connections to conclusions and concept clusters.

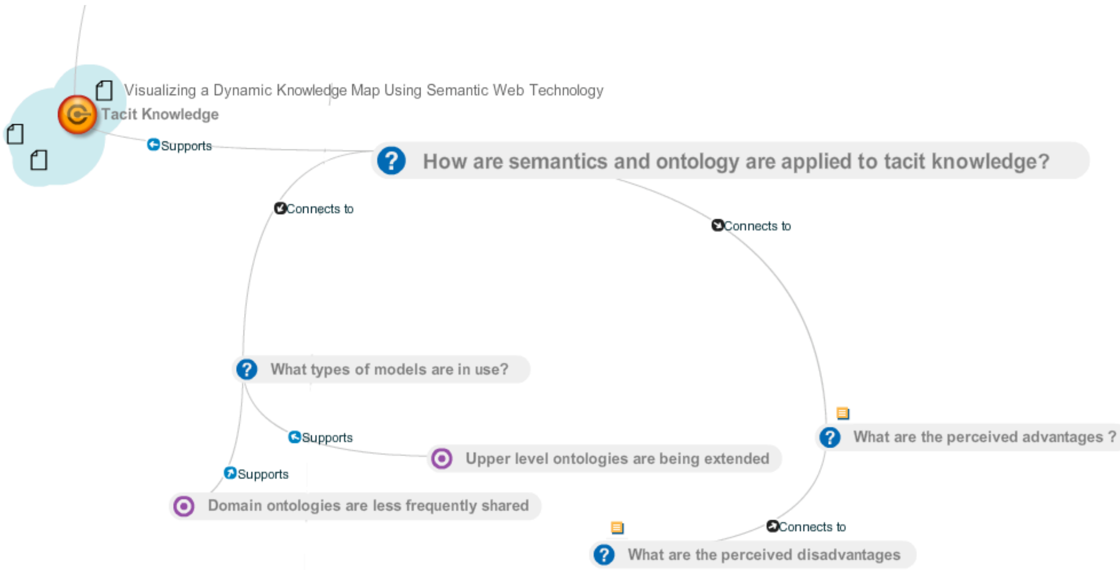

Figure 6. Research questions with connections to conclusions and concept clusters

Observations are also incorporated into the model and related to questions or other concepts. The yellow note icons in Figure 8 represent annotations about the research questions. This model provides a unified view of the literature used in the research, the concepts and coding terms, research questions, and conclusions. Tacit knowledge is captured in the relationships, the visual layout of ideas and concepts, as well as the annotations. This model is provides a context-rich view of the research path and thought process of the researcher and includes direct connections to the source literature to support all assertions.